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Ph.D. THESIS SUMMARY

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Studies on the behaviour of semiconductor laser systems coupled with two external cavities for secure communications

THESIS COMMITTEE

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Content

Chapter 1

Introduction

1.1 Presentation of the field of the doctoral thesis

Semiconductor lasers optically coupled with external cavities, operating in optical reaction mode (optical feedback) have been studied both theoretically and experimentally in relation to their applications: control of nonlinear (chaotic) dynamics of laser emission and generation of chaotic multi-dimensional dynamics for encoding informations [1-3]. Regarding the latter category, studies were carried out to determine both the signature of the external cavity from the measurement of the frequency of the oscillations generated by it and to hide the information about the geometry of the external cavity used [4-6]. Chaotic, double reflecting external cavities laser systems that use diffraction gratings as an external reflecting element have been studied both theoretically and experimentally in connection with the blocking of laser frequencies and the increase in power for applications in fiber optic lasers or the analysis of mixed dynamic state modes [7,8].

1.2 Objective of the doctoral thesis

In this thesis I got a lot of new results on the analysis, control and synchronization of chaotic dynamics in low frequency fluctuations of the emission of laser diodes with external cavity usable in encoding and transmitting information.

Thus we have carried out a series of experimental studies on the chaotic laser emission of laser diodes in single or double external optical cavity and its control by modulating the injection current in a chaotic coupled laser system (master- slave) [9,10].The study of the dynamics of laser diode emission under double optical reaction conditions revealed a high-frequency oscillation regime modulated by low-frequency fluctuations. Changing the feedback intensity in one of the cavities allows high-frequency oscillations to be obtained with the frequency of the grantable in the system consisting of the two external cavities coupled. The results presented in the thesis are the first experimental observations reported in the literature of such frequency behavior of a system with two external cavities (D-ECSL) [11]. These can be applied in the field of encoding and transmitting data using laser carriers because the frequencies involved do not carry information about the geometry of the experimental system.

The experimental study of the dynamics of LFF fluctuations under optical coupling conditions was carried out for two semiconductor laser systems operating in optical feedback mode and coupled in a master-slave system in chaotic synchronized mode. It has been shown that the LFF fluctuations of the slave system can be controlled by modulating the injection current of the master system, depending on the modulation frequency and natural LFF frequencies [10].

For the theoretical approach, I used the numerical simulation of the evolution of the Lang-Kobayashi rate equations, which are considered the best approximation of how a semiconductor laser works in moderate feedback conditions [12]. These simulations allow an evaluation, before performing the experiments, of the results that can be obtained according to the experimentally controllable parameters. The numerical results obtained show that the developed multimodal model simulates the dynamics of the chaotic emission of the experimental D-ECSL system for a particular set of parameter values [13].

1.3 Content of the doctoral thesis

The thesis is structured into 7 chapters, the first two present the field of the doctoral thesis and some general notions about the nonlinear chaotic dynamics of semiconductor laser emission with external optical cavity. Chapters 3-6 present the research performed, and chapter 7 presents the personal contributions in the field of the doctoral thesis.

Chapter 2

Nonlinear chaotic dynamics of semiconductor laser emission with external optical cavity

2.1 Introduction

Laser physics and chaos theory developed independently until 1975 when Haken discovered that an analogy could be made between the Lorentz equations of convective fluid flow and the Maxwell-Block equations describing the interaction between light and matter in a single-mode laser [14]. These early investigations led to the study of the behavior of laser diodes considered as damped nonlinear oscillators [15].

2.2 Semiconductor laser

2.2.1 Construction and operation

The stimulated emission of radiation can occur as a result of the process of recombination of electrons and holes in a pn junction (laser diode) if it is supplied with a direct voltage (dc) whose value allows the population to be reversed in the junction area. Laser diodes are the only devices that allow the modulation of amplitude of the emitted radiation by modulation of the pumping energy. This property allows the use of laser diodes in the optical transmission of information using a modulated laser beam.

For the laser emission to occur at the level of a p-n junction, it is necessary to use a "degenerate" semiconductor structure in which the doping exceeds a certain limit on both donor and accepting impurities. Carriers, electrons and holes are produced in the active area, which ensures the operation with positive optical gain of the laser diode [16].

2.2.2 Laser emission control parameters

The wavelength of radiation emitted by a semiconductor laser depends on a number of parameters, some fixed by construction (the gap, the length of the laser cavity), others that can be experimentally controlled (the temperature of active medium and injection current) [17].

2.2.3 Deterministic chaos in lasers physics

As for the lasers there are certain conditions in which the emission, although coherent, has a chaotic deterministic behavior. Chaos theory has found a number of applications in laser physics for example: use of chaotic laser radiation in encrypted data transmission using chaotic systems, use of a delayed feedback signal to control the dynamics of a stable and adjustable semiconductor oscillator [19].

2.3 External cavity semiconductor laser (ECSL) configuration

2.3.1 Feedback effects on laser dynamics; chaotic dynamics

In the case of semiconductor lasers, chaotic emission behaviour may be highlighted under the conditions of an external optical reaction (feedback) obtained by placing in the path of the laser beam a reflecting optical element that can turn some of the radiation emitted to the active laser medium [20]. The re-injection into the cavity of the laser diode of a small fraction of the emitted radiation determines at the output a chaotic signal formed by the overlapping of several types of waves, characterized by a series of properties. The multitude of dynamics results from the competition between the own relaxation oscillations of the laser diode and the oscillations of the external cavity [21,22].

2.3.2 Low frequency fluctuation regime (LFF)

Low frequency fluctuations are chaotic oscillations that occur in laser emission when an external cavity semiconductor laser system (ECSL) operates at a current close to the laser threshold. This regime is generated by system instabilities and occurs in the form of intermittent oscillations at critical or bifurcation points, in which two different states of a nonlinear system overlap and compete [23,24].

This chaotic regime of a semiconductor laser emission under optical feedback conditions is the most studied, it being presented in the form of periodic drops, close to zero, of the laser intensity. These emission fluctuations occur at low frequency values, in the low band range up to 100 MHz and are different from the fast oscillation regime, with values of the order of 1 GHz.

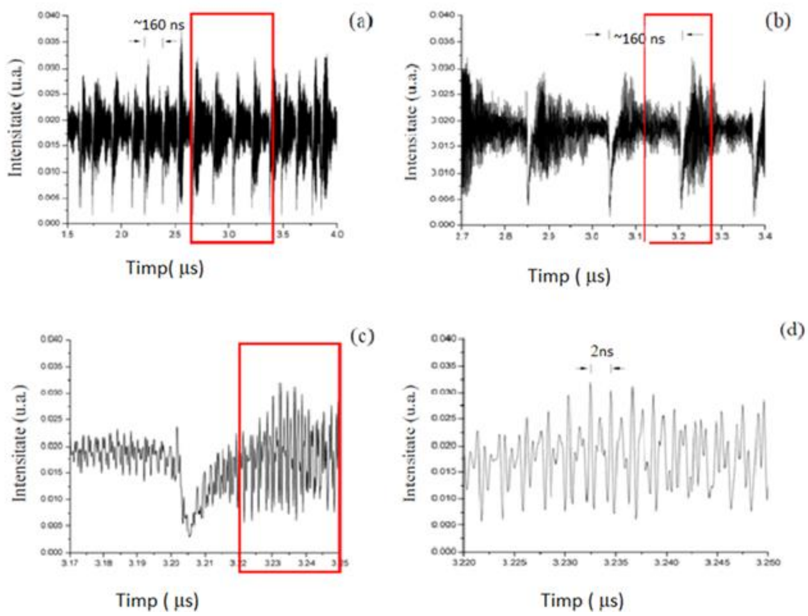

Figure 2.10 *The intensity time series: (a) LFF chaotic dynamic; (b) detail of the area marked in (a); (c) rapid oscillations - detail on the area marked in (b); (d) rapid oscillations - detail on the area marked in (c). Operating parameters: I = 1.04 × Ith, t = 24 ° C and Lext = 30cm. In (a) - (b) and (c) the characteristic average periods of the LFF oscillations and of the oscillations of the external cavity modes are indicated.*

LFF fluctuations are the envelope for other rapid oscillations associated with the modes of the external cavity (Figure 2.10 b-d), which in turn form high frequency pulse trains. It is observed in figure 2.10 c) that these pulse trains are interrupted at irregular intervals by sudden drops in laser intensity, followed by an increase in it. These pulses follow a chaotic scenario. The occurrence of LFF chaotic fluctuations is usually accompanied by an increase in the emission power of the laser system, compared to the threshold emission of the laser in the absence of optical feedback due to the fraction of radiation reinjected into the laser cavity [25]

2.3.3 Single and double external cavity semiconductor laser systems

The observation of the chaotic LFF emission of a semiconductor laser is only possible if an optical feedback is applied. This requires the existence of an external optical cavity that can send back to the laser junction a fraction of the emitted radiation.

The external cavity with double optical reflector (D-ECSL) combines a linear external cavity, limited by a diffraction grating in Littrow configuration, which realizes the optical feedback on the - 1 diffraction order, with a Littman cavity that ensures the optical feedback on the zero diffraction order.

