Dynamical behaviour of current-modulated semiconductor ring lasers

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Abstract

We numerically investigate the dynamical behaviour of a directly modulated semiconductor ring laser (SRL) with the modulation frequency of its injection current significantly lower than the relaxation oscillation frequency. Different dynamical states including periodic, quasi-periodic and chaotic states are found by varying the amplitude and frequency of the modulation current for a fixed bias current. The SRL is found to enter the chaotic regime through an anti-phase period-doubling route. Moreover, the chaotic regime found exhibits an anti-phase dynamics without the involvement of any carrier dynamics.

Introduction

A SRL is a semiconductor laser in which light is confined in a circular waveguide structure. The circular geometry of the active cavity allows a SRL to generate light in two opposite directions, namely, a clockwise mode (CW) and a counterclockwise mode (CCW). Contrary to integrated lasers of the Fabry-Perot type, a SRL does not require cleaved facets or gratings to provide the necessary optical feedback and is thus particularly suited for monolithic integration **[1]**. This device exhibits different operating regimes characterized by bidirectional-continuous waves (bi-CW) to alternate oscillations (bi-A0) and bistable unidirectional (bis-UNI) **[2]**. From the application point of view, the bis-UNI regime opens the possibility of using SRL in systems for all-optical switching, gating, wavelength conversion functions and optical memories **[3]**. The nonlinear dynamics of externally driven semiconductor lasers have been widely investigated because of the important roles semiconductor lasers play in conventional optical communications and in chaotic optical communications. In particular, the study of the dynamical properties of semiconductor lasers subject to current modulation (CM) has received a lot of attention. The majority of works on the directly modulated semiconductor lasers have been performed on conventional edge-emitting lasers and vertical cavity surface-emitting lasers. However, there are no works, to the best of our knowledge, devoted to the study of dynamical behaviour of SRLs under CM. The aim of the present note is to analyze the effect of CM on the dynamics of a solitary SRL. The plan of the paper is organized as follows. In section 2, we present the SRL model, in section 3 the numerical results and end with a conclusion in section 4.

Semiconductor ring lasers rate equations model

We consider a SRL operating in a single-longitudinal and single-transverse mode. The dynamical behaviour of this SRL can be described by the following set of equations **[2]**:

$$\frac{dE_{ccw,\,cw}}{dt} = (1+i\alpha)\left[N\left(1-s\left|E_{ccw,\,cw}\right|^2 - c\left|E_{cw,\,ccw}\right|^2\right)-1\right]E_{ccw,\,cw} - (k_d + i k_c)E_{cw,\,ccw} \quad (1)$$

$$\frac{dN}{dt} = \gamma\left[\mu_{dc}+\mu_m\sin(2\pi f_m t) - N - N\left(1-s|E_{ccw}|^2 - c|E_{cw}|^2\right)|E_{ccw}|^2 - N\left(1-s|E_{cw}|^2 - c|E_{ccw}|^2\right)|E_{cw}|^2\right] \quad (2)$$

Here t is the time, $E_{cw,ccw}$ are the slowly varying complex amplitudes of the counter-propagating waves and N is the carrier density. The parameters of the SRL are: γ=0.002 is the ratio of photon lifetime τ_p= 10ps to carrier lifetime τ_s, the self-saturation coefficient s= 0.005, the cross-saturation coefficients c=0.01 and the linewidth enhancement factor α= 3.5, the dissipative backscattering component k_d=0.000327, the conservative backscattering component k_c=0.0044 **[2]**. The modulation parameters are the dc bias injection current μ_{dc}, the modulation amplitude μ_m and the modulation frequency f_m.

Numerical results

To study the dynamics of SRL under CM, we vary μ_{dc}, μ_m and f_m. We have constructed a map of the dynamical behaviour of a current-modulated SRL, bifurcation diagrams, time traces and Poincaré section. When a sinusoidal time modulation is added to the steady injection current, the SRL behaves like a periodically driven nonlinear oscillator. So everything is unexpected. In order to identify these dynamical regimes in modulation parameter space, we have constructed two parameters (μ_m, f_m) bifurcation diagrams for specific values of μ_{dc} by examining the Lyapunov exponents and time traces for each cell as shown in Fig. 1. For μ_{dc} =1.201 (in bi-CW regime), we have noted from such a bifurcation diagram that the SRL exhibits continuous wave operation without CM, while when the CM is applied only periodic behavior is found. Fig. 1 presents a bifurcation diagram in bi-AO (a) and bis-UNI (b) regimes. Such a diagram will prove useful for future experimental/verification measurements as it can serve as a guide to selecting the appropriate operating parameters for studying a particular dynamical regime. From Fig. (1.a), we see that the system exhibits periodic, quasi-periodic and chaotic behavior. In Fig. (1.b), without CM only stable continuous wave is found whereas applying the CM gives rise to periodic oscillations, quasi-periodicity and even chaos. The bifurcation diagrams depicting the local extrema of the counter-propagating modes intensities as a function of μ_m for fixed values of μ_{dc} and f_m present an anti-phase period-doubling transition to anti-phase chaos. The chaotic behavior is further detailed in Fig. 2 which shows the time traces and the corresponding Poincaré section for specific values of μ_{dc}, μ_m and f_m.

