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COMPLEX DYNAMICS OF SEMICONDUCTOR LASERS WITH QUANTUM WELS AND DOTS ACTIVE MEDIUM

131.03 – STATISTICAL AND KINETIC PHYSICS

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CONCEPTUAL GUIDELINES OF RESEARCH

The topicality of the topic and the importance of the problem investigated

In recent years, semiconductor lasers have become important devices that are widely used in everyday life as well as key elements in research on the interaction between matter and light. Over the years, various stages have followed that led to the creation of stable functional laser structures. Due to the long operating time and stability of laser emission, it was possible to develop the optics branch of modern physics. New laser structures, which have recently appeared, have been developed based on better operation, which generate controllable and stable emission regimes. Lasers have become cheaper and materials are used in their construction in small quantities. Thus, current scientific research has established a priority in this field, to perform theoretical analysis of optical phenomena observed in various laser structures. The emergence of new nonlinear optical effects in lasers has increased interest in theoretical research in nonlinear optics. Some of the most observed effects in semiconductor lasers with optical feedback are self-pulsations, optical bistability, optical chaos, optical resonance, etc. Nonlinear optics is a highly developed field with applications in various branches as a result of the use of semiconductor lasers. Research in nonlinear optics has led to the creation of new laser structures with different topologies. A field such as synergetics is based on principles that are widely applied in semiconductor lasers, in solid state science and in other fields. The principles of operation of optoelectronic devices are based on the phenomenon of self-organization. They are widely used in telecommunications, computer networks, in lighting systems, in medicine, etc. The presented thesis is based on the nonlinear theory applied in semiconductor lasers with quantum dot active medium under the influence of optical feedback coming from several optical cavities.

It is well known that quantum dots have a wide importance in the field of nanotechnologies, being basic elements in their development [1], [2]. The optical properties of quantum dots are determined by their size and structure. From the point of view of application, quantum dots can be considered artificial atoms [3], [4]. The use of quantum dots in semiconductors as artificial atoms forms nano-sized molecules that are structurally and electronically linked. When two or more quantum dots are coupled, an artificial molecule is obtained, which hybridizes at a low temperature [5]. Quantum dots are widely applied in lasers [6], single-electron transistors, single-photon sources, solar cells, LEDs, medical imaging, medical biology research [7]-[10].

Research purpose and objectives

The purpose of the thesis is to develop the theory of nonlinear dynamics of semiconductor lasers with active media of holes and quantum dots; propose new devices with air sections for their use in optical communication systems based on chaos; develop new programs for performing numerical calculations in order to find parameters that correspond to the operation of lasers in chaotic regime, and theoretically explain the phenomena observed in experiments.

The proposed purpose results in the following objectives:

1. Development of a model describing the complex dynamics of semiconductor lasers with quantum dot active medium with optical feedback from an external air cavity resonator.
2. Study of chaos-based communication using quantum well lasers and multiple feedback.
3. Analysis of bifurcations and stationary states that appear in the system of delayed differential equations describing the laser system with feedback from external cavities and obtaining analytical solutions, as appropriate.
4. Determining the parameters and the mode of emergence of various temporal structures such as self-pulsations, optical turbulence and chaos. The latter represents the necessary condition for optical communication systems based on chaos.
5. Determination of the conditions for perfect synchronization of two semiconductor lasers with multiple feedback quantum dots active media and unidirectional coupled air cavities.
6. Analysis of the use of different information encoding techniques in chaos-based communication systems.
7. Simulation of nonlinear dynamic effects of semiconductor lasers with quantum dot active medium using numerical modelling methods.
8. Research on the steady-state behaviour of a quantum dot laser with double feedback: one conventional and one with a filter.
9. Numerical modelling by simulating the nonlinear dynamic effects of self-pulsations, optical turbulence and chaos.

Scientific research methodology

The theoretical support of the thesis was achieved following the analysis of literature in the field of semiconductor laser theory by accessing sources accessible at the Technical University of Moldova, as well as works with open online access.

To successfully achieve the above objectives, the following were applied:

1. Mean field approximations were used.

2. Numerical calculations were performed using methods such as fourth-order Runge-Kutta and Euler developed in FORTRAN and C++.
3. Delayed differential equations of the Lang-Kobayashi and Bloch types were integrated.
4. MATLAB software was used to develop algorithms and calculate the numerical values of the parameters that describe the material of the laser's active medium.
5. The DDE-biftool software was used to determine the stationary, periodic, and bifurcation solutions of the delayed differential equations describing quantum dot lasers with multiple feedback.

Scientific novelty and originality:

1. The nonlinear dynamics for a new semiconductor laser structure with quantum dot active medium under the influence of optical feedback from multiple external cavities was theoretically analysed.
2. The occurrence of various phenomena such as self-pulsations, turbulence, and strong optical chaos in the considered lasers has been demonstrated.
3. It has been theoretically demonstrated that two multiple-feedback quantum dot semiconductor lasers can be unidirectional coupled and perfectly synchronized.
4. For the first time, the encoding and decoding of information by two methods in chaos-based optical communication using chaotic quantum dot lasers with multiple feedback was theoretically analysed.
5. Theoretically, the properties of the quantum dot laser were studied under the influence of double feedback: one conventional and one with a filter.
6. Numerical simulations were performed for the quantum well semiconductor laser under the influence of multiple feedback to realize the process of encrypted optical communication based on chaos.

Scientific problem solved the thesis consists of the theoretical study of new semiconductor laser structures with quantum dots as active medium under the influence of optical feedback from multiple external cavities for applications in chaos-based communication systems. Optical phenomena characterizing the chaotic behaviour of the proposed new laser structures were investigated. Through numerical simulation, the range of parameters characterizing the nonlinear dynamics of the respective lasers was obtained, in particular for the chaotic regions. Also, the parameters obtained in numerical simulations were systematized and transmitted for the experimental realization of quantum dot structures with optical feedback.

The theoretical significance and applicative value of the thesis consists of the following:

- Presentation of a novel theoretical model of a semiconductor laser with quantum dot active medium under the influence of multi-cavity feedback. Obtaining analytical expressions of the stationary states.
- Identification, using the DDE-biftool program, of the bifurcations that appear in the system under conditions of nonlinear dynamic behavior.
- Identification of the domain of occurrence in the two-parameter plane of self-pulsations and strong optical chaos in the considered lasers.
- Development of the connection scheme for two unidirectional coupled lasers to achieve perfect synchronization in the case of identical lasers.
- Theoretical study of optical phenomena occurring in quantum dot lasers that have important value for understanding their operation and subsequent experimental realization.
- Theoretical realization of the chaos-based optical communication process in a unidirectional coupled quantum well laser system in the case of non-identical lasers.
- Proposal of new semiconductor laser devices with quantum dot active medium under the influence of feedback from multiple cavities, some of which are air.

The practical value of the thesis consists of:

- estimation of material and geometric parameters of lasers for regions with strong chaos;
- explaining the phenomena reported in various experiments;
- practical recommendations for lasers with controllable properties in chaos-based optical communication applications;
- The implementation of the results obtained in the thesis was in two scientific projects within state programs funded by ANCD.

Main scientific results submitted for support

1. Theoretical results were presented. Semiconductor laser with quantum dot active medium under the action of optical feedback from multiple cavities. The steady states of the delayed differential equations describing the studied systems were analysed to characterize the laser behaviour.
2. Studies of nonlinear optical phenomena were carried out through numerical modelling.
3. The bifurcations that lead to the occurrence of self-pulsations and dynamic optical chaos phenomena in semiconductor lasers with additional air cavities have been obtained.

4. Lasers with much smaller dimensions than those reported in the literature have been proposed for use in secure communication structures.
5. Two unidirectional lasers were synchronized by coupling them.
6. Chaos-based communication in quantum dot laser systems with optical feedback has been achieved.

Approval of the results obtained

The main scientific results were presented at the following conferences:

1. Seminar, exchange of experience, Trieste, Italy (2019).
2. The 6th International Conference on Telecommunications, Electronics and Informatics, Chisinau, May 24-27, p. 225 – 227, 2018.
3. The 9th International Conference on Microelectronics and Computer Science, Chisinau, October 19-21, pp. 88-81, 2017.
4. TIM18 International Physics Conference, 24 - 26 May 2018, Timișoara, Romania, AIO06.
5. Scientific Conference of Doctoral Students "Contemporary Trends in the Development of Science: Visions of Young Researchers",6th edition, pp. 84-88, 2017
6. ECODAM Doctoral Summer School, Iași, Romania, June 19 – 21, 2017.
7. Humboldt Kolleg on Multidisciplinary in Modern Science, Chisinau, 2017.
8. ECODAM Doctoral Summer School, Iași, Romania, June 21 – 26, 2016.
9. Scientific Conference of Doctoral Students "Contemporary Trends in the Development of Science: Visions of Young Researchers", 5th edition, pp. 84-88, 2016.
10. 59th Scientific Conference for Students of Physics and Natural Sciences, Open Readings 2016, March 15-18, Vilnius, Lithuania.
11. Humboldt Kolleg on Multidisciplinary in Modern Science, Chisinau, 2015.

Publications on the topic of the thesis. The main results of the thesis were published in 18 scientific papers, of which 2 articles in international journals listed in WoS and SCOPUS, 3 in journals from the National Register of specialized journals category B+, 4 articles in proceedings of national conferences with international participation, 9 theses at scientific forums, international conferences. The list of the author's contributions is presented at the end of the thesis in Appendix 1.

Thesis volume and structure. The thesis consists of an introduction, five chapters, general conclusions and recommendations. The thesis is presented on 131 pages of text, with 56 figures. The bibliography contains 147 references. The thesis was developed within the Research Laboratory of Laser Devices and Nanostructured Materials, Department of Physics, Technical

University of Moldova with participation in the project under the State Programs 20.80009.5007.08 entitled "Study of optoelectronic structures and thermoelectric devices with high efficiency" and in the project 15.817.02.22F "Thermoelectric and optical properties of nanostructured materials and quantum dot devices".

THESIS CONTENT

Introduction describes the topicality and relevance of the thesis topic, as well as the purpose, objectives and scientific novelty of the research.

Chapter 1 includes a description of previous results in the field of complex dynamics of semiconductor lasers. In recent years, nonlinear dynamics of optical processes has become a developing research area. Intense research in this field is due to both the fundamental and applied interest of the discovered phenomena. The performance of laser devices can be modified by optical feedback, which occurs at the interface of the elements of integrated photonic circuits, or by reflection from an obstacle. Optoelectronic communication systems are electronic devices that generate, measure, recombine and use light radiation of the optical domain. Optoelectronic devices have an important role and are found in various electrical circuits such as: laser diodes, laser modules, LEDs and accessories for them. In this variety of optoelectronic devices, semiconductor lasers are the key element in the development of optical communication based on chaos. The semiconductor laser has become particularly attractive due to its low price and small size. It is also very effective, unlike most other types of laser.

Chapter 2, in the first part, includes the exposition of numerical results of the dynamic behavior of a semiconductor laser with quantum wells as the active medium, subjected to several optical feedback loops, a laser similar to the one represented in [11]. The laser configuration consists of an active section with quantum wells with distributed feedback, coupled with cavities with several sections. It was demonstrated that, due to the multiple feedback loops and under certain operating conditions, the laser exhibits chaotic behaviors suitable for chaos-based communications. The optimal conditions and parameters of the quantum well laser suitable for chaos generation were identified. The synchronization of two unidirectionally coupled systems of the master-slave type was studied. Finally, examples of encoding and decoding of high-bit-rate messages were described and discussed. At the same time, the way in which the laser can be destabilized by external cavities was analyzed, as well as the use of chaotic oscillations produced by the given configuration in a chaos-based communication system. It was demonstrated that chaos-based communication becomes more attractive because it allows for a further improvement in the security of optical data transmission.