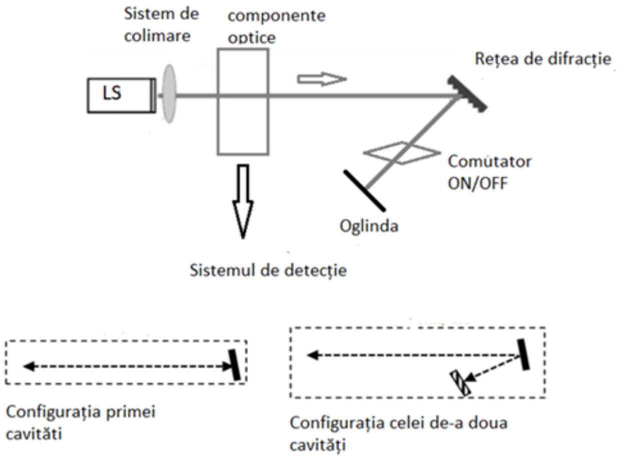

Figure 2.15 *Scheme of D-ECSL experimental setup*

2.4 Fourier analysis of the chaotic dynamics of laser emission; power spectrum

The analysis of the intensity time series can provide information about the existence of a dominant evolution of the system, about the appearance of periodic oscillating processes and how they will evolve in the future. Applying the fast Fourier transform to a time series of a measurable parameter allows to obtain the power spectrum of the parameter and does not allow to maintain information on the frequency of some events in the time series.

2.5 Control of chaotic dynamics by current modulation

The emission of a laser diode can be modulated, without disturbing its dynamics by introducing a periodic signal (small amplitude) applied to the supply current of the laser diode through the control source so that the emission synchronizes with this signal.
This type of modulation is used in digital optical communications where the signal transmitted by the laser diode modulates the optical carrier.

Chapter3

Chaotic low-frequency fluctuations of the laser diode emission at injection currents above the laser threshold

3.1 Introduction

In this chapter, I presented a detailed analysis of the LFF regime and the experimental data obtained in the thesis on the stability of this regime for different values of the experimental parameters

3.2 External-cavity semiconductor laser (ECSL) system

3.2.1 ECSL- experimental system

The experimental set-up used is represented in figure 3.1. It was used to determine the reproducibility conditions and value ranges of the system operating parameters, for which chaotic dynamics such as low frequency fluctuations (LFF) can be obtained.

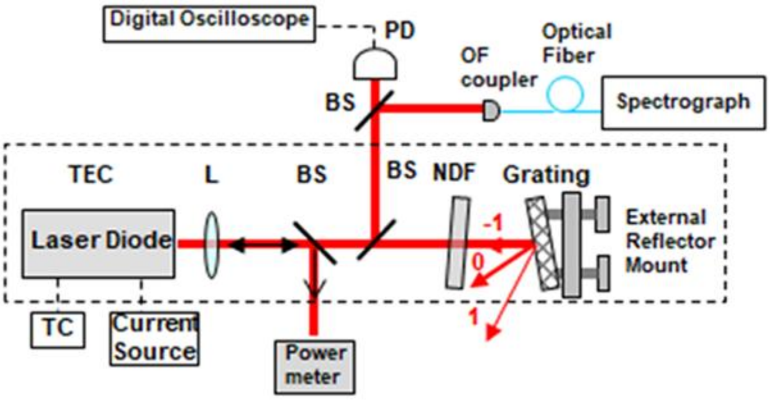

Figure 3.1 The experimental setup. TEC, thermo-electric controller mount; TC, temperature controller; L, collimation lens systems; BS, beam splitters; NDF, neutral continuously variable density filter; PD, photodetector; OF, optical fiber; -1, 0, 1, diffraction orders.

In the experimental set-up (Figure 3.1) a first beam splitter (BS 1) separates from the ECSL emitted power a fraction of 33% to reach the power meter; the remaining 66% goes to the second beam splitter (BS 2), which separates from the laser beam, by reflection, a fraction of 17% which is sanded to a photodetector and transmits a fraction of 82% to the neutral density filter (NDF). Here, the laser beam is transmitted with variable attenuations (set attenuation values) direct to the reflector element, e.g., mirror or diffraction grating. The 17% reflected laser beams are used to analyse the evolution of laser intensity (intensity time series) and the optical spectra structure of the emission.

3.2.2 Technical specifications of the sub-assemblies

The used laser diode is of Fabry-Perot type and it is stabilised by means of an injection current control unit, Lightwave, LDX-3620 type. The used laser for ECSL system is a Mitsubishi laser diode, ML101J8 type. Maximum power (40 mW) is obtained at the optimally operating parameters in continuous wave emission, current I= 109mA and temperature t=24°C, at the wavelength λ=663 nm. In the absence of the optical feedback the laser diode presents a laser emission threshold at I_{0th}= 54 mA. The temperature is controlled using a Lightwave control unit, LDT-5910B type, by means of two Peltier temperature control elements of 16 W type. The optical signal is purchased with the ET-2030A photodetector (Laser 2000), coupled with a Tektronix DPO7254 oscilloscope used to record and analyze the time series of laser intensity. The spectral structure of the LSCE system emission was recorded with a Princeton Instruments monochromator (Acton SpectraPro 2750 type) with an optical resolution of 0.02 nm.

3.3 The power-current characteristic and "mode-hopping" effect

The analysis of the reported literature results shows the usefulness of a high chaotic state for sending a large volume of data, while allowing the laser operation at a power level high enough to synchronize several receivers, but - in order to achieve a stable synchronization in one-point to multi-point configuration (a ECSL transmitter and one or more ECSL receivers) - it is preferable ECSL systems with a low chaotic state.

A possible solution to meet both these requirements is to apply an injection current above the lasing threshold, at a value corresponding to the occurrence of the mode-hopping phenomenon (intensity jump between active laser modes). These jump points, not being specified in the technical details of the laser diodes, are determined only experimentally from the power-current graph, at different temperatures of the laser diode.

In Figure 3.6 is presented a series of 6 consecutives spectra acquisitioned with an exposure time of 100 μs at 24.9 ^{o}C diode temperature and 79.9 mA injection current.

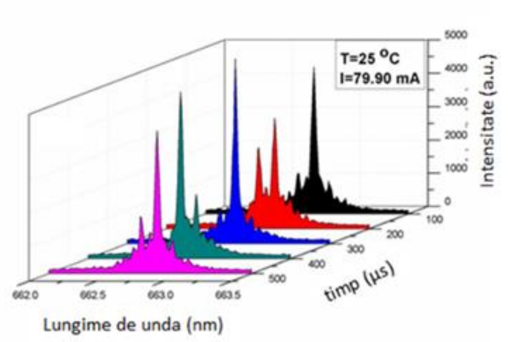

Figure 3.6 The effect of mode-hopping at 79.9 mA injection current and 24.9 ^{o}C diode temperature. Series of optical spectra of laser emission-free acquired at an interval of 100 μs

3.4 Results and discussion

The measurements showed the laser emission characterized by an LFF type dynamics at injection currents higher than the laser threshold current. At a temperature of 24.9°C we made a comparative study on the characteristics of this emission depending on the type of external reflecting element: the total reflecting mirror and the diffraction grating used in reflection in the -1 order. At temperature of 24.9 ^{o}C the laser threshold of free emission appears at I_{th}= 58 mA injection current; critical points appear at the injection currents of 59.7 mA (1.03*Ith) and 79.9 mA (1.38*Ith). In the external optical feedback conditions, in the case of both external reflectors, the LFF stable fluctuation (without alternations between LFF and constant emissions) has been obtained at injection currents I_1= 59.7 mA (1.03*I_{th}) and I_2= 82.36 mA (1.42*I_{th}), in the last case at a value higher than that obtained in the case of free emission.

Figure 3.8 shows the intensity time series for currents I_1 and I_3 and their associated power spectra.

When the diffraction grating was used as external reflector, -1 diffraction order was selected to provide optical feedback. This returns in the cavity a percentage of 43 % of laser power incident on it. Measurements were made at 24.9 °C, and at about the same injection currents as in mirror case (corresponding to critical points).
In both cases, stable low frequency fluctuation regimes (LFF) were obtained at the critical points (mode hopping) on the laser power-current characteristic. Also, it was observed that to obtain stable LFF fluctuations regimes in conditions of ECSL system operation at injection currents different from laser threshold, it is necessary to use feedback intensities of the same order of magnitude as in the case of the laser threshold.

