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ASPECTS OF CHAOTIC DYNAMICS OF THE SEMICONDUCTOR LASER EMISSION OBTAINED IN DIFFERENT EXTERNAL OPTICAL FEEDBACK CONDITIONS

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Abstract. *We present the dynamic characteristics of the emission of a chaotic laser system working in different optical feedback conditions determined by the use of: injection currents higher than that at threshold, double reflector external cavity or current modulation in an optical coupled master – slave lasers system. We show that stable chaotic low-frequency fluctuations (LFF) were obtained at current values above threshold current only in certain conditions depending on intrinsic properties of semiconductor active region, namely, intensity instabilities of mode-hoping type. By changing the feedback intensities in a double reflector cavity, high frequency chaotic oscillations with tunable frequencies are obtained. They show frequency values bounded by those of external cavities' oscillations formed by the two external reflectors. Also, master current modulation at a frequency included in the range bounded by master and slave natural LFF frequencies has, as effect, the clustering of slave dropouts on two frequencies: driven and master natural LFF ones; if modulation frequency is out of range, it has only the role to group slave dropouts periods on two frequencies, different from the modulation one.*

Keywords: external cavity semiconductor laser, chaotic dynamics, double external feedback, high-frequency oscillations, tunable frequency

1. Introduction

The semiconductor laser (SL) is one of the most important devices in information technology having a wide area of applications, from information storage media to information transmission and encoding with optical carriers [1]. Semiconductor lasers which are subject to optical feedback [2] from single or multiple external cavities were studied theoretically and experimentally in connection with their applications, such as, control of non-linear, chaotic dynamics [3]; generation of high-dimensional chaotic dynamics for information data encoding [5]; or, to mask the information on the geometry of the laser system [6,7].

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On the contrary, the extraction of the time delay signature of an external cavity may be produced [8]. Also, double reflector chaotic lasers whose external cavities contain gratings have been studied both, numerically or experimentally in relation to locking laser frequency and increasing laser power in fiber lasers, or for evaluation of mixed-modes dynamic states [9].

When a part of the light emitted by SL is redirected into laser cavity as optical feedback from an external reflecting surface, the emission presents a series of dynamic effects, and the system configuration is known as external-cavity semiconductor laser (ECSL) [2]. Thus, when ECSL system is operated at injection currents close to laser threshold laser intensity shows a non-linear, chaotic dynamic called low frequency fluctuations (LFF) [10].

This dynamic is obtained for a moderate optical feedback, e.g. 1- 10 % of the emitted laser power, and it is manifested in the form of periodic dropouts, to almost zero, of the laser intensity. The intensity fluctuations appear at frequencies with values in the low bandwidth range, up to 100 MHz, and represent envelopes for other rapid oscillations, with values of the order of GHz, formed in the external cavity. The time periods of dropouts depend on the operating parameters of the ECSL system: injection current, laser temperature, and feedback intensity. Increasing laser injection current, the noise character of the emission increases and LFF dynamic disappears. However, under these circumstances we obtained stable chaotic low-frequency fluctuations, but in certain conditions depending on intrinsic properties of semiconductor active region, such as intensity instabilities of mode-hoping type.

In the second part of this work, we analyzed the mixing characteristics of the high frequency chaotic oscillations of laser emission of a double-reflector ECSL (D-ECSL) system which combines a linear (short) external cavity limited by a diffraction grating with a Littman (long) cavity limited by a mirror. The observed chaotic dynamics have a signature associated to multimode chaotic regime of two-color laser systems with spectrally filtered feedback or dual-wavelength systems [11]. We experimentally show that by increasing the long cavity feedback intensity, chaotic oscillations with increased frequency are obtained and the values of frequency ranges are higher as the short cavity feedback increases. We show that characteristic frequencies of D-ECSL emission oscillations are bounded by the frequency of short cavity oscillations and the first harmonic of the long cavity oscillations frequency. In the third part, two chaotic semiconductor lasers were optically coupled into a master - slave synchronization scheme and the effects of the master current modulation on chaotic dynamics of the slave laser emission were analyzed. The injection current of the master is modulated at frequencies close to, but different from master and slave natural LFF oscillations frequencies.

