CHAOTIC LOW-FREQUENCY FLUCTUATIONS OF LASER DIODE EMISSION AT INJECTION CURRENTS ABOVE THRESHOLD

C. ONEA[1], P.E. STERIAN[2], I.R. ANDREI[3], A. BALEANU[4], M.L. PASCU[5]

A complex chaotic behavior can be found in nonlinear dynamics of laser diode emission, only under optical feedback conditions provided by an external reflector. One of the most studied issues on chaotic dynamics is low-frequency fluctuations (LFF) which occur at laser diode operation near lasing threshold.

In this paper an extensive analysis of LFF regime of an external cavity – semiconductor laser system has been carried out. Data about the stability of LFF regimes for different sets of experimental parameters are shown. The injection current was adjusted at values near and over laser threshold current.

Stable LFF regimes were obtained at current values above the threshold current only in certain conditions. These depend on intrinsic properties of semiconductor active region, namely, instabilities of mode-hoping type that are observed when the laser emission is obtained without feedback.

Keywords: external-cavity semiconductor laser, low-frecvency fluctuations, lasing threshold, high injection currents, feedback power, mode-hopping regime

1. Introduction

The semiconductor laser has a wide area of applications, from information storage media to information transmission and encoding on optical carriers [1]. When light emitted by semiconductor laser is redirected into laser cavity as feedback from an external reflecting surface, the configuration is known as external-cavity semiconductor laser (ECSL). In this case the intensity of laser diode emission presents a series of dynamic effects such as nonlinear, chaotic fluctuations called low frequency fluctuations (LFF), obtained when ECSL system operates at injection currents close to lasing threshold. Usually, this intensity dynamics is obtained for a moderate optical feedback, e.g. 1- 10 % of emitted laser power [2], and represents one of the most studied chaotic regimes evidenced in the form of periodic dropouts, almost to zero, of the laser intensity. LFF fluctuations appear at frequency values positioned in low bandwidth range, up to 100 MHz, and represent envelopes for other rapid oscillations, around 1 GHz, given by external cavity oscillations. Time periods of LFF dropouts depend on the operating parameters of ECSL system: injection current, laser temperature, and feedback intensity [3], [4]. LFF chaotic dynamics is specific to semiconductor laser emission with direct application in chaotic synchronization of laser systems. Such a mode of operation has been and still is the subject of numerous theoretical and experimental studies, as well as computer simulations [1], [5]–[10]. The coupling of two chaotic laser systems as described here, or the coupling between a chaotic system and one without chaotic fluctuations with free emission, may result in synchronization into a chaotic regime [11]. This behaviour could be used to achieve encoded (encrypted) communications with chaos between systems of this kind [7], [12]–[17].

In this paper we present new data about the stability of LFF chaotic dynamics of ECSL system emission which works at diode injection currents near and over laser threshold [18]. In the over threshold case, stable LFF regimes were obtained for currents on the diode power-current characteristics where, without external feedback, instabilities of mode-hopping type are present in laser emission dynamics, which depend on the intrinsic properties of active region [19], [20]. We show, for the first time, that for both external reflectors, mirror and grating, at currents over threshold, stable LFF regimes are obtained for feedback powers of the same order of magnitude as at laser threshold.

These results are of technological interest in the case of optical coupling of multiple lasers with application in parallel transmission of encoded data using chaotic carriers. LFF dynamic is used for chaotic synchronization of laser systems due to the high stability over time. Practical disadvantage of LFF chaotic regime is the low laser power of ECSL system due to operation at threshold current, and consequently, the limitation of the possibility to couple multiple laser systems at the same time [12], [21]. In this paper we show that the LFF chaotic regime can be obtained at injection currents over threshold current, namely, in the critical points of laser emission where there are mode-hopping instabilities. In these points, laser beam powers are higher than at threshold [22]. Also, by increasing injection current, the amplitudes of chaotic oscillations increase as well as noisy character of signal, which is of practical importance for data encoding and transmission using laser carriers [23]–[25].

