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HIGH FREQUENCY CHAOTIC DYNAMICS IN A SEMICONDUCTOR LASER WITH DOUBLE-REFLECTOR SELECTIVE CAVITY

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In the emission dynamics of a semiconductor laser operated under double optical feedback conditions, mixing of high frequency oscillations was observed. This consists of high frequency oscillations modulated by low-frequency fluctuations.

The external feedback is provided by a double reflector cavity consisting of one cavity bordered by a diffraction grating which assures the optical injection on -1 -diffraction order and the other one delimited by a mirror which returns the 0 – order of the diffraction grating.

We show experimentally that by changing the feedback intensity of the long cavity, high frequency chaotic oscillations with tunable frequencies are obtained. The chaotic oscillations show function of the long cavity feedback intensity, frequency values bounded by those of the short cavity and first harmonic of the long cavity. Also, the value range of the oscillation frequencies increase with the short cavity feedback intensity increasing.

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

1. Introduction

Semiconductor lasers (SL) have a wide range of applications in several domains, including data encoding and transmission using chaotic optical carriers, due to easy changing of dynamics characteristics of the emission as result of injection of weak to moderate external optical feedback [1–4]. Usually, this is ensured by an external reflector which returns a part of emitted radiation to laser cavity, and the configuration is known as external-cavity semiconductor laser (ECSL) system [5]. As effects of optical feedback on laser emission dynamics it should be mentioned the periodic and quasi-periodic pulsations, low frequency fluctuations (LFF), coherence collapse and chaotic behaviour [4,6].

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On the other hand, semiconductor lasers which are subject to feedback from double or multiple cavities were studied theoretically and experimentally in connection with their applications: control of chaotic dynamics by adjusting the length and feedback intensity of the second cavity [7,8], generate high-dimensional chaotic dynamics [9] for data encoding based on phase shift keying encryption [10–12], mask the information on the geometry of the optical system [13–16] or, on the contrary, extract the time delay signature [17]. Also, double reflector chaotic lasers whose external cavities contain gratings have been studied both, numerically or experimentally. These were performed in relation to locking lasing frequency and increasing laser power in fiber lasers, and in these cases new models for nonlinear coupled laser equations [18,19] were implemented, or for evaluation of mixed-modes dynamic states [20].

In this paper, we use a double-reflector ECSL (D-ECSL) system combining a linear external cavity limited by a diffraction grating, with a Littman cavity limited by a mirror. The grating provides feedback on -1 -diffraction order and mirror on 0 – diffraction order of the grating. The optical path of second (Littman) cavity is with about 1/3 from it longer than the first one. This system is used to analyse the mixing characteristics of the high frequency chaotic oscillation of laser emission. 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 [21]. Thus, 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. Also, a frequency degenerate regime was obtained in which the oscillations frequency shows a double peak character with a separation much lower than the external cavity frequency**.** 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. These were previous numerical predicted [15], but, in addition, we show that the characteristic oscillation frequencies of a D-ECSL system emission are bounded by the short cavity oscillations frequency and the first harmonic frequency of the long cavity oscillations, respectively. The reported results have potential of application in data encoding and information transmission using optical chaotic carriers.

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

The used D-ECSL setup is based on the ECSL system developed in Ref. [22,23]. In this work, besides the optical feedback ensured by grating on -1 -diffraction order, also a new component is received through the 0 -diffraction order

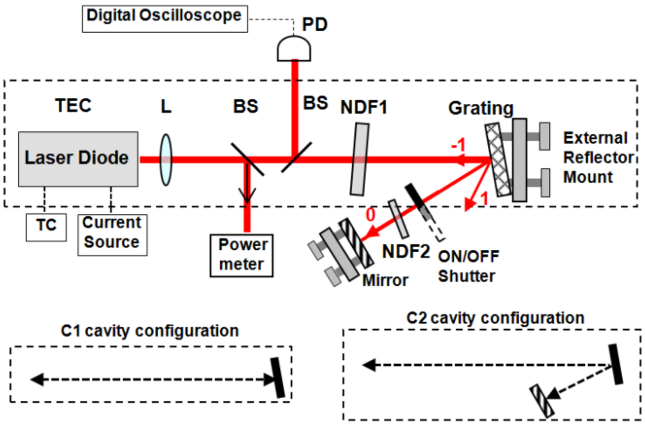

Fig. 1. Scheme of D-ECSL experimental setup. TEC, thermo-electric controller mount; TC, temperature controller; L, collimation lens system; BS, beamsplitters; NDF 1, neutral continuously variable density filter; NDF 2, neutral step-variable density filter; PD, photodetector; -1, 0, 1 - diffraction orders.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

as feedback from an external mirror (Fig. 1). Thus, the D-ECSL system consists in a double reflector cavity, with C1 cavity formed between laser and grating, and with C2 cavity made between laser and mirror (Fig. 1, inset pictures). The C2 forms a Littman cavity and has as common branch the C1 cavity configuration.

