Wavelength multistability in lasers

Antonio Pérez-Serrano
IFISC (UIB-CSIC),
Universitat de les Illes Balears,
E-07122 Palma de Mallorca, Spain.
antonio@ifisc.uib-csic.es

Julien Javaloyes
Departament de Física,
Universitat de les Illes Balears,
E-07122 Palma de Mallorca, Spain.
julien.javaloyes@uib.es

Salvador Balle
IMEDEA (UIB-CSIC),
C/ Miquel Marqués 21,
E-07071 Esporles, Spain.
salvador@imedea.uib-csic.es

***Abstract*—We theoretically discuss the impact of the cavity configuration on the possible longitudinal mode multistability in homogeneously broadened lasers. We present a general method allowing to perform a direct bifurcation diagram and to determine the stability of the solutions of a Travelling wave model. We find, in agreement with recent experimental reports, that multistability is more easily reached in Ring than in Fabry-Pérot cavities which we attribute to the different amount of Spatial-Hole Burning in each configuration.**

Laser Theory, Travelling Wave Model, Ring Lasers.

I. Introduction

Ring Lasers (RLs) present a large variety of dynamical regimes arising from the nonlinear interaction of the counter-propagating waves mediated by the active medium, e.g. bidirectional CW emission, oscillation regimes, mode-locking and chaos. In addition, RLs with low degrees of backscattering present regimes of bistable unidirectional emission [1] which can be exploited for all-optical signal processing and storage [2]. Recently it was experimentally demonstrated [4] that the emission wavelength of bidirectional semiconductor ring lasers (SRLs) can be selected by optical injection at wavelengths corresponding to the modes of the cavity; upon removal of the optical injection, the emission wavelength remains stable at the chosen value. It was found that this multistability can coexist with the directional bistability shown by these devices, therefore it can be of interest for all-optical signal processing applications at higher-logical level [5], as well as to fabricate multi-wavelength sources and fast and widely tunable sources that can generate mm-wave or THz modulated optical carrier. The SRL technology not only can be used to perform the processing, it is also can be used as the direct output of the routing decisions that result from the processing, and can be directly interfaced with the optical networks. On the other hand, this multistability has, to our knowledge, never been explained or reported in Fabry-Pérot (FP) lasers, hence it recalls for an explanation of the different behaviour shown by RLs and FP lasers regarding multistability.

In this contribution, we investigate theoretically the multistability by means of a Travelling Wave Model (TWM) for a homogeneously broadened medium with the appropriate boundary conditions [6] that allow us to model RLs and FP lasers. We take into account that the presence of counter-propagating fields creates a spatial modulation or grating of the population inversion (D_2). We compute the monochromatic steady state solutions of the system via a shooting method and we numerically perform their linear stability analysis by diagonalising the jacobian obtained from the evolution operator of the discretized system.This method allow us to construct direct bifurcation analysis of the TWM.

Performing this analysis, we found that the physical reason for such different behaviour of FP and RLs is the quite different degree of spatial hole burning in the gain. Therefore, high-quality SRLs, with low reflectivity couplers, allow to observe longitudinal mode multistability much more easily than their equivalent FP configurations. FP devices can exhibit multistability if diffusion is strong enough to wash out the grating effectively: in this limit the grating lifetime is much shorter than carrier lifetime, and cross-saturation dominates over self-saturation.

II. Model

For simplicity, we assume the active medium to be composed of two level atoms, although the model and techniques developed can be readily extended to other active medium cases, e.g. semiconductor case.

The presence of the two counter-propagating fields makes that a grating in the carrier density appears which couples in a nonlinear way the two waves; we include this effect by decomposing the carrier density D, in different spatial contributions, and cutting the resulting hierarchy via carrier diffusion. We consider that the electric field is quasi-monochromatic and it is decomposed into forward (+) and backward (-) waves propagating in opposite directions. We also consider a quasi-resonant light matter interaction in the Rotating Wave Approximation (RWA). With these assumptions, the dimensionless equations that defines the TWM read

$$\pm\frac{\partial A_\pm}{\partial s} + \frac{\partial A_\pm}{\partial \tau} = B_\pm - \alpha A_\pm \;, \tag{1}$$