2. External-cavity semiconductor laser (ECSL) system

2.1 ECSL experimental set-up

The experimental set-up (Fig. 1) is used to generate and analyse laser radiation with nonlinear (chaotic) dynamics of its intensity. There were determined experimentally reproducible conditions, i.e. the range of operating parameters of the system, to get chaotic dynamics of LFF type. The set-up includes: laser diode, collimation lens system (L), and a beamsplitter (BS 1) that separates from ECSL emitted power a fraction of 33% sent to powermeter; the remaining 66% go to the second beamsplitter (BS 2), which separates by reflection 17% from laser beam which is sent to a photodetector and further transmits 82% to neutral density filter (NDF). Laser beam is transmitted by the NDF with variable attenuations directly to the reflector, e.g. mirror or diffraction grating. The 17% reflected laser beams are used to analyse the laser intensity time series and the spectra structure of laser emission. Thus, 67% are directed by BS3 toward photodiode coupled to an oscilloscope and the remaining 33% are send through an optical fiber to spectrograph for analysis [26].

2.2 Technical specifications of the sub-assemblies

The used laser diode is of Fabry-Perot type and it is stabilised by means of a Lightwave injection current control unit (LDX-3620). The temperature is controlled using a Lightwave controll unit (LDT-5910B) by means of two Peltier temperature control elements of 16 W each. The laser used in ECSL system is a ML101J8 Mitsubishi laser diode. Maximum power (40 mW) is obtained at optimal operating parameters in continuous wave emission: injection current I=109 mA, temperature t=24 °C, at λ=663.17 nm.

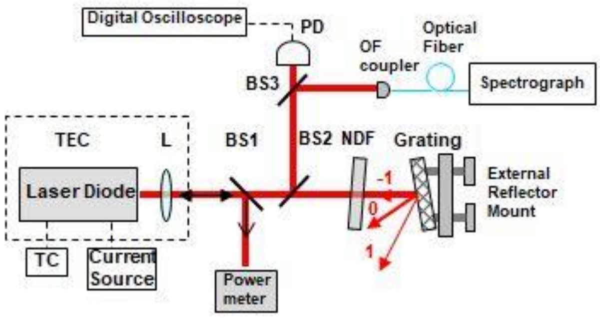

Fig 1. ECSL experimental setup. TEC, thermo-electric controller mount; TC, temperature controller; L, collimation lens systems; BS, beamsplitters; NDF, neutral continuously variable density filter; PD, photodetector; OF, optical fiber; -1, 0, 1, diffraction orders.

Laser emission is single mode with full width at half maximum (FWHM) 0.04 nm (Fig. 2a). In Fig. 2b is shown the optical spectrum of laser emission at threshold current (I_{0th}=54 mA), without optical feedback, presenting a multimode broadband emission. The laser modes spacing is $\Delta\lambda$ ~0.550 nm, which is specific to the used laser (linear dimensions of the active medium of about 0.4 mm). During analysis process each emission (power) spectrum has the intensity scale expressed in arbitrary units which gives information about the relative intensities within the same curve or set of curves but does not allow a comparison of intensities of signals when experimental conditions are changed.

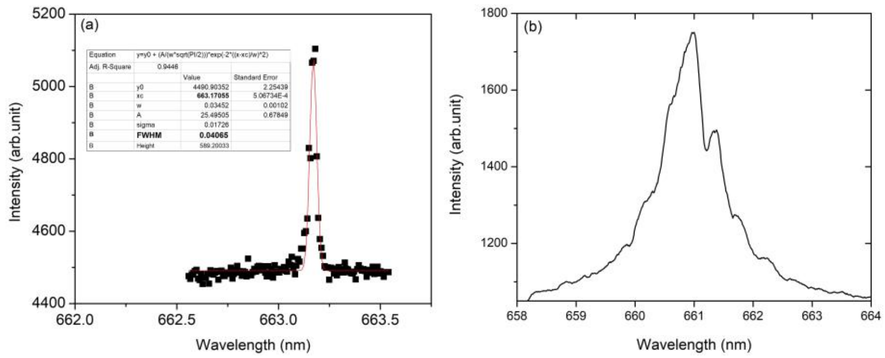

Fig. 2. Emission spectrum of laser diode at (a) optimal operation parameters, and (b) threshold current (I_{0th}= 54 mA). The inset in (a) represents the fitting line report.

The external cavity is formed between the external optical reflector and the beam extracting window of the laser cavity. The divergent radiation emitted by laser diode is collimated with an optical system (L) with a focal length f= 5 mm placed in the laser diode mount (TEC) (Fig. 1). The feedback strength (expressed by the feedback coefficient as the ratio between the laser power reinjected into the active laser medium and the emitted laser power) is controlled by the neutral density filter which can vary its transmission from 0 to 100%.

