Numerical Simulation of Quantum Dot Single Section Fabry-Perot Laser Combs

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Abstract—We present the development of a numerical simulation tool to analyze the self-mode locking in single section Quantum Dot Fabry-Perot comb lasers. The numerical analysis shows that the output optical spectrum is an optical comb because the cavity modes are phase-locked by the four wave mixing. The impact of QD material parameters is also discussed.

Keywords—Fabry-Perot laser, Quantum Dot, Comb lasers; Time Domain Travelling Wave model.

INTRODUCTION
There is an increasing interest on single section Fabry-Perot (FP) Quantum Dot (QD) lasers as comb laser source for terabit communication in data centers [1]. Many experiments have demonstrated that in these devices several cavity longitudinal modes can be spontaneously phase locked and pulses can be generated directly at the laser output [2] or after group delay dispersion (GDD) compensation [3, 4]. There is, however, still a significant lack of modelling work for providing physical explanations on the capability of some lasers of generating several phase locked modes without any saturable absorber section. Quantum Cascade comb lasers at THz and mid-IR wavelengths have been theoretical studied in [5] via Maxwell-Bloch formalism based on a modal decomposition, whereas we have recently developed a Time-Domain Travelling-Wave model to study the comb spectra generation in QD lasers at telecom wavelengths [6]. Both [5] and [6] have shown that the Four Wave Mixing (FWM) together with a short carrier lifetime (in the QC laser case) or a fast gain recovery time (in the QD laser case) is sufficient to explain the phase locking of the modes. We have shown that, in the QD laser case, the large gain compression factor ($\varepsilon = 10^{-16}$) causes the broadening of the optical spectrum and the self-phase locking of the modes. In this contribution, we analyze with numerical simulations the pulse formation in single section FP QD lasers and we discuss how some typical QD material parameters influence the phase locking and the pulse formation.

I. NUMERICAL MODEL

We consider InAs/GaAs self-assembled QD active medium; the QDs having similar size, and therefore similar optical and electrical properties, are collected in sub-groups. We use Multi-Population Rate-Equations [6,7] to describe the carrier dynamics in the QD sub-groups and we assume uncorrelated electron and hole dynamics. The optical properties of each sub-group (gain/absorption and refractive index variation) are described through the slowly varying complex microscopic polarization associated to the sub-group [7]. The material macroscopic polarization (i.e. the sum of all the microscopic contributions) determines the time and space evolution of the slowly varying forward and backward components of the electric field in the TDTW propagation equations [6]. The whole system of differential equations is solved numerically using a finite-difference scheme.

This approach allows a complete and precise description of the optical properties of the QD material including the refractive index dispersion associated to the inhomogeneous material gain (i.e: Kramer-Kronig relation). The drawback is the long computational time because, as shown in the following simulation results, long simulation windows (500 ns or more) are required to stabilize the mode dynamics while very tiny time step (30 fs) is required for simulating the broad optical gain and refractive index spectrum.

II. SIMULATION RESULTS
We consider a 500 µm FP laser with 10 InAs/GaAs QD layers. We start from a reference structure with inhomogeneous broadening of the GS recombination of 40 meV and homogeneous broadening of the GS emission line of 10 meV; we assume 1 ps electron relaxation time from ES to GS and $\varepsilon = 1.5 \times 10^{-16} \text{cm}^3$. We plot in Fig.1a the calculated output power versus time; the laser switches on at $t=0$ with a current step equal to 3 times the threshold current of 150 mA. The output power presents no evident pulses but only some RIN due to mode beating. Fig.1b presents the optical spectrum with -10 dB difference scheme. Numerical Simulation of Quantum Dot Single Section Fabry-Perot Laser Combs
phase of the modes is 0.4ps$^2$. These results validate our model being in very good agreement with experiments in [3] and [4].

With the developed simulation tool, we have tried to understand if and how pulses are generated inside the laser cavity. We consider again the sole laser output (with no GDD compensation) of Fig.1 and, with selective filtering, we plot in Fig. 3a the output due to the 9 modes in the centre of the optical spectrum (1552-1556 nm range) and in Fig. 3b due to the later modes. We surprisingly observe that central modes give periodic pulses at 5.5 ps that is one-half the cavity round trip time; this pulse train is actually made by two interlaced trains shown in red and black in Fig. 3a. On the contrary, the later modes give pulses at the cavity round trip rate. The formation of pulses is another fingerprint of the self-phase locking of the modes. However, the delay among the various pulse trains inhibits the observation of pulses in the total output power collected directly from the FP cavity (similar to a colliding pulse mode-locking) and then it propagates in the two opposite direction of the cavity (see solid and dashed black arrows in Fig. 3c).

These multiple pulses are possible because the gain recovery of the QDs (1ps or less) is much faster than the cavity round trip of 11 ps. Lateral QD sub-groups are on the contrary responsible for the pulses at the cavity round trip rate in Fig. 3b: in this case the pulse is formed only on one side of the FP cavity (see red arrows in Fig. 3d). This asymmetry may be due to the effective refractive index dispersion due to the inhomogeneous broadened gain.

From this preliminary analysis we conclude that the pulse formation is affected by three parameters peculiar of the QD material: the homogeneous broadening linewidth that affects the number of modes resonant with the GS of a QD sub-group, the inhomogeneous broadening of the gain that affects the number of the lasing QD sub-groups and the ES to GS relaxation time that affects the gain recovery time respect to the cavity round trip time. The quantitative impact of these three parameters will be discussed at the conference.

REFERENCES