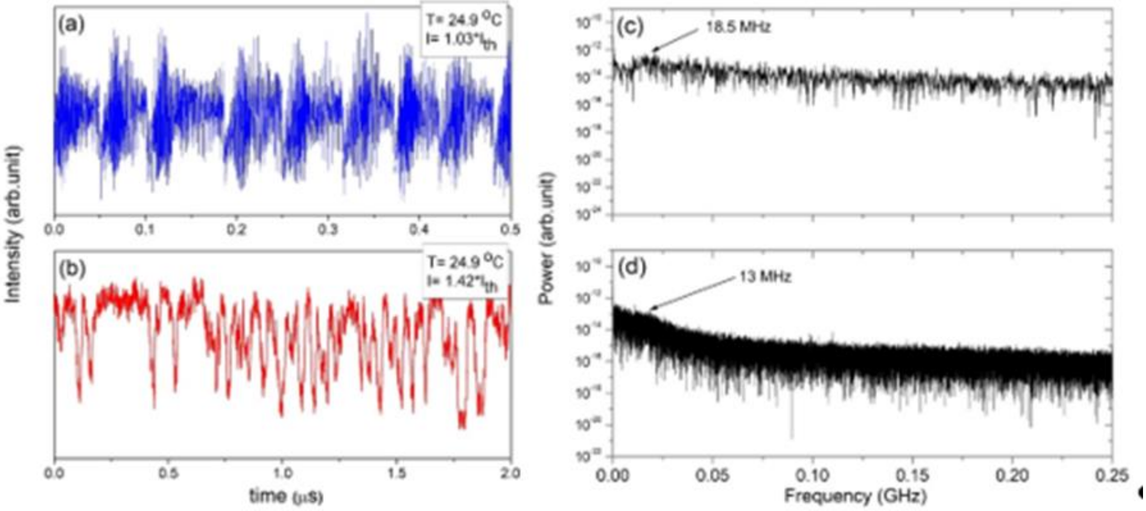

Figure 3.8 *The intensity time series and associated power spectra for the injection currents (a)/(c) $I_1=1.03*I_{th}$ and (b)/(d) $I = 1.42*I_{th}$, when the mirror is used, and I_{th}= 58 mA,t = 24.9^{0}C.*

3.5 Conclusions

Measurements carried out at laser threshold current and at higher values (I_{th}, 1.03 * I_{th}, respectively 1.42 * I_{th}) for a constant diode temperature, showed emission regimes with stable LFF fluctuations for power of feedback of the same order of magnitude as those corresponding to the laser threshold. No stable LFF fluctuation regimes were observed for measurements performed at the same injection currents and feedback coefficients corresponding to reinjected power values by an order of magnitude smaller (or larger) than the values obtained at the laser threshold.

Chapter 4

High frequency chaotic dynamics in a semiconductor laser with double-reflector selective cavity

4.1 Introduction

A semiconductor laser system with a double external cavity consists of a cavity delimited by a diffraction grating, in Littrow configuration, which ensures the reinjection at the laser junction of the -1 order of diffraction, and a second cavity delimited by a flat mirror, Littman cavity that returns the order of 0 diffraction.

This system is used to analyse the characteristics of high frequencies mixing of the chaotic dynamic state. Also, the intensity time series show a pulsing behaviour which consists of high frequency oscillations (HFO), as result from the interference of different longitudinal modes provided by the two external cavities, all of them being modulated by low-frequency fluctuations. By changing the intensity of the feedback in the long cavity, tunable high-frequency chaotic oscillations are obtained.

4.2 Dynamics of the semiconductor laser system with double- reflector selective cavity

The dynamics of external cavity semiconductor lasers (LSCE) have been investigated through theoretical models, the first proposed being the Lang-Kobayashi model. This model was simplified for the local analysis of the chaotic dynamics of LFF in the limit of long delay times in the external cavity and later developed for the study of double cavity ECSL systems [12].

4.3 Double reflector external-cavity semiconductor laser (D-ECSL) system

The used D-ECSL setup is based on the ECSL system but in this case besides the optical feedback ensured by grating on -1 -diffraction order, also a new component is received through the 0 -diffraction order as feedback from an external mirror (Figure 4.1). Thus, the D-ECSL system consists in a double reflector cavity, with C1 cavity formed between laser and grating (with length L_{C1}=42 cm) and with C2 (L_{C2}=64 cm) cavity made between laser and mirror (Figure 4.1, inset pictures). The C2 configuration forms a Littman cavity and has as common branch the C1 cavity configuration.

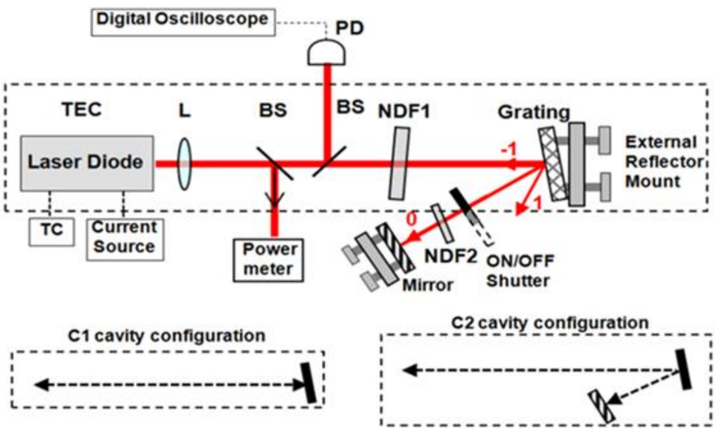

Figure 4.1*Scheme of D-ECSL experimental setup. TEC, thermo-electric controller mount; TC, temperature controller; L, collimation lens system; BS, beam splitters; NDF 1, neutral continuously variable density filter; NDF 2, neutral step-variable density filter; PD, photodetector; -1, 0, 1 - diffraction orders.*
The inset sketches depict C1 and C2 external cavity configurations

The On / Off mechanical switch connects or disconnects the cavity C2, respectively. The feedback intensities in cavities C1 and C2 are transmitted to the laser with variable intensity depending on the coupling coefficients c1 and c2 through the filters C1-NDF and C2-NDF.

4.4 Results and discussion

In Figure 4.4 are shown the power spectra associated to laser intensity time series obtained for D-ECSL system at I_{th} threshold current, c_1= 0.37 and t= 24.9 ^{o}C, working in the configurations:

- only C1 cavity (c_2=0),
- only C2 cavity (c_2=1.0; grating aligned slightly out of the position for which C1 feedback is obtained, and C2 cavity realigned consequently);
- C1C2 cavity with c_2= 1.0, 0.63 and 0.16, corresponding to strong and weak C2 feedback intensities.

For D-ECSL system working only on C1 or C2 external cavities, power spectra present a first frequency component in the base band, associated with low-frequency fluctuations (**υ_{LFF}**) a second component associated to the high frequency oscillations of the external cavity (**υ_{EC}**), followed by its harmonics (**υ_{HFO}**).

For D-ECSL system working on C1C2 coupled cavities at a coupling coefficient c_2 = 1.0, power spectrum presents the same frequency components as for the system operating only with C2. If the C2 feedback intensity is reduced from a coupling coefficient c_2 = 1.0 to 0.63, and then to 0.16, the power spectra also show a component associated with LFF fluctuations.

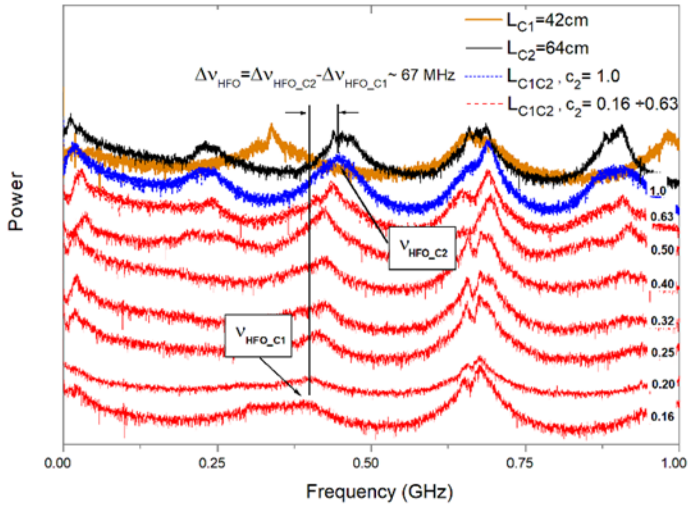

Figure 4.4 *υ_{HFO} frequency shift with C2 feedback variation. Power spectra for C1, C2 and C1C2 (c_2= 1.0) cavity configurations are the same as in Figure 2. Parameters: I_{th} threshold current, c_1= 0.37, and t= 24.9 °C*

The component associated to external cavity oscillations, in the case of c_2 = 0.63 is close but different from that of cavity C2, and in the case of c_2 = 0.16 this is no longer present in spectrum. The frequency of chaotic fast oscillations (υ_{HFO}) of D-ECSL system emission for increasing values of the coupling coefficient c_2 has values in the **Δ**υ_{HFO} frequency range (Figure 4.4). This is limited by the frequency of high-frequency oscillations, υ_{EC1}, when c_2 coefficient is close to the minim and υ_{HFO-C2} has values close to the υ_{EC1} frequency of the C1 external cavity oscillations, and to the frequency of first harmonic corresponding to C2 cavity (υ_{HFO_C2}). Thus, the characteristic frequencies (υ_{HFO}) of the D-ECSL system show higher values as the coupling coefficient c_2 is higher. The analysis of the behavior of υ_{HFO} frequencies was made for two other values of the coupling coefficient c1 of the cavity C1, for feedback powers of 0.03 mW, respectively 0.02 mW in the cavity C1 (Figure 4.5).

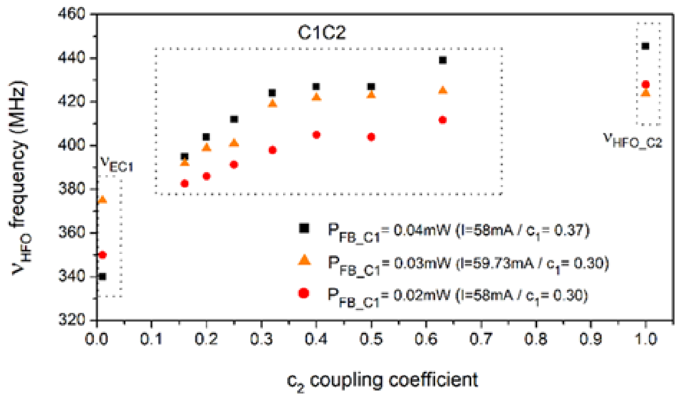

Figure 4.5 *υ_{HFO} frequency behavior function of c_2 coupling coefficient of C2 cavity for three C1 cavity feedback powers (P_{FB_C1})*

In both cases it is observed that the high frequency values, υ_{HFO}, show the same evolution as in the case of the feedback power of 0.04mW used in the C1 cavity. The difference is due to the fact that the υ_{HFO} frequency values are higher as the feedback intensity in the C1 cavity is higher.