The experimental set-up includes: (i) a Fabry-Perot type semiconductor laser (Mitsubishi, ML101J8) operated near laser threshold current, I_{th}= 58 mA, or at I= 59,73 mA injection current, for a temperature t= 24.9 ^{o}C, (ii) the laser mount (TEC) with a collimation lens system (L), (iii) external reflector elements (300 tr/mm unblazed grating for C1 cavity, and totally reflecting mirror for C2 cavity, respectively). The external cavities also include two beamsplitters (BS) that separate from ECSL emission power a fraction of 33% which reaches the powermeter; from the remained 66% laser power, the second beamsplitter separates a fraction of 17% which is sent to a photodetector; the neutral density filters 1 and 2 (NDF 1 and 2), and a 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 NDF 1 and NDF 2 filters, respectively. The 17% beam fraction is used to monitor laser beam power/energy.

3. Results and discussion

Chaotic dynamics of the D-ECSL system emission was investigated using the experimental set-up described in Figure 1 for external cavity lengths fixed at L_{C1} = 42 cm and L_{C2} = 64 cm. Chaotic dynamics, namely the frequencies of the power oscillations obtained through the power spectrum of intensity time series, was evaluated for three C1 feedback powers (effective reinjected beam powers P_{FB_C1} calculated for the ECSL system), 0.04, 0.03 and 0.02 mW. These values were obtained for different pairs of operation parameters, such as diode injection current and C1 feedback coefficient (c_1): I_{th} current and 0.37; I and 0.30, and I_{th} and 0.30. At each C1 feedback power, C2 was adjusted in steps as ratios from the maximum value of C2 feedback intensity (without attenuation). Thus, the c_2 coupling coefficient was varied between 0 and 1, zero corresponding to an uncoupled cavity, and 1 to coupling at maximum power. For ECSL system working with feedback on -1 -diffraction order, beam intensity which reaches the grating is distributed as follows: reflected radiation on -1 diffraction order, 43%; on 0 -diffraction order, 42.6%, and on the others orders, about 14%.

In Figure 2 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 °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 (LFF), a second component associated to the high frequency oscillations of the external cavity, followed by its harmonics. For C1 cavity, the frequency is 339 MHz, and for C2 cavity is 229 MHz. For D-ECSL system working on C1C2 coupled cavities

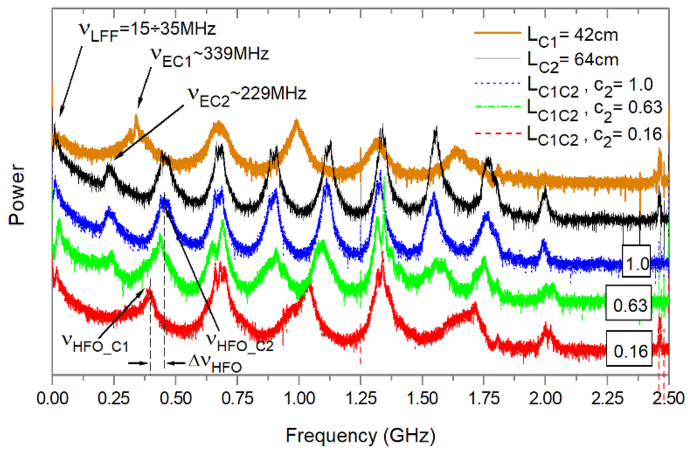

Fig. 2. Power spectra of D-ECSL system emission working on: only C1 or C2 cavity configurations, C1C2 with strong and weak C2 feedback intensities. Parameters: I_{th} current, c_1= 0.37, and t= 24.9 °C. Spectra are vertically shifted one to the other for a better understanding.

at a coupling coefficient c_2 = 1.0, power spectrum presents the same frequency components as for the system operating only with C2. This shows that without feedback attenuation on the C2 cavity the chaotic dynamics of the D-ECSL system is dominated by that of C2 cavity. 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; 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 $\boldsymbol{\Delta}\upsilon_{HFO}$ frequency range (Fig. 2). This is limited by the frequency of HFO, υ_{HFO_C1}, when c_2 coefficient is close to the minimum (case for which υ_{HFO_C1} has values close to the υ_{EC1} frequency), and the frequency of first harmonic corresponding to C2 cavity, υ_{HFO_C2}, when c_2 coefficient is maxim. Thus, the characteristic frequencies (υ_{HFO}) of the D-ECSL system show higher values as the coupling coefficient c_2 is higher.