Driving master laser induces in both laser emissions LFFs with two dominant frequencies. The synchronization state between chaotic dynamics of the coupled lasers and external modulation was studied using the statistical analysis of power dropouts of laser emission of the two coupled lasers.

2. Experimental set-up

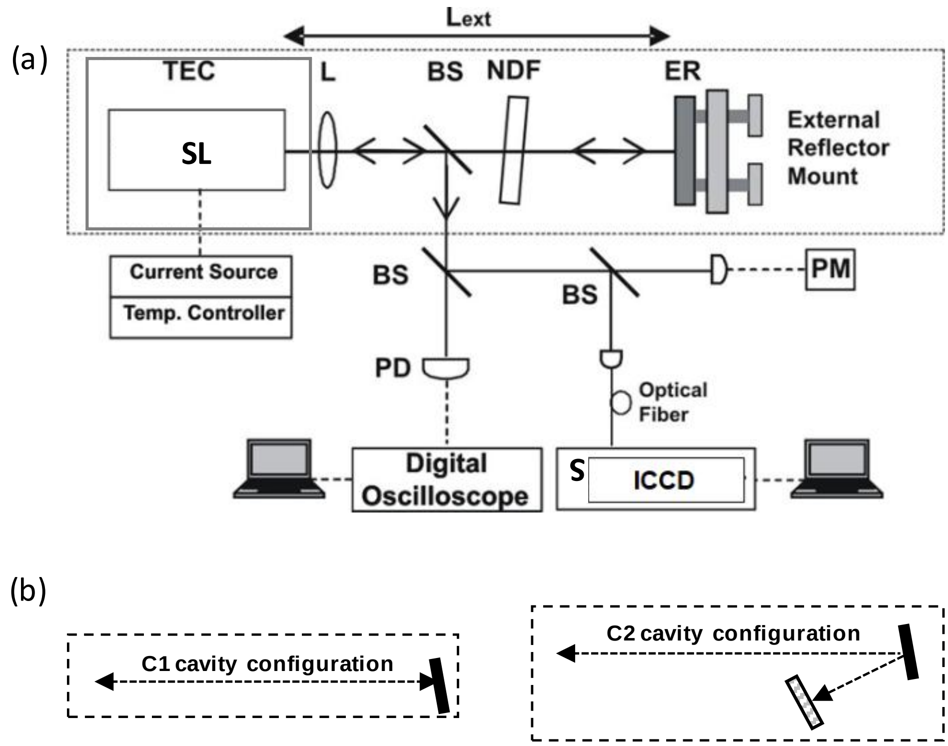

Fig. 1. (a) The ECSL experimental set-up: SL, semiconductor laser; TEC, thermo - electric control mount; L, collimation system; BS, beamsplitter; NDF, neutral density filter; ER, external reflector; PD, photo - detector; PM, power meter; S, spectrometer with intensified CCD camera.
(b) external cavity configurations based on a grating external reflector.

Generally, the external-cavity semiconductor laser set-up (Fig. 1a) includes the SL, a thermo-electric control mount, the collimation lens system (L), a beamsplitter (BS) that separates and sends a fraction of the emitted power to the investigation systems, a variable attenuation filter (NDF), and the external reflector (ER) placed at a L_{ext} distance from laser. The laser beam is transmitted with variable attenuations directly to reflector element, e.g. mirror or diffraction grating. Also, a second beamsplitter placed in the external cavity can be used to optically couple the ECSL system with a second one. The investigation systems including a photodetector (PD), spectrograph (S) with intensified CCD camera (iCCD), and a powermeter (PM) are used to analyze time evolution of laser intensity, optical spectra structure, and power of the emitted beam, respectively.

Thus, a fraction of the laser beam extracted from external cavity is directed to the photodiode, and the remaining part is sent to the powermeter and through an optical fiber to the spectrograph. The used laser diode (Mitsubishi, ML101J8 type) is of Fabry-Perot type and it is stabilised by means of an injection current control unit, Lightwave, LDX-3620 type, and a temperature control unit, Lightwave, LDT-5910B type, by means of two Peltier temperature control elements.

