Self-mode-locking in Quantum Dot unidirectional ring lasers: model and simulations

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***Abstract*—We predicted the occurrence of spontaneous mode-locking phenomena in Quantum Dot based unidirectional ring laser via Risken-Nummedal-Graham-Haken instability of the continuous wave emission. Very interestingly for applications the resulting optical pulses have duration of few picoseconds with a THz repetition rate.**

I. Introduction

We theoretically studied coherent phenomena in the multi-mode dynamics of single section semiconductor unidirectional ring lasers with Quantum Dots (QD) active region similar to those considerend in [1], [2]. To this aim we extend the time domain traveling wave (TDTW) model presented in [3] to include the evolution equation of the medium polarization. Our simulations predict the occurrence of self-mode-locking (SML) in the system leading to ultrashort pulses ($\sim$ few picoseconds) with a THz repetition rate. The Linear Stability Analysis (LSA) of the continuos wave solutions (CW) is in good agreement with the numerics and it allows to establish an analogy between the observed CW instability and the well known Risken-Nummedal-Graham-Haken (RNGH) instability affecting the dynamics of two level lasers and consisting in the amplification of the Rabi frequency [4], [5]. While in the temporal domain this SML is very promising for the realization of compact lasing sources for time resolved measurement of e.g fast molecular dynamics and fast imaging system, in the frequency domain it correspond to a frequency comb made of narrow lines with almost equal amplitude and equal THz separation that let envisage applications in the field of long-range, high-capacity wireless communication based on combined THz photonics and THz electronics [6].

The results presented here well agree with recent theoretical and experimental evidences reported in literatures in the study of broadband Quantum Cascade Lasers that share with QD lasers a similar dynamical behaviour due to the almost symmetric optical response and the fast gain recovery time ($\sim$ few picoseconds) [7], [8].

II. The TDTW model

We consider a multilayer, multi-populations InAs QD laser emitting around 1.3 μm in a unidirectional ring configuration. Extending beyond the adiabatic elimination of the medium polarization the TDTW model presented in [3], the set of nonlinear PDEs that describe the dynamics of the slowly varying envelopes of the electric field E and of the microscopic polarization p_i for the i-th QD population, coupled with that of the occupation probabilities of the QD ground state ρ_i and of the Quantum Well wetting layer ρ_{WL} can be conveniently written in the following adimensional form:

$$\frac{\partial E}{\partial t}+\frac{\tau_d}{\tau_p}\frac{\partial E}{\partial z} = \frac{\tau_d}{\tau_p}\left(-\frac{\alpha_{wg}L}{2}E - C\sum_{i=-N}^{N}\bar{G}_i p_i\right) \quad (1)$$

$$\frac{\partial p_i(z,t)}{\partial t} = [(j\delta_i/\Gamma - 1)p_i - D(2\rho_i - 1)E] \quad (2)$$

$$\begin{aligned}\frac{\partial \rho_i(z,t)}{\partial t} &= \frac{\tau_d}{\tau_{sp}}\left[-\rho_i\gamma_e(1-\rho_{WL})\right.\\ &+ F\rho_{WL}\gamma_C(1-\rho_i) - \rho_i^2\\ &+ \left.H\,Re\,(E^* p_i)\right] \quad (3)\end{aligned}$$

$$\begin{aligned}\frac{\partial \rho_{WL}(z,t)}{\partial t} &= \frac{\tau_d}{\tau_e^{WL}}\left\{\Lambda\tau_e^{WL} - \rho_{WL}\right.\\ &+ \sum_{i=-N}^{N}\left[-\bar{G}_i\rho_{WL}\gamma_C^{WL}(1-\rho_i)\right.\\ &+ \left.\left.\frac{\bar{G}_i}{F}\rho_i\gamma_e^{WL}(1-\rho_{WL})\right]\right\} \quad (4)\end{aligned}$$

The reference frequency ω_0 coincides with one of the ”cold cavity modes” $\omega_n = 2\pi n v_g/L$, $n \in Z$ (v_g = group velocity of the light in the medium) and with the gain peak; τ_d and τ_p are the dipole dephasing time and the photon lifetime respectively, τ_{sp} is the spontaneous carriers decay time, τ_e and τ_C are the escape and capture time from and to the ground state respectively and τ_e^{WL} is the carriers nonradiative decay time in the wetting layer; $\alpha_{wg}/2$ represents the waveguide losses per unit length, $\bar{G}_i$ is the probability that a QD belongs to the i-th population, δ_i and Γ are the central frequency and the FWHM of the homogeneously broadened gain line associated to the i-th population, Λ is the probability per unit time that an injected electron is captured into a wetting level of a QD layer. The constant coefficients C, D, F, H depend on the QD laser geometry and the active material. Time is scaled on τ_d while the longitudinal coordinate is scaled on the cavity length L. Finally E obeys periodic boundary conditions. For all the QD material parameters we refer to those used in [3]. In the following we report some important results obtained in the study of the transition from the single frequency, or CW, emission to the multi longitudinal mode dynamics using the biased current I as control parameter.

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