Fig. 3 presents the intensity time series for D-ECSL system working with weak (0.16) and strong (0.63) c_2 coupling (Fig. 3a and b). For strong coupling, a pulsatory character of the LFF dynamics with power dropouts of high frequency is observed (Fig. 3b). Detailed analysis of intensity time series indicates, in the case of weak feedback, the presence of superimposed high-frequency oscillations of υ_{HFO_C1} frequency and its harmonics. As well, in the case of strong feedback, oscillations of υ_{HFO_C2} frequency and another frequency component close to υ_{EC2} frequency are present.All these oscillations are modulated by LFF envelope.

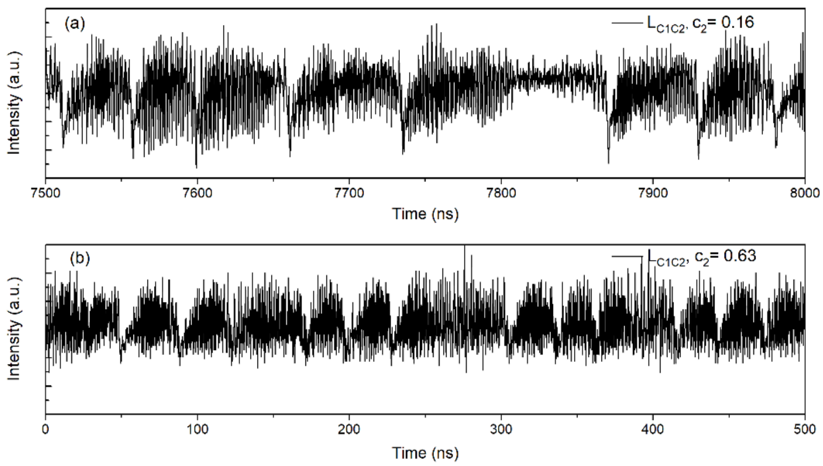

Fig. 3. Intensity time series for D-ECSL system emission with (a) weak (0.16) and (b) strong (0.63) c_2 coupling coefficient. Parameters: I_{th} threshold current, c_1= 0.37, and t= 24.9 ^oC.

Figure 4 shows a detailed analysis of power spectra associated to the intensity time series of D-ECSL system emission, for the frequency range 0 - 1 GHz corresponding to Fig. 2, and c_2 coupling coefficients ranging from 0.16 to 0.63. First of all, it is observed that the υ_{HFO} frequency is tunable function of c_2 coupling coefficient variation. Namely, υ_{HFO} increases with the increase of c_2 coefficient, taking values in the frequency range $\mathbf{\Delta}\upsilon_{HFO} = \upsilon_{HFO\_C2} - \upsilon_{HFO\_C1} \approx 445 - 378$ MHz = 67 MHz. For values of c_2 coupling coefficient varying between 0.16 and 0.40, the first component in the power spectrum, except LFF frequency, is υ_{HFO} frequency. For c_2 values in the 0.50 to 0.63 range, it appears a new frequency component at values lower than υ_{HFO} and close to υ_{EC2} frequency of C2 cavity oscillations, but not identical with it. Thus, it is observed that the frequencies from the power spectrum do not save the information about the geometry of the experimental system. Also, the first harmonic of υ_{HFO} frequency has approximately the same value at all used c_2 coefficients. This corresponds to the overlapping of the first frequency harmonic of C1 cavity with the second harmonic of C2 cavity. Also, first harmonic of the υ_{HFO} frequency shows a frequency degeneration with peaks spacing of approximately LFF frequency values. This behaviour is characteristic to multimode chaotic regime of dual-wavelength laser systems [21].

