Mapping of delayed dynamics in short external cavity

Andrzej Tabaka [1], Marc Sciamanna [2], Irina Veretennicoff [1], Krassimir Panajotov [1, 3]

[1] Department of Applied Physics and Photonics, Vrije Universiteit Brussel (V.U.B.), B-1050 Brussels, Belgium

[2] Service d'Electromagnétisme et de Télécommunications, Faculté Polytechnique de Mons (F.P.Ms), B-7000 Mons, Belgium

[3] Institute of Solid State Physics, 72 Tzarigradsko Chaussee blvd., 1784 Sofia, Bulgaria

We study the influence of delayed optical feedback from a short external cavity on the emission dynamics of semiconductor lasers using the Lang and Kobayashi rate equation model. We present the bifurcation scenario to regular pulse packages (RPP) and analyse regions of feedback parameters for which RPP occurs. Detailed mapping shows that with increasing the delay the windows of RPP broaden, merge and finally shrink when approaching the relaxation oscillation period. In such a way the largest region of RPP occurs for delays around half of the relaxation oscillation period.

Introduction

Semiconductor lasers (SLs) are highly sensitive to optical feedback (OF). OF may induce complex dynamical behavior, such as multistability, self-pulsations and chaos [1]. It has been shown that feedback can narrow or broaden the linewidth of the emitted light [2]. Alternatively, OF may be used for chaotic encryption [3] or for data readout [4]. Extensive experimental and theoretical studies over the last two decades show that qualitatively different dynamics is observed in SL subject to OF depending on the length of the external cavity (EC). Different dynamical regimes arise depending on the ratio of the EC round-trip frequency ν_{EC} to the relaxation oscillation (RO) frequency ν_{RO} [5]. In the case of long EC ($\nu_{RO} > \nu_{EC}$) the dynamics is usually very complicated and the so-called low-frequency fluctuations (LFF) [6] and coherence collapse [7] are typically observed. In the case of short EC ($\nu_{RO} > \nu_{EC}$) the dynamics is expected to be less complicated because of the reduced number of EC modes. New phenomena, as for example sustained microwave oscillations of the emitted power has been recently observed in such a system [8,9] and has been shown to be due to a beating between a stable ECM and a saddle-type ECM (antimode). Lately, stable microwave oscillations corresponding to a beating between two stable ECMs [10-12] and high frequency pulsating solutions [13], emerging from a subcritical Hopf bifurcation have been discovered in SL with OF from short EC.

This paper is devoted to studying another type of dynamics in such a system that has been recently discovered [14]. This dynamics corresponds to packages of high frequency pulses (at ν_{EC}) that are modulated by slower, periodic envelope and is called regular pulse packages (RPP) [5,15]. Here we recall the bifurcation scenario to RPP and give examples of bistability between RPP and time-periodic or steady solutions. Furthermore, we study the bifurcation diagrams with RPP for different time-delays and draw a global map of the RPP dynamics. We will give a general view of how RPP dynamics appears and is destroyed and reveal the parameter condition for which one finds continuous regions of RPP.

Numerical results

Our numerical study is based on the Lang-Kobayashi equations, which are commonly used to describe the influence of OF on the emission dynamics in SLs [1, 14]. RPP dynamics that has been first demonstrated in this model has been shown to agree very well with the experimental findings [5, 15].