Thus, in the first part of this Chapter we demonstrated that the quantum well laser is useful as a key element in chaos-based communication systems. The question then arises whether quantum dot lasers could satisfy the conditions described above, sustainable for quantum well lasers?

In the second part of **Chapter 2,** the theory of lasers with quantum dots and external cavities as active media is presented. The laser scheme consists of a laser with quantum dots as active media operating under the influence of optical feedback from two external cavities. To study the complex dynamics of the laser, a set of equations for dimensionless variables and for optical feedback of the Lang-Kobayashi type is used [12]. The stationary case was studied by obtaining solutions in the form of external cavity modes (ECM). As a result, analytical equations were obtained describing the amplitude of the electric field, the probability of occupancy in quantum dots, the charge carrier density and a transcendental equation for the ECM frequency. The geometric locus of the external cavity modes in the charge carrier density plane and the emission frequency were plotted for different values of the feedback intensity. The analytical equation of the node-saddle bifurcation was obtained. The saddle-node and trans-critical bifurcation lines were plotted for different locations and numbers of the external cavity modes. The bifurcation diagram was obtained for the equilibrium states in the plane of different parameters for different intensities of the optical feedback. The DDE-biftool software was used to study the stability of the stationary states. The geometric locus of the Hopf bifurcations was obtained. The results obtained using DDE-biftool were verified by the method of direct integration of the equations of motion. As a result, the time evolution of the emerging power and the phase portraits for different evolution regimes, such as continuous waves, self-pulsations and chaotic waves, were obtained. The numerically obtained bifurcation diagrams were plotted. The synchronization of two “main-secondary” lasers joined in the longitudinal direction was demonstrated. From the results obtained, it follows that the proposed design for these lasers is promising for practical applications of these lasers in optical communication systems. The schematic of the quantum dot semiconductor laser is shown in Fig. 1. The device consists of an air-cavity quantum dot laser [11] operating under the influence of optical feedback from two external cavities. The first laser mirror is located at a distance l from the side of the laser. Phase φ in the air cavity can be changed by a piezo-element, which is placed at the back facet of the system. The phase of the optical feedback in the second cavity can be controlled by including a current in the passive section. It is assumed that the current injected into the passive section is small and affects the refractive index, so that the optical length of the resonator is changed in sub-wavelength intervals. On the other hand, the phase of the feedback φ can be tuned by changing the delay time between the two mirrors.

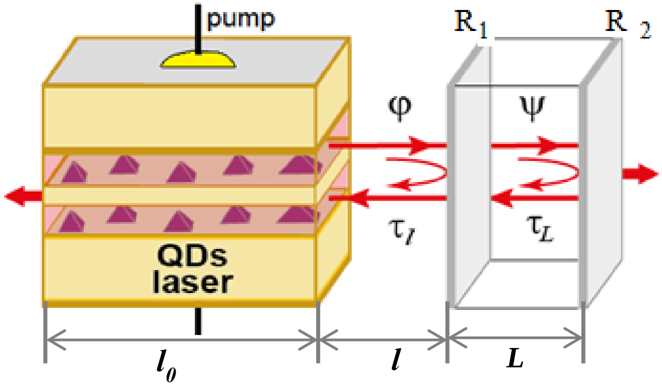

Fig. 1. Laser diagram. l_0 is the length of the laser, l is the distance between the side of the laser and the first mirror of the resonator. *L* is the distance between the mirrors, ω_0 is the laser frequency, φ is the feedback phase in the air cavity, and ψ is the phase inside the resonator. τ_l and τ_L are the time for the respective outer cavities [A1].

To study the complex dynamics of the quantum, dot active medium laser under the influence of a double optical feedback, the following equations are used for dimensionless dimensions and for Lang–Kobayashi type optical feedback [12]

$$\frac{dE}{d\tau}=\frac{1}{2}(1+i\alpha)\left[-\gamma_{np}+g(2\rho-1)\right]E+\Gamma_1 e^{-i\varphi}E(\tau-\tau_l)+\Gamma_2 e^{-i(\varphi+\psi)}E(\tau-(\tau_l+\tau_L)), \quad (1)$$

$$\frac{d\rho}{d\tau}=-\gamma_{ns}\rho-(2\rho-1)|E|^2+(CN^2+BN)(1-\rho), \quad (2)$$

$$\frac{dN}{d\tau}=J-N-2\left[(CN^2+BN)(1-\rho)\right], \quad (3)$$

where E is the complex amplitude of the electric field, N is the density of charge carriers in the quantum well, and ρ is the occupancy probability in the quantum dots. $\tau_l = 0.05$, $\tau_L = 0.2$ is the time for the respective outer cavities, which correspond to $l = 7.5$ mm, and $L = 1$ cm, respectively. $g = 1200$ is the differential gain, and $J = 20$ is the pumping parameter. The constants $B = 0.012$ and $C = 40$ describe the transport of charge carriers by the charge-photon interaction. These values of the mentioned parameters are used as a basis to describe the obtained results and present them with the help of diagrams in this Chapter. However, some of these parameters will have variations that will be included in the figure legends. The parameters Γ and τ describe the feedback connection and the delay time. Γ_1 and Γ_2 represent the feedback levels that maintain the reflectivity of mirrors R_1 and R_2, respectively. It is assumed that both facets of the cavities are covered with material that can change their reflectivity. The feedback phase φ can be modified by a small current or can be checked using a piezo-element. Thus, the feedback intensity Γ_1 and Γ_2, as well as the phase in the air cavity φ are the main parameters that vary during the investigation.

The stationary solutions of the system of equations (1) – (3) are expressed by the external cavity modes in the form

$$E = E_s e^{i\omega_s \tau},\ N = N_s,\ \rho = \rho_s . \tag{4}$$

Using (4) from (1) - (3) we obtain a transcendental equation for the emission frequency ω_S

$$\begin{aligned}\omega_s = -\Gamma_1\left(\alpha\cos(\omega_s\tau_l+\varphi)+\sin(\omega_s\tau_l+\varphi)\right)- \\ -\Gamma_2\left[\alpha\cos\left(\omega_s(\tau_l+\tau_L)+\varphi+\psi\right)++\sin\left(\omega_s(\tau_l+\tau_L)+\varphi+\psi\right)\right],\end{aligned} \tag{5}$$

also the equations for the occupancy probability, the carrier density and the emergent signal intensity

$$\rho_s = \frac{1}{2g}\left\{\gamma_{np} + g - 2\left[\Gamma_1\cos(\omega_s\tau_l+\varphi)+\Gamma_2\cos\left(\omega_s(\tau_l+\tau_L)+\varphi+\psi\right)\right.\right., \tag{6}$$

$$N_s = -\frac{2B(1-\rho_s)+1}{4C(1-\rho_s)} + \frac{\sqrt{\left[2B(1-\rho_s)+1\right]^2 + 8C(1-\rho_s)J}}{4C(1-\rho_s)}, \tag{7}$$

$$|E_s|^2 = \frac{J - N_s - 2\gamma_{ns}\rho_s}{2(2\rho_s - 1)} . \tag{8}$$

If the laser system operates under the influence of a conventional optical feedback, the modes of the outer cavities MCE are in the form of an ellipse. If the conventional optical feedback is absent, and the device operates under the influence of an optical feedback coming from two outer cavities, the modes of the outer cavities acquire a shape different from the elliptical one. Figure 2 represents the locus in the (N_s - ω_s) plane for different values of the feedback power. We consider, first, the case of conventional optical feedback, i.e. $\Gamma_1 = 10$ and $\Gamma_2 = 0$. In this case, the reflection occurs only from the first facet of the outer resonator. For these values of the feedback power, the locus of the modes is considered to be an ellipse (Fig. 2(a)). The case when the optical feedback is conventional has been discussed in detail for two decades. In the following we analyse the influence of double feedback on the location of the outer modes. When the feedback intensity $\Gamma_1 = 10$ and Γ_2 varies up to 10 the central ellipse deforms and outer satellites appear (see Fig. 2(b). In Fig. 2(c) it is observed that when Γ_2 varies up to 20 the central ellipse is more deformed and acquires the shape of a flattened figure eight. When both optical feedback powers Γ_1 and Γ_2 are increased to 20 the ellipse splits into three circles on which the outer cavity modes are located. Also, additional satellites appear on the right and left (Fig. 2(d)).

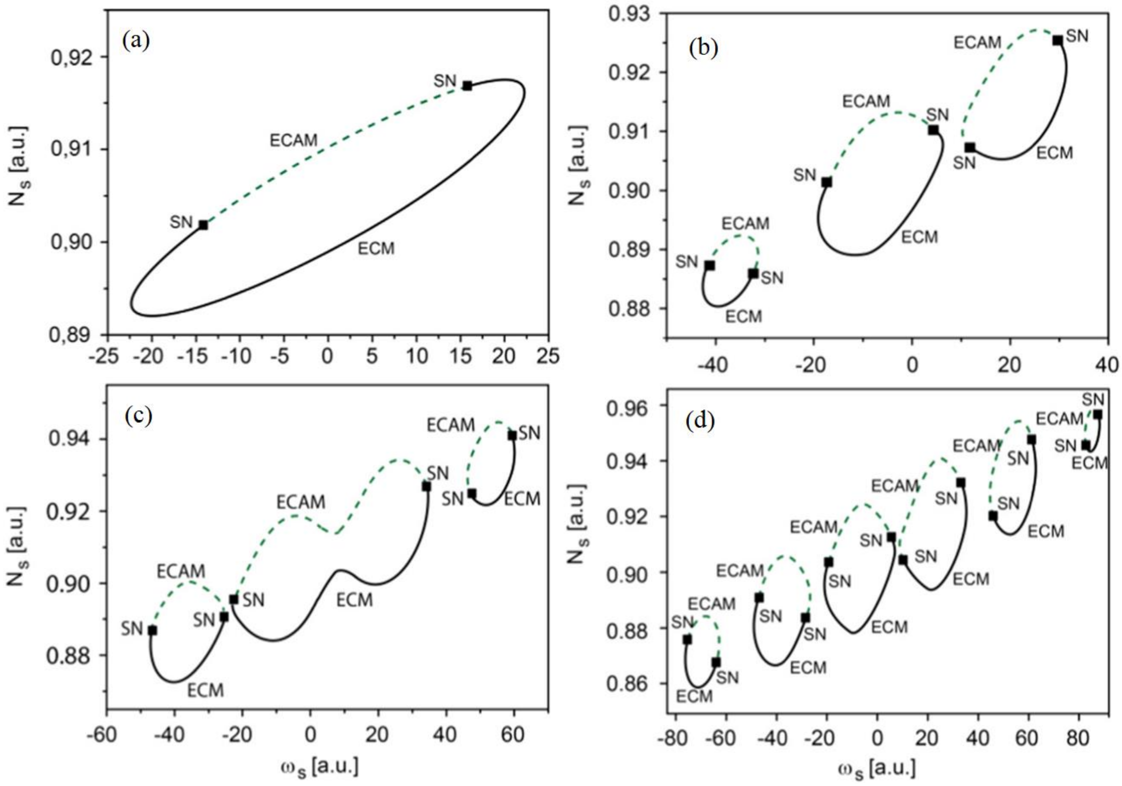

Fig. 2. The locus of the external cavity modes in the (Ns -ω_S) for the fixed feedback phase$\psi = \pi/2$ and different values of feedback strength (a) $\Gamma_1 = 10$, $\Gamma_2 = 0$ (COF), (b) $\Gamma_1 = 10$, $\Gamma_2 = 10$, (c) $\Gamma_1 = 10$, $\Gamma_2 = 20$, (d) $\Gamma_1 = 20$, $\Gamma_2 = 20$. Anti-modes of the AMCE outer cavities. SN is the saddle–node bifurcation[A1].

