Numerical investigation of semiconductor ring lasers with two external cavities

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We report results on the numerical analysis of the behaviour of a semiconductor ring laser under the influence of feedback from two external cavities. Double feedback arises naturally in a semiconductor ring laser, e.g. at the end facets of an outcoupling waveguide. We find that, under certain conditions, the system displays quasi-periodic and chaotic behavior.

Introduction

Semiconductor ring lasers (SRLs) are becoming key components in photonic integrated circuits. Contrary to integrated lasers of Fabry-Perot type, they do not require cleaved facets or gratings to provide the necessary optical feedback [1]. They have been proposed in applications such as wavelength filtering, unidirectional travelling-wave operation and multiplexing/demultiplexing applications [2–7].

Monolithic SRLs can exhibit a bistable unidirectional operation. This bistability between counter-propagating modes makes them highly desirable for use in systems for all-optical switching, gating, wavelength-conversion functions and optical memories [4,8].

Semiconductor lasers from the Fabry-Perot type subject to delayed optical feedback can generate chaotic dynamics with intensity pulsations on subnanosecond time scales. Such dynamics does not only occur due to optical feedback, but happens also when coupling semiconductor lasers to each other even for short propagation distances [9]. This chaotic dynamics can in some cases be unwanted. However, the unpredictability of the optical chaotic signal can be put to good use by way of chaos encryption techniques [10].

Here, we study how stable the dynamical response of the SRL is to delayed optical feedback coming from reflections in the output coupler. In this case, the delayed signal of the clockwise mode of the SRL will be injected in the counter-clockwise mode and vice versa. This cross-feedback is a unique property of the device structure of the SRL and can not be achieved in other semiconductor laser structures.

Setup and the model

The system under study is depicted schematically in Figure 1. It consists of a SRL coupled to a straight waveguide. The end facets of the waveguide will provide for the optical feedback. We assume that multiple reflections do not occur in between the two end facets.

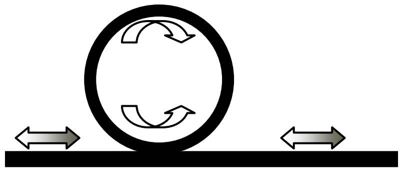

Fig. 1. A SRL with its directionally coupled straight waveguide. Feedback occurs at the end-facets of the waveguide.

The dynamics of this system is studied by way of rate equations. We propose the following model, which is an extension of an established rate equation model for a SRL operating in a single longitudinal mode regime [2-3]. Terms accounting for the injection of the delayed optical field of the counter-propagating mode are added according to Lang-Kobayashi. This results in the following set of equations for the complex field amplitudes $E_1(t)$ and $E_2(t)$ of the two counter-propagating modes and the carrier density $N(t)$:

$$\begin{aligned}
\dot{E}_1 &= (1+i\alpha)\left[N\left(1-s|E_1|^2-c|E_2|^2\right)-1\right]E_1-(k_d+ik_c)E_2+\eta_2 e^{i\theta_2}E_2(t-\tau_2),\\
\dot{E}_2 &= (1+i\alpha)\left[N\left(1-s|E_2|^2-c|E_1|^2\right)-1\right]E_2-(k_d+ik_c)E_1+\eta_1 e^{i\theta_1}E_1(t-\tau_1),\\
\dot{N} &= \gamma\left[\mu-N-N\left(1-s|E_1|^2-c|E_2|^2\right)|E_1|^2-N\left(1-s|E_2|^2-c|E_1|^2\right)|E_2|^2\right].
\end{aligned}$$

where η_1 and η_2 are the feedback strengths. τ_1 and τ_2 are the respective delay times and θ_1 and θ_2 are the accumulated optical phases during propagation in the straight waveguide. Phase-amplitude coupling is modeled by α=3.5. Nonlinear gain saturation effects are taking into account using s=0.005, the self-saturation coefficient, and c=0.01, the cross-saturation coefficient. The two fields are coupled linearly by way of internal backscattering or reflection at output coupler. This gives rise to both a dissipative (k_d=0.000327) and conservative component (k_c=0.0044). γ=0.002 is the ratio of photon lifetime (τ_p=10ps) to carrier lifetime. The dedimensionalized injection current is represented by μ=1.7. Time has been rescaled to the τ_p. The dynamical behaviour of the system is studied by numerical integration of the model equations using the 4-th order Runge-Kutta method.