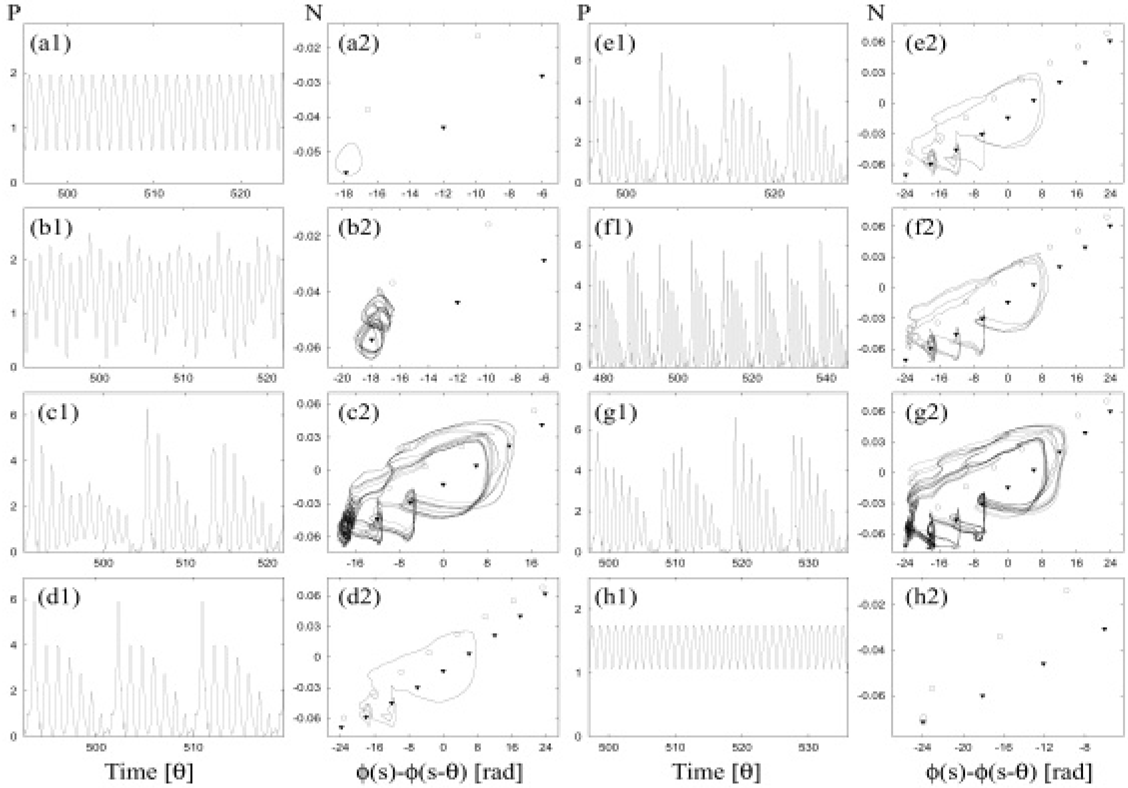

Figure 1. Transition to RPP. Time traces (panels (1)) and phase portraits (panels (2)) . The feedback rate h **is: (a)** 0.061, (**b) and** (**c**) 0.064, **(d) 0.0688, (e) 0.0707, (f) 0.073.**

In Fig. 1 we show a bifurcation cascade which unveils the emergence of RPP and which is calculated with the feedback rate η as a bifurcation parameter while the time delay is fixed (θ=70). All the parameters are taken from our previous work on RPP [14]. Here, the time-traces are complemented with phase portraits of the excess carrier number N as a function of phase difference ϕ(s)-ϕ(s- θ). As we increase η ECMs appear in pairs. One of them is potentially stable (and therefore called mode) and the other one is always unstable (called antimode). Here modes are represented by triangles and anti-modes by circles. Figure 1(a) shows a time periodic solution that has been created through a Hopf bifurcation. With increasing the feedback rate η quasiperiodic solutions emerge in Fig. 1(b). This destabilization of time-periodic solutions might also give rise to packages of pulses Figs. 1(c). The laser intensity exhibits pulsations at the EC frequency, which are modulated by a slower envelope. In the time of the pulse package, ECMs are visited in direction to the maximum gain ECM, but then the laser system is repelled back to unstable ECMs with larger N Fig. 1(c2).

When the system passes the unstable region the output power drops to zero and the phase difference slips to its maximal value. The phase space reveals that the system is repelled above the unstable branch of the ellipse when a collision between the quasiperiodic torus around one of the ECMs and the nearest EC antimode takes place.