Figure 3(a) represents the bifurcation diagram when the feedback strength Γ_1 is the bifurcation parameter.

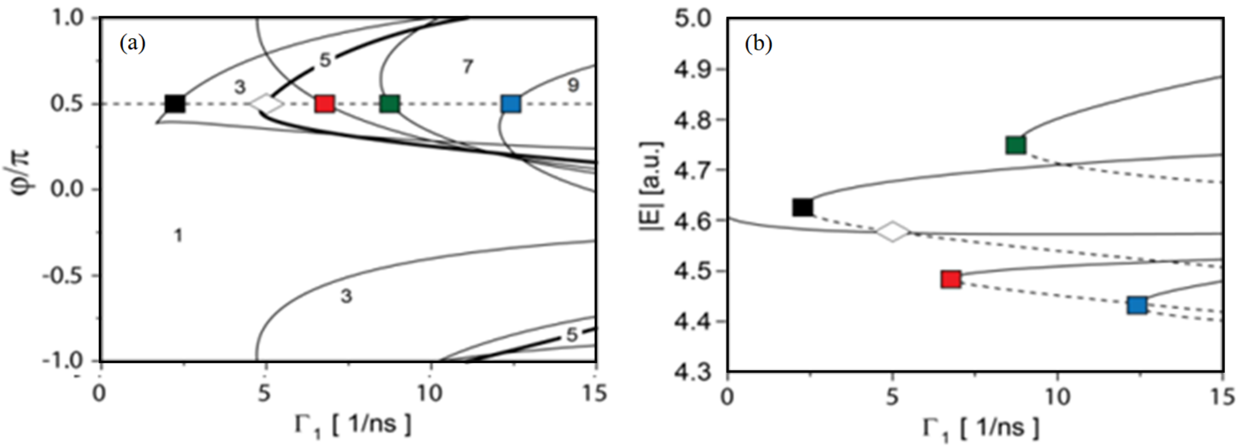

Fig. 3. (a) Saddle-node (thin) and trans-critical (thick) bifurcation lines for different locations and numbers of the MCE corresponding to the respective regions. (b) Bifurcation diagram for the equilibrium states in the |E| plane as a function of the feedback strengthΓ_1 for$\varphi = \pi/2$. The solid lines represent the modes, and the dotted lines the anti-modes. The squares indicate the saddle-node bifurcations. The diamond characterizes the trans-critical bifurcation. $\Gamma_2 = 10$ [A1].

For small feedback intensities there is a region where only a single mode is present. Additional outer cavity modes (in pairs) appear when the saddle-node curve is traversed (thin lines). The transcritical bifurcation is shown by the thick lines. Figure 3(b) resembles the situation when the phase $\varphi = \pi/2$(see dotted lines in Fig. 3(a)). Each symbol on this line is reproduced in Fig. 3(b). Figure 4 represents the Hopf bifurcations in the plane (φ–Γ_1) for fixed phase value $\psi = \pi/2$, and different values Γ_2. The regions along these lines are unstable.

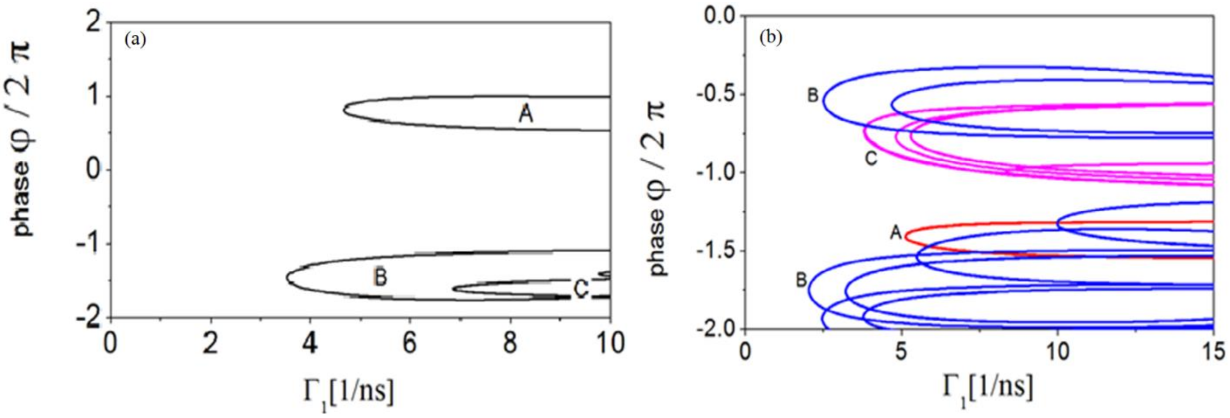

Fig. 4. The lines that determine the Hopf bifurcations of the external cavity modes for $\psi = \pi/2$ at various locations in the plan($\varphi - \Gamma_1$)for (a) Γ_2 =10 and (b) Γ_2 =20 [A1].

Returning to equations (1)-(3), separating the real and imaginary parts, we obtain a system of differential equations with delay. In the following, the solutions of the system of equations for the real and imaginary parts of the quantities in (1) – (3) are numerically analysed to describe the dynamic behaviour in detail. Figure 5 represents the time evolution of the emerging power and the phase portrait. They were obtained after integration by the 4th order Runge Kutta method. By this method we can obtain the figures that describe the time evolution of the emerging power, the phase portrait for different values of the phase, the bifurcations depending on phase φ, bifurcation parameter and different strengths of feedback. Figure 5(a) shows continuous waves, in which the stable stationary region contains a stable focus when the phase is $\varphi = \pi/2$. Figure 5(b) shows the time evolution of the emergent intensity for stable behaviour and self-pulsations. In this case the trajectory phase becomes a limited stable circle($\varphi = 0$). The frequency of the pulses in Figure 5(b) is approximately 20 GHz. When the phase is $\varphi = \pi$, the emerging intensity oscillations become much more complicated, and the chaotic behaviour becomes according to the phase portrait a strange attractor (see Figure 5(c)).

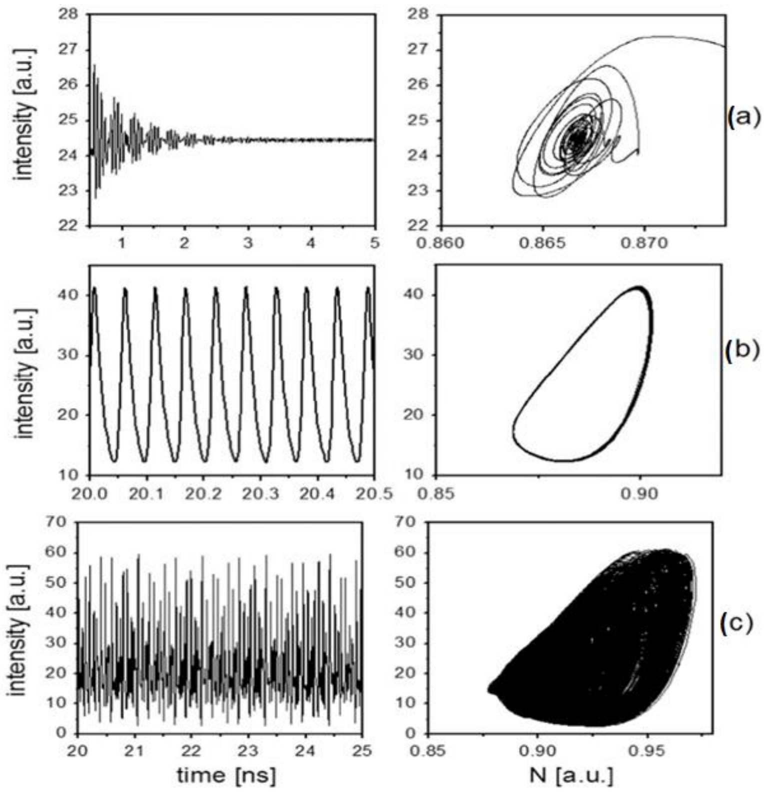

Fig. 5. Time evolution of the emerging power (left) and phase portrait (right) for different phase values. phase φ(a) φ = π/2, where do you continue, (b) φ = 0, self-pulsations, and (c)φ = π, chaotic behaviour. Other parameters: Γ_1 = 20, Γ_2 = 20, ψ = π/2 [A1].

A calculation of the bifurcations is shown in Fig. 6, when the feedback parametersΓ_1(left) and Γ_2(right) are the bifurcation parameter. This figure shows the dependence of the maximum and minimum of the number of photons. It is observed that the chaotic regions are wide with large amplitudes. In Fig. 6 (left) it is observed that the chaotic regime also appears for reduced feedback Γ_1. This is because of the feedback Γ_2 which is due to the high value of the reflection coefficient of the posterior facet.

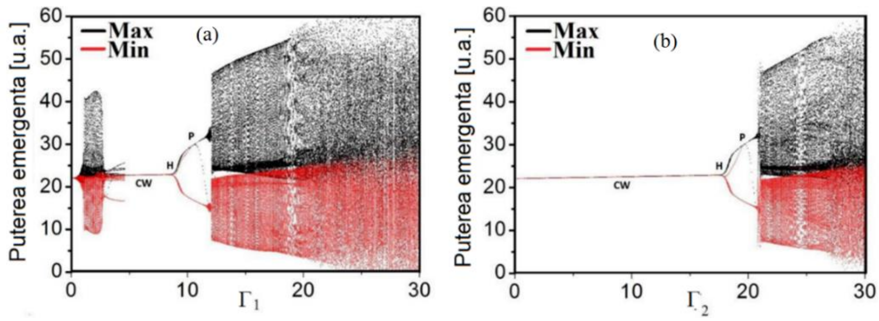

Fig. 6. Bifurcation diagram obtained numerically for the values of Γ_1 (left) and Γ_2 (right). CW indicates the continuous wave regime, the small circle H marks the Hopf bifurcation, and P denotes the maximum of the periodic solutions. The parameters are: B = 0.01, C = 40, J = 20, g = 1200, γ_{ns} = 1.0, γ_{np} = 500.0, α = 2.0 [A1].

Next, we study the synchronization process of two "master-slave" lasers of the type shown in Fig. 1 that are joined in the longitudinal direction. It is well known that synchronization can be quantified by measuring the cross-correlation coefficient $\left[C = \langle P_m(t)P_s(t)\rangle / \left(\langle |P_m(t)|\rangle \langle |P_m(t)|\rangle\right)\right]$. Fig.7(a) above shows the chaotic behaviour of the master laser. It is obvious that the laser oscillates in a chaotic regime. Regarding the amplitude, we can say that it takes values from zero to 70 a.u. Fig. 7(b) shows the synchronization process between both lasers. It is observed that the amplitude of the "master" laser signal is smaller than that of the "slave" laser. The reason is that the laser signal is amplified in the slave laser. In Fig. 7(c) the emitted power of the slave system is represented compared to the power of the master laser, the so-called synchronization diagram. It is observed that such lasers as in Fig. 1 joined in the longitudinal direction can synchronize. Cross-correlation coefficients 0.95.