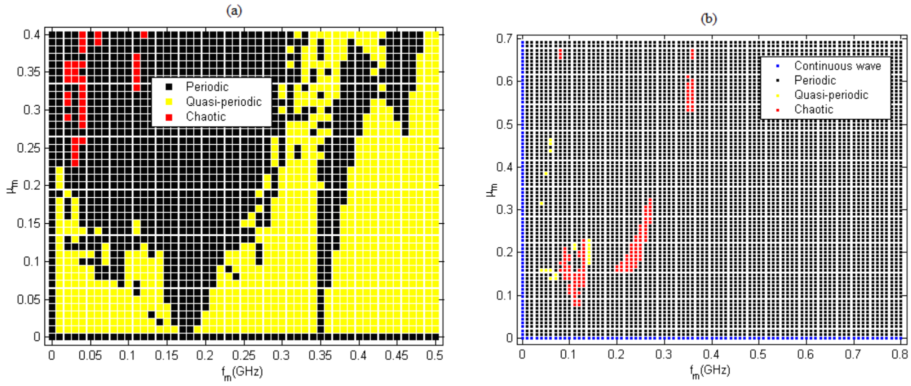

Figure 1: Regions of dynamical behavior in the parameter space spanned by f_m and μ_m for specific values of μ_{dc}: (a) $\mu_{dc} = 1.4$ (in bi-A0 regime) and (b) $\mu_{dc} = 1.704$ (in bis-UNI regime).

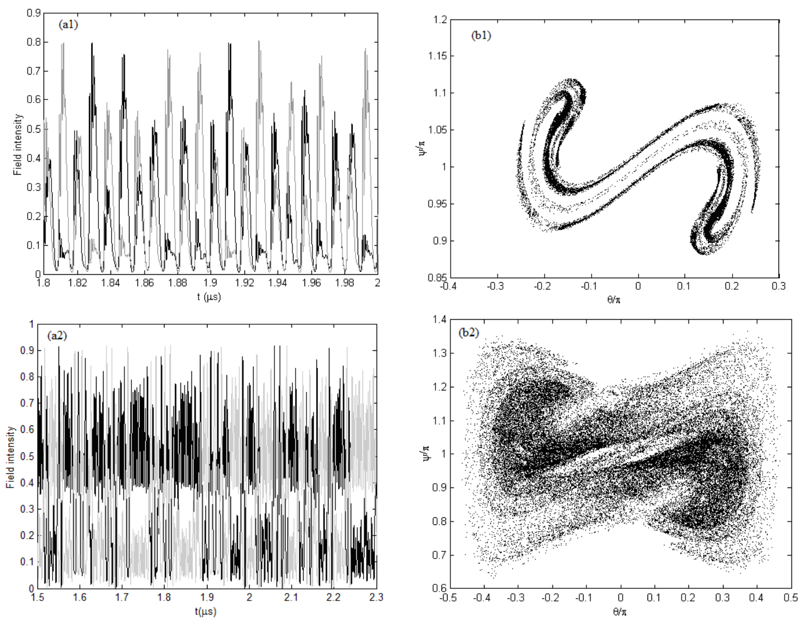

Figure 2: In panel (1) we plot time traces of $I_{\text{ccw, cw}}$ while in panel (2), we depict the corresponding Poincaré section for specific values of μ_{dc}, μ_m and f_m: (a) $\mu_{dc} = 1.4$, $\mu_m = 0.35$ and $f_m = 110MHz$ and (b) $\mu_{dc} = 1.704$, $\mu_m = 0.233$ and $f_m = 240MHz$. In (a) black (grey) line indicates time trace of I_{CCW} (I_{CW}). $\theta = 2\arctan\left(\left|E_{cw}\right| / \left|E_{ccw}\right|\right) - \pi/2 \in \left[-\pi/2, \pi/2\right]$ represents the relative modal intensity, $\psi \in \left[0, 2\pi\right]$ is the phase difference between the counter-propagating modes **[4]**.

In Fig. 2, we note that the two counter-propagating modes show two situations of anti-phase chaotic intensity. The anti-phase relationship between the modes is that individual chaotic mode intensity pulsations alternate (see Fig. (2.a1)). This type of anti-phase dynamics has been observed in optically pumped NH_3 bidirectional ring laser **[5].** However in Fig. (2.a2), the anti-phase relationship is different as all intensity variations of the counter-propagating modes are in the opposite sense, which has also been observed in **Ref. [5].** A more rigorous confirmation of the anti-phase dynamics is given by the time trace of the total power inside the SRL which remains approximately constant throughout the simulation and oscillates at f_m (not shown). From Fig. 2, we can also note the topological resemblance of Figs. (2.b1) and (2.b2) to the Poincaré section of the chaotic behaviour of a periodically forced Duffing oscillator.

Conclusion

In this paper, we have studied the dynamics of current-modulated SRL with the f_m of its injection current significantly lower than the relaxation oscillation frequency. We have shown that current-modulated SRL in bi-CW regime exhibits only periodic behavior. While in bi-AO and bis-UNI regimes the current-modulated SRL presents periodic, quasi-periodic and chaotic behaviors depending on the value of f_m and μ_m. Bifurcation diagrams have been reported showing an anti-phase period doubling transition to anti-phase chaos. Two situations of anti-phase chaotic intensity variations of the counter-propagating modes are found. An interesting work under investigation is the study of chaos synchronization and communication in directly modulated SRL.

Acknowledgments

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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, 2095- 2097, 1990.

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

[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, vol. 432**,** 206- 209, 2004.

[**4]** G. Van der Sande, L. Gelens, P. Tassin, A. Scirè, and J. Danckaert, "Two-dimensional phase-space analysis and bifurcation study of the dynamical behaviour of a semiconductor ring laser", J. Phys. B, vol. 41, 095402-095409, 2008.

[5] D. Y. Tang and N. R. Heckenberg, "Antiphase dynamics of a chaotic multimode laser" Phys. Rev. A, vol. 56, 1050-1052, 1997.