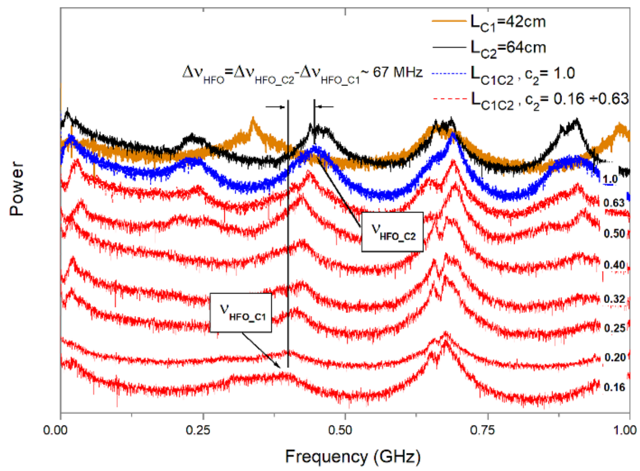

Fig. 4. Power spectra associated to D-ECSL laser emission function of c_2 coupling coefficient. Power spectra for C1, C2 and C1C2 (c_2= 1.0) cavity configurations are the same as in Figure 2. Parameters: I_{th} threshold current, c_1= 0.37, and t= 24.9 °C.

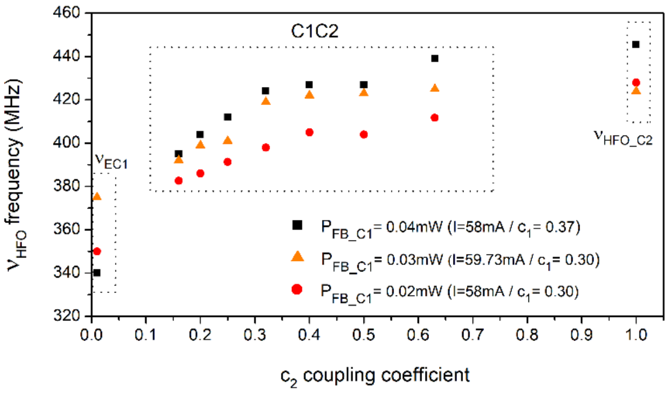

Fig. 5. Dynamics of υ_{HFO} frequency function of c_2 coupling coefficient for three C1 cavity feedback powers (P_{FB_C1}).

The analysis of υ_{HFO} frequency behaviour was also made for other two sets of values for operation parameters, injection current and c_1 coupling coefficient from C1 cavity: I= 59.73 mA and c_1=0.30 (P_{FB_C1}= 0.03 mW), and I_{th}= 58 mA and c_1=0.30 (P_{FB_C1}= 0.02 mW), respectively (Fig. 5). In both cases, it is observed that the υ_{HFO} frequency values show the same evolution as for P_{FB_C1}= 0.04 mW (I_{th} = 58 mA and c_1 = 0.37). 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. Thus, for all used C1 feedback powers υ_{HFO} frequency values are placed between those of the C1 external cavity, υ_{EC1}, and the first harmonic of C2 cavity, respectively.

In this paper, it was shown experimentally that one may generate chaotic oscillations with tunable high frequencies (υ_{HFO}) in the emission of a semiconductor laser working in external optical feedback conditions provided by two external reflectors with fixed lengths. The turnability was previous predicted numerically [15], but, furthermore, we have shown that the frequency range is limited by that of chaotic oscillations (υ_{EC1}) from short cavity and the first frequency harmonic of the chaotic oscillations (υ_{HFO_C2}) of long cavity. Also, the υ_{HFO} frequency values and the width of their domain increase with the feedback power increase in the C1 external cavity. For c_2 coupling coefficients over 0.5, besides the υ_{HFO} frequency, a new frequency component close to the υ_{EC2} frequency (but not identically) appears in the power spectrum. Since these frequencies do not match to those of the C1 or C2 cavities, they do not carry information about the geometry of the D-ECSL system. By using an additional external cavity combined with the variation of feedback intensity provide by it, the chaotic HFO frequency of D-ECSL system emission can be tuned almost continuously over tens of MHz (67 MHz). These results have potential of application in data transmission using laser carriers where a stable and controllable chaotic dynamic over the time is required. The high frequency oscillations mixing increases the noise character of the signal as well, which is of practical importance for data encoding using laser carriers [24–26].

4. Conclusions

We investigate experimentally the chaotic oscillation dynamics of the double cavity ECSL system emission function of the feedback intensity applied on the two branches of the system, namely C1 and C2 cavity configurations. Chaotic oscillations have shown υ_{HFO} frequencies whose values increase with the C2 feedback intensity increase, and the frequency range has higher values as C1 cavity feedback powers increase. The reported frequency behaviour was previous predicted numerically. In addition, for large external cavities we shown that the frequency range of chaotic oscillations is bounded by those of C1 external cavity, and first harmonic of C2 external cavity, respectively. Due to the mixing process of the C1 si C2 chaotic oscillations, υ_{HFO} frequency do not carry information about the geometry of D-ECSL system for c_2 coupling coefficient up to 0.50. Over this value, besides of υ_{HFO} frequency, a new frequency component close to the υ_{EC2} frequency appears in the power spectrum. The results shown here are first experimental observations of such behavior of HFO frequencies of a D-ECSL system.