The above results show us that two quantum dot lasers with optical feedback can be synchronized. This result is an indication that these lasers may be good candidates for light sources for chaos-based communication.

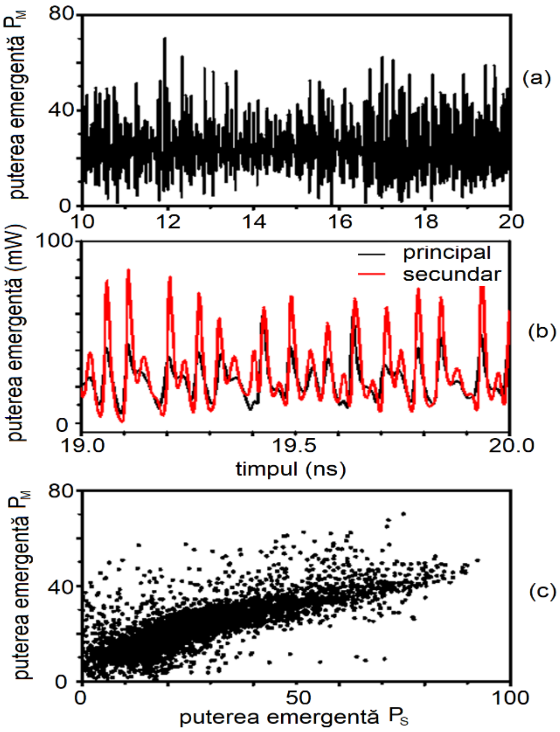

Fig. 7. The synchronization process of two identical lasers shown in Figure 2.1. (a)the pulse path of the main laser showing chaotic behaviour. (b) The pulse paths of the master and slave lasers in the synchronization process. (c) Synchronization diagram[A1].

In this Chapter, we also studied the synchronization of two unidirectional coupled systems (master-slave) when there is a mismatch in the parameters on the quality of synchronization.

Usually, to obtain chaotic behaviour of conventional lasers with feedback from a distant mirror, a round-trip delay time of at least a few nanoseconds is required. In this case, the mirror must be placed at a distance of several tens of centimetres from the back face of the laser. On the other hand, lasers with multisection external cavities can be suitable candidates for integrated chaotic emitters that have small dimensions. Lasers subject to feedback from air-gap cavities have been considered in this Chapter. It has been shown that synchronization is degraded when there is a mismatch in the material and device parameters of the master and slave lasers. However, the number of quantum dots does not strongly affect the synchronization characteristics of quantum dot lasers. We mention that in the UTM research group a new design of the laser with many sections, some of them being air, was proposed for investigation and studied theoretically. Later it was grown, investigated experimentally and used in chaos communication schemes in Pavia Italy. The experimental results confirm the theoretical predictions of the synchronization phenomena.

Figure 8 shows the structure of the semiconductor laser with quantum dots as the active medium under the influence of feedback from equally distributed external cavities. We consider a single-mode DFB laser coupled to multiple cavities in the longitudinal direction. The first mirror is located at a distance l_1 from the laser facet, and the distance between the mirrors is also taken as l2. The feedback part is composed of air and phase sections. The phase sections are controlled by a small current passing through them. We assume that in the phase sections the injected current 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 range of tenths of wavelengths.

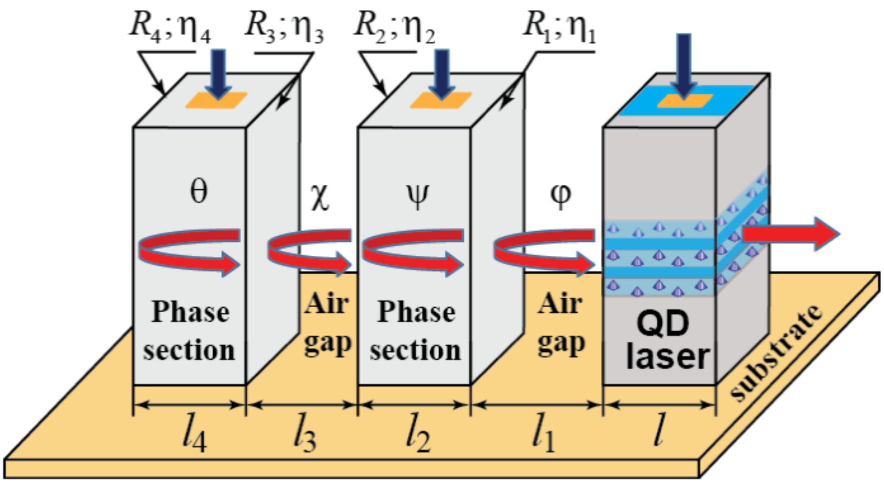

Fig. 8 Scheme of the laser with quantum dot active medium under the influence of an external multiple optical feedback. The phases ψ and ϴ are controlled by an applied current. R_1 and R_2 are the reflectivity of the air-material facet of the first phase section. R_3 and R_4 are the reflectivity of the second phase section [A4].

The equations describing the dynamics of the system represented in Fig. 8 have the form [13]

$$\frac{dE}{d\tau} = -kE + 2Z^{QD}\Gamma gP + \frac{Z^{QD}\Gamma\beta}{\tau_{eff}E}\left(\frac{D+1}{2}\right)^2 + \eta_1 e^{-i\varphi}E(\tau-\tau_1) + \eta_2 e^{-i\psi}E(\tau-\tau_2) \tag{9}$$

$$+\eta_3 e^{-i\chi}E(\tau-\tau_3) + \eta_4 e^{-i\theta}E(\tau-\tau_4) + \zeta E,$$

$$\frac{dP}{d\tau} = -\gamma P + gDE, \tag{10}$$

$$\frac{dD}{d\tau} = -4gEP + \frac{d_0 - D}{T_1} - \frac{1}{\tau_{eff}}\left(\frac{D+1}{2}\right)^2, \tag{11}$$

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, and β represents the coupling and spontaneous emission factors [13], where g is the gain, Z^{QD} is the number of quantum dots in the active region of the laser; Γ represents the confinement factor characterizing the fraction of quantum dots in the volume of the mode, which contribute to the laser emission; T_1 and d_0 are the inverse of the lifetime and the pumping intensity; η_i and are the intensities of the feedbacks varying in reflectivity R_i, respectively; ζ represents the coupling forces; τ_i are the round-trip times in the outer cavities. The dimensionless parameters have the values k = 300, Z^{QD} = 1000, Γ = 0.01, β = 1.0, d_0 = 0.95, γ = 100, T_1 = 0.01, g = 48.86,τ_{eff}= 0.001, $\eta_1 = \eta_2 = \eta_3 = \eta_4 = 25$, ζ =20.

Figure 9 shows the dependence of the cross-correlation coefficient on the phase difference (phase master − phase slave) for feedback intensities η_1 = 25 and coupling coefficients η_3 = 20. The black line shows the degradation of synchronization due to a phase mismatch φ of the master and slave lasers in the first air section. The phase φ_s of the slave laser is kept at zero, while the phase φ_m of the master is varied from 0 to π. The following conclusion can be seen. When the feedback phases coincide, the system shows perfect synchronization with a cross-correlation coefficient approaching unity (see point A in Fig. 9). An increase in the feedback phase mismatch induces a rapid degradation of synchronization, which is indicated by a reduction in the cross-correlation coefficient. This rapid degradation is followed by a slow one. The red line shows the effect of a mismatch in the second feedback phase χ of the air cavity. We consider the phase χ of the secondary laser to be zero and vary the phase χ_m of the master laser. As the phase mismatch χ is increased, the degradation is clearly less severe than inthe case of feedback phase mismatch φ of the first air gap. Thus, the phase of the shorter cavity is more sensitive to the mismatch than that of the long cavities.

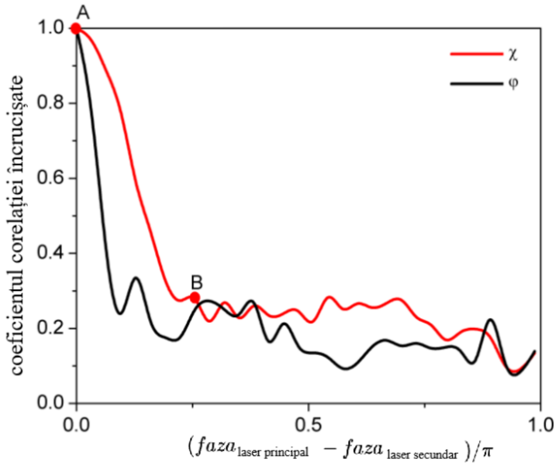

Fig. 9. Cross-correlation coefficient as a function of the reaction phase difference (phase master − phase slave) for the coupling ζ = 20. Parameters: $\varphi_s = 0$, $\psi_m = \psi_s = \pi/5$, $\chi_s = 0$, $\theta_m = \theta_s = \pi/4$[A4].

Figure 10 shows the time evolution of the optical power of the master (black) and slave (red) lasers and the timing diagrams for points A and B in Fig. 9, respectively.

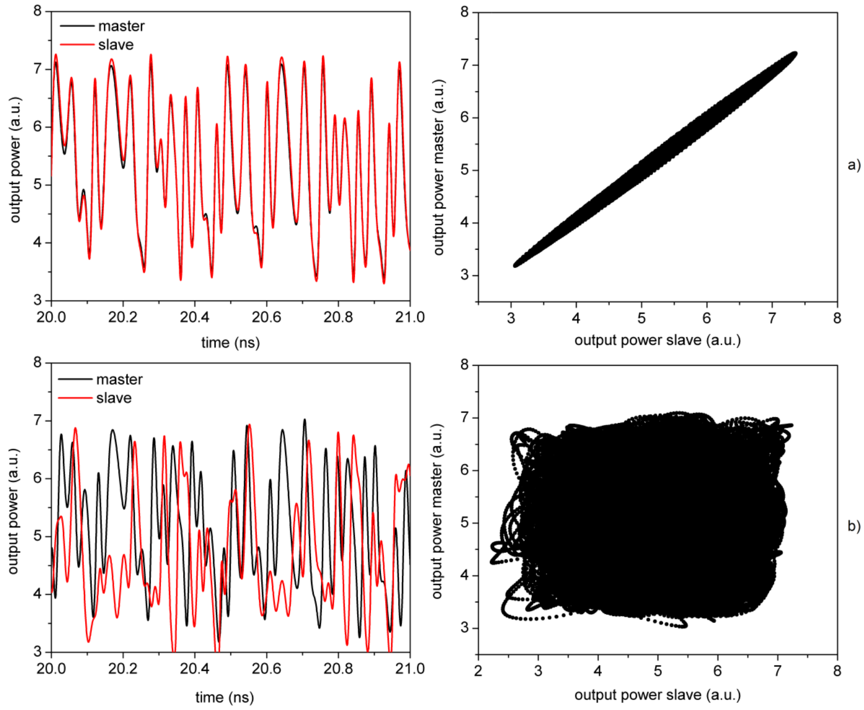

Fig. 10. Synchronization for point A(a) and B (b) from Fig. 9. [A4].