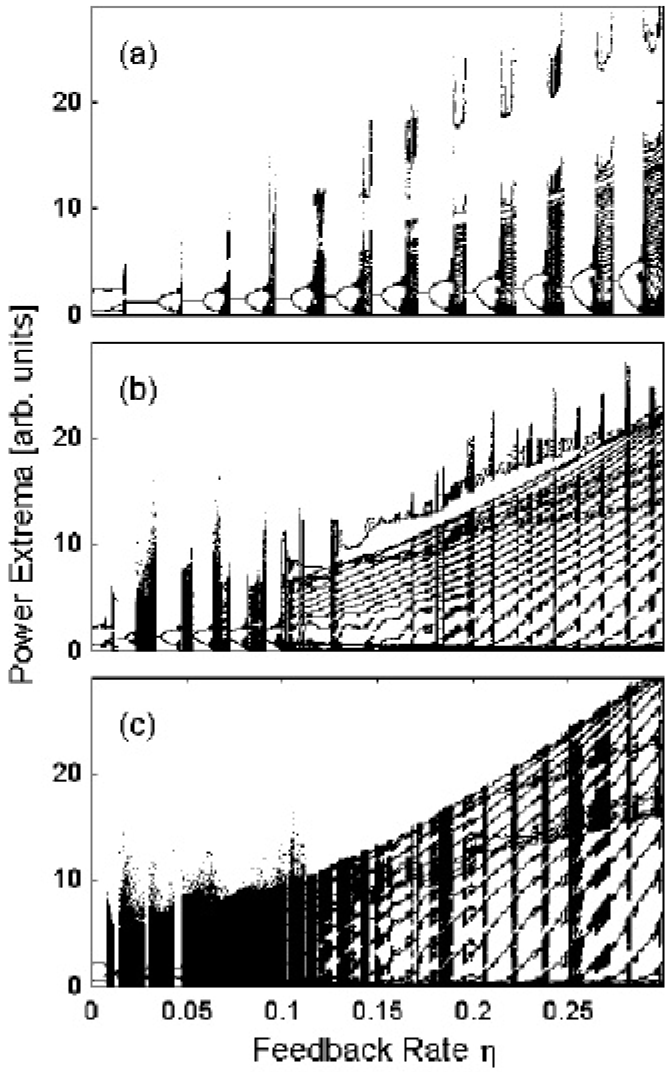

Figure 2. Bifurcation diagrams. In (a) q=50, (b) 70 and (c) 90 respectively.

This is called a crisis in nonlinear dynamics and is similar to the dynamics observed in the case of LFF [6]. Here the pulse packages are still not regular, which might be due to the coexistence with the quasiperiodic attractor (b). As a matter of fact the laser system is bistable between quasiperiodic torus and irregular pulse packages in Figs. 1(b) and 1(c). With further increase of η the quasiperiodic attractor disappears and the pulse packages become very regular (RPP), i.e. the laser system follows the same path visiting particular ECMs - Fig. 1(d). We have already shown in [14] that RPP may undergo period-two bifurcation, i.e. first RPP repeats every two cycles as in Fig. 1(e). Then RPP becomes period-four as in Fig. 1(f). The regularity of pulse packages is afterwards destroyed as depicted in Fig. 1(g). These irregular pulse packages coexist with a time-periodic solution that originates from a newly born ECM – see Fig. 1(h). Decreasing η from periodic solution (h) brings the system to this newly born ECM steady state. This ECM has already appeared in Fig. 1(d) but did not yet play a role in the RPP dynamics.

The presence of the RPP dynamics can be observed due to the fact that the maxima of the pulses are always on the same level and the shape of the pulses is sustained. This gives the fingerprints of the RPP dynamics in the form of sets of lines in the bifurcation diagrams (Fig. 2) where we plot the extrema of the power for different feedback strength η. Figure 2 shows the bifurcation diagrams of the laser intensity P as a function of η for three different values of the delay-time θ. For small delay, θ=50 in Fig.2(a), the windows of RPP are narrow and broaden with increasing the OF strength η. For intermediate level of delay, θ=70 in Fig. 2(b) the windows of RPP merge together at larger level of feedback rate and broad windows of RPP appear. For larger delay, θ=90 in Fig. 2(c), the RPP dynamics is destroyed for small feedback level and as a result the window of RPP shrinks.