4.5 Conclusions

By using the D-LSCE system it was shown that tunable high frequency (υ_{HFO}) chaotic oscillations can be generated in the semiconductor laser emission. By using a second external cavity combined with the change in feedback intensity, the frequency of high oscillations of the D-ECSL system can be adjusted almost continuously over a range of tens of MHz.

The results shown here are the first experimental observations reported in the literature of such behavior of HFO frequencies of a D-LSCE system and can be used in encoding and transmission of data and information using optical carriers since the frequencies involved do not carry information about the geometry of the geometry of D_ECSL system.

Chapter 5

Control of slave chaotic dynamics by master current modulation in a chaotic coupled laser system

5.1 Introduction

Two laser semiconductor systems operating in optical feedback mode can be coupled in a MASTER-SLAVE (transmitter-receiver) assembly, forming a system that works in chaotic synchronized mode. Frequency modulation of the master laser current induces periodic drops in the emission power in the Slavic system, observing two dominant frequencies: one induced and one natural.

5.2 Experimental set-up

The experimental set-up (Figure 5.1) is based on two identical ECSL assemblies with a length of approximately 64 cm (feedback delay time τ = 4.3ns). The two ECSL systems were optically coupled using a coupling attenuator in a two-way delayed timing assembly. We used a Mitsubishi ML101J8 single-mode laser diode with a wavelength of 663 nm.

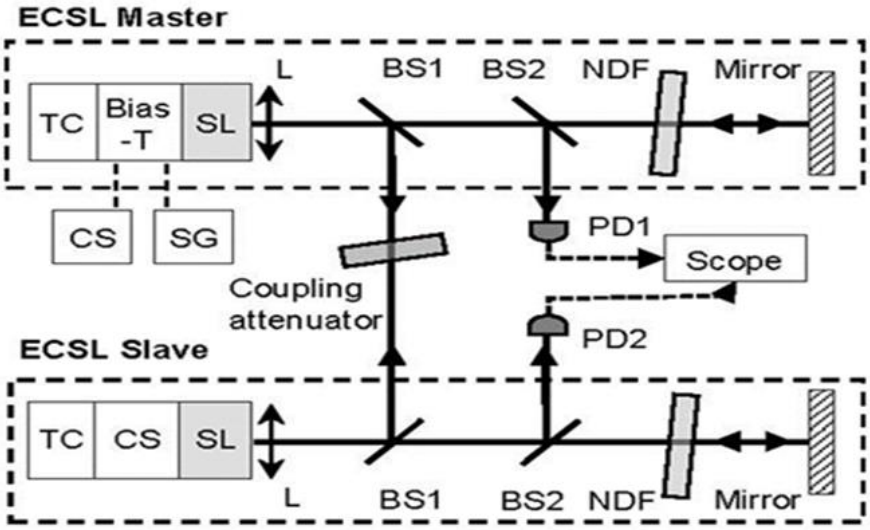

Figure5.1 *Setup of two chaotic lasers bidirectionally coupled into a master-slave synchronization scheme. Master laser is driven by a periodic signal generator (SG);SL-semiconductor laser; ECSL-external cavity semiconductor laser system; BS-beam-splitter; TC-temperature controller; CS- direct current source Bias-T-frequency multiplexor.*

5.3 Results and discussions

The dynamics of the coupled laser system in the presence of external modulation was studied for two frequencies, with a modulation factor m = 3.4 × 10-2, where ***m*** is defined as a fraction between the intensity of the modulation RF current and the intensity of the direct current.

The method used to characterize the synchronization state between the laser and the modulator is based on Shannon entropy, being evaluated the entropy of the assembly constituted by the time intervals between the consecutive zero power drops. The rate of power drops of the optically coupled master and slave was investigated according to the frequency of the modulation current. Using for the modulation of the master two frequencies, 8 MHz, respectively 15 MHz, signal power drops are induced with a period of 0.125 μs, respectively 0.067 μs, resulting in laser emission LFF type fluctuations at two dominant frequencies, one natural and one induced by modulation. It has been observed that the LFF fluctuations of the slave system become more ordered in the coupled system; also, when the master is modulated at 8 MHz, respectively close to the natural frequency of its LFF type oscillations (10 MHz), the two systems, the master and the slave have the same frequency (Figure. 5.5).

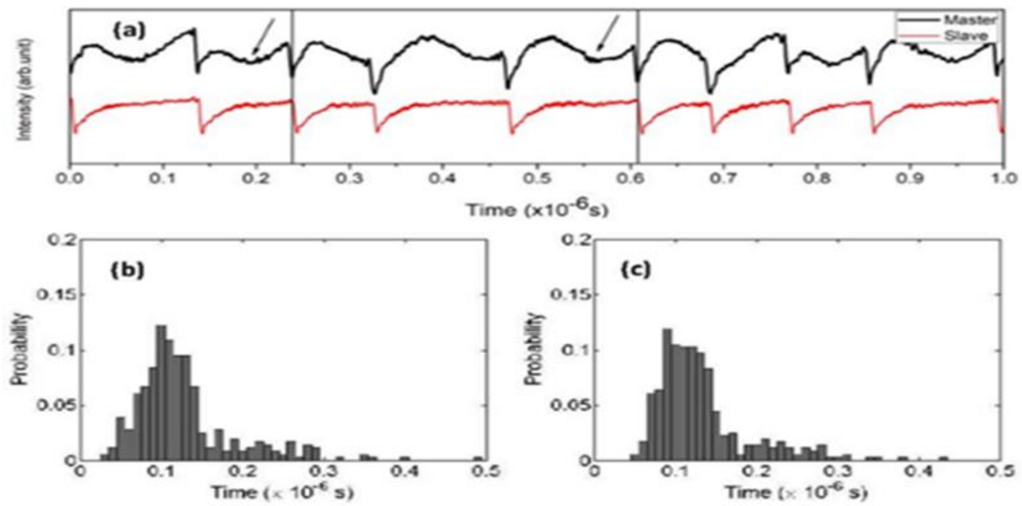

Figure 5.5 *Master and slave systems chaotically coupled at 8 MHz: (a) intensity time series for master and slave coupled systems; (b) and (c) histograms of power dropouts for master and slave, respectively. Arrows indicate intensity oscillations induced by the modulation for which master LFF dynamics does not engage*

5.4 Conclusions

Driving master laser induces periodic dropouts with two dominant frequencies. The modulation of the master at a frequency that is not in the range delimited by the natural LFF frequencies of the master and the slave has no influence on the chaotic dynamics of the slave. It only serves to group the periods of power dropouts, but at other frequency values than modulation. The reported results on the behavior of the chaotic dynamics of laser emissions obtained in different conditions of external optical feedback show a wide range of possibilities for generating and controlling chaos; this has potential for application in data encoding and information transmission using chaotic optical carriers [19,33,34].

Chapter 6

Numerical simulation of chaotic multimode dynamics of a semiconductor laser optical coupled with two external cavities

6.1 Introduction

This chapter presents a numerical simulation of chaotic multimode dynamics of a semiconductor laser external cavity, optical coupled with two reflectors (double external feedback) previously developed (D-LSCE). The numerical model, according to the experimental observations, simulates the 3 active laser modes of the D-ECSL system emission by coupling 3 single-mode systems that have the same feedback source and operate at different feedback values. A multimode extension of the Lang - Kobayashi rate equation model was used to develop the model [2, 12, 35]

6.2 Experimental system and simulation model

6.2.1 Experimental system

The experimental system of D-ECSL has been described previously. In this case, the diffraction grating assures optical feedback on 0-th diffraction order and the mirror on 1st diffraction order of the grating. The photodiode and oscilloscope used to analyze the intensity time series, a spectrograph was also used to monitor the D-ECSL emitted optical spectra. The used parameters were injection current I= 58mA, semiconductor case temperature t=24.9^{o}C, and coupling coefficients, c_1=1.0 and c_2=0.72, corresponding to the neutral density filter transmissions in C1 and C2 cavities, respectively. The C1 and C2 cavities alignement and the other used parameters were described in detail in the thesis.

At the used parameter, the D-ECSL system emits at λ=662 nm a total power P_0=1.79 mW, for a calculated feedback power P_{FB}=0.313 mW, which correspond to a moderate total feedback intensity, 17%.Under these conditions, the opyical spectrum shows a multimode structure with 3 active modes. (Figure 6.1 a).

