Semiconductor laser dynamics at IFISC

Dinámica de láseres de semiconductor en el IFISC

P. Colet(*), I. Fischer, C. R. Mirasso, A. Pérez-Serrano, A. Scirè

Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), Campus Universitat Illes Balears, E-07122 Palma de Mallorca, Spain

(*) pere@ifisc.uib-csic.es

Recibido / Received: 30/10/2010. Aceptado / Accepted: 15/12/2010

ABSTRACT:

We present here a brief overview of the main topics studied in the Institute for Cross Disciplinary Physics and Complex Systems (IFISC) within the context of semiconductor laser dynamics. In particular we study nonlinear effects and chaos in edge emitting lasers, feedback and delay effects, dynamics of coupled lasers and multimode dynamics in ring cavity lasers, with the perspective of possible applications in information and communication technologies.

Keywords: Semiconductor Laser, Semiconductor Ring Laser, Optoelectronic Delay Systems, Nonlinear Dynamics, Instabilities, Chaos, Synchronization, Feedback, Delay Coupling, Optical Communications, Encrypted Communications, Mode Competition and Switching.

RESUMEN:

Aquí presentamos un breve resumen de los temas estudiados en el Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC) en el contexto de dinámica de láseres de semiconductor. Se estudian en particular efectos no lineales y caos en láseres de emisión lateral, efectos de realimentación y de retraso, dinámica de láseres acoplados y dinámica multimodo en láseres de anillo, todo ello con la perspectiva de posibles aplicaciones en tecnologías de la información y de las comunicaciones.

Palabras clave: Láser de Semiconductor, Láseres de Semiconductor de Anillo, Sistemas Optoelectrónicos con Retraso, Dinámica No Lineal, Inestabilidades, Caos, Sincronización, Realimentación, Acoplamiento con Retraso, Comunicaciones Ópticas, Comunicaciones Codificadas, Competición y Salto entre Modos.

REFERENCES AND LINKS

[1]. S. Donati, C. Mirasso, Edts., Feature Issue on Optical Chaos and Applications to Cryptography, *IEEE J. Quantum Elect.* **38**, 9 (2002).

[2]. C. R. Mirasso, "Chaotic optical communications", *IEEE LEOS Newsletter* **19**, 12 (2005).

[3]. P. Colet, R. Roy, "Digital communication with synchronized chaotic lasers", *Opt. Lett.* **19**, 2056-2059 (1994).

[4]. C. R. Mirasso, P. Colet, P. García-Fernández, "Synchronization of chaotic semicondcutor lasers: Application to encoded communications", *IEEE Photonic Tech. L.* **8**, 299-301 (1996).

[5]. I. Fischer, Y. Liu, P. Davis, "Synchronization of chaotic semiconductor laser dynamics on subnanosecond time scales and its potential for chaos communication", *Phys. Rev. A.* **62**, 011801 (2000).

[6]. A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. García-Ojalvo, C. R. Mirasso, L. Pesquera, K. A. Shore, "Chaos-based communications at high bit rates using commercial fibre-optic links", *Nature* **438**, 343-346 (2005).

[7]. M. C. Soriano, P. Colet, C. R. Mirasso, "Security implications of open- and closed-loop receivers in all-optical chaos-based communications", *IEEE Photonic Tech. L.* **21**, 426-428 (2009).

[8]. R. M. Nguimdo, R. Larov, P. Colet, M. Jaquot, Y. Kouomou Chembo, L. Larger, "Effect of fiber dispersion on broadband chaos communications implemented by electro-optic nonlinear delay phase dynamics", *IEEE J. Lightwave Tech.* **28**, 2688-2696 (2010).

[9]. V. Z. Tronciu, C. R. Mirasso, P. Colet, M. Hamacher, M. Benedetti, V. Vercesi, V. Annovazzi-Lodi, "Chaos generation and synchronization using an integrated source with an air gap", *IEEE J. Quantum Elect.* **46**, 1840-1846 (2010).

[10]. T. Heil, I. Fischer,W. Elsasser, J. Mulet, C. R. Mirasso, "Chaos synchronization and spontaneous symmetry breaking in symmetrically delayed coupled semiconductor lasers", *Phys. Rev. Lett.* **86**, 795-797 (2001).

[11]. J. Mulet, Claudio R. Mirasso, T. Heil, I. Fischer, "Synchronization Scenario of two distant mutually coupled semiconductor lasers", *J. Opt. B - Quantum Semicl. Opt.* **6**, 97-105 (2004).