The optical signal is obtained through an amplified photodetector (Laser 2000, ET-2030A) which has bandwidth from 75 KHz to 1.2 GHz, and a rise-time < 0.5 ns. The photodetector is coupled with a Tektronix oscilloscope, DPO7254 with 2.5 GHz bandwidth which is used to record and analyze time series of laser beam intensity. Spectral structure of ECSL emission has been registered using a Princeton Instruments spectrograph (Acton SpectraPro 2750), which has optical resolution up to 0.02 nm. The spectrograph is equipped with a diffraction grating with 2400 traces/mm; an input slit of 10 μm and exposure times up to 500 μs were used and an average of 10 spectra was traced.

2.3. The power-current characteristics and mode-hopping effect

The analysis of literature results shows that it is more useful a high chaotic state for sending large volume of data, while allowing laser operation at a power level high enough to synchronize several receivers [24]. In order to achieve a stable synchronization in point to multi-point configuration (an ECSL transmitter and one or more ECSL receivers), ECSL systems with low chaotic states arepreferable [12]. A possible solution to meet both requirements is to apply an injection current above lasing threshold, at a value corresponding to the occurrence of mode-hopping phenomenon (intensity jump between active laser modes) [19]. In those critical points of laser emission, fluctuations of laser intensity were measured from one laser mode to another, as happens at laser emission at threshold. The difference is that while at laser threshold instabilities are determined by the change between laser and LED type of emissions, with periodic dropouts to zero of the intensity, at mode-hopping points the dynamics instabilities are determined by intensity oscillations between the different active laser modes, but without intensity dropouts to zero.

In Fig. 3a, power-current (P-I) characteristics obtained for different diode temperatures are shown, and the critical points at which intensity instabilities of the mode-hopping type appear are specified. At low temperatures, up to 22.5 °C, mode-hopping effects have not been observed during laser emission (results not shown).

In critical points, LFF oscillations have lower or closer frequencies, with amplitudes higher than those at laser threshold, and no coherence collapse. However, in ECSL emission it is difficult to obtain oscillations of mode-hopping type because the critical points (intensity instabilities when active laser mode is changing) are not specified in laser diode data sheet. Most laser diodes present a discreet jump between active modes, without mode-hopping oscillations, once the injection current is modified. These points of instability can be only experimentally identified point by point by measuring at different diode temperatures the power - current characteristics [19], [20].

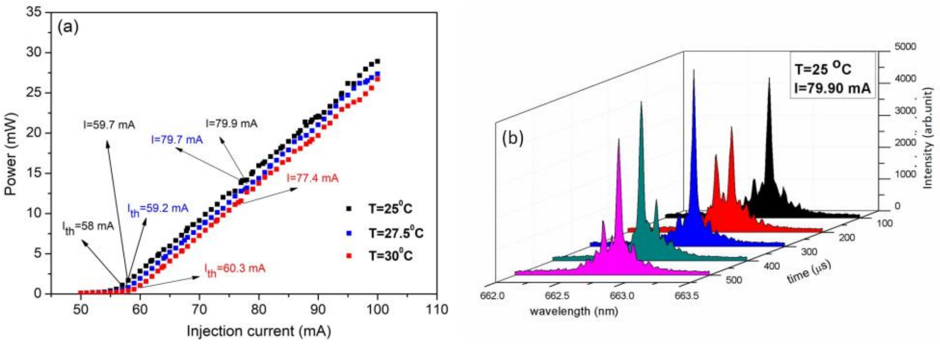

Fig. 3. (a) The power-current characteristics at different temperatures. Instabilities of mode-hopping types and corresponding currents are marked. (b) Series of optical spectra with mode-hopping effects at 79.9 mA and 24.9 ºC.

In Fig. 3b is presented a series of 5 spectra acquired with an exposure time of 100 µs for t=24.9 ºC and I= 79.9 mA. One may observe the jumps of laser intensity between different active laser modes from one spectrum to another, which is characteristic for mode-hopping effect.