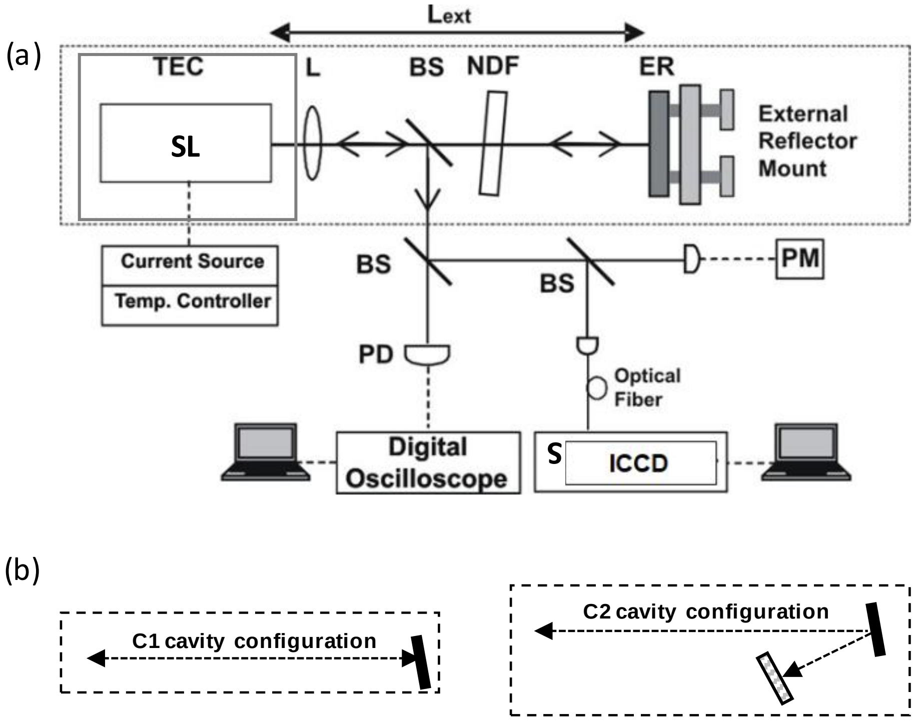

Fig. 1. (a) The ECSL experimental set-up: SL, semiconductor laser; TEC, thermo - electric control mount; L, collimation system; BS, beamsplitter; NDF, neutral density filter; ER, external reflector; PD, photo - detector; PM, power meter; S, spectrometer with intensified CCD camera. (b) external cavity configurations based on a grating external reflector.

In the case of chaotic dynamics studied in the conditions of a double reflector external cavity the used D-ECSL setup is based on the ECSL system presented in Fig.1a, were as ER element was used a diffraction grating.

In this case, besides the optical feedback ensured by grating on -1 - diffraction order (linear cavity), a new feedback component is received through the 0 -diffraction order as feedback from an external cavity limited by a mirror.

Thus, D-ECSL system consists in a double reflector cavity, with C1 cavity formed between laser and grating, and C2 cavity formed between laser and mirror (Fig. 1b). The C2 forms a Littman cavity and has as common branch C1 cavity configuration.

The investigation of chaotic dynamics of the laser emission obtained in conditions of chaos synchronization and injection current modulation was performed using an experimental setup consisting of two identical ECSL systems optical coupled through a coupling attenuator in a bidirectional lag synchronization scheme.

The coupling ratio between chaotic lasers was about 1.2, being defined as the ratio of master optical injection and solitary (without feedback) slave laser output power.

3. Results and discussion

Chaotic dynamic at higher laser injection currents

The experiments performed at injection currents higher than laser threshold current, show a laser emission dynamic characterized by chaotic low-frequency fluctuations [12]. At 24.9 ^{o}C diode temperature it has been carried out a comparative study about LFF dynamics function on the external reflector (ER) type: total reflector mirror, and a diffraction grating used in reflection in the -1 order.

In Figure 2 is presented the power-current (*P-I*) characteristics measured at 24.9 ^{o}C diode temperature.

The laser threshold current (I_{th}) of free emission appears at 58 mA and critical points characterized by intensity fluctuations of mode-hopping type appear at injection currents I_1= 59.7 mA (1.03*I_{th}) and I_2 = 79.9 mA (1.38*I_{th}).