[12]. J. Mulet, C. Masoller, C. R. Mirasso, "Modelling Bidirectionally Coupled Single-Mode Semiconductor Lasers", *Phys. Rev. A* **65**, 063815 (2002).

[13]. R. Vicente, S. Tang, J. Mulet, C. R. Mirasso, J. M. Liu, "Synchronization properties of two selfoscillating semiconductor lasers subject to delayed optoelectronic mutual coupling", *Phys. Rev. E* **73**, 047201 (2006).

[14]. I. Fischer, R. Vicente, J. M. Buldú, M. Peil, C. R. Mirasso, M. C. Torrent, J. García-Ojalvo, "Zerolag long-range synchronization via dynamical relaying", *Phys. Rev. Lett.* **97**, 123902 (2006).

[15]. R. Vicente, I. Fischer, C. R. Mirasso, "Synchronization properties of three delay-coupled semiconductor lasers", *Phys. Rev. E* **78**, 066202 (2008).

[16]. R. Vicente, L. L. Gollo, C. R. Mirasso, I. Fischer, G. Pipa, "Dynamical relaying can yield zero time lag neuronal synchrony despite long conduction delays", *P. Natl. Acad. Sci. USA* **105**, 17157-17162 (2008).

[17]. L. L. Gollo, C. Mirasso, A. Villa, "Dynamic control for synchronization of separated cortical areas through thalamic relay", *Neuroimage* **52**, 947-955 (2010).

[18]. R. Vicente, C. R. Mirasso, I. Fischer, "Simultaneous bidirectional message transmission in a chaosbased communication scheme", *Opt. Lett.* **32**, 403-405 (2007).

[19]. http://ifisc.uib-csic.es/phocus

[20]. M. Sorel, G. Giuliani, A. Scirè, R. Miglierina, S. Donati, P. J. R. Laybourn, "Operating regimes of GaAs-AlGaAs semiconductor ring lasers: experiment and model", *IEEE J. Quantum Elect.* **39**, 1187-1195 (2003).

[21]. T. Perez, A. Scirè, G. Van der Sande, P. Colet, C. R. Mirasso, "Bistability and all-optical switching in semiconductor ring laser", *Opt. Express* **15**, 12941-12948 (2007).

[22]. A. Pérez-Serrano, R. Zambrini, A. Scirè, P. Colet, "Noise spectra of a semiconductor ring laser in the bidirectional regime", *Phys. Rev. A* **80**, 043843 (2009).

[23]. A. Pérez-Serrano, A. Scirè, "Theoretical analysis of a new technique for inertial rotation sensing using a semiconductor ring laser", *IEEE Photonic Tech. L.* **21**, 917-919 (2009).

[24]. S. Fürst, A. Pérez-Serrano, A. Scirè, M. Sorel, S. Balle, "Modal structure, directional and wavelength jumps of integrated semiconductor ring lasers: experiment and theory", *Appl. Phys. Lett.* **93**, 251109 (2008).

[25]. A. Pérez-Serrano, J. Javaloyes, S. Balle, "Bichromatic emission and multimode dynamics in bidirectional ring lasers", *Phys. Rev. A* **81**, 043817 (2010).

[26]. M. J. Strain, G. Mezosi, M. Sorel, A. Pérez-Serrano, A. Scirè, S. Balle, G. Verschaffelt, J. Danckaert, "Semiconductor snail laser", *Appl. Phys. Lett.* **96**, 121105 (2010).

[27]. A. Pérez-Serrano, J. Javaloyes, S. Balle, "Longitudinal mode multistability in ring and Fabry-Pérot lasers: the effect of spatial hole burning", *Opt. Express* **19**, 3284-3289 (2011)

1. Introduction

From the origins of the laser many efforts have been done to stabilize their optical emission. It is known, for example, that small reflections coming from lenses, facets of optical fibers, beam splitters, etc., can give rise to an unstable emission of a semiconductor laser. This emission is characterized by a light whose power and frequency (or wavelength) fluctuate irregularly. Semiconductor lasers are used in a wide variety of practical applications and while in many instances these instabilities are considered as undesirable, they turn out to be useful in other instances. At IFISC we study the nonlinear dynamics and instabilities in semiconductor lasers aiming at possible applications in information and communication technologies. One topic of research focuses on the use of chaotic lasers to increase the security in optical communication systems, studying the chaotic dynamics of lasers subject to optical or electro-optical feedback and their synchronization. Another topic focuses on the effects of delay in mutually coupled semiconductor lasers and finally a third topic focuses on mode switching in semiconductor ring cavity lasers for all-optical signal processing (signal regeneration, optical gating).

