Multi-Population Rate Equation Simulation of Quantum Dot Semiconductor Lasers with Feedback

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***Abstract*— We present a numerical model based on multi-population rate equations for the simulation of quantum dot lasers with weak external optical feedback. The model accounts for the peculiar characteristics of the quantum dot material (inhomogeneous distribution of the QD size, presence of excited state and wetting layer ...) and can be used to calculate numerically the bifurcation diagram of the laser as function of several material and device parameters.**

I. Introduction

It was predicted that QD laser diodes can be insensitive to external optical feedback thanks to the ideally zero α-parameter (or linewidth enhancement factor LEF) that could be obtained from a QD material with a perfectly symmetric gain spectrum. It is now well understood that the LEF of the self-assembled QDs grown on GaAs or on InP can not be zero at room temperature because of the inhomogeneous broadening of the gain as well as the carrier thermalization in additional states with high energy such as the excited state (ES) or the two dimensional wetting layer (WL) [1,2]. In [2] we have shown that the carrier distribution among the various states (ES and ground state of QD of different size, WL) has significant consequences on the phase and frequency dynamics (chirp) of the QD single mode laser (QD-SML) subject to current modulation. In this work we use the multi-population rate equation (MPRE) model [3] to study the case of a QD-SML, working in CW condition with a weak external optical feedback. The model presented here uses as input data all the physical parameters of the QD material (inhomogeneous and homogeneous broadening, carrier capture and relaxation times, dot density) and does not require, as for example in [1], equivalent parameters (ie: linewidth enhancement factor, differential gain, gain compression factor) that are generally extracted from the measurement of the laser response to small signal current modulation. The model we present can be used to analyze the effect of several parameters (bias current, laser operating wavelength, carrier capture and escape times, homogeneous and inhomogeneous broadening, feedback strength, field delay) on the response of the QD-SML in presence of feedback. It also allows a comparison with simpler models that make use of equivalent parameters as for example [1].

II. Numerical model and Results

The numerical model for representing the carrier dynamics is based on a MPRE system presented in detail in [2]. It consists of a set of several rate equations that describe the carrier capture from the WL in the QDs of different size and the relaxation of carriers from the ES into the GS. The rate equations of carriers are coupled with the delayed differential equation [1] of the electric field, $E(t)$, at the lasing wavelength of the laser. The laser is assumed single mode (SML). The equation of the field is written as:

$$\frac{dE}{dt} = -\frac{E(t)}{2\tau_p} + v_g \frac{\sum_n g_{nGS} + g_{nES}}{2} E(t) + j2\pi\delta f(t)E(t) + k_{feedback}E(t-\tau) \quad (1)$$

where τ_p is the photon lifetime, $k_{feedback}$ is the strength of the optical feedback and τ is the delay due to the round trip in the external cavity. The gain at the lasing mode frequency is written as the sum of the gain from QDs of different size (index n) due to stimulated emission from the ground states GS (gain g_{nGS}) or from the ES (gain g_{nES}). The detailed expressions of these gain terms are reported in [2]. The phase variation due to carrier fluctuation is included in the frequency chirp $\delta f(t)$ which is proportional to the refractive index change. The refractive index change is calculated as variation respect to the cold cavity; it is written as the sum of two contributions due to carriers in the QDs (Kramers-Kronig contribution) and in the WL (free carrier contribution) [2]. As shown in [2] the amount of the refractive index variation is significantly dependent on the homogeneous broadening of the emission line which couples the variation of carrier in all of the states to the variation of refractive index at the lasing frequency. In the case of a QD-SML with weak external feedback, the carrier fluctuation in the various states is caused by a variation of stimulated emission due to the beating of the cavity photons with the delayed field. We have two mechanisms responsible for the carrier fluctuation: 1) the photons deplete the resonant states inside the homogeneous broadening of the gain and 2) the carriers in the non-resonant states (outside the homogeneous broadening of the gain) readjust through the coupling with the common WL and via relaxation/capture and escape processes.

The model can be used to study the response of the laser in presence of weak external feedback (for example external mirror reflectivity $R_f = 1.5 \cdot 10^{-3}$) and the dependence of this response on several material and device parameters. As an example of this analysis, we show here how the laser response (stable, self-pulsating, chaotic-like ...) is dependent on the bias current and on the width of the homogenous

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broadening linewidth due to the exciton dephasing process. In Fig.1we report for reference the spectra of the gain (Fig. 1a) and of the LEF (Fig. 1b) calculated at the laser threshold for three different values of the homogeneous broadening (ΔE_{hom} =20 meV, 12 meV and 6 meV). The inhomogeneous broadening due to QD size dispersion is set to 40 meV. The QD-SML is emitting from the GS with emission energy of 945 meV (indicated with the arrow in Fig. 1a and 1b). In the inset of Fig. 1b we also report the value of the LEF at the QD-SML threshold calculated for each value of ΔE_{hom}. We point out that the LEF values are reported here only for reference and for an easy comparison with the measurements usually done in the lab, but we stress that these calculated LEF at threshold is not used in the calculation of the frequency fluctuations $\delta f(t)$ above threshold. The chirp $\delta f(t)$ is indeed calculated from the refractive index variation with the quantum mechanics expressions reported in [2]. In presence of weak