In external optical feedback conditions, for both external reflectors, the LFF stable fluctuation has been obtained at threshold and injection currents I_1 and I_3 = 82.36 mA (1.42*I_{th}), in the last case at a value higher than that obtained for free emission.

Temporal analysis of the optical spectrum behavior of free emission (Fig. 2, the inset picture) shows that there are periodic fluctuations of laser mode intensities. The spectral structure of ECSL system emission shows two dominant laser modes in the spectral range 662.5 nm ÷ 663 nm when the mirror and 79.9 mA injection current are used.

In Figure 3 are presented the intensity time series of laser emission for I_1 and I_3, as well as the power spectra associated with them. The power spectra show the frequency components associated to the periodic oscillations present in the intensity time series.

Thus, at I_1, close to laser threshold, a well-defined peak associated to LFF fluctuations is observed at 18.5 MHz, and at I_3, a peak associated with LFF fluctuations is observed centered on 13 MHz, as well.

When 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 diode temperature, at about the same injection currents as in mirror case (corresponding to critical points): I_1= 1.03*I_{th}, I_2= 1.38*I_{th}, and I_3= 1.42*I_{th}, where I_{th}== 58 mA.

As in mirror case, it was observed that to obtain stable LFF chaotic regimes it is necessary to use feedback intensities of the same order of magnitude as at threshold.

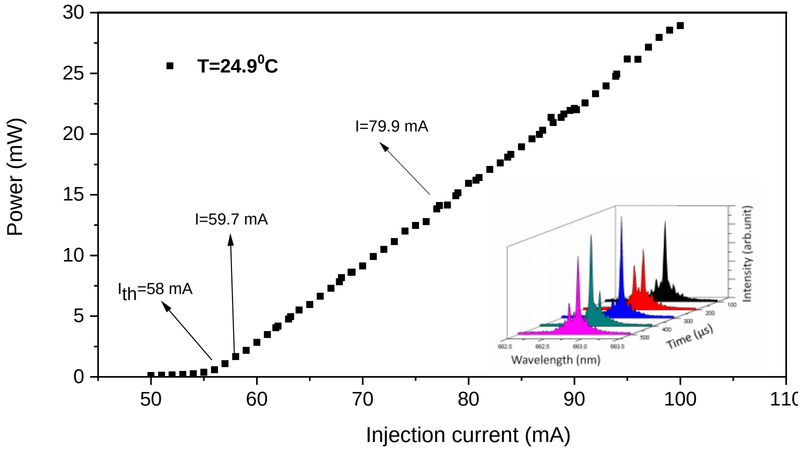

Fig. 2. The power-current characteristics without feedback at 24.9 °C and the used injection currents I_{th}=58 mA, and I_1=1.03*I_{th}, and I_2 = 1.38*I_{th}. The inset picture shows series of optical spectra with mode-hopping effects at I_2 = 79.9 mA.

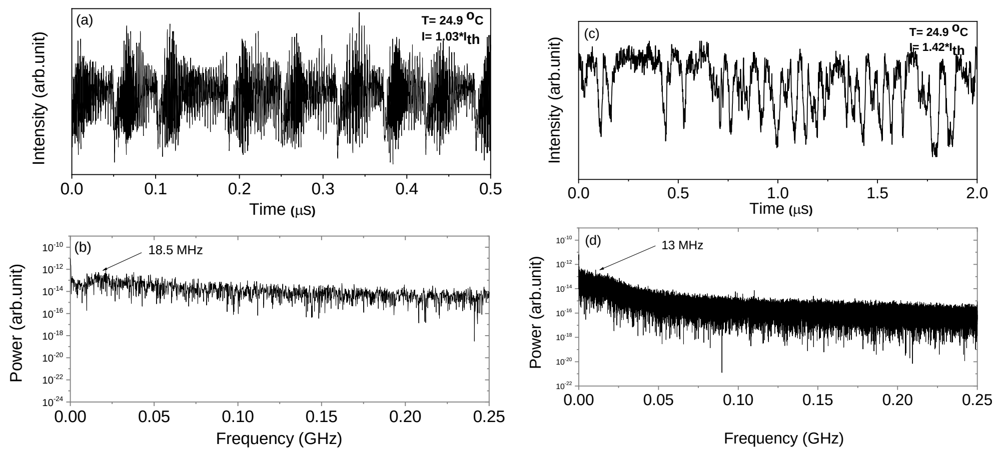

Fig. 3. Intensity time series and associated power spectra at injection currents I_1=1.03*I_{th}, (a, b) and I_3 = 1.42*I_{th},(c, d), respectively, when the mirror is used; I_{th}= 58 mA, t = 24.9 ^{0}C.