$$\frac{1}{\gamma}\frac{\partial B_\pm}{\partial \tau} = -(1+i\delta)B_\pm + g(D_0 A_\pm + D_{\pm 2}A_\mp) \;, \tag{2}$$

$$\frac{1}{\epsilon}\frac{\partial D_0}{\partial \tau} = J - D_0 + \Delta\frac{\partial^2 D_0}{\partial s^2} - (A_+ B_+^* + A_- B_-^* + c.c.), \tag{3}$$

$$\frac{1}{\eta}\frac{\partial D_{\pm 2}}{\partial \tau} = -D_{\pm 2} - \frac{\epsilon}{\eta}(A_\pm B_\mp^* + A_\mp^* B_\pm) \;, \tag{4}$$

where $A_\pm$ are the slowly varying components of the counter-propagating electric fields, $B_\pm$ are their respective polarizations, D_0 is the quasi-homogeneous inversion density and $D_{\pm 2}$ are the spatially-dependent contributions to the grating in the population inversion density, g is a gain coefficient, α are the internal losses, δ is the detuning, Δ is the diffusion coefficient, ϵ and η are the decay times for D_0 and $D_{\pm 2}$ respectively, γ determines the spectral width of the gain spectrum and J is the pump. Equations (1-4) must be completed with the boundary conditions for the electric fields which read

$$\begin{aligned} A_+(0) &= tA_+(1)e^{i\gamma\omega_0} + rA_-(0), \\ A_-(1)e^{-i\gamma\omega_0} &= tA_-(0) + rA_+(1)e^{i\gamma\omega_0}, \end{aligned} \tag{5}$$

where ω_0 is the carrier frequency, r and t represents the reflectivity and transmissivity of the waves at the point coupler, then $|t|^2 + |r|^2 = 1 - \phi$, where ϕ are the losses at the point coupler. In the following we shall take $\gamma\omega_0 = 2\pi m$ where $m = 0, 1, 2...$ then $i\gamma\omega_0 = 1$ without loss of generality: it simply means that we take as the carrier frequency ω_0 that corresponding to one of the modes of the cavity.

III. Numerical analysis and results

The numerical analysis consisted in using a multidimensional shooting algorithm to find the monochromatic solutions [7]. The linear stability analysis of these solutions was performed using a temporal map that advances the solution one time step including the boundary conditions, that allows to find the Floquet matrix that represents the linear operator governing the time evolution for the perturbations around one given monochromatic solution. Finally, the Floquet multipliers that determine the eigenvalues of the system were found. Fig. 1 shows the computed eigenvalues for mode number $m = 2$, (a) $J = 3$ and (b) $J = 4$ for a RL with typical semiconductor parameters. The monochromatic solution for $m = 2$ is unstable (stable) for $J = 3$ ($J = 4$). We reapeat this process to construct bifurcation diagrams like the one shown in Fig. 1 (c). We found that in the regime of stable unidirectional emission, RLs exhibit multistability among several longitudinal modes even when one mode is resonant with the atomic gain line. In this regime the emission wavelength can be selected among that of several cavity modes by injection of external optical pulses, in agreement with experimental reports [4]. However, multistability is not found for an equivalent FP laser (see Fig. 1 (d)), the resonant mode is stable until it reaches a multi-mode instability.

The physical reason for such different behaviour of FP and RLs is the quite different degree of spatial hole burning in the gain. Fig 2 (a) shows the absolute value of D_2 averaged along the cavity. In the ring laser, $\langle|D_2|\rangle$ saturates at a comparatively low value as soon as the pitchfork bifurcation leading to unidirectional emission occurs; for FP configurations, the necessarily higher reflectivity of the facets makes $\langle|D_2|\rangle$ larger than in the equivalent ring, and it increases continuously with the pump level. In order to confirm that the grating term is what destroys multistability in the FP, we consider a system with very high diffusion, which reduce the values of D_2. As shown in Fig. 2 (b), in this case multistability is reached.