Symmetric case

Without optical feedback (η_1=η_2=0), the SRL is operating in the bistable unidirectional regime. We start by considering the fully symmetric case: η_1=η_2, θ_1=θ_2, τ_1=τ_2. If we increase the feedback strength slightly, the SRL will start emitting bidirectionally. We study the different dynamical regimes by noting the maxima of the intensity of the unidirectional modes as the feedback strength is increased. Figure 2 shows this intensity bifurcation diagram for θ_1=θ_2=0 and the delay times fixed τ_1=τ_2=0.5ns.

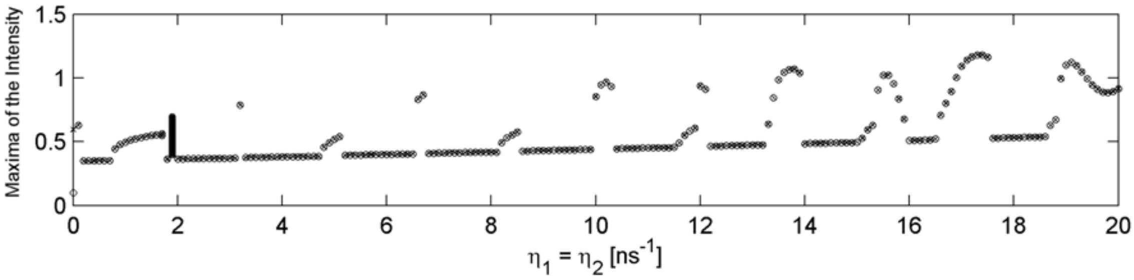

Fig. 2. Bifurcation diagram for the intensity of the propagating modes of the SRL. The bifurcation parameter is the feedback strength. The maxima of the clock-wise mode (x) and of the counter-clockwise mode (o) are recorded.

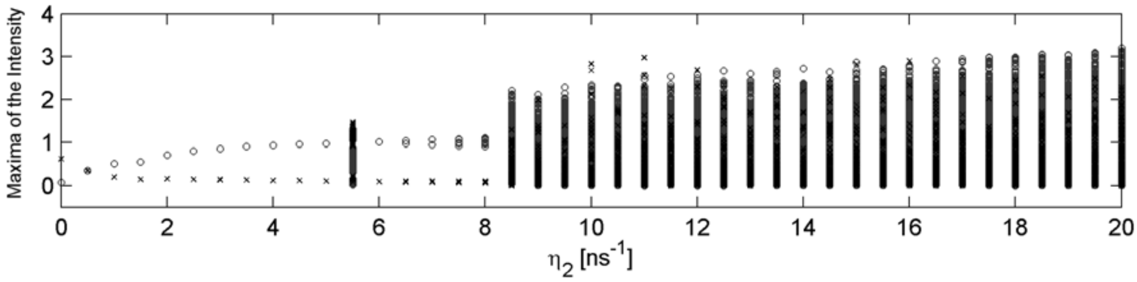

Fig. 3. Bifurcation diagram for the intensity of the propagating modes of the SRL. The bifurcation parameter is the feedback strength η_2, while η_1=0.5ns^{-1} is kept fixed. The maxima of the clock-wise mode (x) and of the counter-clockwise mode (o) are recorded.

The dynamics of the SRL subject to delayed optical feedback is relatively stable in the symmetric case. Parameter regimes of stable operation are alternated with period 1 oscillations. Dynamics which is more complex is not observed. This indicates that at least for this symmetric case the SRL is very immune to optical feedback noise.

Asymmetric case

However, in the asymmetric case ($\eta_1 \neq \eta_2$), more complex dynamics emerges. The corresponding bifurcation diagram ($\theta_1=\theta_2=\pi$) is shown in Figure 3. We have scanned the entire feedback strength parameter regime in Figure 4. We indicate for all different combinations η_1 and η_2 what kind of dynamical behavior is observed. While when $\eta_1=\eta_2$, only stable continuous wave (CW) and period 1 oscillations (P1) are found, increasing the difference between the feedback strength gives rise to period 2 oscillations (P2), quasi-periodicity (QP) and even chaos (Ch). If one wants to use SRLs for chaos communications, one has to make sure that the asymmetry is large enough to obtain chaos with enough complexity.