In both external reflector cases, there were obtained stable LFF regimes at injection currents over threshold, namely in the critical points (mode-hopping) of laser power-current characteristic. The feedback power necessary to obtain stable chaotic LFF regimes in the critical points was quantified as being of the same order of magnitude for both reflectors, and of the order of that obtained for ECSL system operation at laser threshold.

Chaotic dynamics in conditions of double reflector external cavity

The D-ECSL setup is based on ECSL system presented in Figure1a. Besides the optical feedback ensured by grating on -1 -diffraction order (C1 external cavity configuration), also a new feedback component is received through the 0 - diffraction order as feedback from an external mirror (Fig.1b, C2 external cavity configuration). Thus, the D-ECSL system consists in a double reflector cavity, with C1 cavity formed between laser and grating of length L_{C1}= 42 cm, and with C2 cavity made between laser and mirror of length L_{C2}= 64 cm [13]. The C2 forms a Littman cavity and has as common branch the C1 cavity configuration. The experimental set-up includes a 300 tr/mm unblazed grating as external reflector elements for C1 cavity, and totally reflecting mirror for C2 cavity, respectively. The C2 external cavity also includes an ON/OFF mechanical switch for coupling or uncoupling the C2 cavity. C1 and C2 feedback intensities are transmitted to the laser with variable attenuations function of coupling coefficients, c_1 and c_2, corresponding to C1 NDF and C2 NDF filters, respectively. In Figure 4a are shown the power spectra associated to laser intensity time series for D-ECSL in different configurations at I_{th}, c_1= 0.37 and t= 24.9 ^{o}C:

- 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 associated with low-frequency fluctuations (υ_{LFF}), a second component associated to external cavity oscillations (υ_{EC}) and its harmonics (υ_{HFO}). For D-ECSL system working with C1C2 coupled cavities at a coupling coefficient c_2= 1.0 (without feedback attenuation), power spectrum presents the same frequency components as for the system operating only with C2. This shows that the chaotic dynamics of the system is dominated by that of C2 cavity. If the C2 coupling coefficient is reduced to 0.63, and then to 0.16, at a C1 feedback power of 0.04 mW, the power spectra also show a component associated with LFF fluctuations. In this case υ_{EC} component, for c_2 = 0.63 close, though different, from that of C2 cavity, and in the case of c_2 = 0.16 this is no longer present in spectrum. The υ_{HFO} frequency for increasing values of c_2 coupling coefficient has values in the $\boldsymbol{\Delta}\upsilon_{HFO}$ frequency range (Fig. 4b).

This is limited by υ_{EC1} frequency, when c_2 coefficient is close to the minimum, and υ_{HFOC2} frequency, when c_2 coefficient is maximum.

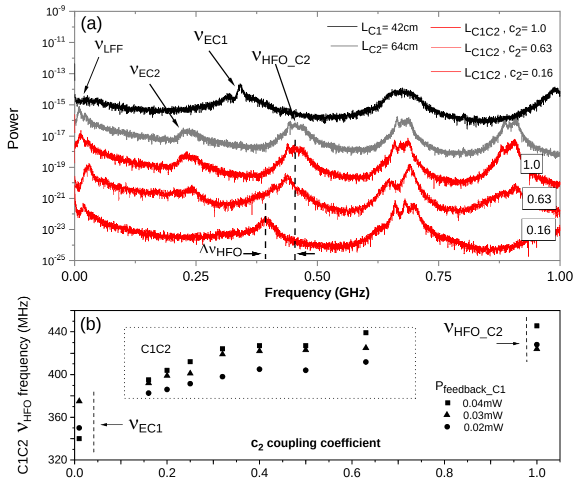

Fig. 4. (a) Power spectra associated to the intensity time series of D- ECSL system emission, at injection current 58 mA, C1 cavity feedback power 0.04 mW, and *t*= 24.9 °C; and (b) dynamics of the high-frequency oscillation frequency (υ_{HFO}) function of c_2 coupling coefficient for three C1 cavity feedback powers. Spectra are vertically shifted one to the other for a better view.

