Theoretical and experimental investigation of excitability in semiconductor ring lasers

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In this contribution, we report theoretically and experimentally on excitability in semiconductor ring lasers. Theoretically, we reveal a general mechanism of excitability for systems close to Z_2-symmetry. The global shapes of the invariant manifolds of a saddle in the vicinity of a homoclinic loop determine the origin of the excitable behavior and the features of the excitable pulses. Moreover, we demonstrate how to realize this excitability experimentally by breaking the Z_2-symmetry of the semiconductor ring laser in a controlled way. The experiments performed on an InP-based multi-quantum-well SRL with a racetrack geometry confirm our theoretical predictions.

Introduction

Although ring lasers have been studied in the 70's and 80's in the context of He-Ne ring lasers [1] and solid state lasers [2], in recent years, there has been an renewed and increased interest in semiconductor ring lasers (SRLs) for two main reasons. On the one hand, these semiconductor lasers where the laser cavity consists of a ring-shaped waveguide have been shown to be promising components in photonic integrated circuits. In particular, their possibility of bistable directional operation paved the way to encoding digital information in the direction of emission of SRLs [3]. On the other hand, SRLs are ideal optical prototypes for the large class of systems which are characterised by central reflection invariance. Such symmetry, known as Z_2 invariance is one of the most common in nature, and it is encountered in a wide number of bistable systems. Therefore, an in-depth study of SRLs, both theoretically and experimentally, can prove to be interesting for researchers working in different fields.

On the more generic level, experiments on SRLs can unveil many dynamical regimes and bifurcations that are typical for the class of Z_2-symmetric systems, while from a more application oriented point-of-view the theoretical and experimental characterization of SRLs can help to optimize the physical design of the SRL to meet the necessary technological requirements. From the technological viewpoint, SRLs do not require cleaved facets or gratings for optical feedback and are thus particularly suited for monolithic integration [4]. SRLs have been suggested to fulfill several practical applications [5, 3, 6]. All optical flip-flops based on a single or two coupled microrings have been fabricated which can be switched between counter-propagating modes by injection of a signal counter-propagating to the lasing mode [3]. On the other hand, switching schemes based on injection only on one side of the SRL have been suggested as well [7, 8]. Monolithic SRLs exhibiting unidirectional operation are also highly desirable in applications because of their wavelength stability[5]. The bistability of the SRLs opens the possibility of using them in systems for all-optical switching, gating, wavelength-conversion functions, and optical memories [3].

The current revived interest in SRLs has not only lead to an increased number of technological publications, but has also spawned the interest in the theoretical modeling of SRLs. A general rate-equation approach has been suggested in Ref. [5]. The model consists of two mean-field equations for the counter-propagating modes in the SRL, and a third rate equation for the carriers. While it is true that certain features can only be explained by such a general rate-equation model or even a more involved traveling-wave model [9], it has been shown that many of the experimentally observed features can be predicted by a two-dimensional reduced SRL model [10, 11, 12]. In Ref. [13] the original laser equations have been reduced to two equations. The resulting asymptotic description of the SRL is valid on time scales slower than the relaxation oscillations. Not only do these Z_2-symmetric reduced equations considerably simplify the bifurcation analysis of the SRL, they also allow for a clear two-dimensional phase-space interpretation of the different dynamical regimes of the SRL. In particular, based on the bifurcation analysis of this reduced SRL model in Ref. [8], the specific structure of the invariant manifolds of the saddle point in the Z_2-symmetric system has allowed to understand and predict particular experimental features of stochastic mode-hopping in a bistable regime [10] and even a multistable regime [11].

In this work, we consider a natural extension of the Z_2-symmetric asymptotic model from Ref. [13] where the Z_2-invariance is broken. Insight into the phase-space structure of the SRL with broken Z_2-symmetry allows us to understand under which circumstances the SRL becomes excitable. By breaking the symmetry of the SRL in a controllable way, we have managed in Ref. [12] to experimentally demonstrate such excitable behavior.

Asymptotic model for SRLs with broken Z_2-symmetry

Consider a SRL operating in single-transverse and single longitudinal mode. Two directional modes, clockwise (CW) and counter-clockwise (CCW), can operate in the ring cavity with different intensities $P_{CW/CCW}$ and phases $\phi_{CW/CCW}$. A linear coupling parameter with amplitude K and phase ϕ_K is used to describe the transfer of power between CW and CCW. The two directional modes operate in antiphase, conserving the total power $P_{CW}+P_{CCW}$ [5, 13, 10, 11], such that an asymptotic two-dimensional set of equations can model the SRL operation:

$$\begin{aligned} \dot{\theta} &= J\sin\theta\cos\theta + 2(1-\delta)\cos(\phi_k+\psi) \\ &\quad - (1-\sin\theta)\left[(1-\delta)\cos(\phi_k+\psi)\right. \\ &\quad \left.+ (1+\delta)\cos(\phi_k-\psi)\right] \end{aligned} \tag{1}$$

$$\begin{aligned} \cos\theta\dot{\psi} &= \alpha J\sin\theta\cos\theta \\ &\quad - (1+\delta)(1-\sin\theta)\sin(\phi_k-\psi) \\ &\quad + (1-\delta)(1+\sin\theta)\sin(\phi_k+\psi) \end{aligned} \tag{2}$$