2. Chaos-based optical communications

Privacy and security are two major issues in today's communication systems. Up to know, these issues have been covered by software encryption although the development of faster and more efficient computers threatens this technique. Consequently, the development of new and innovative ways to encode information is highly desirable. During recent years new methods offering cryptography based on physical principles have come up: Quantum Cryptography and Chaos-based Cryptography. Quantum cryptography can provide very high security levels, although the transmission rates and distances are relatively low. At the same time, secure optical communications based on chaotic carriers [1,2] has the potential to open new prospects and complement the other methods, wherever high performance, and in particular enhanced privacy at high transmission rates, are required.

The idea behind optical communication that uses chaotic carriers resides in the fact that under appropriate conditions two spatially separated lasers operating in the chaotic regime can synchronize to each other. This means that the irregular time evolution of the emitter output is reproduced by the receiver laser. If it is realized, synchronization is robust against small perturbations. In this situation the chaotic output of the emitter laser can be used as a carrier in which a small amplitude message can be encoded. The receiver synchronizes to the chaotic carrier suppressing the codified message (as if it were a perturbation). Therefore, comparing the input (carrier with message) with the output (carrier only) of the receiver the message can be extracted (Fig. 1). Effective synchronization (and thus decoding) requires the use of very similar components for emitter and receiver with close matching parameters and operating conditions. In 1994 we theoretically propose optical communications using chaotic solid state lasers [3]. In 1996 we considered the use of semiconductor lasers with optical feedback emitting in the chaotic regime [4] (Fig 2).

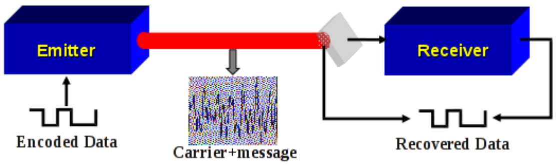

Fig. 1: Schematic representation of chaos-based optical communication.

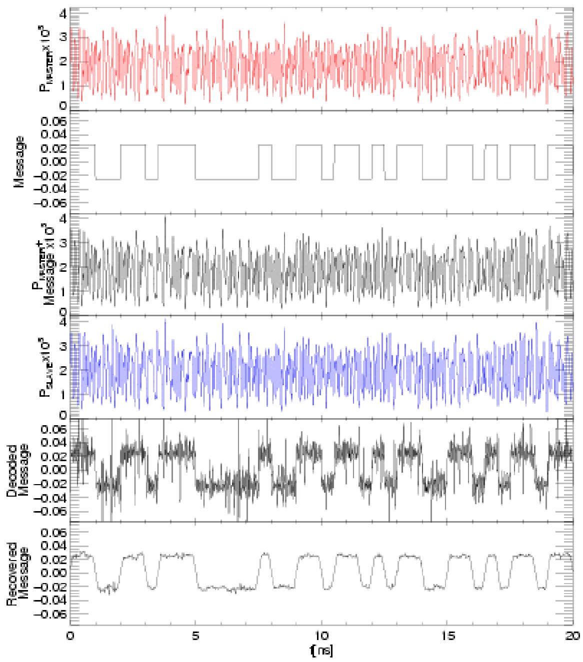

Fig. 2: From top to bottom, chaotic output intensity of a semiconductor laser with optical feedback (carrier), message, transmitted signal (carrier with message), receiver output, decoded message and decoded message after filtering.

In fact, semiconductor lasers are ideal candidates for the realization of these non-linear emitter and receiver systems. They are already inherently non-linear devices that under various operation conditions exhibit non-linear dynamical behavior associated with, e.g., fast irregular pulsations of the optical power. The properties of these carriers, and the way the message is encoded, are such that linear filtering, and frequency-domain analysis fail.

Our pioneering theoretical work was later confirmed experimentally in the lab [5]. In 2005 the first field experiment was carried out using the metropolitan optical fiber network of Athens. Optical fiber transmissions were performed over 100 km, at an encoding rate faster than 1 Gbit/s with an error rate of the order of 10^{-7} [6].