When the synchronization is perfect, the cross-correlation coefficient is close to unity C = 0.995 (see Fig. 10a). The synchronization diagram shows a clear synchronization process. Figure 10b) shows the same dependencies for point B, when synchronization degradation is observed and the cross-correlation coefficient is C = 0.3. The trajectories of the master and slave lasers move away from each other, and the synchronization diagram is a cloud of points showing the lack of correlation between the signals. In this Chapter, the synchronization properties of the chaotic quantum dot laser under the influence of multi-section optical feedback were studied. The feedback involves a complex behaviour, but keeps the device compact.

In **Chapter 3**, for the first time, the results of numerical simulations on the chaotic behaviour of the quantum dot laser subjected to T-type optical feedback were presented. It was demonstrated that under specific conditions, due to the influence of external feedback, the system exhibits a strong chaotic behaviour, suitable for chaos-based communications. The influence of relevant device parameters, such as the phases and the feedback intensity on the laser dynamics was demonstrated. The autocorrelation time that delimits the chaotic and continuous wave regions was calculated. The synchronization of two unidirectional coupled lasers was demonstrated. Finally, the suitable conditions for encoding messages with a high bit rate by the chaos modulation technique using compact quantum dot lasers under the influence of T-type feedback loops were obtained. After the process of perfect synchronization of the main (transmitter) and secondary (receiver) lasers, the message is decoded at the receiver by comparing the input signal with the output signal. This method was also used in experiments. Later we came up with proposals for new photonic devices with passive sections and air cavities at the nanoscale. The laser structure consists of the active section coupled to an air layer and multiple outer sections. It was found that due to the multiple optical feedback, under certain operating conditions, the system has a chaotic behaviour with increased amplitudes. A new scenario of chaos emergence under the influence of multiple feedback has been demonstrated. The power spectrum is wide and portrait phase is a strange attractor. It has been shown that the transmitted and decoded signals are the same and it is possible to encode and decode messages at various information transmission speeds. These lasers have improved performance compared to previous ones, especially in applications where the encoding rate must be high.

Figure 11 represents the structure of the device, which consists of a quantum dot laser under the influence of an optical feedback from the T-shaped external cavities. The intensity of the optical feedback from the two external cavities Γ_1 and Γ_2 are determined by the reflections R_1 and R_2 with the phases φ and ψ, τ_1 and τ_2 being the delay times, respectively.

An advantage of the proposed system compared to the conventional optical feedback system is that chaotic behaviour occurs for small cavity lengths, which make the device much more compact.

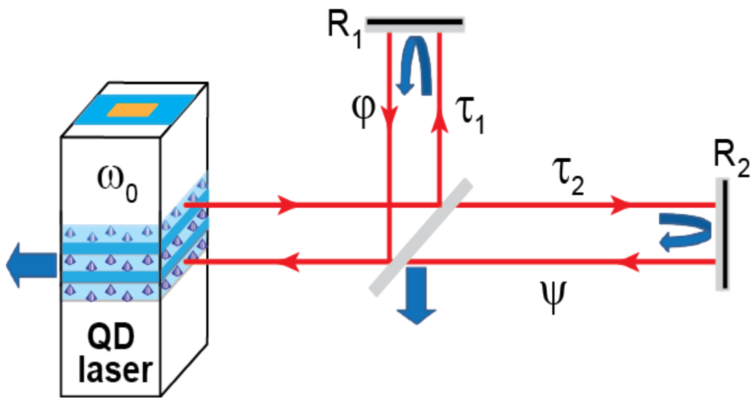

Fig. 11. Scheme of a semiconductor laser under the influence of feedback double optical coming from the T-type outer cavities[A2].

Thus, we will study the dynamics of quantum dot lasers, especially the chaotic properties, the possibility of synchronizing two such lasers, as well as the chaotic modulation technique applied using the device in Figure 11 and the rate equations according to model (1) – (3) with the equation for the electric field amplitude in the form

$$\frac{dE}{d\tau}=\frac{1}{2}(1+i\alpha)\left[-\gamma_{np}+g(2\rho-1)\right]E+\Gamma_1 e^{-i\varphi}E(\tau-\tau_1)+\Gamma_2 e^{-i\psi}E(\tau-\tau_2)\,. \qquad (12)$$

We consider the single loop approximation and neglect multiple reflections inside the cavities. Other parameters are: Henry factorα= 2, and τ_1= 0.3,τ_2= 0.5 are the round trip times of the outer cavities. g = 1200 is the differential gain, and J = 20 is the pumping parameter.

Figure 12(a) shows the time evolution of the emergent power for Γ_1 = 15, Γ_2 = 16.2. The phase portrait represents a stable limit cycle. This limit cycle is stable throughout the integration interval of 100 ns. Figure 12(b) shows the period doubling for Γ_1 = 15, Γ_2 = 20. The phase portrait is a deformed limit cycle, and new oscillations are present in the power spectrum. It is observed that only a small increase in the feedback intensity Γ_2 leads to a new bifurcation the period doubling. With the increase in the intensity of the feedbacks Γ_1 and Γ_2 leads to a chaotic time evolution of the emergent power. Figure 12(c) illustrates a strange attractor for the following values of the feedback intensities Γ_1 = 20 and Γ_2 = 30. Thus the time evolution of the emergent power represents chaotic oscillations. If we analyse the power spectrum, we notice that it is broad and has no dominant harmonic.

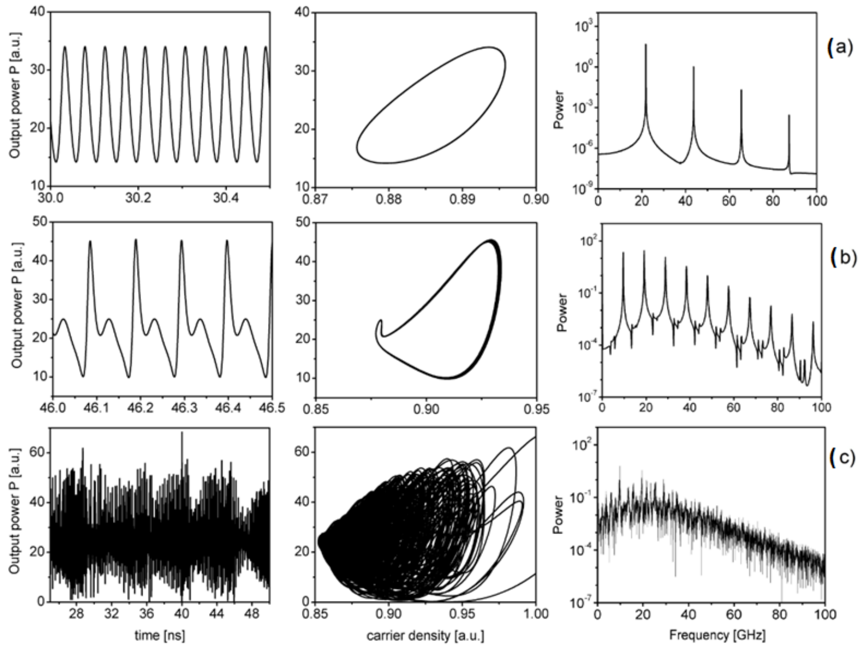

Figure 12. Time evolution of the emerging power (left), phase portrait (centre) and power spectrum (right) of the semiconductor laser under the influence of an optical feedback coming from the external T-type cavities: (a) $\Gamma_1 = 15$, $\Gamma_2 = 16.2$ (periodic behaviour); (b) $\Gamma_1 = 15$, $\Gamma_2 = 20$ (double period); (c) $\Gamma_1 = 20$, $\Gamma_2 = 30$ (chaotic behaviour). The phases are $\phi = \pi/2$, $\psi = 3\pi/2$[A2].

An important characteristic of the optical output signal is the autocorrelation time. The dynamics of the quantum dot laser has a more pronounced chaotic behaviour when the autocorrelation time is smaller. To establish these regions, we calculate the autocorrelation time in the semiconductor quantum dot laser under the influence of an optical feedback from the T-cavities. The results of these calculations are presented in Figure 13 in the phase plane (ψ - ϕ). Here the red regions correspond to the strongly chaotic regions of the semiconductor laser with the autocorrelation time smaller than 0.1 ns.

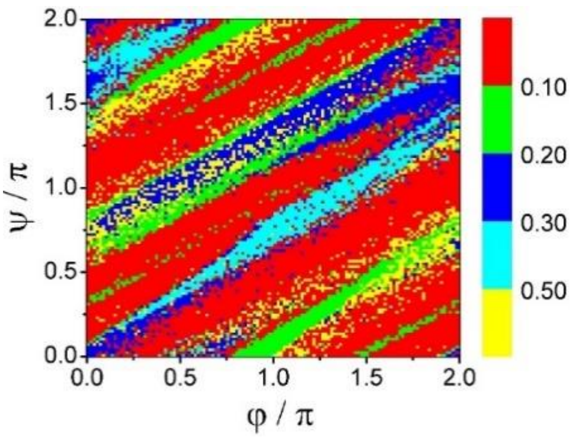

Fig. 13. Autocorrelation time in the (ψ - ϕ) plane when the feedback intensities are $\Gamma_1 = 20$ and $\Gamma_2 = 25$. The phase variation step is 0.05 radians[A2].

In the following, we will consider two identical lasers, connected according to the transmitter – receiver configuration, as shown in Fig. 14. We will study the synchronization of the two devices and the possibility of using them for encoding and decoding messages in optical communication based on chaos. For this, we use the signal modulation technique [14], [15], in which the message encoding consists of modulating a small amplitude added to the emitted field of the main laser. After the process of perfect synchronization of the main (transmitter) and secondary (receiver) lasers, the message is decoded at the receiver by comparing the input signal with the output signal. This method has also been used in experiments and, as said above, verified in [17].

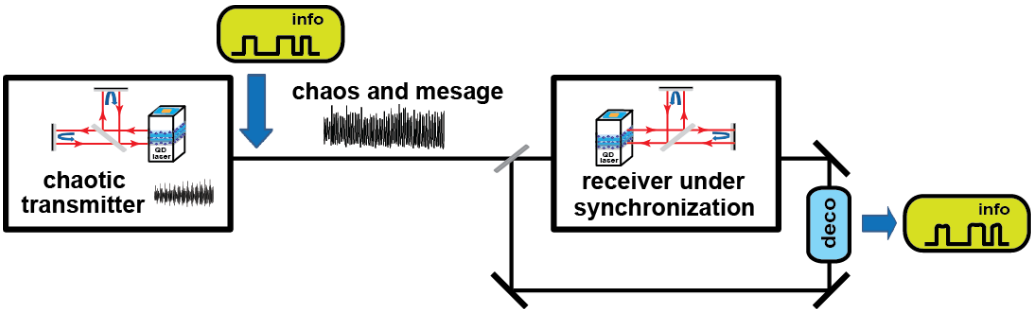

Fig. 14. Schematic representation of the modulation technique[A2].

Considering that both semiconductor lasers are connected unidirectional, we present the numerical analysis of the synchronization properties of this system. At first we will consider that the parameters of both lasers are almost identical. The signals of the master and slave lasers will be most synchronized when the correlation coefficient is close to unity (Fig. 15). This parameter can be controlled in the experiment by filtering the signal that hits the master laser at the slave one.

