Romanian Reports in Physics **69**, 401 (2017)

ANTICIPATED SYNCHRONIZATION OF SEMICONDUCTOR LASERS WITH PASSIVE DISPERSIVE REFLECTORS

NELLU CIOBANU[1,a], SPIRIDON RUSU[2], VASILE TRONCIU[2]

[1]Department of Human Physiology and Biophysics, State University of Medicine and Pharmacy Nicolae Testemitanu, Chisinau, Moldova,
Email: [a]*cnellu@gmail.com*
[2]Department of Physics, Technical University of Moldova, Chisinau, Moldova

Received October 9, 2016

Abstract. We explore a new model for anticipated synchronization of distributed feedback lasers with passive dispersive reflectors. The influence of device parameters on the anticipated synchronization is discussed. The conditions for delayed, perfect, and anticipated synchronizations are analyzed.

1. INTRODUCTION

During the last decade the phenomenon of synchronization between various types of oscillators has been the subject of significant studies due to its fundamental and applied interests [1]. Much attention has been paid recently to so called anticipating synchronization.

The first model that describes anticipating synchronization of two chaotic dissipative systems with time-delayed feedback was proposed by Voss [2]. The phenomenon of anticipated synchronization is especially important for nonlinear systems, e.g., information security and transmission [3]-[5], communication, and complex systems in biological sciences [6]-[8]. The idea of anticipated synchronization is that for two or many identical systems connected in master-slave configuration under the appropriate conditions the anticipated synchronization can be observed if the slave system anticipates the master one. This concept was also explored for chaotic semiconductor lasers with optical feedback [9], where the anticipated synchronization was observed for the synchronized slave laser and delayed coupling time regime. Thus, this phenomenon is of significant interest from both theoretical [10] and experimental point of views [11]. Various new models were proposed to enhance the anticipation time of different schemes [12], [13]. Interesting implementation of this idea was done for the chaotic semiconductor lasers [14], [15], quantum dot lasers [16], and electronics circuits [17].

Interesting anticipating synchronization was observed by the renormalization of the time scale in the driven system [18], or if the slave system is subject to the inhibitory feedback [19]. The existence of anticipated synchronization and the conditions for its stability were also studied for two coupled two-dimensional complex Ginzburg-Landau systems [20]. The synchronization with a large anticipation time was observed for master systems coupled with two slave systems without time delay terms [21].

It is well known that optical feedback can considerably influence the dynamical behaviour of a semiconductor laser. Already simple reflections from an external mirror can cause different phenomena as coherence collapse, low frequency fluctuations, and self-pulsations chaotic behavior. These phenomena have been investigated intensively since many years [22]-[26]. In this context, multisection lasers with a distributed feedback (DFB) active region section and passive dispersive reflector (PDR) could be suitable candidates for realization of anticipated synchronization. Due to the continuing technological progress, multi-section lasers have reached stable and compact configurations, which include integrated sections with common waveguides tunable phase shifts [27]. In this paper, we present a new setup and model for anticipated synchronization of DFB lasers with PDR. The paper is organized as follows. A short description of the setup and of the rate equation model is presented in Sec. 2. The influence of parameters on anticipated synchronization is discussed in Sec. 3. For appropriate parameters we obtain anticipated, perfect, and delayed synchronization. We investigate the transition from delayed to anticipated synchronization regimes. Finally the conclusions are given in Sec. 4.

2. MODEL AND EQUATIONS

We start in this Section with the description of our physical model. The master and slave DFB lasers with passive dispersive reflector are connected in an unidirectional configuration, as shown in Fig. 1. It is considered that slave laser is connected to an external optical circuit, where a finite time interval (τ_0) is required for the light to provide the optoelectronic coupling.

The output photon numbers of master and slave lasers are expressed by P_1 and P_2, respectively, while n_1 and n_2 correspond to the carrier numbers in the active regions of master and slave lasers, respectively.