Here the angular variable $\theta = 2\arctan\sqrt{P_{CCW}/P_{CW}} - \pi/2$ quantifies the power partitioning between the counterpropagating modes. The phase difference $\psi = \phi_{CCW} - \phi_{CW}$ is the second dynamical variable in the system. J is the rescaled bias current and α is the linewidth-enhancement factor. The Z_2-symmetry of Eqs. (1)-(2) is continuously broken

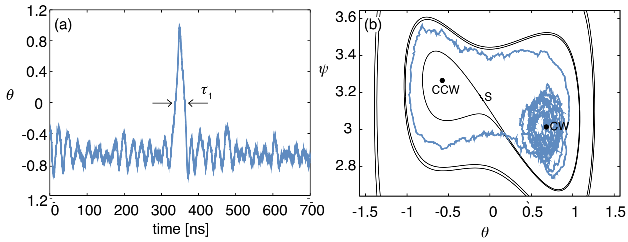

Figure 1: Numerical solutions of Eqs. (1)-(2) revealing a single excitable pulse in time domain (a) and its projection on the phase space (b). The parameters are the following: $\delta = 4.5\%$, $\phi_K = 1.5$. (a) $J = 0.659$, (b) $J = 0.691$.

by the introduction of an asymmetry ΔK in the mode-coupling. The dimensionless parameter $\delta = \Delta K / 2K$ measures the relative magnitude of the symmetry breaking.

Phase-space picture of excitable excursions in the SRL

The phase space of the SRL consists of two stable states *CW* and *CCW* whose basins of attraction are separated by the two branches of the stable manifold of a saddle *S* [10, 11]. The main changes in the topology take place when the current J crosses a critical value J_{hom} which corresponds to a homoclinic bifurcation of an unstable limit cycle. Close to this homoclinic bifurcation, the distance between the branches of the stable manifold of the saddle becomes negligible when compared to the diffusion length-scale induced by the noise. The generation of an excitable pulse therefore corresponds to a noise activated crossing of two arbitrarily close thresholds. An example of an excitable pulse in time domain is given in Fig. 1(a) and the corresponding phase space trajectory is shown in Fig. 1(b). Experiments have been performed on an InP-based multiquantum-well SRL with a racetrack geometry and a free-spectral-range of 53.6 GHz. The device operates in a single-transverse, single-longitudinal mode at $\lambda = 1.56\mu$m. When analyzing the output power of the *CCW* mode using a fast photodiode connected to an oscilloscope, similar excitable pulses have been observed in these experiments.

Conclusion

In conclusion, we have investigated excitability for generic planar systems close to Z_2-symmetry and disclosed how the shape of the invariant manifolds lead to noise-activated pulses. An optical excitable unit based on this concept has been implemented using a multi quantum-well SRL with slightly asymmetric mode-coupling. Such unit can in principle be integrated on chip and does not require external optical injection or feedback from an external cavity. A topological analysis allows to predict the features of different types of excitable pulses, as well as quantitative relations between the relevant time-scales. The predictions of the theory have been confirmed by the experiments.

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References

[1] L. N. Menegozzi and W. E. Lamb. “Theory of a ring laser”, *Phys. Rev. A*, 8:2103–2125, 1973.

[2] H. Zeghlache, P. Mandel, N. B. Abraham, L. M. Hoffer, G. L. Lippi, and T. Mello. “Bidirectional ring laser: Stability analysis and time-dependent solutions”, *Phys. Rev. A*, 37:470, 1988.

[3] 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*, 432:206–209, 2004.

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

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

[6] S. Fürst and M. Sorel. “Cavity-enhanced four-wave mixing in semiconductor ring lasers”, *IEEE Photon. Technol. Lett.*, 20:366–368, 2008.

[7] L. Gelens, S. Beri, G. Van der Sande, J. Danckaert, N. Calabretta, H. J. S. Dorren, R. Nötzel, E. A. J. M. Bente, and M. K. Smit. “Optical injection in semiconductor ring lasers: backfire dynamics”, *Opt. Expr.*, 16:16968–16974, 2008.

[8] L. Gelens, G. Van der Sande, S. Beri, and J. Danckaert. “Phase-space approach to directional switching in semiconductor ring laser”, *Phys. Rev. E*, 79:016213, 2009.

[9] J. Javaloyes and S. Balle. “Emission directionality of semiconductor-ring lasers: a travelling-wave description”, *IEEE J. Quantum Electron.*, 45:431–438, 2009.

[10] S. Beri, L. Gelens, M. Mestre, G. Van der Sande, G. Verschaffelt, A. Sciré, G. Mezosi, M. Sorel, and J. Danckaert. “Topological insight into the non-arrhenius mode hopping of semiconductor ring lasers”, *Phys. Rev. Lett.*, 101:093903, 2008.

[11] L. Gelens, S. Beri, G. Van der Sande, G. Mezosi, M. Sorel, J. Danckaert, and G. Verschaffelt. “Exploring multistability in semiconductor ring lasers: Theory and experiment”, *Phys. Rev. Lett.*, 102:193904, 2009.

[12] S. Beri, L. Mishal, L. Gelens, G. Van der Sande, G. Mezosi, M. Sorel, J. Danckaert, and G. Verschaffelt. “Excitability in optical systems close to z_2 symmetry”, unpublished

[13] G. Van der Sande, L. Gelens, P. Tassin, A. Sciré, and J. Danckaert. “Two-dimensional phase-space analysis and bifurcation study of the dynamical behavior of a semiconductor ring laser”, *J.Phys.B*, 41:095402, 2008.