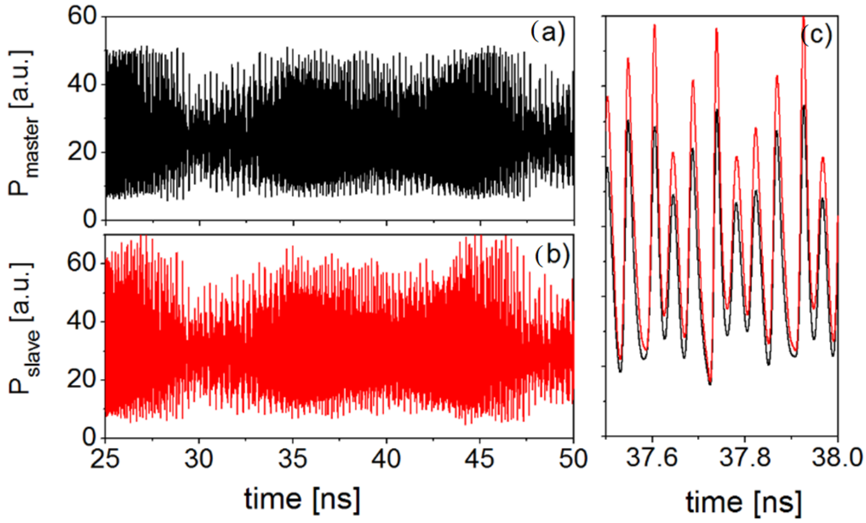

Fig. 15. Synchronization phenomenon of two unidirectional coupled semiconductor lasers for the coupling parameter k = 50. Time evolution of the emergent power of the (a) main (b) secondary lasers. (c) both signals of the main and secondary lasers. Other parameters: $\Gamma_1 = 20$ and $\Gamma_2 = 25$, $\phi = \pi/2$, $\psi = 3\pi/2$[A2].

The transmission and reception of the digital message by the system consisting of two identical lasers connected unidirectional as shown in Figure 16 was analysed. We examine the encryption and decryption of the 10 Gb/s digital message in the chaotic modulation technique.

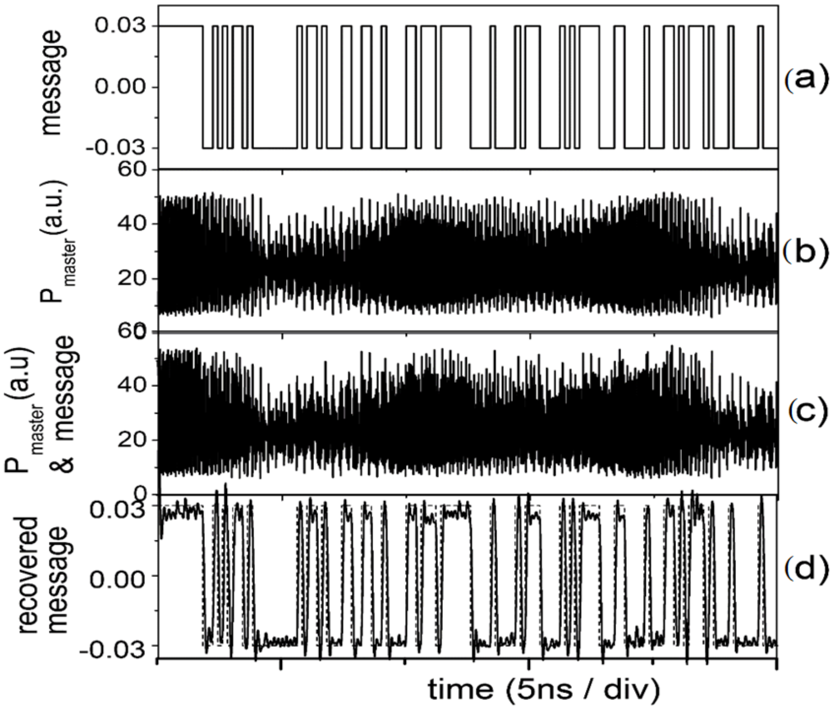

Fig. 16. Results of numerical calculations of encoding and decoding a 15-bit digital message Gbit/s. (a) Encoded digital message; (b) Main laser output signal without message; (c) Transmitted signal (with message); (d) Decoded message and message reconstruction after filtering (solid line) and transmitted message (dashed line). Other parameters: Γ_1 = 20, Γ_2 = 25, $\phi = \pi/2$, $\psi = 3\pi/2$, and k = 50[A2]**.**

Thus, in Chapter 3, the complex dynamics of the semiconductor laser with quantum dot active medium under the influence of optical feedback from multiple cavities was studied. This system configuration has smaller dimensions compared to existing systems and is compatible with existing optical communication systems.

In **Chapter 4**, a new theoretical method was developed to treat the influence of filtered feedback on the dynamics of single-mode quantum dot lasers (Fig. 17).

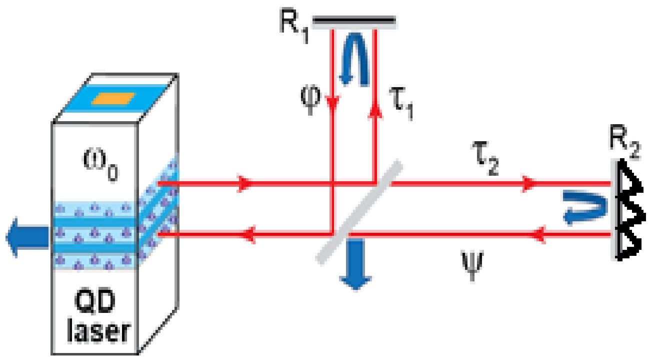

Fig. 17. Quantum dot laser with conventional feedback and a filter[A2].

The stationary states are expressed by MCE. The system of equations was presented and each stage of obtaining the quantities that can be applied for investigating the complex dynamics of the laser was described. Thus, semiconductor lasers with quantum dot active medium operating under the influence of double optical feedback, one conventional and the other filtered, are suitable basic elements in optical communication. The phase of the optical feedback has a special role in controlling the laser emission. In this chapter, we have theoretically demonstrated that the stability of the outer cavity modes, the Hopf bifurcation, continuous, periodic and chaotic waves can be obtained by the numerical calculation method. This allows improving the laser structure and complex dynamics. The theory developed in this chapter offers new research perspectives at the experimental level.

The rate equation for the complex field amplitude E(t) and F(t) and the charge carrier density N(t) is

$$\frac{dE}{d\tau}=\frac{1}{2}(1+i\alpha)\left[-\gamma_{np}+g(2\rho-1)\right]E+\gamma_1 e^{i\varphi}E(\tau-\tau_1)+\gamma_2 F\ , \tag{13}$$

$$\frac{dF}{d\tau}=\Lambda E(\tau-\tau_2)\mathrm{e}^{i\psi}+(i\Delta\omega-\Lambda)F(\tau)\,, \tag{14}$$

$$\frac{d\rho}{d\tau}=-\gamma_{ns}\rho-(2\rho-1)|E|^2+(CN^2+BN)(1-\rho)\,, \tag{15}$$

$$\frac{dN}{d\tau}=J-N-2[(CN^2+BN)(1-\rho)]\,, \tag{16}$$

where ρ is the occupancy probability in the quantum dots, J is the dimensionless pump current, τ_1 and τ_2 are the round trip times through the external cavities, γ_1 and γ_2 the feedback power controlled by the reflection in the resonators. The optical centre frequency of the filter ω and Λ are quantities that describe maximum filtration.

The steady states of equations (13)-(16) for *E, F, ρ* and *N* are expressed by the solutions external cavity modes of the following type

$$E = E_S e^{i\omega_S \tau}\,;\, F = F_S e^{i\omega_S \tau + i\Phi_S}\,;\, \rho = \rho_S\,;\, N = N_S\,, \qquad (17)$$

where E_s, F_s, ω_s, Φ_s, Ns are real time-independent constants that can only take positive values. The frequency for the stationary case is obtained using (17)

$$\omega_S = -\gamma_1[\sin(\omega_S\tau_1 - \varphi) + \alpha\cos(\omega_S\tau_1 - \varphi)] + \\ + \gamma_2\left[\left(\frac{F_1}{E_1}\sin\Phi_S - \alpha\cos\Phi_S\right) + \left(\frac{F_2}{E_1}(\cos\Phi_S + \alpha\sin\Phi_S\right)\right]. \qquad (18)$$

The complex amplitude of the field is obtained from (13) and (14)

$$E_S = \sqrt{\frac{J - N_S - 2\gamma_{ns}\rho_S}{2(2\rho_S - 1)}}\,. \qquad (19)$$

Thus for N_s we obtain

$$N_S = \frac{-[2B(1-\rho_S)+1] + \sqrt{[2B(1-\rho_S)+1]^2 + 8C(1-\rho_S)J}}{4C(1-\rho_{S)}}\,. \qquad (20)$$

Taking into account (19) the occupancy probability ρ_s was obtained for the stationary case

$$\rho_S = \frac{1}{2g}\left\{\gamma_{np} + g - 2\gamma_1\cos(\omega_S\tau_1 - \varphi) - \frac{2\gamma_2}{\Omega^2+1}[\cos(\omega_S\tau_1 - \varphi) - \Omega\sin(\omega_S\tau_1 - \varphi)]\right\}. \qquad (21)$$

In Fig. 18 the location of the modes for different values of the feedback power in the presence of the filter is shown.

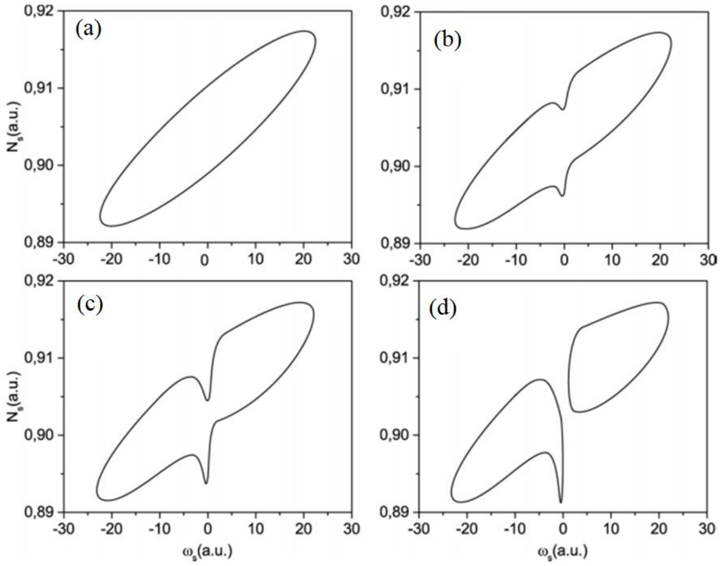

Fig. 18. Location of the external cavity modes for invariant values of the conventional optical feedback intensity (γ_1=0) and different values of the feedback intensity in the presence of the filter: a) γ_2= 0, b) γ_2= 5, c) γ_2= 10, d) γ_2= 15[A3].

The value for $\Delta\omega$ is equal to zero. In Fig. 18a) the outer cavity modes are located on an ellipse. In this case γ_2=0. In Fig. 18b) γ_2 varies up to 5 and the ellipse deforms. Another deformation of the ellipse is observed for γ_2=10. For higher values of γ_2, the ellipses will transform into two circles as indicated in Fig. 18d). After obtaining these results it was observed that by means of the secondary branch it is possible to control the stationary states of the outer cavity modes.

The time evolution of a semiconductor laser with double feedback, one of which is a filter, can be investigated using the system of equations (13)-(16). The Runge-Kutta method was used to numerically integrate this system of equations. By integration, results are obtained for which the feedback power is considered equal in both branches of the semiconductor laser. In Fig. 19 the time evolution of the output power is represented (left side). In the middle is the phase portrait that describes the dependence of the charge density as a function of the optical power *N*. On the right side we observe the power spectrum.