Thus, the characteristic frequencies (υ_{HFO}) of D-ECSL system show higher values when coupling coefficient c_2 is higher. The analysis of υ_{HFO} frequency behaviour was also performed for other two c_1 coupling coefficients from C1 cavity, with C1 feedback powers 0.03 mW, and 0.02 mW, respectively (Fig. 4b).

In both cases, it is observed that the υ_{HFO} frequency show the same evolution as for C1 feedback power 0.04 mW. The difference is due to the fact that υ_{HFO} frequency values are higher as the feedback intensity in C1 cavity is higher. By using D-ECSL system it was shown that one may generate chaotic high frequency oscillations with tunable υ_{HFO} frequency in the SL emission. By using an additional external cavity combined with the modification of feedback intensity provided by it, the chaotic high frequency oscillations frequency of D-ECSL system emission can be tuned almost continuously over tens of MHz. High frequency oscillations mixing increases the noise character of the signal as well, which is of practical importance for data encoding using laser carriers.

Chaotic dynamics of two coupled chaotic lasers

In this case were used two ECSL systems as that presented in Figure 1a, with equal external cavity lengths of about 64 cm (feedback delay time τ=4.3 ns). These were optically coupled through a coupling attenuator in a bidirectional lag synchronization scheme [14]. Lasers were operated near threshold I_{th} = 54 mA where emission is multimodal.

The operation parameters were, for master, $I = 1.05*I_{th}$ and $t = 22.5$ °C, and slave, $I = 1.05*I_{th}$ and $t = 23.67$ °C, chosen to obtain the same spectra domain of SL free emission (without feedback).

A waveform generator adds a sinusoidal signal to DC injection direct current applied on master laser using a multiplexor ZFBT-6GW bias-tee device [15]. For laser emission signals acquisition and analysis, two photodetectors (Becker&Hickl, APM-400-P, and Laser 2000, ET-2030A) were used. A 2.5 GHz Tektronix DPO7254 digital oscilloscope acquired simultaneously the signals. Time series of 5×10^5 points acquired at a 2×10^{-10} s sampling interval were recorded for dropout statistics.

The dynamics of coupled lasers with master external modulation has been studied at two frequencies, 8 and 15 MHz, around master natural (without modulation) LFF frequency (10 MHz or 0.1 µs time period) (Fig. 5a), and different from that of slave LFF oscillations (3.4 MHz or 0.3 µs time period) (Fig. 5b).

It was achieved a correlation of the rate of power dropouts for master and slave laser intensities under optical coupling conditions with modulation frequency. Driving the master at the two frequencies, induces dropouts with a periodicity of 0.125 µs (Fig. 6a), and 0.067 µs (Fig. 6b), respectively, resulting in LFFs with two dominant frequencies, the natural and the driving one.

It was observed that slave LFFs become more regular in the coupled system; also, when master is modulated at 8 MHz, close to master natural LFF frequency, the master and slave LFF oscillations have the same frequencies (Fig. 6c, d). Modulation at 15 MHz, out of the frequency range bounded by the master and slave natural LFF frequencies induces in chaotic dynamics of both lasers a clustering of the dropouts at two frequencies, as well: the modulation and master natural frequencies, for master (Fig. 6e); and, the master natural frequency and another, different from the modulation one, for slave (Fig. 6f).