There is no doubt that the definitive applicability of this technique in real optical communications systems will depend as much on the security degree that can offer as on the robustness and compactness of the emitter and receiver sources. In this sense recent topics studied at IFISC include the characterization of the performance of different kinds of receivers used in systems with all-optical feedback [7], the use of compact sources such a as multisection semiconductor lasers [9] and the use of systems with electro-optical feedback which generate a carrier with constant intensity and in which the message is encoded in the chaotic phase [8].

3. Dynamics and applications of delay-coupled lasers

The understanding of the dynamics of nonlinearly coupled oscillators is essential for a wide range of scientific investigations. In real systems, the coupling often exhibits a significant delay due to the spatial separation between the subsystems. The infinite degrees of freedom added by the delay qualitatively alter the dynamical behavior of these delay-coupled oscillator systems. For instance, weakly bidirectionally coupled semiconductor lasers (SCLs), in a face-to-face configuration with a delay that is much larger than the internal time scale of the lasers, exhibit localized synchronization of periodic oscillations. Under stronger couplings SCLs exhibit instabilities characterized by fast intensity fluctuations of the light on a subnanosecond time scale in combination with much slower pronounced intensity dropouts for lasers pumped close to threshold. These intensity dropouts, as well as the fast fluctuations, can be strongly correlated between both lasers, however, always exhibit a constant time lag between the two signals. This delay between the leading laser (leader) and the lagging laser (laggard) corresponds to the coupling delay and is the manifestation of a spontaneous symmetry breaking in the system [10, 11]. In figure 3 we show experimental time traces for the two lasers (panel (a)), the maxima of the cross correlation as a function of the coupling strength (panel (b)) as well as the cross correlation function (panel (c)). The latter clearly show peaks of maximum correlation at the coupling time and multiples of it. Despite the symmetry of the system, it turns out that the solution of both lasers pulsating at the same time, with zero-lag, exists but it is unstable [12]. This particular aspect was also found in two lasers that were bidirectionally coupled but through their injection currents [13].

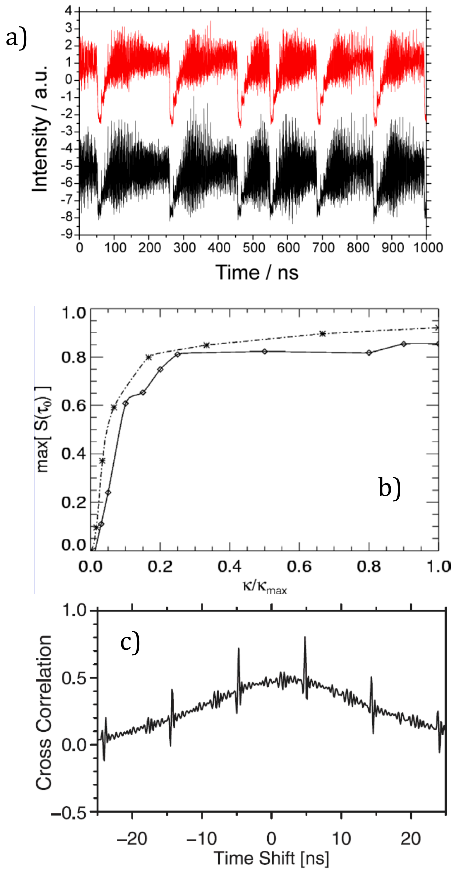

Fig. 3: Intensity time series of the two lasers (the lower is inverted for an easy comparison) (b) maximum degree of correlation achieved as function of the coupling strength. (c) experimental cross-correlation function.

When the module composed by two SCLs is extended to include a third identical laser coupled bidirectionally along a chain, zero lag identical synchronization is observed between the outer lasers in the chain [14,15]. The central element then acts as a relay of the dynamics between the outer ones. This stable isochronous synchronization solution is possible irrespective of the distance between the two outer lasers, provided that the two branches connecting the central element have similar lengths. Moreover, the solution is very robust to mismatches in the relay laser with respect to the others. However, closely matched lasers have to be placed at the end of the chain such that high synchronization is attained. A very interesting aspect is that, in many cases, the central laser dynamically lags the two outer ones. Therefore, it can be excluded that the outer lasers are simply driven by the central one, highlighting the emergence of a true collective behaviour among the three-coupled SCLs. In Fig. 4 we show experimental time traces of the three lasers superimposed to see how the intensities correlate. It can be clearly seen that laser 1 and 3 are identically synchronized, while the respective neighbours are not.