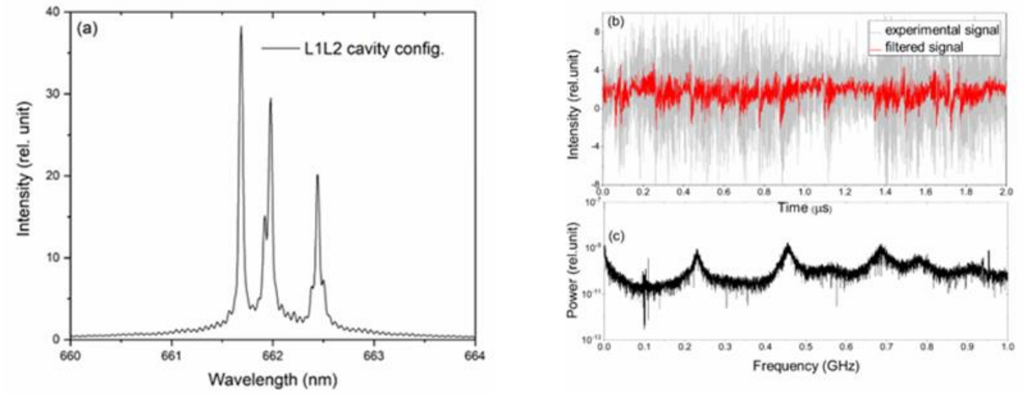

Figure 6.1 *D-ECSL system emission characteristics; (a) optical spectrum, (b) power intensity time series and (c) associated power spectrum for I= 58 mA, t= 24.9 °C, c_1= 1.0 și c_2=0.72.*

In the C1 configuration case it is returned the same power ratio for each mode, while in the C2case the power is returned differentiated for each mode separately, depending on the position of the grating and the mirror. For used experimental conditions, the components of the power spectra (frequencies) can correspond to low frequency fluctuations (LFF) with maxima up to 100 MHz, to external cavities oscillation frequencies, 337 MHz (C1 case) and 230 MHz(C2 case) and to their harmonics or to a mixture of them [9,36].

6.2.2 Differential equation system for modeling D-ECSL emission

The numerical simulation of the chaotic emission of the D-ECSL system is based on the Lang- Kobayashi [12] type rate equations for complex field, written for a compound cavity obtained by adding a selective mode of external feedback term to the standard equations. The dynamics of a semiconductor laser system, operating multimode with moderate feedback is given, for every laser active mode, by the set of equations describing the rates of variation of the internal field E_m (in complex form) and of the carrier density, N,[34,34]:

$$\frac{dE_m(t)}{dt} = (1+i\alpha)(G_m(t)-\gamma_m)\frac{E_m(t)}{2} + \frac{k}{\tau_L}E_m(t-\tau)e^{-i\omega_{0m}\tau} + \sqrt{2\beta N(t)}\xi(t) \quad (6.1)$$

$$\frac{dN(t)}{dt} = \frac{I}{e} - \frac{1}{\tau_s}N(t) - \sum_{m=-M}^{M} G_m(N)|E_m(t)|^2 \quad (6.2)$$

$$G_m(t) = G_c(N-N_0)\left[1-\left(\frac{m\Delta\omega_L + \frac{d\Phi_m}{dt} - \omega_N(N-N_{th})}{\Delta\omega_g}\right)^2\right] \quad (6.3)$$

were the spontaneous emission is modelled by a complex, not correlated, Gaussian white noise term ξ of zero mean, and with a spontaneous emission rate β [34].

The coupled differential equations show a delay feedback of the cavity represented by the term $E_m(t-\tau)e^{i\omega\tau}$. The first equation models the low frequency envelope of the electromagnetic field in the cavity, the second and third equations represent the time variation of the carriers in the cavity, and the mode dependent gain, respectively [12].

The used parameters where m= 0, ±1 (3 active modes; i.e. M= 1), and m = 0 corresponds to the mode located at the maximum of the gain curve of the solitary laser.

6.2.3 Development of the numerical simulation model

Numerical simulations were performed using Mathlab / Simulink. The simulation and analysis of the chaotic phenomena of the D-LCSE system was done by sequential correlation between the physical experiment and the results of the numerical simulations [13].

A test program was developed for a simple single-mode system with visible emission, starting from equations (6.1-6.3), to verify the typical behaviors of the system, and to be later able to easily modified it in order to adapt the behavior of the model to the different types of modeling we want to analyze. After this stage was developed the model that simulates a system with 3 coupled simple single-mode systems (3 modes).The values of the parameters used for the simulation are in the thesis, and for the numerical solution of the differential equations a Runge-Kutta pair of Bogacki - Shampine integrations was used. The routines are attached in the annexes at the end of this thesis.

All the modes (chaotic oscillators) are coupled having the same “feed” source (N), but being under diffrent feedback conditions (B_m, and τ_m).

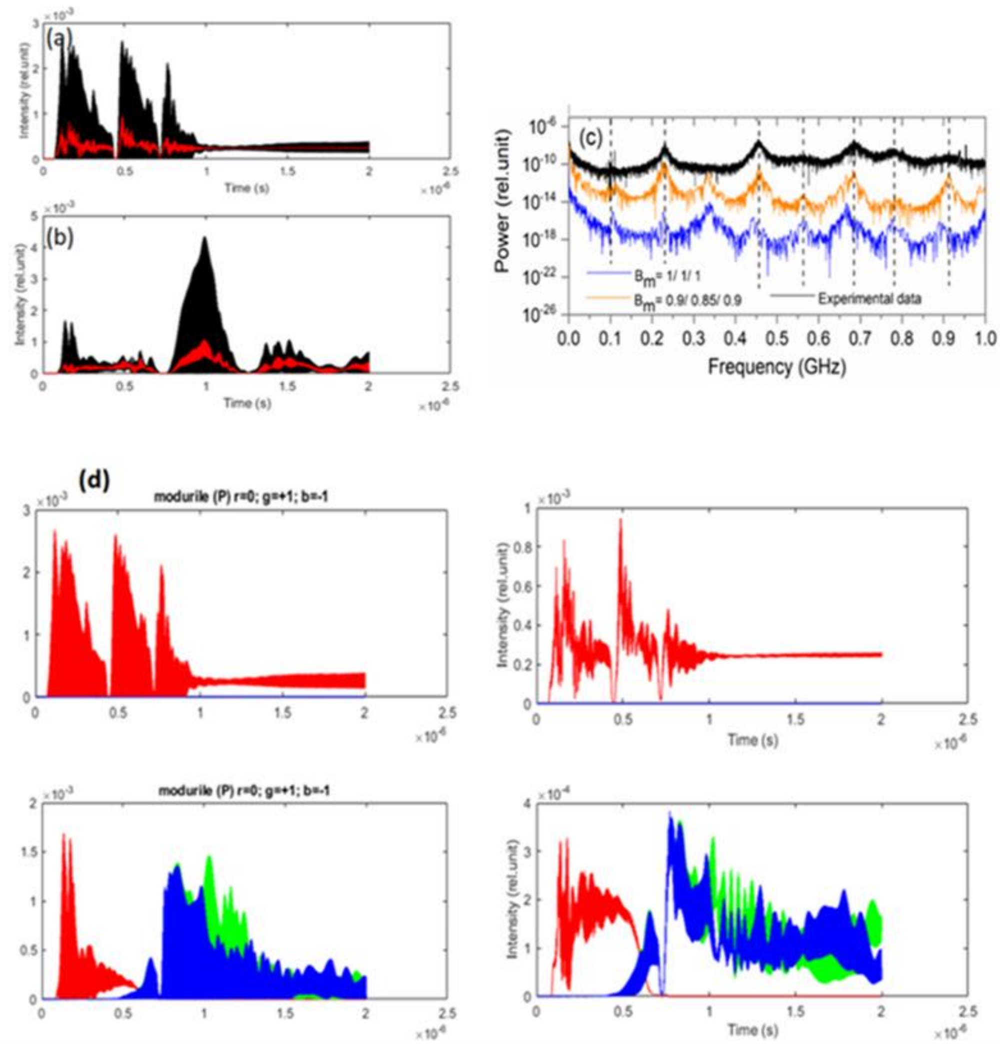

Figure 6.4 *Multimode numerical simulations where (a), (b) represent time series of D-LSCE system emission power (black) and the optically filtered signal (red) for Bm = 1/1/1 and Bm = 0.9 / 0.85 / 0.9, (c) the power spectra associated with the time series of the power highlighted for each mode separately and (d) unfiltered (left) and filtered (right) modes, the signal being presented filtered at a frequency close to that of an ordinary optical detector , both for the case Bm = 1/1/1 (up) and Bm = 0.9 / 0.85 / 0.9 (down).*

6.3 Results and discussions

In D-ECSL system, if we are in the case of facilitating the occurrence of LFF (injection current near the threshold, I= 18.630 mA) and high coupling coefficients are used, several modes, in our case 3 modes are present in the system emission spectrum and a chaotic behavior similar to the cases in which only one mode is active is observed in the emission dynamics .The time series of the power was obtained by summing the signals generated by the three modes and the duration of the power drops is similar to the single-mode case, ≈0.5μs. It should be mentioned that the simulation was performed for non-selective extended cavities, grating and mirror that return the same power ratio for each mode. It should also be noted that each mode assumed to interacts only with its delayed field, with no influences of the neighboring modes.

6.4 Conclusions

In this chapter was developed a numerical model for simulating the chaotic dynamics of multimode visible emission of a system with compound external cavity, with two optical reflectors, experimentally implemented. In the experimental conditions, D-ECSL emission optical spectrum shown 3 active modes. The components of the power spectrum (frequencies) associated to intensity time series correspond to low frequency fluctuations, external cavities oscillation frequencies, their harmonics, and to a mixture of them.

Next was developed the model that simulates a system with 3 coupled single-mode systems (3 modes). All the modes are coupled having the same “feed” source (N) and working under different feedback conditions. Thus, the time series of the power was obtained by summing the signals generated by the three modes.