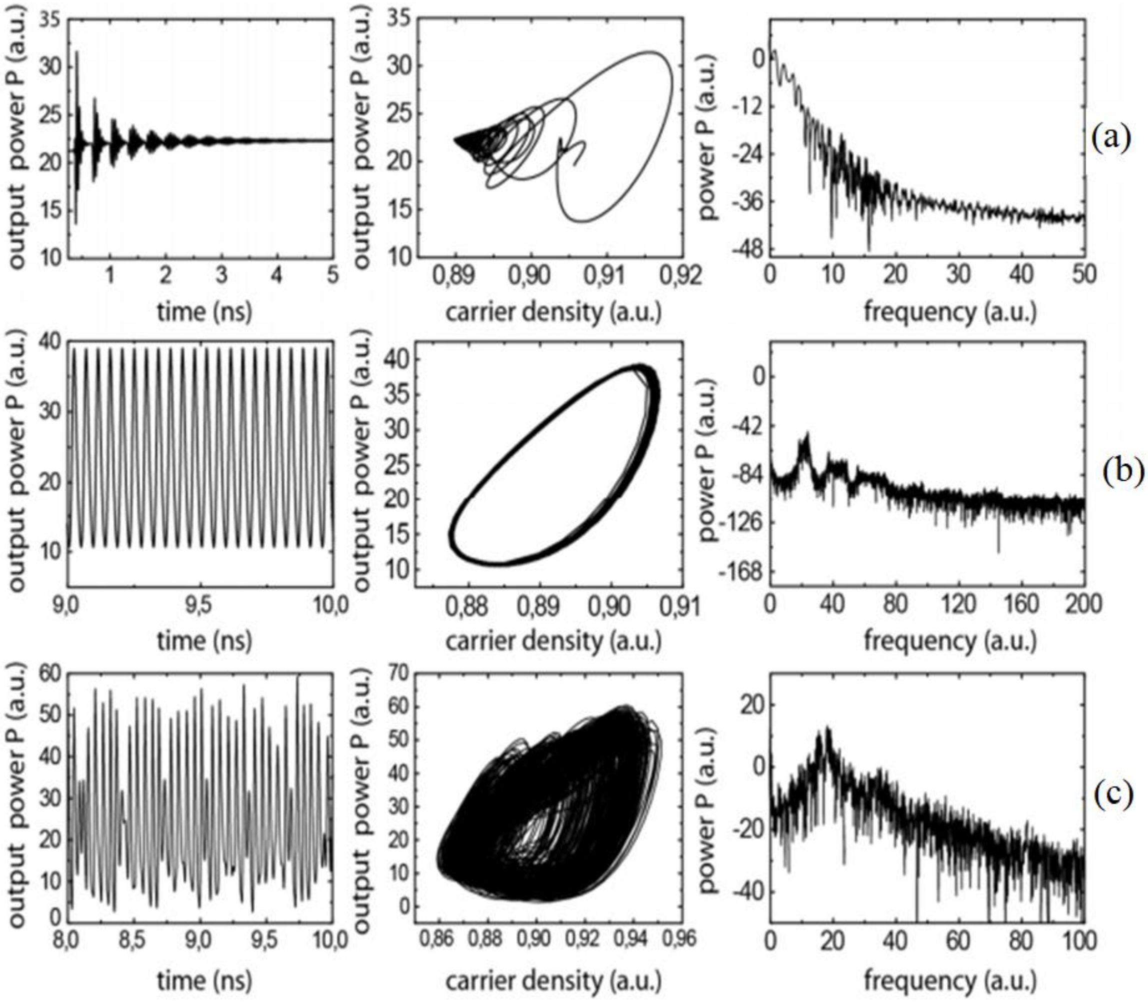

Fig. 19. Graphical representation of output power versus time (left side), phase portrait (centre) and power spectrum (right side): (a)$\gamma_1 = \gamma_2$= 15, (b)$\gamma_1 = \gamma_2$ = 20, (c)$\gamma_1 = \gamma_2$ = 40[A3].

When the feedback intensity is equal to 15 it is possible to see free oscillations for a few nanoseconds whose phase portrait represents waves that oscillate constantly by stabilization. An increase from 15 to 20 of the feedback intensity the pulsations are obtained periodic, and the phase portrait becomes a circle within the limit of some values of the feedback power. The values of the feedback intensity being equal to 40 allow to obtain a chaotic behaviour of the pulsations as observed in the left part of Fig. 19(c). Also, in this figure in the middle part a deformation of the non-periodic waves and multiple oscillations in the shape of a circle is observed. The chaotic behaviour is well analysed by observing the power spectrum represented in the right part of Fig. 19(c).

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The importance of this thesis lies in the presentation of theoretical results on the nonlinear dynamics of semiconductor lasers with quantum dot active medium influenced by optical feedback from multiple external cavities. The conclusions are as follows:

1. We analysed the theoretical model of advanced, small-sized semiconductor laser structures with quantum well active media. The presence of chaos in a multiple feedback laser was demonstrated. This chaotic regime was then employed in an optical communication system based on chaos. Under certain conditions, it was shown that two such laser systems could be synchronized when operating in a transmitter-receiver configuration. Perfect synchronization was achieved and the feasibility of encrypting and decrypting messages using chaotic modulation was demonstrated. Furthermore, it was demonstrated that the message could be adequately restored by the receiver, even at a signal transmission speed of over 10 Gb/s. (Chap. 2, § 2.2).
2. The nonlinear dynamics of the semiconductor quantum dot laser under the influence of optical feedback from several cavities were analysed. It was shown that the stationary states are no longer located on an ellipse, but rather, they have a complex shape. A study of the stability of these stationary states indicates that they become unstable due to Hopf bifurcation. A period-doubling scenario upon transitioning to chaotic oscillations was obtained. Phase portraits represent limit cycles for periodic evolution and strange attractors for chaotic evolution. Synchronization of two lasers degrades when the material and geometric parameters of the primary and secondary devices mismatch. A mismatch of the feedback phases has been observed to lead to loss of synchronization. Additionally, a mismatch of the laser amplification coefficients has been shown to lead to a significant degradation of synchronization. However, the number of quantum dots does not

significantly impact the synchronization characteristics of quantum dot lasers. Results obtained using the DDE-BIFTOOL program are consistent with those of direct numerical integration (Chap. 2, § 2.3). (Chap. 2, § 2.3).

3. The complex dynamics of a semiconductor laser under the influence of T-type optical feedback from two cavities were investigated theoretically. It was demonstrated that this system configuration is much smaller in size than existing chaos generation systems intended for chaos-based communication. Autocorrelation times smaller than 0.1 ns were obtained, indicating chaotic behaviour in the system. Additionally, the cross-correlation coefficient in the feedback phase plane was found to be greater than 0.95. This result demonstrates that two lasers can be synchronized via unidirectional coupling when the values of the primary and secondary laser parameters are identical. In a numerical experiment, digital signals from the transmitter were successfully decoded, even at high transmission speeds (>15 Gb/s). (Chap. 3, §§ 3.2, 3.3).
4. Two advanced photonic devices were theoretically proposed for experimental realization, in which optical feedback comes from several external horizontal cavities. Due to their improved stability and reduced development time and raw materials, these structures can be used in various experiments. Numerical calculations have shown that the proposed devices exhibit a chaotic regime over a wide range of parameters and that synchronization is easily achieved. This is a necessary condition for chaotic communication systems. (Chap. 3, § 3.4).
5. The nonlinear dynamics of a quantum dot laser structure under the influence of double optical feedback-one conventional and one with a filter-was investigated. The values of the parameters characterizing the second branch of the feedback were determined to control laser emission. It was demonstrated that such a laser could operate in two modes: continuous wave emission or as an optical chaos generator. We obtained analytical equations for stationary states with a complex distribution in the two-parameter plane. A chaotic regime of system evolution was obtained in a numerical calculation. (Chapter 4, §§ 4.2 and 4.3).

Recommendations:

1. It is recommended to implement the theoretical results obtained in practice.
2. It is recommended to develop software and calculation methods to obtain representative results in the field of semiconductor lasers.

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Annex 1 List of publications on the topic of the thesis

Articles in ISI and SCOPUS-listed international journals:

[A1] RUSSIAN, SS; OLOINIC, T.; TRONCIU, VZ Quantum dots lasers dynamics under the influence of double cavity external feedback, Optics communications, v. 381, p. 140 – 145, 2016. IF=2.12 https://doi.org/10.1016/j.optcom.2016.06.082

[A2] OLOINIC, T.; RUSSIAN, SS; TRONCIU, VZ Numerical simulations of quantum dots lasers under the influence of T-type external optical feedback. Applications to chaos-based communication. Romanian Reports in Physics, vol. 70. 411 p. 1-10(2018). IF=1.5 https://rrp.nipne.ro/2018/AN70411.pdf

In journals from the National Register of specialized journals, indicating the category:

[A3] RUSU, Spiridon OLOINIC, Tatiana CHISTOL, Vitalie, TRONCIU Vasile Characteristics of quantum dots laser subjected to conventional and filtered optical feedback, Journal of Engineering Science, Vol. XXVII, no. 2 (2020), pp. 44 – 51 DOI: 10.5281/zenodo.3784341 Category B+

[A4] OLOINIC, Tatiana; RUSU, Spiridon; TRONCIU, Vasile Synchronization of chaotic quantum dot lasers with external feedback under parameter mismatch, Moldavian Journal of the Physical Sciences, Vol. 17, 3-4, p. 142-147 2018 Categoria C.

[A5] OLOINIC, T.; RUSU, S.S; TRONCIU, V. Z. Communication with chaos using semiconductor lasers with an air gap, Moldavian Journal of the Physical Sciences, v.14, N. 1 – 2, p.113, 2016, categoria C. https://mjps.utm.md/archive/2015/article/43395

Proceedings of national conferences with international participation:

[A6] OLOINIC, Tatiana; RUSU, Spiridon; PÎRŢAC, Constantin; TRONCIU, Vasile Influence of parameter mismatch on synchronization of quantum dots lasers Telecommunications, Electronics and Informatics Conferința "Telecommunications, Electronics andInformatics" Ed. 6, 2018 Chișinău, Moldova, 24-27 mai 2018 p. 225-226 https://ibn.idsi.md/sites/default/files/imag_file/225-226_0.pdf

[A7] OLOINIC, T.; RUSU, S.; GRIGORIEV, E.; TRONCIU, V. Comunicarea optică bazata pe haos cu ajutorul laserelor cu puncte cuantice și feedback optic, 2016 Fizica şi tehnologiile moderne, 25-27 august 2016, Chişinău. Chișinău, Republica Moldova: Universitatea Tehnică a Moldovei, 2016, Ediția a 22-a, pp. 78-83. Disponibil: https://ibn.idsi.md/ro/vizualizare_articol/156675

[A8] OLOINIC, T.; RUSU, S.S; TRONCIU,V.Z. Comunicarea optică bazată pe haos cu ajutorul laserelor cu puncte cuantice, Tendințe contemporane ale dezvoltării științei: viziuni ale tinerilor cercetători ediția a V-a, UnASM, Chişinău, 2016, p.48-52. https://ibn.idsi.md/sites/default/files/imag_file/48-52_6.pdf

[A9] OLOINIC, T. Dinamica neliniară a laserelor cu puncte cuantice sub influenţa feedback-ului multiplu. Aplicaţii, Tendințe contemporane ale dezvoltării științei: viziuni ale tinerilor cercetători, ediția a VI-a, Chişinău, 2017, p.84-88. https://ibn.idsi.md/sites/default/files/imag_file/Tendinte%20contemporane_Vol_I%2C%202017.pdf

Theses at scientific forums and international conferences

[A10] OLOINIC, Tatiana The dynamic behavior of quantum dots laser under the influence of external optical feedback from five external cavities, NANO 2019 Conferința "SPINTECH Summerschool "S/F HybridStructures for Spintronics"" 2019, Chişinău, Moldova, 24-27 septembrie 2019 p.96 https://ibn.idsi.md/ro/vizualizare_articol/93034

[A11] OLOINIC, T.; RUSU, S.; TRONCIU V. Complex dynamics of quantum dots lasers under the influence of external multiple optical feedback. Conferința "International Conference on Materials Science and Condensed Matter Physics" Ediția 9, Chișinău, Moldova, 25-28 septembrie 2018 p.87 https://ibn.idsi.md/ro/vizualizare_articol/70650

[A12] OLOINIC, T.; RUSU, S.; TRONCIU, V. Dynamics of quantum dots semiconductor lasers under the influence of doublecavity feedback. Abstr.59th Scientific Conference for Students of physics and Natural Sciences, Open Readings Vilnius, Lituania, p. 196, 2016.