The center laser can be even replaced by a semitransparent mirror as relay, still inducing isochronous synchronization. It is worth mentioning that the same kind of motif was analyzed in neuronal models applied to the feature binding problem [16,17] yielding qualitatively similar results and highlighting the generality of the phenomenon.

The dynamical states generated by such delay coupled systems open novel and interesting applications. The chain of three delay-coupled lasers, or even the two lasers coupled through the semitransparent mirror, can be used, for instance, in bidirectional chaos-based communications or key exchange protocols used for information encryption [18]. The broadband chaos of these systems has potential to be utilized for high-speed random bit sequence generation as well. Finally, network motifs of delay coupled SCLs, including its simplest manifestation of a SCL subject to optical feedback, have been proposed as promising systems to process information mimicking our brain, implementing the concept of reservoir computing [19]. These are only few examples of the fascinating and emerging field related to the dynamics of delay-coupled SCLs that members of IFISC plan to develop further in the near future.

4. Dynamics Semiconductor Ring lasers

In the field of optoelectronics, one of the most interesting devices for future applications in all-optical circuits are Semiconductor Ring Lasers (SRLs). The peculiar geometry of SRLs (see Fig. 5) allows the existence of two counter-propagating electric fields acting in different types of dynamical behaviours [20]. One of these behaviours is the unidirectional emission allowing the switching between the directions of emission, i.e. SRLs show directional bistability. A bistable SRL is regarded as a logic unit able to switch at picoseconds time scale, moreover the absence of mirrors and the circular geometry permits spatial arrangement of compound structure (complex photonic networks) for non-conventional (neural) logic operations.

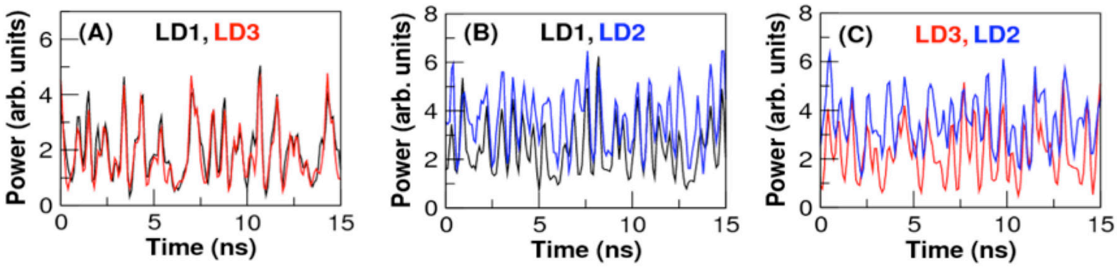

Fig. 4: (a), (b) and (c) Intensity time traces of SCLs 1-3, 1-2 and 3-2 respectively.

At IFISC we are modelling SRLs from different perspectives including rate equations models and traveling wave models. The rate equations model [20] offers a good quantitative description of the single-mode dynamics of the SRL, and allows us to simulate the directional switching dynamics [21]. We have obtained switching times of 100 - 20 ps for a 300 um radius SRL. We noticed that the switching time depends on the energy of the input pulse, but not in their shape. Moreover, for increasing energy pulses the switching time reduces. We have also found peculiar spectrum features when studying the noise properties of a SRL [22] that we explain as a consequence of the energy exchange between the two counter-propagating modes, which are well confirmed with measurements. Our theoretical work reveals how the backscattering coefficient can be estimated from the experimentally measured light spectra.

From the applicability point of view, we have proposed these devices as inertial rotation sensors [23]. We have studied the effect of the backscattering and the pump current on the responsivity function of the sensor taking into account quantum fluctuations that are converted into noise equivalent rotation rates. We conclude that using a SRL as a rotation sensor is viable, and it is not necessarily limited by locking effects. Moreover, the responsivity and noise performance are quite interesting compared to commercial laser gyroscope, taking into account the cost and size benefits of semiconductor laser technology.

From the point of view of the traveling wave models, where the spatial effects are retained and the multimode behaviour is taken into account, we investigated as a preliminary study the modal structure of such kind of devices [24]. We have found that the residual reflectivity in the light extraction sections determine the modal structure, and together with the redshift of the material gain, explains the amount of wavelength jumps and directional switching displayed by the SRL as the pump current increases.