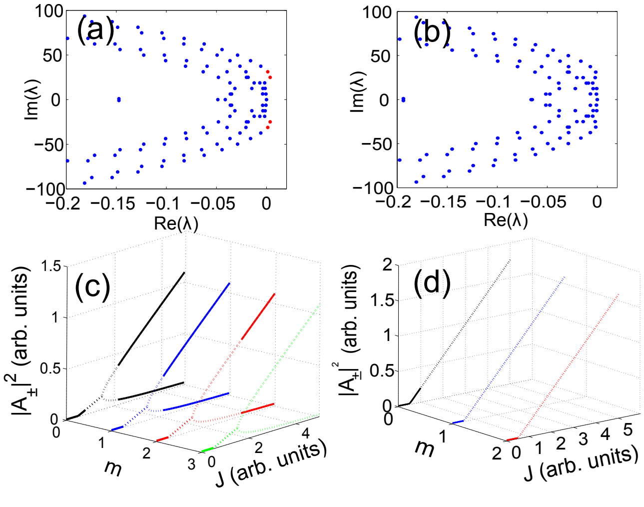

Fig. 1. Real versus imaginary part of the eigenvalues for $m = 2$, (a) $J = 3$ and (b) $J = 4$. Eigenvalues in blue (red) have $Re(\lambda) < 0$ ($Re(\lambda) > 0$). Bifurcation diagram for the first modes of a RL (c) and for an equivalent FP laser (d). Solid (dashed) lines represent the stable (unstable) solutions.

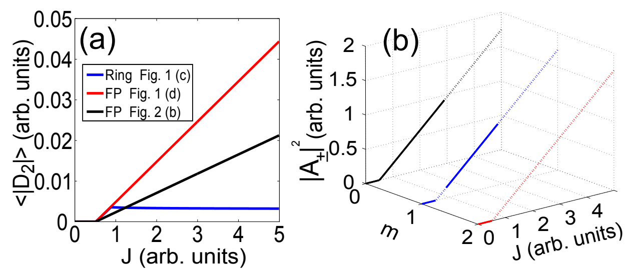

Fig. 2. (a) $\langle|D_2|\rangle$ versus J for the RL in Fig. 1 (c) and FP lasers in Fig. 1 (d) and panel (b). (b) Bifurcation diagram for a FP laser showing multistability after increasing the diffusion.

Acknowledgment

A.P. thanks financial support from the Govern Balear. J.J. thanks financial support from the Ramón y Cajal program by Spanish MICINN. S.B. thanks financial support from project ALAS (TEC2009-14581-C02-01).

References

[1] M. Sorel, G. Giuliani, A. Scire, R. Miglierina, S. Donati, and P. J. R. Laybourn, "Operating regimes of GaAs-AlGaAs semiconductor ring lasers: experiment and model," *Quantum Electronics, IEEE Journal of*, vol. 39, no. 10, pp. 1187–1195, Oct. 2003.

[2] M. T. H. *et al.*, "A fast low-power optical memory based on coupled micro-ring lasers," *Nature*, vol. 432, no. 7014, pp. 206–209, Nov 2004.

[3] Z. Wang, G. Yuan, G. Verschaffelt, J. Danckaert, and S. Yu, "Storing 2 bits of information in a novel single semiconductor microring laser memory cell," *Photonics Technology Letters, IEEE*, vol. 20, no. 14, pp. 1228 –1230, july15 2008.

[4] K. Huybrechts, B. Maes, G. Morthier, and R. Baets, "Tristable all-optical flip-flop using coupled nonlinear cavities," in *2008 IEEE/LEOS Winter Topical Meeting Series*, January 2008, pp. 16–17, IEEE/LEOS Winter Topical Meeting, Sorrento, Italy, Jan 14-16, 2008.

[5] A. Pérez-Serrano, J. Javaloyes, and S. Balle, "Bichromatic emission and multimode dynamics in bidirectional ring lasers," *Phys. Rev. A*, vol. 81, no. 4, p. 043817, Apr 2010.

[6] A. Pérez-Serrano, J. Javaloyes, and S. Balle, "Longitudinal mode multistability in ring and fabry-pérot lasers: the effect of spatial hole burning," *Opt. Express*, vol. 19, no. 4, pp. 3284–3289, Feb 2011. [Online]. Available: http://www.opticsexpress.org/abstract.cfm?URI=oe-19-4-3284