The obtained numerical results show that the developed multimode model simulates with good approximation the chaotic dynamic (power spectrum) of experimental D-ECSL system for a specific set of parameter values.

Chapter 7

General conclusions, obtained results, original contributions and perspectives for further developments

This thesis is a synthesis study on the chaotic dynamics of a laser system with external cavity operating under different feedback conditions determined by: currents above the threshold value, double reflective external cavity, operation in the presence of injection current modulation in a coupled chaotic system master -slave. The study is completed by a numerical simulation of the multimode emission of an optically coupled semiconductor laser with two external reflective cavities.

7.1 Obtained results

1.I studied the laser emission in the conditions of a chaotic dynamics of LFF type at currents higher than the laser threshold current, at values where the intensity of the laser emission has permanent fluctuations, and in the optical spectrum there are “mode-hopping” oscillations. A comparative study on the characteristics of this emission depending on the type of external reflector element: mirror and diffraction grating used in reflection on the order of -1 was performed at a temperature t =24.9° C. The measurements performed at the threshold current, I_0 = 58mA, showed emission regimes with stable LFF fluctuations for P_{FB} reinjected powers whose value varies by an order of magnitude, 0.2mW, respectively 0.02mW. For currents above the threshold, I_1 = 59.7mA and I_2 = 82.3 mA, respectively, the emission regimes with stable LFF fluctuations were obtained for P_{FB} reinjected powers whose value is of the order of magnitude of small values from the laser emission threshold 0.05mW, 0.03mW, respectively 0.007mW, 0.02mW. For the measurements performed at these currents, at feedback coefficients corresponding to P_{FB} reinjected power values with an order of magnitude smaller (or larger) than the values obtained at the laser threshold, were not observe stable LFF fluctuation regimes.
2.I studied the chaotic dynamics of the D-ECSL system in the operating conditions at different values of the feedback intensity applied to the two branches formed by the

configurations of cavities C1 and C2. feedback in cavity C1 is higher. The results obtained, numerically anticipated in advance, showed that for large external cavities (of the order of tens of cm lengths) the frequency of chaotic oscillations corresponding to the D-ECSL system is limited by the frequency of oscillations of the external cavity C1 and the frequency of the first harmonic of chaotic oscillations in cavity C2.I observed that due to the mixing of the υ_{HFO} frequencies they do not contain information about the geometry of the D-ECSL system for values of the coupling coefficient c_2 up to 0.5. Above this value, in along with the υ_{HFO} frequency in the power spectrum, a new frequency component appears close to the υ_{EC2} frequency. The results obtained and presented in the thesis are the first experimental observations of such behavior of the HFO frequencies of a D-ECSL system.

3. By measurements performed for injection current modulation in a system consisting of two semiconductor laser diodes coupled in a chaotic master-slave system I have shown that it is possible to synchronize their chaotic emissions. The injection current of the master was modulated at 8 MHz and 15Mhz, values different from the natural frequencies of the LFF type oscillations of the master (10 MHz) and the slave (3.4 MHz). Modulating the master laser at the frequencies of 8MHz and 10 MHz induces emission power drops with a periodicity of 0.125 μs, respectively 0.067μs, which causes LFF type oscillations with two dominant frequencies. I analyzed by a statistical method the grouping of power drops of coupled ECSL systems and I observed that: the periods of these power drops are:

(a) the same for master and slave and correspond to the natural LFF frequencies of the master, when the master laser and modulator are operating in phase;

(b) different for master and slave, when the master and modulator are not in phase, even if the periodic signal applied is resonant in frequency with the LFF-type oscillations of the master laser.

The obtained results show that the modulation of the master system at a frequency that does not belong to the range of natural frequencies of LFF oscillations has no control effect on the chaotic dynamics of the slave system. In the latter case the effect of modulation determines a periodic grouping of power drops but at values different from those of the modulation frequency.

4.I proposed a numerical model for simulating the chaotic dynamics of multimode emissions in the visible spectrum for a system with a double external optical cavity (composed of a mirror and a diffraction grating), developed experimentally (D-LSCE system). Under the experimental conditions, the D-LSCE optical emission spectrum showed 3 active modes. The components of the power spectra (frequencies) correspond to the low frequency fluctuations, the oscillation frequencies of the external cavities, their harmonics and a mixture of them.

The theoretical model developed simulates a system with 3 coupled single-mode systems (3 modes). All modes are coupled with the same "feed" source, under different feedback conditions. The power time series was obtained by summing the signals generated by the three modes. The results obtained from the numerical simulations show that the multimode model developed describes with a good approximation the chaotic emission dynamic of the D-ECSL system for a particular set of parameter values. The results obtained are a first, because the chaotic dynamics of

D-ECSL systems have been numerically modeled only for single-mode infrared emissions.

7.2 Original contributions

The main results presented in this thesis were obtained during my research performed in the Laser Spectroscopy and Optics group at the National Institute of Laser, Plasma and Radiation Physics, Măgurele, under the coordination of Prof. Dr. Phys. Mihai Lucian Pascu and the scientific coordinator. A particular guidance and contribution to my laboratory activity and data interpretation had Dr. Ionut Relu Andrei from the same laboratory.

Personal results and contributions can be formulated as follows:

1.Study of the dynamics of chaotic low-frequency fluctuations of the laser diode emission at injection currents above the laser threshold**.** At the critical points of the power-current characteristic of a laser diode, the "mode hopping" effect appears. At these critical points in the evolution of laser emission, there is a transfer of intensity between laser emission modes without zero drops of intensity and the application of a moderate feedback of about 1% of the emitted power has the role of controlling the periodicity of nonlinear oscillations at certain characteristic frequencies. the value of the control parameters of the laser system.

a. I studied chaotic regimes such as low frequency fluctuations (LFF) in the emission of an LSCE system at values of injection currents above the laser threshold current, in order to the possibility of chaotic coupling of such systems.

b. I made a comparative study of the chaotic emissions according to the type of the reflecting element: the total reflecting mirror and the diffraction grating in the -1 order of diffraction. The measurements performed at the threshold current, I0 = 58mA, showed that emission regimes are obtained. with stable LFF fluctuations for PFB reinjected powers whose value varies by an order of magnitude, 0.2 and 0.02 mW, respectively. At values of currents above the threshold stable LFF regimes for PFB reinjected powers whose value is of the order of magnitude of the small values from the laser threshold.

c. For measurements performed at threshold currents, at feedback coefficients corresponding to reinjected power values with an order of magnitude smaller (or higher) than the values obtained at the laser threshold, no stable LFF fluctuation regimes were observed.

2. Publication of some early results in the article from UPB Bulletin, series C No. 81/2091: **C. Onea**, PE Sterian, IR Andrei, A. Baleanu, ML Pascu, Chaotic Low-Frequency Fluctuations of Laser Diode Emission at Injection Currents Above Threshold, UPB Science. Bull. Series C, 81 (2019), proves the acceptance of these contributions by the international scientific world as having a novelty, of interest for different applications.

3. Study of high frequency chaotic dynamics in a semiconductor laser with double-reflector selective cavity.

The emission dynamics of a semiconductor laser operating in double optical feedback conditions consists of a mixture of high frequency oscillations modulated by low frequency fluctuations (LFF type). External feedback is provided by an external optical cavity with double reflector consisting of a cavity delimited by a diffraction grating, which ensures the reinjection at the laser junction of the -1 order of diffraction, and a second cavity delimited by a flat mirror that turns the order 0 diffraction.

The frequency of the chaotic oscillations of the double cavity laser emission depends on the feedback coefficient in the long cavity (delimited by the mirror), and the values obtained are in a range delimited by the natural frequencies of the short cavity (delimited by the diffraction grating) and the frequency of the first harmonic. long cavity. By changing the intensity of the feedback in the long cavity, tunable high-frequency chaotic oscillations are obtained.

a. I studied the chaotic dynamics of the D-LSCE system in the operating conditions at different values of the feedback intensity applied to the two branches formed by the configurations of cavities C1 and C2. The analysis of the chaotic oscillations showed that the values of υ_{HFO} frequencies increase with the increase of the feedback intensity in the C2 cavity, the frequency range having higher values when the feedback power in the C1 cavity is higher.

b. I observed that the obtained υ_{HFO} frequencies do not contain information about the geometry of the D-ECSL system.

c. The results presented are the first experimental observations reported in the literature of such behavior of the υ_{HFO} frequencies of a D-ECSL system

4. The results presented above were published in the article: **C. Onea**, P.E. Sterian, I.R. Andrei, M.L. Pascu, High Frequency Chaotic Dynamics in a Laser Semiconductor with Selective Cavity Double-Reflector, U.P.B. Sci. Bull., Series A, 81 (2019) 261–270 are applicable in the encoding and transmission of data and information using chaotic optical carriers.