These preliminary studies show us the important role of the cavity shape in the dynamics of the devices. A further step was to develop a traveling wave model [25] which allow us to simulate any kind of cavity by applying the appropriate boundary conditions to the system of Partial Differential Equations (PDEs), e.g., if we suppose a ring cavity (Fig. 5 panel b)) with only one coupler, if the transmission coefficients are vanishing we have a Fabry-Pérot cavity. Moreover, this model can be applied to different gain materials by using the correct parameters values. With this model we investigated multimode dynamics [25], we have found novel dynamical regimes where the emission in each direction occurs at different wavelengths, each direction being associated with a different longitudinal mode. We also have recovered dynamical behaviours shown experimentally in other kinds of ring lasers, such as fiber, gas or solid-state ring lasers; that include mode-locked emission or different oscillation regimes where the different excited modes of the ring cavity play

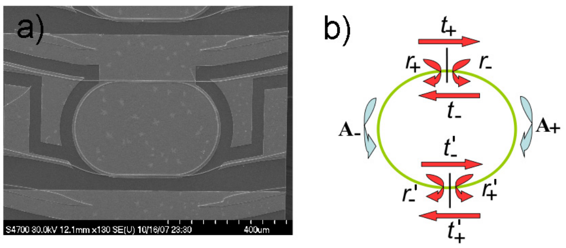

Fig. 5: a) Micrograph of a SRL with light extraction optical waveguides and electrical contacts. The ring radius is 150 µm. (Courtesy of the University of Glasgow). b) Schematic representation of the SRL with the counter-propagating fields A+ and A-. The transmission and reflection coefficients take into account the effect of the couplers and the waveguides, and they can in general depend on the frequency.

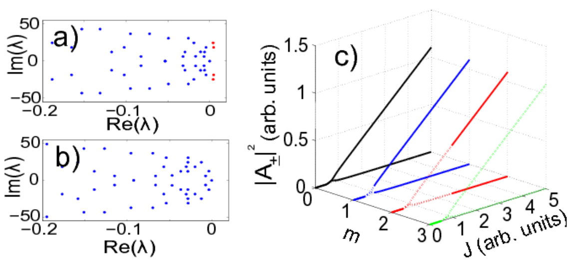

Fig. 6: a) Real versus imaginary part of the eigenvalues for a SRL for mode m = 2 and pump current J =2, showing unstable behavior. The eigenvalues in blue (red) have Re(λ)<0 (Re(λ)>0) . b) Same as a) for mode m = 2 and J = 3, showing stability. c) Stability diagrams for four modes of a SRL. $|A_{\pm}|^2$ are the intensities of the two counter-propagating electric fields. The dashed (solid) lines represent unstable (stable) solutions.

a fundamental role. We have studied the influence of the detuning and the width of the gain spectrum in these dynamical behaviours [25]. Moreover, the traveling wave model allows us to study different types of cavities. We have investigated new laser geometries that are related with the SRL geometry as the snail laser [26]. This modification of the ring laser geometry produces a high efficiency unidirectional laser emission as demonstrated theoretically and experimentally.

We are currently studying the experimentally observed phenomena of wavelength multistability in SRLs [27], i.e. one can select the wavelength emission by injecting light at this wavelength, and the emission remains stable. We aim to understand the physical mechanisms that lead to multi-stability in ring lasers but not in Fabry-Pérot lasers. Using a novel numerical treatment that allows calculating the spatial profiles of the monochromatic solutions and its stability we conclude that amount of spatial hole burning (degree of inhomogeneity in the spatial distribution of electron-hole re-combinations) in a ring laser is lower than for an equivalent Fabry-Pérot laser. The standing waves formed in a Fabry-Pérot configuration favour the spatial hole burning, while the traveling waves developed inside a ring tend to decrease or saturate it. As a consequence, ring lasers show longitudinal modal multistability more easily than in Fabry-Pérot lasers. Fig. 6 shows the numerically calculated eigenvalues for different current values for mode m=2, and the stability diagrams for four modes for a SRL.

Acknowledgements

We acknowledge financial support from the European Commission Projects PICASSO Grant IST-2005-34551, PHOCUS Grant FP7-ICT-2009-C-240763 and IOLOS Grant FP6-IST-2005-34743 and from MICINN (Spain) and FEDER (EU) through Projects TEC2006-1009/MIC (PhoDECC), TEC2009-14101 (DeCoDicA) and FIS2007-60327 (FISICOS). A.P. acknowledges financial support from the Govern Balear.