3. Results and discussion

The measurements have highlighted the laser emission characterized by LFF chaotic dynamic at injection currents higher than laser threshold current. For 24.9 ºC diode temperature, a comparative study about LFF dynamics function of the external reflector type: a total reflector mirror and a diffraction grating used in reflection in the -1 order, has been carried out. At 24.9 ^{o}C temperature, laser threshold of diode free emission appears at injection current I_{th}= 58 mA; critical points appear at injection currents 59.7 mA (1.03*I_{th}) and 79.9 mA (1.38*I_{th}). In external optical feedback conditions, for both external reflectors, stable LFF fluctuations (without alternations between LFF and constant emissions) have been obtained at injection currents 59.7 mA (1.03*I_{th}) and 82.36 mA (1.42*I_{th}), and, only for grating in some conditions of feedback, at 80.2 mA (1.38*I_{th}). In the last cases, the stable LFF regimes are obtained at current values higher than those used for free emission.

3.1. External reflector element: mirror

The spectral structure of ECSL emission when the mirror is used for an injection current of 79.9 mA, shows two dominant modes between 662.5 nm and 663 nm (Fig.4). Temporal analysis of laser emission shows that in this case periodic fluctuations in laser mode intensities are present.

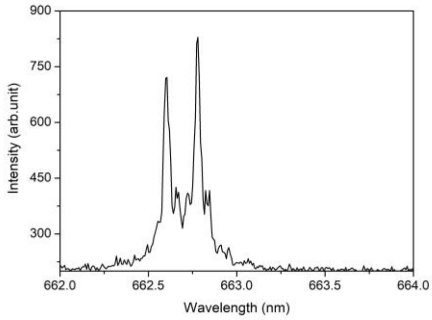

Fig. 4. Spectrum of laser emission at 79.9 mA current when mirror as external reflector is used.

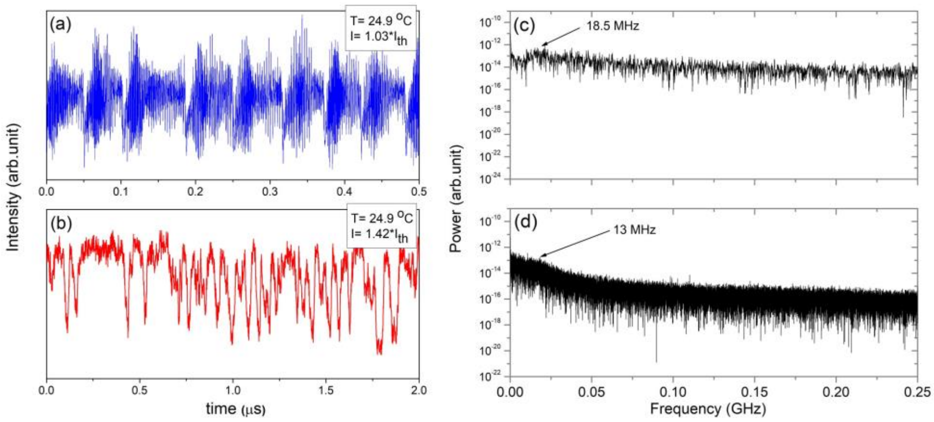

Fig. 5. Intensity time series (a and b) and associated power spectra (c and d) when the mirror is use, at injection currents (a) I=59.7 mA =1.03*I_{th} and (b) I =82.36 mA= 1.42*I_{th}; with I_{th}= 58 mA, t = 24.9 ^{0}C, and feedback powers of 0.03 mW

In Fig. 5 are shown the intensity time series of laser emission and the power spectra associated with them, for two injection currents at t=24.9 °C and feedback powers of 0.03 mW. The power spectra show the frequency components associated to the periodic oscillations present in intensity time series. At 59.7 mA, close to laser threshold, are observed (i) in the base-band frequency range (below 100 MHz) a well-defined peak at 18 MHz, associated to LFF fluctuations, and (ii) in the high frequency range a peak at 340 MHz, associated with high frequency oscillations caused by the time delay in external cavity (result not shown). At 82.36 mA, a maximum centered at about 13 MHz, which is associated with LFF fluctuations is observed. In this case, due to a small fraction of ECSL laser power used as feedback, the effect of intensity oscillations caused by external cavity is irrelevant.

3.2. External reflector element: diffraction grating

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 t= 24.9 °C, and at about the same injection currents as in mirror case (corresponding to critical points): I_1= 1.03*I_{th}= 59.73 mA, I_2= 1.38*I_{th}= 80.2 mA or I_3= 1.42*I_{th} = 82.36 mA, where I_{th}=I_0= 58 mA. The optical spectra obtained for these parameters highlighted the mode-hopping effects as well.

In Table 1 is given a summary of operation parameters values used to determine the conditions in which one may obtain from ECSL a stable LFF chaotic regime.