The rate equations that describe the dynamics of setup shown in Fig. 1 are given by

$$\frac{dP_1}{dt} = TG(n_1)P_1(t), \tag{1}$$

$$\frac{dn_1}{dt} = J - n_1(t) - [1 + n_1(t)]\Gamma(n_1)P_1(t), \tag{2}$$

$$\frac{dP_2}{dt} = TG(n_2)P_2(t) + K[P_1(t) - \beta P_2(t - \tau_0)], \tag{3}$$

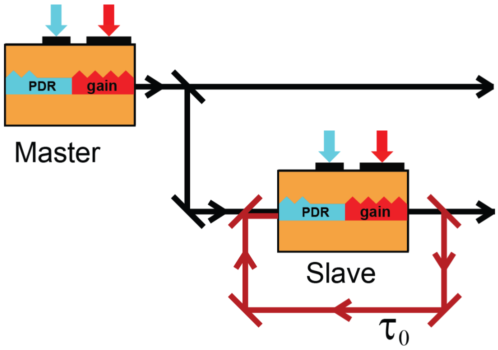

Fig. 1 – (Color online) Setup of master and slave DFB lasers with PDR for realization of anticipated synchronization.

$$\frac{dn_2}{dt} = J - n_2(t) - [1 + n_2(t)]\Gamma(n_2)P_2(t), \tag{4}$$

where the parameter T is the ratio between the carrier and photon lifetimes. Here J is the relative excess injection rate and for lasers operating sufficiently above threshold regime, its value corresponds to $1 < J < 10$. The parameter K is the coupling constant. The delay time between master and slave lasers is considered to be known and is a fixed parameter.

The rate equation functions $\Gamma(n_i)$ and $G(n_i)$ of (1)-(4) characterize the influence of PDR of laser behavior and have the following form [28]

$$\Gamma(n_i) = \Gamma_0 + \frac{A_i W_i^2}{2(n_i - n_{0i})^2 + W_i^2}, \tag{5}$$

$$G(n_i) = n_i + \alpha_i \Delta n_i \tanh(\frac{n_i}{\Delta n_i}). \tag{6}$$

The function (5) was approximated by a Lorentzian, where its resonance position is given by n_0. The width W_i and height A_i of Lorentzian depend mainly on the reflector type and its characteristics. The rate equation function $G(n_i)$ in (6) represents the slope enhancement region within a finite density interval, that is characterized by the parameter Δn_i (for more details see [28]). The following parameter values are used for the calculated results that are shown in all figures of the paper: $J_1 = J_2 = J = 2$, $\Gamma_{01} = \Gamma_{02} = 1$, $A = 0.1$, $W_1 = W_2 = 0.02$ and $n_{01} = n_{02} = -0.01$.

3. ANTICIPATED SYNCHRONIZATION AND DISCUSSION OF THE RESULTS

In what follows, we are interested in the dynamics of the setup shown in Fig. 1 of master and slave lasers connected unidirectionally, and explore the possibility to

