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 Quatum Dot Fabry-Perot comb lasers. The numerical analysis shows that the output optical spectrum is an optical comb because the cavity modes are phased-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 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 ($\varepsilon = 10^{-16}$-10^{-15} cm^3) 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 (ie: 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 10meV; we assume 1 ps electron relaxation time from ES to GS and $\varepsilon = 1.5\cdot10^{-16}$ 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 bandwidth of approximately 10nm. To analyse the intensity dynamics of the longitudinal modes, we plot in Fig.1c the intensity versus time of each lasing wavelengths. Initially only few modes turn on and then start transferring power to the other adjacent modes thanks the quite large gain compression of the QDs. This transient concludes at 250 ns leaving a rather broad optical spectrum. The fact that the total output power shows a rather low RIN despite the large number of lasing modes is a fingerprint of a non-random phase relation among the modes [6]. As done in experiments [3,4], the phase locking is evaluated by the possibility of generating narrow pulses after numerically simulating the GDD compensation of the FP laser output field. If the modes are in a stable phase relation one respect to the other, the GDD compensation corrects the non-linear phase variation and allows the pulse formation . The numerical results in Fig.2 demonstrate stable and narrow pulses (about 500fs FWHM) at the cavity round trip repetition rate of 11 ps. The value of GDD to compensate for the non-linear

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phase of the modes is 0.4ps^2. These results validate our model being in very good agreement with experiments in [3] and [4].

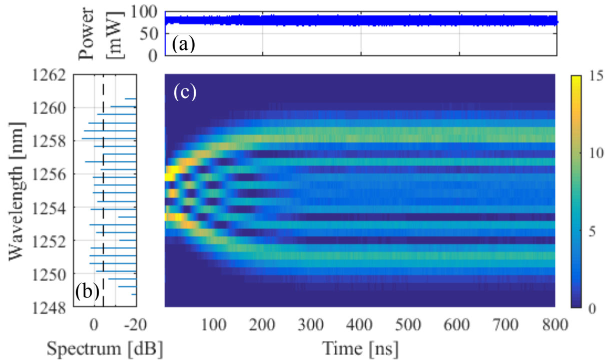

Fig. 1 (a) Power versus time, (b) optical spectrum, (c) mode intensity versus time.

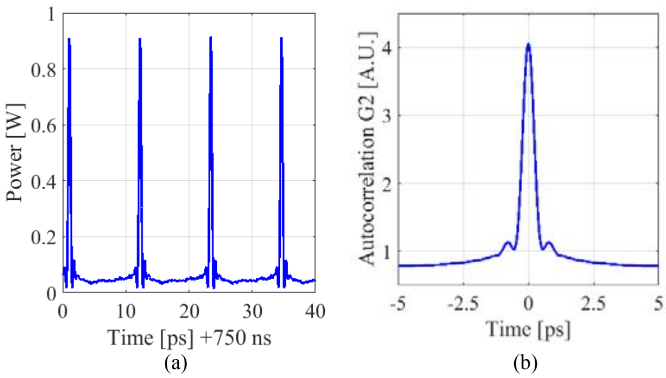

Fig. 2 Calculated pulses after GDD compensation (a) and corresponding autocorrelation (b).

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 the FP output facet. Such pulses can therefore be recovered by compensating the relative delays as done in Fig. 2. To better understand the origin of the pulse trains, we plot in Fig. 3c and 3d the distribution of the photon densities in the cavity and versus time. In Fig. 3c we present the photons resonant with the GS of the central (most dense) QD sub-group and in Fig. 3d the photons resonant with the GS of a lateral (less dense but lasing) QD sub-group. We see that photons emitted by the central QD sub-group are those responsible for the pulse train at twice the cavity repetition rate: the pulse is formed at the centre of 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.

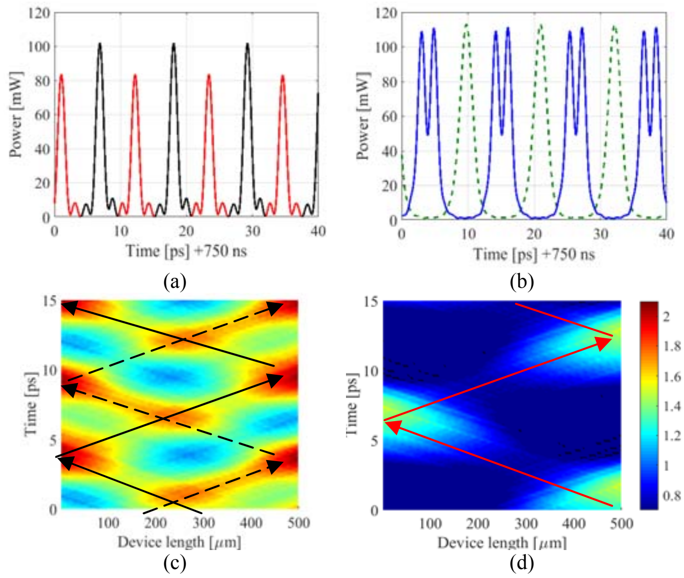

Fig. 3 Pulse train due to the central modes of the optical spectrum (a); pulse train due to the lateral modes on the blue (blue line) and red (dashed line) wavelength side of the optical spectrum. Photon density resonant with the GS of the central (c) and lateral (d) QD sub-groups.

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

[1] C. Schulien, Photonic Integrated Circuit International Conf., Brussels, PIC 2016, 1-2 March 2016

[2] Z.G. Lu et al., Opt. Express, vol. 16, no. 14, 10835-10840, Jul. 2008.

[3] R. Rosales et al., Opt. Express, vol. 20, no. 8, 8649-8657, Apr. 2012.

[4] T. Sadeev et al., Appl. Phys. Lett., vol. 106, 031114, 2015

[5] G. Villares et al., Opt. Express, vol. 23, no. 2, 1651-1669, Jan. 2015.

[6] M. Gioannini et al., *IEEE* J. Sel. Top.Quantum Electron., vol. 21, no. 6, pp. 698-708, Nov.-Dec. 2015.

[7] M. Rossetti et al., IEEE J. Quantum Electron., vol. 47, no. 2, pp. 139-150,2011