Table 1.

The values of operation parameters of ECSL system
and the calculated ones used to obtain stable LFF fluctuations (bolded values).

Injection current / Power without feedback	Transmission coefficient (C_{FB})	P_R (mW)	P_0 (mW)	P_{FB} (mW)
I_0 = 58 mA P = 0.55 mW	*T = 80%*	0.87	2.64	**0.2**
	T = 44%	0.83	2.52	**0.06**
	T = 37%	0.76	2.30	**0.04**
	T = 28%	0.71	2.15	**0.02**
I_1 = 1.03*I_0 = 59.7 mA P = 1.20 mW	T = 37%	1.0	3.27	**0.05**
	T = 30%	1.1	3.06	**0.03**
	T= 9%	0.94	2.85	0.003
	T= 9%	0.96	2.91	0.003
I_2 = 1.38 * I_0= 80.2 mA P= 5.17mW	T= 10%	5.14	15.6	**0.02**
I_3 = 1.42 *I_0= 82.3 mA P= 5.60 mW	T= 6%	5.70	17.27	**0.007**
	T= 5%	5.73	17.36	0.005
	T= 1%	5.67	17.18	-
	T= 1%	5.70	17.27	-

The stability of LFF regime has been assessed function of feedback power P_{FB}, reinjected into the active media. It was first determined the value of total losses caused by optical elements inserted in external cavity and diffraction grating (losses coefficient noted with C); out of these, losses produced by neutral density filter, C_{FB}, used to control the feedback intensity were excepted. Thus, it has been calculated a losses coefficient C= 12% (constant value) as percent of total power P_0 of the ECSL system emission. The reinjected power P_{FB} has been calculated function of P_0, C and C_{FB}: $\boldsymbol{P_{FB} = P_0 \times (C_{FP})^2 \times C}$, where C_{FB} was varied to obtain stable LFF fluctuations for a set injection current.

In Table 1, P and P_R parameters represent 33% from ECSL power used to calculate the P_0 for free emission, and in optical feedback conditions, respectively. With T was denoted NDF filter transmission, expressed in percent, and C_{FB} coefficient was considered the dimensionless value associated to transmission T.

For measurements carried out at threshold, $I_{th} = I_0 = 58$ mA, laser emission with stable LFF oscillations has been obtained for reinjected P_{FB} powers varying from 0.2 to 0.02 mW; at $I_1 = 59.7$ mA, emission regimes with stable LFF oscillations have been obtained for reinjected powers whose values, 0.05 and 0.03 mW, were close to the smaller value obtained at threshold. For measurements made at $I_2 = 80.2$ mA (completed with measurements made at $I_3 =$ 82.3 mA), emission regimes with stable LFF oscillations have been obtained for reinjected P_{FB} powers, 0.007 and 0.02 mW, that are also of the order of magnitude of the smaller values obtained at threshold. Measurements carried out at I_1 and I_2 currents, but for P_{FB} values with an order of magnitude lower (e.g. 0.005 mW for I_3) or higher than the minimum values obtained at laser threshold, have not led to stable LFF emission regimes. Thus, it was observed that for obtaining stable LFF fluctuations regimes in ECSL system at injection currents different from laser threshold, it is necessary to use feedback intensities of the same order of magnitude as at threshold.

Next, the evolution of optical and power spectra of the ECSL laser emission obtained for operation parameters with values corresponding to Table 1 is presented. In Fig. 6 are presented the optical spectra for the three injection currents at different feedback intensities. With current increasing, there is a shift of emission band towards red and a reduction of laser active modes. Also, in the case of stable LFF emission at currents above laser threshold, emission wavelength is limited within 662 - 663 nm spectral range.