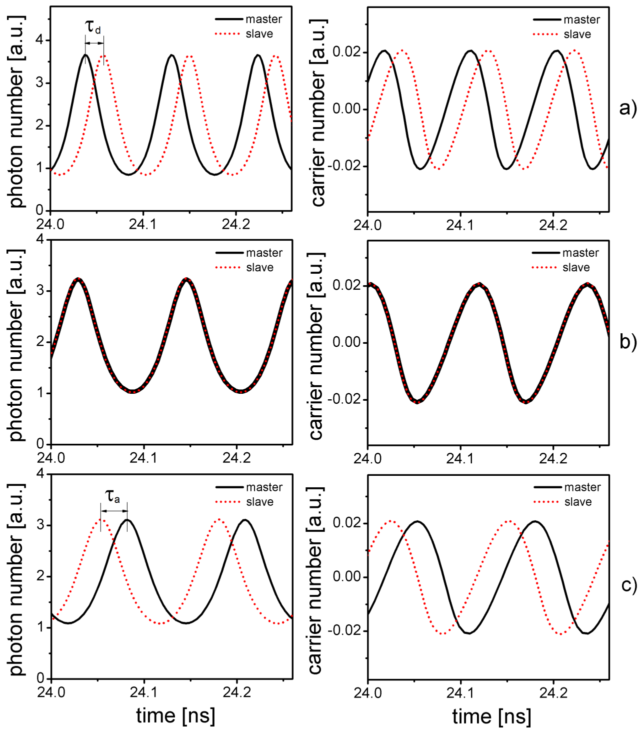

Fig. 2 – (Color online) Time dependence of the output photon number (left) and carrier number (right) of master (black) and slave (red) lasers for a) $T = 400$, b) $T = 270$, and c) $T = 180$. The other values of parameters are $\tau_0 = 0.5$, $K = 0.05$, $\alpha = 5$, and $\Delta n = 0.1$.

obtain anticipated synchronization regimes varying the PDR parameters. We notice that the synchronization phenomenon is studied numerically.

First, we consider the influence of the ratio between the carrier and photon life times T, on the phenomenon of synchronization. The temporal evolution of photon number P and carrier number n of master and slave lasers for different values of parameter T is shown in Fig. 2. We consider that master and slave lasers are identically, i.e., $\Gamma(n_1) = \Gamma(n_2)$ and $G(n_1) = G(n_2)$. The synchronization time $\tau = t_M - t_S$ is defined as the interval between nearest the maximal values of photon numbers of master and slave lasers (see Fig. 2a - left). When the pulse trace of master laser is located in the front of slave laser we observe delayed synchronization. In this case the delayed synchronization time is denoted by τ_d. In the opposite situation, i.e., the slave laser is ahead to master, the anticipated synchronization takes place and the anticipating synchronization time is given by τ_a (see Fig. 2c - left).

Figure 2a shows the evolution of photon numbers (left) and carrier number (right) for the realization of delayed synchronization for $T = 400$. We mention that,

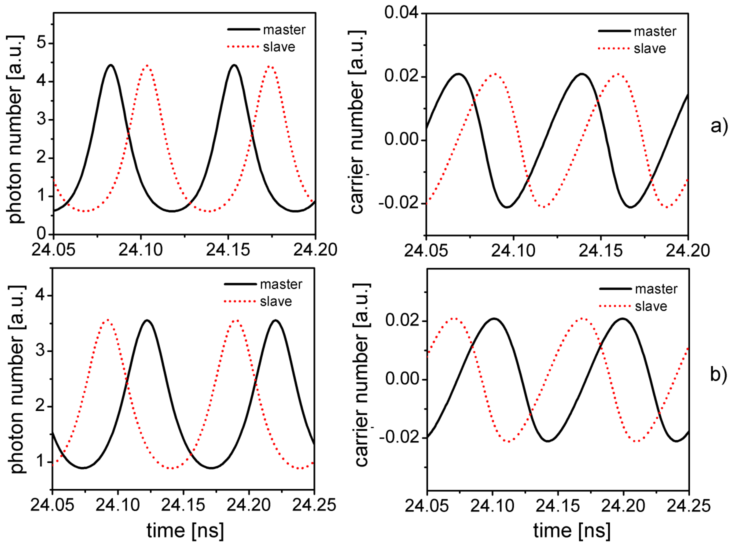

Fig. 3 – (Color online) The output photon numbers (P_1, P_2) and carrier numbers (n_1, n_2) of lasers as function of time for a) $\alpha = 7.5$ and b) $\alpha = 3.25$. Other parameters are $\tau_0 = 0.5$, $T = 500$, $K = 0.05$, and $\Delta n = 0.25$.

the delayed synchronization time in this case is $\tau_d = 19$ ps. When we reduce the ratio between the carrier and photon lifetimes to $T = 270$ the so called *perfect synchronization* occurs (see Fig. 2b) where the pulse traces of master and slave lasers overlap. Thus, in this case we reach the same evolution of master and slave lasers. A similar situation is observed also for the carrier numbers (see Fig. 2 - right). When we reduce more the parameter $T = 180$, the phenomenon of *anticipated synchronization* is observed (see Fig. 2c). We observe anticipation in the pulse trace of slave laser compared to that of master. The anticipation time is $\tau_a = 28$ ps. As a result, we conclude that the parameter T plays an important role for obtaining anticipation synchronization regimes.