These observations are better depicted in Fig. 3 where we plot a detailed map of the RPP in the parameter space η-θ. As can be seen from Fig.3, the highest probability

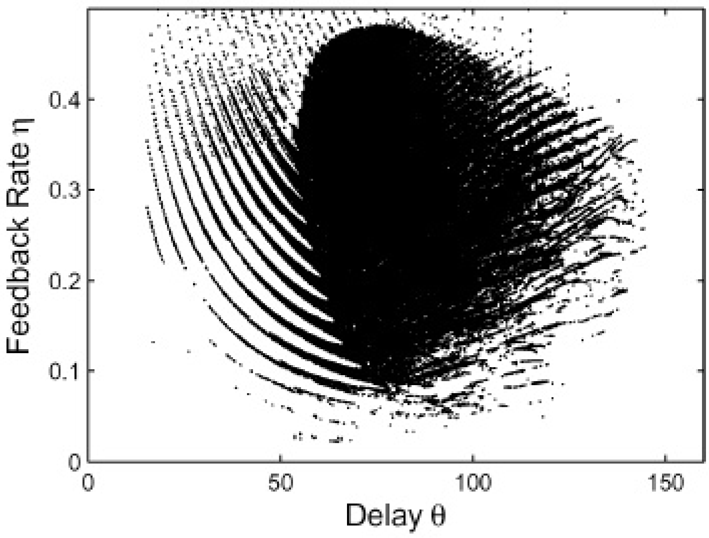

Figure 3. Map of RPP dynamics in the parameter space h-q.

of finding RPP is for a delay of about $\theta \sim 70$, i.e. half of the RO period ($\nu_{RO} \sim 170$). For smaller delays we observe well defined windows of RPP, separated by a distance in the feedback parameters, which corresponds to the creation of new ECMs. These windows of RPP broaden with θ and merge together at θ approximately equal to half of the RO period. When the delay θ approaches the RO period the RPP loses synchronization and therefore windows of RPP shrink and finally disappear.

Conclusions

We analyzed the influence of the optical feedback from a short EC on SL using the Lang and Kobayashi rate equation model. We presented the bifurcation scenario to RPP and analyzed regions of feedback parameters for which RPP occurs. Detailed mapping showed that with increasing the delay the windows of RPP broaden, merge and finally shrink when approaching the RO period. In such a way one finds the largest region of RPP for delays around half of the RO period.

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References

[1] K. Petermann, IEEE J. Select. Topics of Quantum Electron. **1**, 480 (1995).
[2] G. P. Agraval, IEEE J. Quantum Electron. vol. **20** pp. 468-471, (1984).
[3] I. Fischer, Y. Liu, and P. Davis, Phys. Rev. A **62**, 011801/1 (2000).
[4] V. Gómez, A. Tabaka, K. Koltys, H. Thienpont, K. Panajotov, Proc. of the IEEE/LEOS Benelux Chapter Workshop on Low-Cost Photonics, Mons, 2003.
[5] T. Heil, I. Fischer, W. Elsäßer, and A. Gavrielides, Phys. Rev. Lett. **87**, 243901/1 (2001).
[6] T. Sano, Phys. Rev. A 50, 2719 (1994).
[7] D. Lenstra, B. Verbeek, and A. den Boef, IEEE J. Quantum Electron. **21**, 674 (1985).
[8] A. Tager and B. Elenkrig, IEEE J. Quantum Electron. **29**, 2886 (1994).
[9] A. Tager and K. Petermann, IEEE J. Quantum Electron. **30**, 1553 (1994).
[10] M. Sciamanna *et. al.*, Opt. Lett. **27**, 875(E) (2002).
[11] M. Sciamanna *et. al.*, Phys. Rev. A **65**, 041801/1(R) (2002).
[12] T. Erneux, A. Gavrielides, and M. Sciamanna, Phys. Rev. A **66**, 033809/1 (2002).
[13] M. Sciamanna et al., Proc. IEEE/LEOS Annual Meeting 2002 p. 00 (2002).
[14] A. Tabaka, M. Sciamanna, I. Veretennicoff and K. Panajotov, Proc. of the 2002 Symposium IEEE/LEOS Benelux Chapter, pp.43-46, 2002.
[15] T. Heil, I. Fischer, W. Elsäßer, B. Krauskopf, K. Green, and A. Gavrielides, Phys. Rev. E **67**, 066214 (2003).