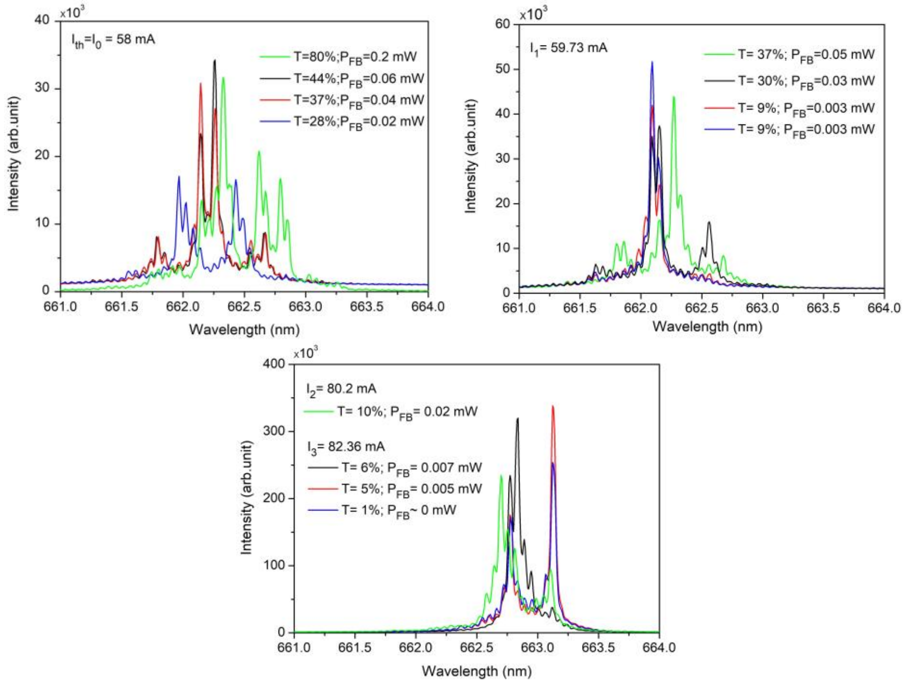

Fig. 6. Optical spectra obtained for I_0=I_{th} , I_1=1.03*I_{th} , I_2= 1.38*I_{th} and I_3= 1.42*I_{th}, at t= 24.9 °C.

For power spectra associated to intensity time series measurements were made at the same injection currents as for optical spectra: I_{th} = I_0, I_1, and I_2, I_3 (Fig. 7).

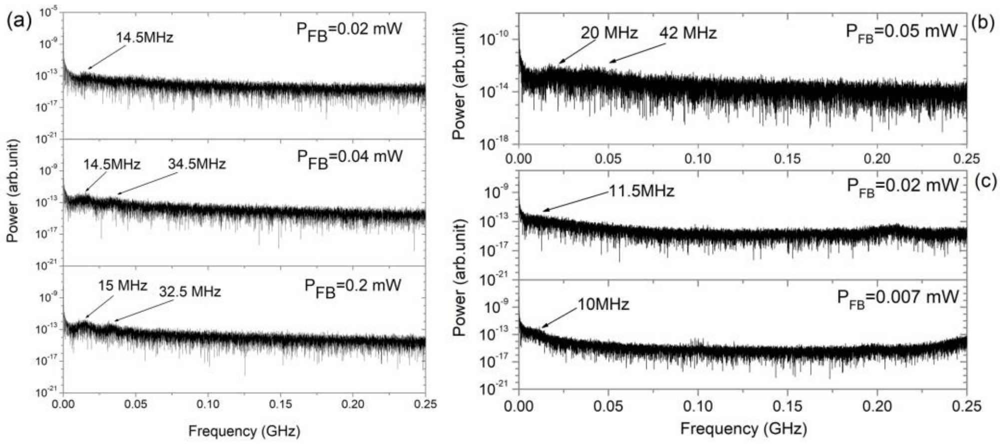

Fig. 7. Power spectra obtained for (a) I_0=I_{th} , feedback powers of 0.02, 0.04 and 0.2 mW; (b) I_1, feedback power of 0.05 mW; (c) I_2 and I_3, feedback powers, 0.02 and 0.007 mW, at t= 24.9 °C.

In Fig. 7a are shown the power spectra at laser threshold current, at three different feedback powers, 0.02, 0.04 and 0.2 mW. It should be noted that during the feedback power increase, LFF fluctuations appear with two dominant frequency values, at about 14.5 and 32.5 MHz.

At I_1 (Fig. 7b), near threshold, LFF frequencies appear below 100 MHz, with two peaks centered at 20 and 42 MHz. In this case, a stable regime has been obtained for feedback powers of 0.05 and 0.03 mW. Measurements performed at higher NDF attenuations did not reveal the existence of stable LFF regimes. For I_2 and I_3 currents (Fig. 7c) one may see in both power spectra a peak associated to LFF fluctuations, 11.5 and 10 MHz, corresponding to 80.2 mA and 82.3 mA, respectively. Also, a peak at about 210 MHz associated to the fast oscillations caused by 42 cm external cavity is present.