Now we discuss in more detail the influence of other parameters on the phenomenon of synchronization. The temporal evolution of output photon number and carrier number of master and slave lasers for different values of parameter α is shown in Fig. 3. One can observe the increase of delayed and anticipated synchronization times. Thus, these figures suggest that there is a switch between anticipated and delayed regimes by changing parameters. We mention that this switch takes place *via* the regime of perfect synchronization.

In order to estimate the synchronization time, the numerical simulations were carried out in the plane of the width of the slope enhancement region Δn *versus* maximum slope α. The results plotted in Fig. 4, where the blue region separate

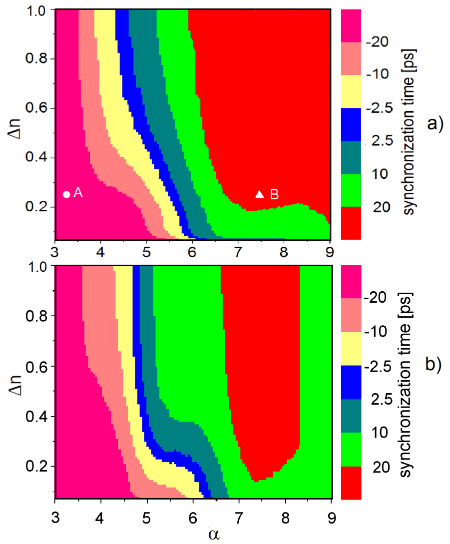

Fig. 4 – (Color online) Synchronization time in $(\alpha, \Delta n)$ plane for a) $\tau_0 = 0.5$ and b) $\tau_0 = 0.7$. Other parameters are $K = 0.05$ and $T = 500$.

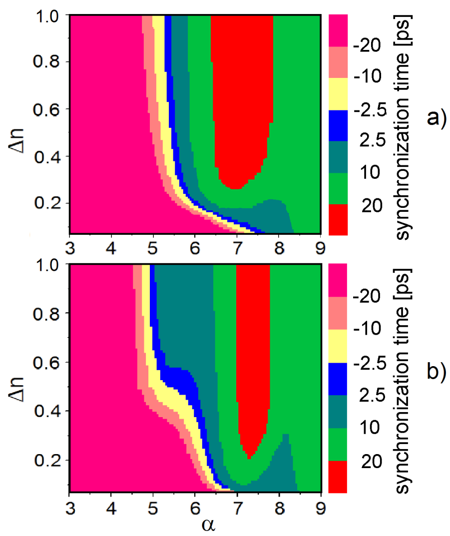

Fig. 5 – (Color online) Synchronization time in $(\alpha, \Delta n)$ plane for $K = 0.1$ and a) $\tau_0 = 0.5$ and b) $\tau_0 = 0.7$. Other parameters are as in Fig. 4.

the anticipated and delayed regimes for different values of delay time τ_0 of the external optical circuit of slave laser and for the coupling coefficient $K = 0.05$. We mention that perfect synchronization is considered for the delay time in the output pulses in the range from -2.5 to 2.5 ps (see Fig. 4a). Anticipated regime corresponds to synchronization time $\tau < -2.5$ ps, while delayed synchronization takes place for $\tau > 2.5$ ps. The circle A is the operation point for pulse traces given in Fig. 3a, while the triangle B for operation point in Fig. 3b. It can be seen how the synchronization time changes in the plane of these two parameters and the transition from anticipated to delayed synchronization takes place. For small values of α the anticipated time becomes higher. One can observe a wide anticipated region for small values of the parameter Δn. For larger values of α the regimes of large delayed synchronization time persist. Figure 4b shows that an increase of the delay time of external optical circuit of slave laser τ_0 leads to a significant modifications of synchronization effect. Thus, the delayed synchronization takes place with larger delayed synchronization time $(\tau_d > 20)$. One can observe the wide region (green color in Fig. 4b) of delayed synchronization with $10 < \tau_d < 20$.