Conclusion

In conclusion, we have studied the double delayed optical feedback that arises naturally for semiconductor ring lasers. We find that when this cross-feedback is symmetric, the dynamical behavior of the semiconductor ring laser has very low-complexity. Only, when this symmetry is broken, complex dynamics such as chaos can emerge.

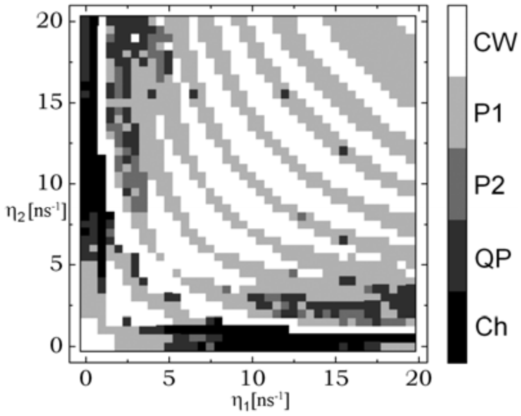

Fig. 4. Map of the dynamical behaviour of the SRL subject to delayed feedback. The notations are: CW – continuous wave; P1, P2 – period one and two oscillations, respectively; QP – quasi-periodicity; Ch – chaotic dynamics.

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References

[1] T. Krauss, P.J.R. Laybourn and J. S. Roberts, “CW operation of semiconductor ring lasers”, Electron. Lett., vol. 26, pp. 2095–2097, 1990.

[2] M. Sorel, P.J.R. Laybourn, A. Scire, S. Balle, G. Giuliani, R. Miglierina and S. Donati, “Alternate oscillations in semiconductor ring lasers”, Opt. Lett., vol. 27, pp. 1992–1994, 2002.

[3] M. Sorel, G. Giuliani, A. Scire, R. Miglierina, J.P.R. Laybourn and S. Donati, “Operating regimes of GaAs–AlGaAs semiconductor ring lasers: experiment and model”, IEEE J. Quantum Electron., vol. 39, pp 1187–1195, 2003.

[4] J.J. Liang, S.T. Lau, M.H. Leary and J.M. Ballantyne, “Unidirectional operation of waveguide diode ring lasers”, Appl. Phys. Lett., vol. 70, pp 1192–1194, 1997.

[5] S. Zhang, Y. Liu, D. Lenstra, M.T. Hill, H. Ju, G.D. Khoe and H.J.S. Dorre, “Ring-laser optical flip-flop memory with single active element”, IEEE J. Sel. Top. Quantum Electron., vol. 10 pp. 1093–1100, 2004.

[6] V.R. Almeida, C.A. Barrios, R.P. Panepucci, M. Lipson, M.A. Foster, D.G. Ouzounov and A.L. Gaeta, “All-optical switching on a silicon chip”, Opt. Lett., vol. 29, pp. 2867–2869, 2004.

[7] V.R. Almeida and M. Lipson, “Optical bistability on a silicon chip” Opt. Lett., vol. 29, pp. 2387–2389, 2004.

[8] M.T. Hill, H.J.S. Dorren, T. de Vries, X.J.M. Leijtens, J.H. den Besten, B. Smalbrugge, Y.S. Oei, H. Binsma, G.D. Khoe and M.K. Smit, “A fast low-power optical memory based on coupled micro-ring lasers”, Nature, vol. 432, pp. 206–209, 2004.

[9] I. Fischer, G.H.M. van Tartwijk, A.M. Levine, W. Elsasser, E. Gobel and D. Lenstra, “Fast Pulsing and Chaotic Itinerancy with a Drift in the Coherence Collapse of Semiconductor Lasers” Phys. Rev. Lett., vol. 76, pp. 220-223, 1996.

[10] A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. Garcia-Ojalvo, C. R. Mirasso, L. Pesquera, and K. A. Shore, “Chaos-based communications at high bit rates using commercial fiberoptic links”, Nature, vol. 438, pp. 343–346, 2005.