[A13] OLOINIC, T., RUSU, S. S; TRONCIU, V.Z. Chaos-based optical communication of semiconductor lasers with air gaps, International Conference Scienceand Society: the use of light. Humboldt Kolleg, Chisinau, 2015, p.31. https://www.repository.utm.md/handle/5014/20295?show=full

[A14] SANDUȚA, A.; OLOINIC, T.; RUSU, S.S.; TRONCIU,V. Z. Synchronization of chaos of quantum dots lasers under the influence of external cavity optical feedback. International Conference Scienceand Society: the use of light. Humboldt Kolleg, Chisinau, 2015, p. 30. https://repository.utm.md/bitstream/handle/5014/20294/Workshop-Science-Society-Use-Light-2015-p-30.pdf?sequence=1

[A15] ANTOHI, I.; OLOINIC, T.; SANDUȚA, A.; RUSU, S.S.; TRONCIU, V.Z. Multi Sections Semiconductor Laserswith an Air Gap for Chaos Based Communication, International Conference Scienceand Society: the use of light. Humbold Kolleg, Chisinau, 2015, p.28. https://repository.utm.md/bitstream/handle/5014/20292/Workshop-Science-Society-Use-Light-2015-p-28.pdf?sequence=1&isAllowed=y

[A16] OLOINIC, T.; RUSU, S.; TRONCIU, V. Nonlinear dynamics of quantum dots lasers under the influence of double cavity external feedback, NANO-2016: Ethical, Ecological and Social Problems of Nanoscienceand Nanotechnologies, p. 39-40, Chișinău, 2016. https://ibn.idsi.md/sites/default/files/imag_file/39-40_22.pdf

[A17] OLOINIC, T.; RUSU, S.S,; TRONCIU, V.Z. Chaos based communications with quantum dots lasers under the influence of multiple feedbacks, 8th International conference on materials science and condensed matter physics, p. 215, Chișinău, 2016 https://repository.utm.md/bitstream/handle/5014/9960/Conf_on%20Materials_Science%26Condens_Matter_2016_p215.pdf?sequence=1&isAllowed=y

[A18] OLOINIC, T.; RUSU, S.S.; TRONCIU, V.Z. Chaos communication with quantum dots lasers under the influence of multiple feedback. Multidisciplinarity in Modern Science for theBenefit of Society, Chişinău, 21-22 septembrie, 2017, p.45. https://repository.utm.md/bitstream/handle/5014/18740/Workshop-Multidisciplinarity-Modern-Science-Benefit-Society-2017-p45.pdf?sequence=3&isAllowed=y

ADNOTARE

la teza „**Dinamica complexă a laserelor semiconductoare cu mediu activ gropi și puncte cuantice**”, prezentată de Tatiana OLOINIC pentru conferirea gradului de doctor în științe fizice la specialitatea 131.03 „ Fizică statistică și cinetică”. Chisinău 2025.

Structura tezei include: introducere, 4 capitole, concluzii generale și recomandări. Teza se expune pe 131 pagini, bibliografia care constă din 147 titluri, și 56 figuri. Rezultatele prezentate în teză sunt publicate în 18 lucrări științifice.

Cuvinte cheie: lasere semiconductoare cu puncte cuantice, comportament haotic, bifurcații, dinamica complexă, sincronizare, comunicare optică bazată pe haos.

Domeniul de studiu: Științe ale naturii.

Scopul tezei: Scopul tezei constă în dezvoltarea teoriei dinamicii neliniare a laserelor semiconductoare cu mediu activ gropi și puncte cuantice prin propunerea de noi dispozitive cu secțiuni aer pentru utilizarea lor în sistemele optice de comunicare bazată pe haos.

Obiectivele: Dezvoltarea unui model ce descrie dinamica complexă a laserelor semiconductoare cu mediu activ puncte cuantice cu feedback optic provenit de la un rezonator exterior cu cavitate aer. Simularea efectelor dinamice neliniare a laserelor semiconductoare cu mediu activ puncte cuantice prin metodele modelării numerice. Analiza bifurcațiilor și stărilor staționare care apar în sistemul de ecuații diferențiale cu întârziere ce descriu sistemul laser cu feedback de la cavități exterioare și obținerea soluțiilor analitice. Determinarea parametrilor și a modului de apariție a diferitor structuri temporale precum autopulsații, turbulență optică și haos. Determinarea condițiilor de sincronizare perfectă a două lasere semiconductoare cu mediu activ puncte cuantice cu feedback multiplu și cavități aer cuplate unidirecțional. Analiza utilizării diferitor tehnici de codificare a informației în sistemul de comunicare bazate pe haos. Cercetarea comportamentului staționar al laserului cu puncte cuantice cu feedback dublu: unul convențional, iar altul cu filtru.

Noutatea şi originalitatea ştiinţifică a rezultatelor: în premieră este prezentat o structură nouă al laserului semiconductor și s-a analizat funcționarea acestuia sub influența unui feedback optic provenit de la mai multe cavități exterioare. S-a observat prezența unui comportament haotic în evoluția puterii emergente. De asemenea, s-a studiat funcționarea sincronă a două lasere semiconductoare cu mediu activ și puncte cuantice prin cuplarea lor unidirecțională. S-a realizat codificarea și decodificarea informației transmise prin astfel de sistem.

Problema ştiinţifică soluţionată în teză constă în studiul teoretic al structurilor noi ale laserului cu semiconductoare cu mediu activ puncte cuantice sub influența unui feedback optic provenit de la mai multe cavități exterioare pentru aplicații în sistemele de comunicare bazate pe haos. Prin simulare numerică a fost obținut domeniul parametrilor ce caracterizează dinamica neliniară a laserelor propuse, în particular pentru regiunile haotice.

Semnificaţia teoretică şi aplicativă constă în prezentarea unui model teoretic inedit al laserului semiconductor cu mediu activ puncte cuantice sub influența feedback-ului de la mai multe cavități unele fiind aer. Obținerea expresiilor analitice ale stărilor staționare. Identificarea, cu ajutorul programului DDE-biftool, a bifurcațiilor ce apar în sistem în condițiile comportamentului dinamic nelinear. Identificarea domeniului de apariție în planul a doi parametri a autopulsațiilor și haos optic puternic în laserele considerate. Elaborarea schemei de conectare a două lasere cuplate unidirecțional pentru a realiza sincronizarea perfectă în cazul laserelor identice. Studierea teoretică a fenomenelor optice ce apar în laserele cu puncte cuantice care prezintă interes major pentru înțelegerea funcționării lor și ulterior realizarea experimentală. Abordarea teoretică a procesului de comunicare optică bazată pe haos într-un sistem de lasere cu gropi cuantice cuplate unidirecțional în cazul laserelor non-identice.

Implementarea rezultatelor ştiinţifice: rezultatele acestei teze au fost cu succes implementate în cadrul proiectului din cadrul Programelor de Stat 20.80009.5007.08.

SUMMARY

of the thesis "**Complex dynamics of semiconductor lasers with active medium quantum wells and dots**", presented by Tatiana Oloinic to obtain the PhD degree in physical science in the specialty 131.03 "Statistical and kinetic physics".

The structure of the thesis includes: introduction, 4 chapters, general conclusions and recommendations. The thesis is presented on 131 pages, the bibliography which consists of 147 titles, and 56 figures. The results presented in the thesis are published in 16 scientific papers.

Keywords: semiconductor quantum dot lasers, chaotic behaviour, bifurcations, complex dynamics, timing, chaos-based optical communications.

Research field: Natural Sciences.

The main purpose of the thesis consists in developing the theory of nonlinear dynamics of semiconductor lasers with active medium holes and quantum dots; proposing new air-section devices for their use in optical chaos-based communication system; the development of new programs for performing numerical calculations in order to find parameters that correspond to the operation of lasers in a chaotic regime, the theoretical explanation of the phenomena observed in the experiments.

The objectives: Development of a model that describes the complex dynamics of semiconductor lasers with active medium quantum dots with optical feedback from an external resonator with an air cavity. Analysis of bifurcations and steady states occurring in the system of delayed differential equations describing the laser system with feedback from external cavities and obtaining analytical solutions, as appropriate. Determining the parameters and the mode of appearance of different temporal structures such as self-pulsations, optical turbulence and chaos. The latter is the necessary condition for optical communication systems based on chaos. Determination of perfect synchronization conditions of two active medium semiconductor lasers with multiple feedback quantum dots and unidirectional coupled air cavities. Analysis of the use of different information coding techniques in chaos-based communication system. Simulations of nonlinear dynamic effects of semiconductor lasers with quantum dot active medium through numerical modelling methods. Investigating the steady state behaviour of double feedback quantum dot laser: one conventional and one with filter. The study of chaos-based communication using quantum-hole lasers and multiple feedback. Numerical modelling by simulating the nonlinear dynamical effects of self-pulsations, optical turbulence and chaos.

Scientific novelty and originality of the results: for the first time, a new structure of the semiconductor laser is presented and its operation under the influence of optical feedback from several external cavities was analysed. The presence of chaotic behaviour in the evolution of emerging power was observed. The synchronous operation of two active medium semiconductor lasers and quantum dots by their unidirectional coupling was also studied. Coding and decoding of the information transmitted through such a system was achieved. Numerical modelling by simulating the nonlinear dynamical effects of self-pulsations, optical turbulence and chaos.

The scientific problem solved consists in proposing new structures of semiconductor lasers with quantum dot active media, with the aim of a theoretical analysis of the dynamic behaviour and its operation for their use in chaos-based optics.

Theoretical and practical significance: in this thesis, the complex dynamics of semiconductor lasers with active medium quantum dots under the influence of optical feedback from several external cavities is demonstrated. New structures of lasers were proposed and optical phenomena such as optical turbulence, unidirectional synchronization of lasers were theoretically investigated. According to the presented theoretical results, lasers have their applicability in various fields and in everyday life their rapid development is a current requirement.

Implementation of scientific results: the results of this thesis were successfully implemented within the project within State Programs 20.80009.5007.08.

TATIANA OLOINIC

COMPLEX DYNAMICS OF SEMICONDUCTOR LASERS WITH HOLE AND QUANTUM DOTS ACTIVE MEDIUMS

131.03 – STATISTICAL AND KINETIC PHYSICS

Scientific summary of the doctoral thesis in physical sciences

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