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R E F E R E N C E S

[1] *I.R. Andrei, M.L. Pascu, M. Bulinski,* The analysis of data encoding characteristics for chaotic coupling of two multimode laser diodes with external cavity, Romanian Reports in Physics, 57 (2005) 406–411.

[2] *A. Wang, L. Wang, Y. Wang,* Applications of chaotic laser in optical communications, in: 2016 15th International Conference on Optical Communications and Networks (ICOCN), IEEE, Hangzhou, 2016: pp. 1–3.

[3] *P. E. Sterian, V. Ninulescu, A.-R. Sterian, B. Lazăr,* Optical Communication Methods Based on Chaotic Laser Signals, UPB Scientific Bulletin, Series A: Applied Mathematics and Physics, 72 (2010) 83–94.

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

[5] *M. Bulinski, M.L. Pascu,* Chaos in laser diode light emission, Romanian Journal of Optoelectronics, 19 (2001) 1–34.

[6] *M.J. Wishon, A. Locquet, C.Y. Chang, D. Choi, D.S. Citrin*, Crisis route to chaos in semiconductor lasers subjected to external optical feedback, Physical Review A, 97 (2018).

[7] *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.

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

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

[10] *V.Z. Tronciu, I.V. Ermakov, P. Colet, C.R. Mirasso*, Chaotic dynamics of a semiconductor laser with double cavity feedback: Applications to phase shift keying modulation, Optics Communications, 281 (2008) 4747–4752.

[11] *M. Peil, T. Heil, I. Fischer, W. Elsäßer*, Synchronization of Chaotic Semiconductor Laser Systems: A Vectorial Coupling-Dependent Scenario, Physical Review Letters, 88 (2002).

[12] *T. Heil, J. Mulet, I. Fischer, C.R. Mirasso, M. Peil, P. Colet, W. Elsasser*, ON/OFF phase shift keying for chaos-encrypted communication using external-cavity semiconductor lasers, IEEE Journal of Quantum Electronics, 38 (2002) 1162–1170.

[13] *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.

[14] M.W. Lee, P. Rees, K.A. Shore, S. Ortin, L. Pesquera, A. Valle, Dynamical characterisation of laser diode subject to double optical feedback for chaotic optical communications, IEE Proceedings - Optoelectronics, 152 (2005) 97.

[15] *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.

[16] *Y. Hong, M.W. Lee, K.A. Shore*, Chaotic optical data encryption using external-cavity VCSELs, in: M. Ross, A.M. Scott (Eds.), London, United Kingdom, 2004: p. 72.

[17] *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.

[18] *M. Ahmed, S.W.Z. Mahmoud, M. Yamada*, Numerical analysis of optical feedback phenomenon and intensity noise of fibre-grating semiconductor lasers, International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, 20 (2007) 117–132.

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

[20] *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.

[21] *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.

[22] *I.R. Andrei*, Characterization of chaotic emission of a laser diode in optical feedback conditions produced by different external reflectors, OAM-RC, 4 (2010) 1440–1444.

[23] *M.L. Pascu, A. Pascu, A. Staicu, I.R. Andrei, V. Nastasa*, Tunable lasers at the laser spectroscopy group: short form history from the beginnings to date, Romanian Reports in Physics, 62 (2010) 455–480.

[24] *L. Rondoni, M.R.K. Ariffin, R. Varatharajoo, S. Mukherjee, S.K. Palit, S. Banerjee*, Optical complexity in external cavity semiconductor laser, Optics Communications, 387 (2017) 257–266.

[25] *B.O. Rasheed, S.F. Abdalah, K.A.M. Al Naimee, M.H. Al Hasani, P.M. Aljaff, R. Meucci, F.T. Arecchi,* Exploring noise effects in chaotic optical networks, Results in Physics, 7 (2017) 1743–1750.
[26] *A. Argyris, E. Pikasis, D. Syvridis,* Highly Correlated Chaotic Emission From Bidirectionally Coupled Semiconductor Lasers, IEEE Photonics Technology Letters, 28 (2016) 1819–1822.