The results shown here are the first observations about the stability of LFF chaotic dynamics of ECSL system when the mode-hopping dynamics of laser free emission is considered. We obtained stable LFF regimes in such critical points (mode-hopping) of laser power-current characteristic at injection currents over the threshold one, for both ECSL external reflectors, mirror and grating, respectively. We quantified the feedback power necessary to obtain stable chaotic regimes in critical points 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.

The LFF frequencies present unimportant differences for measurements performed at different injection currents and, also, between mirror and grating cases. Actually, for mirror case, at the two used injection currents, I_1 and I_2, there is a single LFF frequency in the power spectra centered at 18.5, and 13 MHz, respectively. A LFF frequency of the same value, varying between 10 and 20 MHz, is present in the grating case at all used injection currents. Also, for grating case, and measurements performed at $I_0 = I_{th}$ (feedback powers of 0.02 and 04 mW), and I_1, the power spectra have shown a second LFF frequency positioned at 32.5 and 34.5 MHz, and 42 MHz, respectively. These results appear to be in contradiction with those reported in [2], where LFF frequency increase with injection currents increasing. But, considering (1) our particular measurement conditions, namely, laser working at specific currents corresponding to mode-hopping dynamics (laser intensity fluctuations similar to those at laser threshold) and fine adjusting of parameters (injection current and feedback power) pursuing a stable LFF regime, and (2) the fact that same order of magnitude have been resulted for feedback powers at all injection currents, it is to note that we have obtained LFF regimes with frequencies similar to those of the threshold. In these particular conditions, it is possible that the mechanism of LFF forming do not change much with respect to that from laser threshold. This is to be further investigated.

4. Conclusions

A comparative study about the characteristics of low-frequency fluctuations (LFF) chaotic regimes depending on external reflector type (mirror, and diffraction grating used in -1 diffraction order) for an ECSL system operated at laser threshold and mode-hopping (power jumps between active laser modes) currents, and 24.9 ^{o}C temperature, is reported.

Measurements made at threshold current, I_{th}, show emission with stable LFF fluctuations for optical feedback powers varying by one order of magnitude, from 0.2 to 0.02 mW for grating case, and of 0.03 mW for mirror case. Measurements at I_1 =1.03*I_{th} have evidenced for both external reflectors emission regimes with stable LFF fluctuations for feedback powers of the order of magnitude to that at laser threshold, 0.05 and 0.03 mW, respectively. At higher currents, I_2 =1.38*I_{th} and I_3 =1.42 *I_{th}, laser emission with stable LFF regimes have been obtained for feedback powers which are also of the order of magnitude to that from laser threshold, 0.02 and 0.03 mW, respectively.

Stable LFF chaotic regimes were obtained for both, mirror and grating external reflectors at injection currents over threshold current, and fixed diode temperature, for feedback powers of the order of magnitude of those obtained at laser threshold. The results shown here are the first observations of such a behavior of the ECSL systems.

R E F E R E N C E S

[1] J. Ohtsubo, Semiconductor Lasers: Stability, Instability and Chaos, 4th Edition, vol. 111. Cham: Springer International Publishing, 2017.

[2] M. Port and K. J. Ebeling, “Intensity noise dependence on the injection current of laser diodes with optical feedback,” IEEE Journal of Quantum Electronics, vol. 26, no. 3, pp. 449–455, Mar. 1990.

[3] R. Lang and K. Kobayashi, “External optical feedback effects on semiconductor injection laser properties,” IEEE Journal of Quantum Electronics, vol. 16, no. 3, pp. 347–355, Mar. 1980.

[4] M. Bulinski and M.L. Pascu, “Chaos in laser diode light emission,” Romanian Journal of Optoelectronics, vol. 19, no. 2, pp. 1–34, 2001.

[5] Y. Liu, N. Kikuchi, and J. Ohtsubo, “Controlling dynamical behavior of a semiconductor laser with external optical feedback,” Physical Review E, vol. 51, no. 4, pp. R2697–R2700, Apr. 1995.

[6] G. J. Rodgers, “From order into chaos,” Physics Education, vol. 27, no. 1, pp. 14–17, Jan. 1992.

[7] P.E. Sterian, “Communications based on chaotic signals,” Proceedings of the Romanian Academy, vol. 3, no. 1–2, 2002.