5. The study of the chaotic synchronization of master-slave type of two laser systems in the presence of injection current modulation, is another contribution.

a. Two semiconductor laser systems operating in coupled optical feedback mode MASTER-SLAVE (transmitter-receiver) form a system that works in chaotic synchronized mode. Experiments have shown that the low frequency fluctuations of an external cavity semiconductor laser system (ECSL) can be controlled by modulating the injection current, which becomes more orderly when the modulation signal is close to the natural LFF oscillation frequency of laser.

b. Frequency modulation of the master laser current induces periodic drops in emission power observing that there are two dominant frequencies: one induced and one natural. These frequencies at which the signal drop of the coupled system were observed are correlated with the frequency of the modulation signal as well as with the frequencies of the natural oscillations of the two chaotic laser systems.

c. I studied the state of synchronization between the laser (of low frequency fluctuations) and the external modulator by performing a statistic of zero drops of laser emission intensity (laser power) using Shannon entropy.
6. The results listed above were published by Optoelectronics and Advanced Materials - Rapid Communications Vol. 13, No. 5-6, May-June 2019, pp. 284-289: I. R. ANDREI, **C. Onea**, P. E. STERIAN, I. IONITA, M. L. PASCU, Control Of Slave Chaotic Dynamics By Master Current Modulation In A Chaotic Coupled Laser System, being of applicative interest in scientific studies on information encryption in optical communications.
7. The study of some aspects of the chaotic dynamics of a semiconductor laser system obtained in different conditions of external optical feedback.
a. I have made a synthesis of studies on the dynamics of chaotic emission of a laser system with external cavity operating under different feedback conditions determined by: injection currents above the threshold, double reflective external cavity, operation in the presence of injection current modulation in a coupled master-slave chaotic system.
b. All these operating modes of an external cavity laser system are currently the subject of research and scientific interest due to the applications in encoding and transmitting information using chaotic optical carriers. The results of these studies were published in the Annals of the Academy of Romanian Scientists Series on Science and Technology of Information Volume 12, Number 1/2019 ISSN 2066 - 2742: **C. Onea**, P.E. Sterian, I.R. Andrei, M.L. Pascu, Aspects of Chaotic Dynamics of the Semiconductor Laser Emission Obtained In Different External Optical Feedback Conditions.
8. Numerical simulation of the multimode chaotic emission of an optically coupled semiconductor laser with two external cavities.
a. Using the equations of rates and electromagnetic field specific to semiconductor laser systems with external cavity I proposed a numerical simulation with which it was possible to evaluate, before performing experiments, the results that could be obtained according to a series of controllable system parameters. The proposed program simulates the process of LFF-type low-frequency oscillations of a double-cavity external semiconductor (D-ECSL) system. The experimental determination of the threshold current of the diode used allowed the identification of the nature of the chaotic trajectory followed by the system and the identification of the conditions for the occurrence of LFF oscillations. The injection current close to the threshold value favors the appearance of this type of chaotic behavior which consists in drops of the emission power of the system with periods that can vary between 10^{-9} s and 10^{-6}s.
b. The model was proposed and developed to simulate the chaotic dynamics of multimode emissions in the visible spectrum for a system with a composite external optical cavity, with two optical reflectors (double external feedback), experimentally developed (D-ECSL system).
c. Under the experimental conditions, the optical emission spectrum D-LSCE showed 3 active modes. The components of the power spectra (frequencies) correspond to the low frequency fluctuations, the oscillation frequencies of the external cavities, their

harmonics and a mixture of them. The developed model simulates a system with 3 single- mode coupled systems (3 modes). The numerical results obtained show that the developed multimode numerical model simulates with a good approximation the chaotic emission dynamic of the D-LSCE experimental system for a particular set of parameter values.
d. In the literature there are publications on multimodal emission in the visible field, but only for LSCE systems with unique external feedback and the dynamics of D-ECSL systems has been studied numerically, but only for single-mode infrared emissions. To my knowledge, the proposed model is a first for the analysis of multimode emission in the visible field for a D-ECSL system.
9. Publication of previous results in the U.P.B. Sci. Bull., Series A, Vol. 83, Iss. 1, 2021, ISSN 1223-7027: C. Onea, I.R. Andrei, P.E. Sterian, M.L. Pascu, M. Bulinski, Numerical Simulation of Chaotic Multimode Dynamics Of A Semiconductor Laser Optical Coupled With Two External Cavities, demonstrates the novelty of contributions and their appreciation in the scientific world.
10.Dissemination of the results obtained at scientific communication sessions:

- National: Conference of the Faculty of Physics, University of Bucharest, Magurele, June 21-22, 2018 and June 21-22, 2019, ELI-NP Summer School, September 8-13. 2019, Sinaia, Romania, Annual Symposium of Doctoral School of Electronics, Telecommunications and Information Technology, July 9, 2018 and July 4, 2019.
- International: Joint Iscp-Indlas 2018 Conference, 03 - 07 September, 2018, Alba-Iulia, Romania, The 6th International Colloquium “Physics of Materials” Bucharest, 15-16 November 2018.

The results presented were appreciated by the participants as valuable, with concrete possibilities of application in the coding and coded transmission of information using optical carriers.

The results obtained within this thesis will be used and developed within the PED project which obtained funding from the Laboratory in which I completed the thesis, guided by Mr. Prof. Dr. fiz. Mihail-Lucian Pascu, in a project competition, responsible for the project being Mr.Dr. fiz.Ionuț- Relu Andrei. I also thank these scientific personalities for their support and competent guidance.

7.3 List of original publications

Articles published in scientific journals, papers presented at national and international scientific conferences and research reports prepared during doctoral studies:

1. **C. Onea**, P.E. Sterian, I.R. Andrei, M.L. Pascu, High Frequency Chaotic Dynamics In A Semiconductor Laser With Double-Reflector Selective Cavity, U.P.B. Sci. Bull., Series A, 81 (2019) 261–270.

2. **C. Onea**, P. E. Sterian, I. R. Andrei, A. Baleanu, M. L. Pascu, Chaotic Low-Frequency Fluctuations Of Laser Diode Emission At Injection Currents Above Threshold, U.P.B. Sci. Bull. Series C, 81 (2019).
3. I. R. Andrei, **C. Onea**, P. E. Sterian, I. Ionita, M. L. Pascu, Control Of Slave Chaotic Dynamics By Master Current Modulation In A Chaotic Coupled Laser System, Optoelectronics And Advanced Materials – Rapid Communications Vol. 13, No. 5-6, May-June 2019, p. 284-289.
4. **C. Onea**, P.E. Sterian , I.R. Andrei, M.L. Pascu, Aspects Of Chaotic Dynamics Of The Semiconductor Laser Emission Obtained In Different External Optical Feedback Conditions, Annals of the Academy of Romanian Scientists Series on Science and Technology of Information Volume 12, Number 1/2019 ISSN 2066 – 2742**.**
5. **C. Onea**, I.R. Andrei, P.E. Sterian, M.L. Pascu, M. Bulinski, Numerical Simulation Of Chaotic Multimode Dynamics Of A Semiconductor Laser Optical Coupled With Two External Cavities , U.P.B. Sci. Bull., Series A, Vol. 83, Iss. 1, 2021, ISSN 1223-7027 .
6. I. R. Andrei, **C. Onea**, P. E. Sterian, M. L. Pascu,Experimental Control Of Low-Frequency Fluctuations By Current Modulation In A Laser Diode Chaotic Coupled System, Conferința Facultatii de Fizica, Universitatea din Bucuresti, Magurele, 21-22 Iunie 2018.
7. I.R. Andrei, **C. Onea**, P.E. Sterian, I. Ionita, M.L. Pascu **,**Experimental Control Of Slave Chaotic Dynamics By Master Current Modulation In A Chaotic Coupled Laser System, Joint Iscp-Indlas 2018 Conference, 03 - 07 September, 2018, Alba-Iulia, Romania
8. **C. Onea**, P.E.Sterian, I.R.Andrei, M.L.Pascu, Chaotic Low-Frequency Fluctuations Of The Laser Diode Emission At Injection Currents Above The Laser Threshold, Annual Symposium of Doctoral School of Electronics, Telecommunications and Information Technology,9.07.2018
9. **C.Onea**, P.E Sterian, I.R.Andrei, M.L.Pascu, Mixing of High Frequency Oscillations Induced by a Selective Reflector in Diode Laser Emission Dynamics ,The 6th International Colloquium ”Physics of Materials” Bucharest, 15-16 november 2018
10. I.R. Andrei, **C. Onea**, P.E. Sterian, I. Ionita, M.L. Pascu, Control Of Slave Chaotic Dynamics By Master Current Modulation In A Chaotic Coupled Laser System, Annual Symposium of Doctoral School of Electronics, Telecommunications and Information Technology, 4.07.2019.
11. **C.Onea**, P.E Sterian, I.R.Andrei, M.L.Pascu, Chaotic,tunable high frecquencies oscillations induced in a double-reflector external cavity semiconductor laser, Conferinta Facultatii de Fizica, Universitatea din Bucuresti, Magurele, 21-22 Iunie2019 .
12. I.R. Andrei, C. Onea, P.E. Sterian, M.L. Pascu, Chaotic, tunable high frequencies oscillations induced in a double-reflector external cavity semiconductor laser, ELI-NP Summer School, 08-13 Sept. 2019, Sinaia, Romania.

13. C.Onea ,Chaotic Low-Frequency Fluctuations Of Laser Diode Emission At Injection Currents, the first scientific research report, scientific coordinator Prof. Univ.Dr.Paul E.Sterian.
14. C.Onea,Control Of Slave Chaotic Dynamics By Master Current Modulation In A Chaotic Coupled Laser System, the second scientific research report, scientific coordinator Prof. Univ.Dr.Paul E.Sterian.
15. C.Onea, High Frequency Chaotic Dynamics In A Semiconductor Laser With Double-Reflector Selective Cavity, the third scientific research report, scientific coordinator Prof. Univ.Dr.Paul E.Sterian.
16. C.Onea, Aspects Of Chaotic Dynamics Of The Semiconductor Laser Emission Obtained In Different External Optical Feedback Conditions, Fourth scientific research report, scientific coordinator Prof. Univ.Dr.Paul E.Sterian.
17. .C.Onea, Numerical Simulation Of Chaotic Multimode Dynamics Of A Semiconductor Laser Optical Coupled With Two External Cavities, Fifth scientific research report, scientific coordinator Prof. Univ.Dr.Paul E.Sterian.