Figure 5 shows the influence of the coupling coefficient K on the synchronization effect. When we increase of coupling coefficient to $K = 0.1$, one can see the reduction of the delayed synchronization for higher values of the parameter α. On the other hand, the wide region of anticipated synchronization with higher $\tau_a > 20$ ps was observed for lower values of α. Thus an increase of coupling coefficient leads to a more pronounced anticipated synchronization.

4. CONCLUSIONS

In this paper we presented a novel setup and model of anticipated synchronization of single mode DFB lasers with passive dispersive reflector. The anticipation regime was explored for different values of governing parameters. We showed the presence of delayed, perfect, and anticipated synchronization in the master-slave unidirectional configuration. It was found that the coupling coefficient K as well as the delay time τ_0 play major roles in the laser dynamics. The region of anticipated synchronization increases for high coupling coefficient. The lower values of maximum slope α gives the highest anticipated synchronization time. It was found that the increase of parameter T (the ratio between the carrier and photon lifetimes) induces the small region of anticipated synchronization.

We believe that our work provides a good basis for future studies, and, in particular, it provides some insights for more detailed investigations on anticipated synchronization of DFB lasers with passive dispersive reflector.

Acknowledgements. This work was supported by the project STCU - 5993 and 14.02.116F. VZT acknowledges the support from the Alexander von Humboldt Foundation and CIM Returning Experts Programme. NC acknowledge the financial support of the project NATO EAP SFPP 984890.

REFERENCES

1. A. Pikovsky, M. Rosenblum, and K. Kurths, *Synchronization: A Universal Concept in Nonlinear Sciences*, Cambridge University Press, Cambridge, 2003.
2. H. Voss, *Anticipating chaotic synchronization*, Phys. Rev. E **61**, 5115 (2000).
3. I. Fischer, Y. Liu, and P. Davis, *Synchronization of chaotic semiconductor laser dynamics on subnanosecond time scales and its potential for chaos communication*, Phys. Rev. A **62**, 011801(R) (2000).
4. F. Rogister, D. Pieroux, M. Sciamanna, P. Megret, and M. Blondel, *Anticipating synchronization of two chaotic laser diodes by incoherent optical coupling and its application to secure communications*, Optics Comm. **207**, 295 (2002).
5. S. Sivaprakasam and K. A. Shore, *Demonstration of optical synchronization of chaotic external-cavity laser diodes*, Opt. Lett. **24**, 466 (1999).
6. R. Toral, C. Masoller, C. R. Mirasso, M. Ciszak, and O. Calvo, *Characterization of the anticipated synchronization regime in the coupled FitzHugh-Nagumo model for neurons*, Physica A **325**, 192 (2003).
7. M. Ciszak, F. Marino, R. Toral, and S. Balle, *Dynamical mechanism of anticipating synchronization in excitable systems*, Phys. Rev. Lett. **93**, 114102 (2004).
8. F. S. Matias, P.V. Carelli, C. R. Mirasso, and M. Copelli, *Anticipated synchronization in biologically plausible model of neuronal motifs*, Phys. Rev. E **84**, 021922 (2011).
9. C. Masoller, *Anticipation in the synchronization of chaotic semiconductor lasers with optical feedback*, Phys. Rev. Lett. **86**, 2787 (2001).
10. K. Pyragas and T. Pyragiene, *Coupling design for a long-term anticipating synchronization of chaos*, Phys. Rev. E **78**, 046217 (2008).
11. S. Sivaprakasam, E. M. Shahverdiev, P. S. Spencer, and K. A. Shore, *Experimental Demonstration of Anticipating Synchronization in Chaotic Semiconductor Lasers with Optical Feedback*, Phys. Rev. Lett. **87**, 154101 (2001);
Y. Liu *et al.*, *Experimental observation of complete chaos synchronization in semiconductor lasers*, Appl. Phys. Lett. **80**, 4306 (2002).
12. A. Uchida, Y. Liu, I. Fischer, P. Davis, and T. Aida, *Chaotic antiphase dynamics and synchronization in multimode semiconductor lasers*. Phys. Rev. A **64**, 023801 (2001).
13. E. M. Shahverdiev, S. Sivaprakasam, and K. A. Shore, *Parameter mismatches and perfect anticipating synchronization in bidirectionally coupled external cavity laser diodes*, Phys. Rev. E **66**, 017206 (2002).
14. T. Dahms *et al.*, *Noninvasive optical control of complex semiconductor laser dynamics*, European Phys. J. **191**, 71 (2010).
15. S. Tang and J. M. Liu, *Experimental verification of anticipated and retarded synchronization in chaotic semiconductor lasers*, Phys. Rev. Lett. **90**, 194101 (2003).
16. B. A. Ghalib, G. A. Hafedh, and A. H. Al Khursan, *Synchronization of Quantum Dot Lasers with an Optoelectronic Feedback Circuit*, J. of Electronic Materials **44**, 953 (2014).