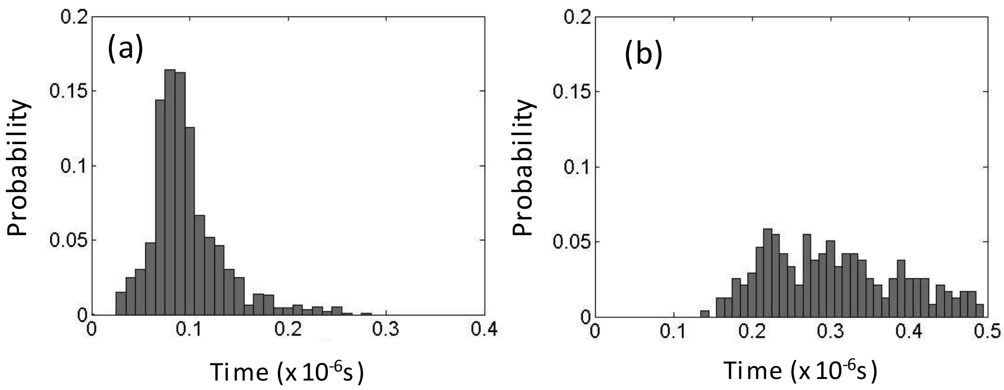

Fig. 5. Histograms of power dropouts associated to master (a) and slave (b) laser intensity time series, in the absence of master - slave optical coupling.

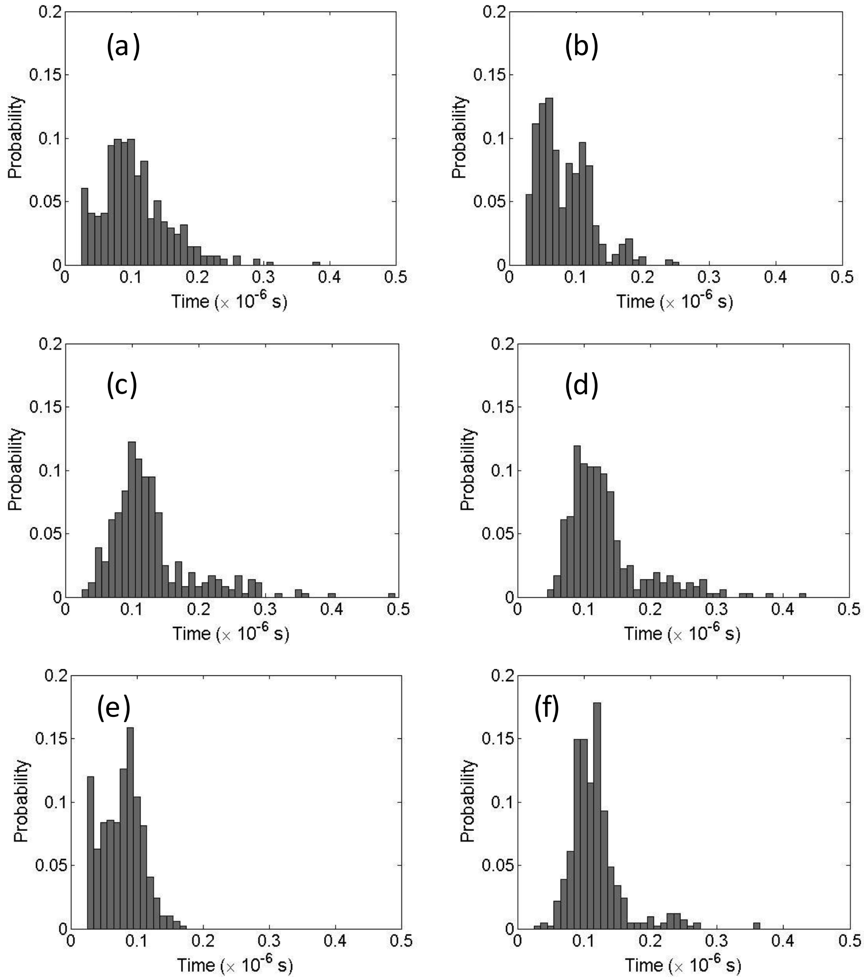

Fig. 6. Histogram of power dropouts associated to intensity time series of laser emission for master system with modulation at 8 MHz (a) and 15 MHz (b); master (c) and slave (d) systems optically coupled, with modulation at 8 MHz; master (e) and slave (f) systems optically coupled, with modulation at 15 MHz.

The chaotic dynamics of master and slave ECSL systems, once coupled, are changed in the presence of modulation compared to the case without modulation. Experiments show that function of modulation frequency, the slave dynamics only couples (synchronizes) to the master one, and not to that determined by the external modulator. So, at this modulation frequency, only the oscillations induced by the modulator to which master dynamics synchronizes can induce changes in the dynamics of another system that is synchronized with master.-The reported results about chaotic dynamic behavior of laser emission obtained in different external optical feedback conditions show a wide range of possibilities to chaos generation and control; this has potential of application in data encoding and information transmission using optical chaotic carriers.

