DSTA 2021 dys-ta.com
16th INTERNATIONAL CONFERENCE
Dynamical Systems – Theory and Applications
December 6-9, 2021, On-line

Nonlinear Chaotic Dynamics of Laser Diodes with an Additional Optical Injection: Dynamical and Topological Invariants

SERGEY V KIR'YANOV[1], EUGENY V TERNOVSKY[1*], DMITRY A NOVAK[1] AND IGOR I BILAN[1]

1. Odessa State Environmental University, Mathematics Depr., L'vovskaya str. 15, 65009, Odessa
* Presenting Author

Abstract: Nonlinear chaotic dynamics of the chaotic laser diodes with an additional optical injection is computed within rate equations model, based on the a set of rate equations for the slave laser electric complex amplitude and carrier density. To calculate the system dynamics in a chaotic regime the known chaos theory and non-linear analysis methods such as a correlation integral algorithm, the Lyapunov's exponents and Kolmogorov entropy analysis are used. There are listed the data of computing dynamical and topological invariants such as the correlation, embedding and Kaplan-Yorke dimensions, Lyapunov's exponents, Kolmogorov entropy etc. New data on topological and dynamical invariants are computed and firstly presented. It has been developed an effective tenporal evolutionary dynamics prediction model.

Keywords: chaotic dynamics, laser diodes, dynamical and topological invariants

1. Introduction. Nonlinear Dynamics of Chaotic Laser Diodes

The elements of chaotic dynamics in different laser systems and devices, including semiconductor lasers, laser diodes, resonators etc are of a great importance and interest because of their potential applications in laser physics and quantum electronics, optical secure communications and cryptography, and many others. At the same time, the laser's relaxation oscillation limits the bandwidth of chaotic light emitted from a laser diode and similar devices with single optical injection or feedback. This circumstance as well as a general interest to new theoretical dynamics phenomena make necessary the further studying and improvement the main features of the optical chaos communications. In Ref. [1] the authors experimentally and numerically demonstrate the route to band width enhanced chaos in a chaotic laser diode with an additional optical injection; they used the own unique experimental setup, which includes a distributed feedback (DFB) laser with a 4 m fiber ring feedback cavity (the slave laser) and the other solitary DFB laser as an injection laser (the master laser) to enlarge the bandwidth of the chaotic laser (see detailed description in Ref. [1]). The concrete technological characteristics are as follows: slave laser is biased at 28.0 mA (1.27 times threshold), and its wavelength is stabilized at 1553.8 nm with 0.3 nm linewidth (at −20 dB) and a 35 dB side mode suppression ratio; respectively, the laser's output power is 0.7 mW, and the relaxation frequency and modulation bandwidth were about 2 GHz and 5 GHz. The original set of the chaotic states before optical injection is obtained with −6.1 dB optical feedback (the feedback injection strength with a scale of the solitary slave laser's power). In this paper it has been presented the detailed numerical analysis, modelling and forecasting nonlinear dynamics of the chaotic laser diode with an additional optical injection and characteristic dynamical and topological invariants are computed.

2. Results and Discussion

The dynamics of the system can be described by a set of rate equations for the slave laser electric complex amplitude *F* and carrier density *n*, correspondingly and is represented as follows:

$$\frac{dF}{dt} = \frac{1+i\beta}{2}\{\frac{g(n-n_0)}{1+\delta|F|^2} - \tau_p^{-1}\}F + \frac{k_f}{\tau_I}F(t-\tau)\cdot exp[-i2\pi\eta\tau] + \frac{k_I}{\tau_I}F_j\, exp[i\Delta\eta t], \quad (1)$$

$$\frac{dn}{dt} = \frac{i}{qV} - \frac{n}{\tau_N} - \frac{g(n-n_0)}{1+\delta|F|^2}|F|^2 + G(n) \quad (2)$$

where k_f and k_j denote the feedback and injection strength, the amplitude of injection laser $|F_j|$ is equal to that of the solitary slave laser, and $\Delta\eta=\eta_j-\eta_s$ is the detuning between the injection and the slave lasers. The feedback delay τ=20ns is chosen according to [1]. As the input data for the solving the rate equations system the numerical values of the parameters have been used as: transparency carrier density $n_0=0.455\times10^6\,m^{-3}$, threshold current $i_{th}r$ =22 mA, differential gain $g=1.414\times10^{-3}\,\mu m^3 ns^{-1}$, the carrier lifetime τ_N=2.5 ns, photon lifetime τ_p=1.17ps, round-trip time in laser intracavity τ_i=7.38 ps, the linewidth enhancement factor β=5.0, gain saturation parameter $\delta=5\times10^{-3}\,\mu m^3$and active layer volume $V=324m^3$; the simulated slave laser is biased at $1.7i_{thr}$ with 5.2 GHz modulation bandwidth. Under k_j=0, growth of the parameter k_f results in a period-doubling bifurcation route to chaos, followed by a reversed route out of chaos. A chaos is realized in the region ~0.04–0.16 of k_f and bandwidths are ~4.0–6.2 GHz. The rate equations system is numerically solved and the corresponding time series for amplitude and density are obtained. Computational processing allows to receive the following values of the correlation dimension d_2, the Kaplan-York attractor dimension (d_L), the Lyapunov's exponents (λ_i), Kolmogorov entropy (K_{entr}), the Gottwald-Melbourne parameter (look Table 1).

Tab. 1. Correlation dimension d_2, Lyapunov's exponents (λ_i, i=1,2), Kaplan-York attractor dimension (d_L), Kolmogorov entropy (K_{entr}), Gottwald-Melbourne parameter K_{GW}

d_2	λ_1	λ_2	d_L	K_{entr}	K_{GW}
2.94	0.358	0.096	2.80	0.454	0.94

3. Concluding Remarks

To conlcude, it is presented the numerical analysis, modelling and forecasting nonlinear dynamics of the chaotic laser diode with an additional optical injection. There are listed the advanced numerical data on the topological and dynamical invariants (correlation, Kaplan-York dimensions, Lyapunov's exponents etc) of chaotic dynamics for the semiconductor laser and optical resonator systems.

References

[1] WANG A-B, WANG Y-C, WANG J-F: Route to broadband chaos in a chaotic laser diode subject to optical injection. *Optics Lett*. 2009, 34(8):1144-1146.

[2] GLUSHKOV AV: *Methods of a Chaos Theory*. Astroprint: Odessa, 2012

[3] BUYADZHI V, BELODONOV A, MIRONENKO D, MASHKANTSEV A, KIR'YANOV S, BUYADZHI A GLUSHKOV A: Nonlinear dynamics of external cavity semiconductor laser system with elements of a chaos. In: AWREJCEWICZ J, KAZMIERCZAK M, OLEJNIK P AND MROZOWSKI J (EDS.) *Engineering Dynamics and Life Sciences*. Lodz,. 2017:89-96.

[4] GLUSHKOV A, SVINARENKO A, BUYADZHI V, ZAICHKO P AND TERNOVSKY V: Chaos-geometric attractor and quantum neural networks approach to simulation chaotic evolutionary dynamics during perception process. In: BALICKI J (ED) *Advances in Neural Networks, Fuzzy Systems and Artificial Intelligence, Series: Recent Advances in Computer Engineering*. WSEAS: Gdansk, 2014, **21**:143-150.