17. H. Weia and L. Li, *Estimating parameters by anticipating chaotic synchronization*, Chaos **20**, 023112 (2010).
18. Y. Hayashi, S. J. Nasuto, and H. Eberle, *Renormalized time scale for anticipating and lagging synchronization*, Phys. Rev. E **93**, 052229 (2016).
19. F. S. Matias, L. L. Gollo, P. V. Carelli, C. R. Mirasso, and M. Copelli, *Inhibitory loop robustly induces anticipated synchronization in neuronal microcircuits*, Phys. Rev. **E 94**, 042411 (2016).
20. M. Ciszak, C. Mayol, C. R. Mirasso, and R. Toral, *Anticipated synchronization in coupled complex Ginzburg-Landau systems*, Phys. Rev. E **92**, 032911 (2015).
21. T. Pyragiene and K. Pyragas, *Anticipating synchronization in a chain of chaotic oscillators with switching parameters*, Phys. Lett. A **379**, 3084 (2015).
22. J. Sacher, D. Baums, P. Panknin, W. Elsasser, and E. O. Gobel, *Intensity instabilities of semiconductor lasers under current modulation, external light injection, and delayed feedback*, Phys. Rev. A **45**, 1893 (1992).
23. K. Petermann, *External optical feedback phenomena in semiconductor lasers*, IEEE J. Selected Topics in Quantum Electron. **1**, 480 (1995).
24. M. Yousefi and D. Lenstra, *Dynamical behavior of a semiconductor laser with filtered external optical feedback*, IEEE J. Quantum Electron. **35**, 970 (1999).
25. B. Krauskopf and D. Lenstra, *Fundamental issues of nonlinear laser dynamics*, AIP Conf. Proc. p. 548 (2000).
26. E. Schoell and H. G. Schuster (eds.), *Handbook of Chaos Control*, Wiley-VCH, Weinheim 2008.
27. S. Bauer, O. Brox, J. Kreissl, B. Sartorius, M. Radziunas, J. Sieber, H.-J. Wuensche, and F. Henneberger, *Nonlinear dynamics of semiconductor lasers with active optical feedback*, Phys. Rev. E **69**, 016206 (2004).
28. V. Z. Tronciu, H.-J. Wuensche, J. Sieber, K. Schneider, and F. Henneberger, *Dynamics of single mode semiconductor lasers with passive dispersive reflectors*, Optics Commun. **182**, 221 (2000).