7.4 Perspectives for further developments

The research continues with the development of the system with two lasers synchronized to a device with automatic control of operation but also the study of chaotic dynamics through modulation and experimentation of chaos encryption techniques. For this purpose, the results obtained in this thesis in the study of the chaotic dynamics of a semiconductor laser system with double external cavity will be used and developed and a development of the numerical model of the multimode emission of a semiconductor laser optically coupled external cavities to track the effect of selective and non-selective feedback.

I mention that some of these objectives have already been achieved by participating in the competition of PED projects - Experimental project - demonstration within the National Program PN III, competition 2019, and obtaining funding for a project (420PED / 2020). Thus, the results obtained in the thesis contributed to obtaining funding for the PED project entitled: Chaotic technology for testing methods and platforms used in encryption systems, Project Manager INFLPR Bucharest, Project Manager I.R. Andrei. The main objective of this project is the development of an experimental platform with automatic remote control, based on the synchronization of two semiconductor lasers with optical feedback and control of chaotic dynamics by modulation, and testing of encryption methods using the chaotic optical carrier.

Bibliography

1. Nilushi Wijeyasinghe (2019) Laser Diodes & Direct Diode Lasers 2019-2029: Technologies, Markets & Forecasts. IDTechEx
2. Ohtsubo J (2017) Semiconductor Lasers: Stability, Instability and Chaos, 4th Edition. Springer International Publishing, Cham
3. S. Banerjee, L. Rondoni, S. Mukhopadhyay (2011) Synchronization of time delayed semiconductor lasers and its applications in digital cryptography,. Optics Communications 284, 19, 4623 – 4634
4. Ruiz-Oliveras FR, Pisarchik AN (2006) Phase-locking phenomenon in a semiconductor laser with external cavities. Optics Express 14:12859. https://doi.org/10.1364/OE.14.012859
5. Argyris A, Syvridis D, Larger L, et al (2005) Chaos-based communications at high bit rates using commercial fibre-optic links. Nature 438:343–346. https://doi.org/10.1038/nature04275
6. Liang Jun-Sheng, Wu Yuan, Wang An-Bang, Wang Yun-Cai (2012) Extracting the external-cavity key of a chaotic semiconductor laser with double optical feedback by spectrum analyzer. Acta Physica Sinica 61:034211. https://doi.org/10.7498/aps.61.034211
7. C. Onea, P.E. Sterian, I.R. Andrei, M.L. Pascu, (2019) Chaotic, tunable high frequencies oscillations induced in a double-reflector external cavity semiconductor laser, . in: Annual Scientific Conference, Faculty of Physics - University of Bucharest, Magurele,
8. C. Onea, P. E. Sterian, I. R. Andrei, A. Baleanu, M. L. Pascu (2019) Chaotic low-frequency fluctuations of laser diode emission at injection currents above threshold,. UPB Sci Bull Series C,
9. C. Onea, P. E. Sterian, I.R. Andrei, M.L. Pascu (2019) High frequency chaotic dynamics in a semiconductor laser with double-reflector selective cavity. UPB Sci Bull, Series A in press:
10. I. R. Andrei, C. Onea, P. E. Sterian, et al (2019) Control of slave chaotic dynamics by master current modulation in a chaotic coupled laser system. OAM-RC 13:
11. C. Onea, P.E. Sterian, I.R. Andrei, M.L. Pascu (2019) Chaotic, tunable high frequencies oscillations induced in a double-reflector external cavity semiconductor laser. Annual Scientific Conference, Faculty of Physics - University of Bucharest, Magurele
12. Lang R, Kobayashi K (1980) External optical feedback effects on semiconductor injection laser properties. IEEE Journal of Quantum Electronics 16:347–355. https://doi.org/10.1109/JQE.1980.1070479
13. Cristina ONEA, Ionut Relu ANDREI, Paul E. STERIAN, Mihai Lucian PASCU, Mircea Bulinski Numerical Simulation Of Chaotic Multimode Dynamics Of A Semiconductor Laser Optical Coupled With Two External Cavities. UPB Sci Bull, Series A, Vol. 83, Iss. 1, 2021:
14. Haken H (1975) Analogy between higher instabilities in fluids and lasers. Physics Letters A 53:77–78. https://doi.org/10.1016/0375-9601(75)90353-9
15. M. Bulinski, M.L. Pascu (2001) Chaos in laser diode light emission. Romanian Journal of Optoelectronics 19:1–34

16. Paul E.Sterian, Nicolae N.Pușcaș (1988) Laseri și procese multifotonice. Ed.Tehnică
17. Lorenz, E.N (1963) Deterministic Nonperiodic Flow,. J Atmos Sci, Vol 20, pag 130 - 142,
18. Ghys, E (2013) The Lorenz attractor, a paradigm of chaos. , Chaos, Vol 34, pag 1 – 54,
19. Paul E. Sterian (2002) Communication based on chaotic signals. Proceedings of the roumanian academy,Series A 3:
20. Mork J, Tromborg B, Mark J (1992) Chaos in semiconductor lasers with optical feedback: theory and experiment. IEEE Journal of Quantum Electronics 28:93–108. https://doi.org/10.1109/3.119502
21. Erneux T, Gavrielides A, Sciamanna M (2002) Stable microwave oscillations due to external-cavity-mode beating in laser diodes subject to optical feedback. Phys Rev A 66:033809. https://doi.org/10.1103/PhysRevA.66.033809
22. Heil T, Fischer I, Elsäßer W, Gavrielides A (2001) Dynamics of Semiconductor Lasers Subject to Delayed Optical Feedback: The Short Cavity Regime. Phys Rev Lett 87:243901. https://doi.org/10.1103/PhysRevLett.87.243901
23. Sacher J, Baums D, Panknin P, et al (1992) Intensity instabilities of semiconductor lasers under current modulation, external light injection, and delayed feedback. Physical Review A 45:1893–1905. https://doi.org/10.1103/PhysRevA.45.1893
24. Fischer I, van Tartwijk GHM, Levine AM, et al (1996) Fast Pulsing and Chaotic Itinerancy with a Drift in the Coherence Collapse of Semiconductor Lasers. Phys Rev Lett 76:220–223. https://doi.org/10.1103/PhysRevLett.76.220
25. C. Onea, P.E. Sterian , I.R. Andrei, M.L. Pascu: Aspects Of Chaotic Dynamics Of The Semiconductor Laser Emission Obtained In Different External Optical Feedback Conditions. Annals of the Academy of Romanian Scientists Series on Science and Technology of Information Volume 12:
26. D.Deleanu (2019) Indicatori ai teoriei haosului. Ed.Nautica
27. G. J. Rodgers (1992) From Order into Chaos, Phys. Educ. 27, 14-17
28. K. Pyragas (1992) Continuous control of chaos by self-controlling feedback. Phys Lett A 170, 421
29. Tronciu VZ, Ermakov IV, Colet P, Mirasso CR (2008) Chaotic dynamics of a semiconductor laser with double cavity feedback: Applications to phase shift keying modulation. Optics Communications 281:4747–4752. https://doi.org/10.1016/j.optcom.2008.05.053
30. Peil M, Heil T, Fischer I, Elsäßer W (2002) Synchronization of Chaotic Semiconductor Laser Systems: A Vectorial Coupling-Dependent Scenario. Physical Review Letters 88:. https://doi.org/10.1103/PhysRevLett.88.174101
31. Heil T, Mulet J, Fischer I, et al (2002) ON/OFF phase shift keying for chaos-encrypted communication using external-cavity semiconductor lasers. IEEE Journal of Quantum Electronics 38:1162–1170. https://doi.org/10.1109/JQE.2002.801950
32. Vicente R, Mirasso CR, Fischer I (2007) Simultaneous bidirectional message transmission in a chaos-based communication scheme. Optics Letters 32:403. https://doi.org/10.1364/OL.32.001271
33. Bulinski M, Pascu ML, Andrei IR (2004) Phase synchronization and coding chaos with semiconductor lasers. Journal of Optoelectronics and Advanced Materials 6:77–86

34. Sanchez-Diaz A, Mirasso CR, Colet P, Garcia-Fernandez P (1999) Encoded Gbit/s digital communications with synchronized chaotic semiconductor lasers. IEEE Journal of Quantum Electronics 35:292–297. https://doi.org/10.1109/3.748833
35. Z. Fang, H. Cai, G. Chen, R. Qu (2017) External Cavity Semiconductor Lasers, in: Single Frequency Semiconductor Lasers,. Springer Singapore, Singapore. https://doi.org/: pp. 117–166.
36. A. Bakry, S. Abdulrhmann, M. Ahmed Theoretical modeling of the dynamics of a semiconductor laser subject to double-reflector optical feedback. Journal of Experimental and Theoretical Physics 122 (2016):960–969
37. J.M. Buldu, F. Rogister, J. Trull, C. Serrat, M.C. Torrent, J. Garc a-Ojalvo, C.R. Mirasso, (2002) Asymmetric and delayed activation of side modes in multimode semiconductor lasers with optical feedback. Journal of Optics B: Quantum and Semiclassical Optics 415–420