[8] A. R. Sterian, “Computer Modeling of the Coherent Optical Amplifier and Laser Systems,” in Computational Science and Its Applications – ICCSA 2007, vol. 4705, O. Gervasi and M. L. Gavrilova, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 436–449.

[9] D.-A. Iordache, P. Sterian, A. R. Sterian, and F. Pop, “Complex Computer Simulations, Numerical Artifacts, and Numerical Phenomena,” International Journal of Computers Communications & Control, vol. 5, no. 5, pp. 744–754, Dec. 2010.
[10] Y. Cunyun, Tunable External Cavity Diode Lasers. WORLD SCIENTIFIC, 2004.
[11] I. R. Andrei, G. V. Popescu, and M. L. Pascu, “Optical spectrum behaviour of a coupled laser system under chaotic synchronization conditions,” Journal of the European Optical Society: Rapid Publications, vol. 8, p. 13054, Aug. 2013.
[12] Q. Li et al., “Point-to-multipoin and ring network communication based on chaotic semiconductor lasers with optical feedback,” Appl. Optics, vol. 58, no. 4, pp. 1025–1032, Feb. 2019.
[13] J. Ohtsubo, “Chaos Synchronization in Semiconductor Lasers,” in Semiconductor Lasers, vol. 111, Cham: Springer International Publishing, 2017, pp. 459–510.
[14] C. Xue, N. Jiang, G. Li, Y. Lv, and K. Qiu, “High Speed Bidirectional Chaotic Communication Based on Bidirectionally Coupled Semiconductor Lasers,” in 2017 16th International Conference on Optical Communications & Networks (icocn 2017), New York: Ieee, 2017.
[15] A. Uchida, F. Rogister, J. García-Ojalvo, and R. Roy, “Synchronization and communication with chaotic laser systems,” in Progress in Optics, vol. 48, Elsevier, 2005, pp. 203–341.
[16] A. Sanchez-Diaz, C. R. Mirasso, P. Colet, and P. Garcia-Fernandez, “Encoded Gbit/s digital communications with synchronized chaotic semiconductor lasers,” IEEE Journal of Quantum Electronics, vol. 35, no. 3, pp. 292–297, Mar. 1999.
[17] V. Ninulescu and A.-R. Sterian, “Dynamics of a Two-Level Medium Under the Action of Short Optical Pulses,” in Computational Science and Its Applications – ICCSA 2005, 2005, pp. 635–642.
[18] M.-W. Pan, B.-P. Shi, and G. R. Gray, “Semiconductor laser dynamics subject to strong optical feedback,” Optics Letters, vol. 22, no. 3, p. 166, Feb. 1997.
[19] T.A. Heumier and J.L. Carlsten, “Mode hopping in semiconductor lasers - Application Note, ILX Lightwave Corporation.” 2003.
[20] F. Bertinetto, M.-L. Pascu, M. A. Greco, and M. Bisi, “Studies on tunable lasers as sources for spectroscopy measurements,” 1995, vol. 2461, pp. 317–324.
[21] K. Hicke, X. Porte, and I. Fischer, “Characterizing the deterministic nature of individual power dropouts in semiconductor lasers subject to delayed feedback,” Physical Review E, vol. 88, no. 5, Nov. 2013.
[22] Y. T. Younis, S. K. Musa, S. F. Abdalah, A. K. Ahmed, R. Meucci, and K. A. Al Naimee, “The rule of bias current of semiconductor laser in chaos communications,” Results in Physics, vol. 6, pp. 243–251, 2016.
[23] L. Rondoni, M. R. K. Ariffin, R. Varatharajoo, S. Mukherjee, S. K. Palit, and S. Banerjee, “Optical complexity in external cavity semiconductor laser,” Optics Communications, vol. 387, pp. 257–266, Mar. 2017.
[24] B. O. Rasheed et al., “Exploring noise effects in chaotic optical networks,” Results in Physics, vol. 7, pp. 1743–1750, 2017.
[25] A. Argyris, E. Pikasis, and D. Syvridis, “Highly Correlated Chaotic Emission From Bidirectionally Coupled Semiconductor Lasers,” IEEE Photonics Technology Letters, vol. 28, no. 17, pp. 1819–1822, Sep. 2016.
[26] I.R. Andrei, “Characterization of chaotic emission of a laser diode in optical feedback conditions produced by different external reflectors,” OAM-RC, vol. 4, no. 10, pp. 1440–1444, 2010.