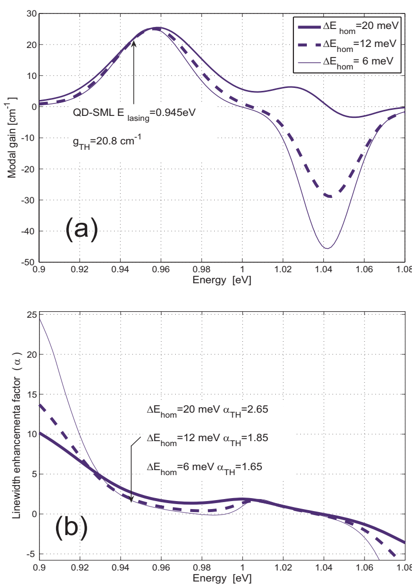

Fig. 1. Spectra of (a) the modal gain and (b) the LEF at the threshold of the QD-SML calculated for three different values of homogeneous broadening ΔE_{hom}.

external feedback we have solved the MPRE system coupled with equation (1). For each value of bias current we have obtained the evolution of the number of cavity photons as function of time($|E(t)|^2$). From this response we have extracted the maxima and the minima of $|E(t)|^2$ and we have collected all of the points in the bifurcation diagrams shown in Fig.2. These diagrams, calculated for the three different values of the homogeneous broadening, are useful to identify the conditions that give a chaotic-like response (several points in the bifurcation diagram, response as in the inset of Fig. 2a), a self-pulsating response (two points in the bifurcation diagram, response as in the inset of Fig. 2b) or a stable response (one point in the bifurcation diagram, response as in the inset of Fig. 2c). Separating the various contributions to the chirp due to carrier fluctuation in the GS, ES and WL, we have observed that the carrier variation in the ES and in the WL causes the most significant variation of the refractive index at the lasing mode and it is therefore the main cause for the instability. Reducing the width of the homogeneous broadening the carrier fluctuation in the ES produces a smaller variation of refractive index at the lasing mode of the GS and the laser gets more stable. As shown in Fig. 2c, with ΔE_{hom} =6 meV, self-pulsating or chaotic-like response are indeed obtained only for very few values of bias current.

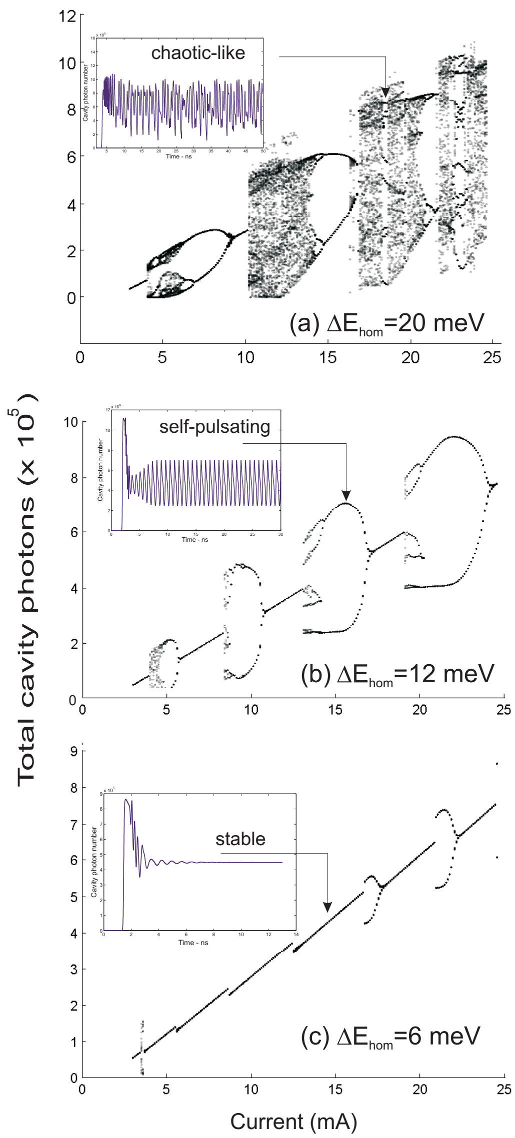

Fig. 2. Bifurcation diagram obtained from the maxima and minima of $|E(t)|^2$ for the QD-SML with three different values of homogenous broadening. The insets show $|E(t)|^2$ in few selected points of the diagrams.

III. Conclusion

We have presented a model for the analysis of the response of a QD-SML with weak external optical feedback. The model is used to study the stability of a QD-SML at increasing bias current and the dependence of the response on the width of the homogeneous broadening linewidth.

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