4. Conclusions

A comparative study about the characteristics of chaotic dynamics of ECSL system emission in different external optical feedback conditions is reported.

Studies were performed using an ECSL system that works at injection currents near laser threshold, as well as at higher currents where in the optical spectra of free laser emission, oscillations of mode-hopping type (power jumps between active laser modes) are present.

Measurements made at laser threshold current and higher than this (I_{th}, 1.03*I_{th}, 1.42 *I_{th}, respectively), for fixed diode temperature, have evidenced emission regimes with stable LFF fluctuations for feedback powers of the order of magnitude to those at laser threshold.

In the case of a double reflector ECSL system chaotic emission was analyzed function of the feedback powers applied on the two branches of the system, namely C1 and C2 cavity configurations.

It was shown that for large external cavities the frequency υ_{HFO} of high frequency chaotic oscillations increase with the C2 feedback intensity increase, and the frequency range is bounded by those of C1 external cavity, and first harmonic of C2 external cavity, respectively; $\upsilon\upsilon_{HFO}$ frequency do not carry information about the geometry of the chaotic system if a C2 coupling coefficient up to 0.50 is used.

In the case of two ECSL systems coupled into a master-slave synchronization scheme the control of chaotic dynamics has been investigated under master dc current modulation conditions.

Driving master laser induces dropouts (LFFs) with two dominant frequencies.

The master modulation at a frequency that is not in the range bounded by master and slave natural LFF frequencies has no control on slave chaotic dynamics.

It has only the role to clustering the periods of dropouts, but at values other than the modulation one.

Acknowledgments

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R E F E R E N C E S

[1] Nilushi Wijeyasinghe, Laser Diodes & Direct Diode Lasers 2019-2029: Technologies, Markets & Forecasts, IDTechEx, **2019**.

[2] J. Ohtsubo, Semiconductor Lasers: Stability, Instability and Chaos, 4th Edition, Springer International Publishing, Cham, **2017**.

[3] F.R. Ruiz-Oliveras, A.N. Pisarchik, Phase-locking phenomenon in a semiconductor laser with external cavities, Optics Express, 14 (**2006**) 12859.

[4] F. Rogister, D.W. Sukow, A. Gavrielides, P. Mégret, O. Deparis, M. Blondel, Experimental demonstration of suppression of low-frequency fluctuations and stabilization of an external-cavity laser diode, Optics Letters, 25 (**2000**) 808.

[5] A. Többens, U. Parlitz, Dynamics of semiconductor lasers with external multicavities, Physical Review E, 78 (**2008**).

[6] 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.

[7] J.-G. Wu, G.-Q. Xia, Z.-M. Wu, Suppression of time delay signatures of chaotic output in a semiconductor laser with double optical feedback, Optics Express, 17 (**2009**) 20124.

[8] Liang Jun-Sheng, Wu Yuan, Wang An-Bang, Wang Yun-Cai, Extracting the external-cavity key of a chaotic semiconductor laser with double optical feedback by spectrum analyzer, Acta Physica Sinica, 61 (**2012**) 034211.

[9] D.W. Sukow, M.C. Hegg, J.L. Wright, A. Gavrielides, Mixed external cavity mode dynamics in a semiconductor laser, Optics Letters, 27 (**2002**) 827.

[10] R. Lang, K. Kobayashi, External optical feedback effects on semiconductor injection laser properties, IEEE Journal of Quantum Electronics, 16 (**1980**) 347–355.

[11] M. Matus, M. Kolesik, J.V. Moloney, M. Hofmann, S.W. Koch, Dynamics of two-color laser systems with spectrally filtered feedback, Journal of the Optical Society of America B, 21 (**2004**) 1758.

[12] 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**).

[13] C. Onea, P.E. Sterian, I.R. Andrei, M.L. Pascu, 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, **2019**.

[14] 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, OAM-RC, 13 (**2019**).

[15] C.M. Ticoş, I.R. Andrei, M.L. Pascu, M. Bulinski, Experimental control of power dropouts by current modulation in a semiconductor laser with optical feedback, Physica Scripta, 83 (**2011**) 055402.