FDTW Approach for Simulation of QD lasers and SOAs

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Asbtract *We present a Finite Difference Travelling Wave (FDTW) approach for the simulation of InAs/GaAs quantum dot devices. Several examples of applications will be discussed starting from simple QD-SLDs structures up to passive single section and two section mode-locked lasers.*

In the field of Quantum Dot (QD) semiconductor laser modeling, we have seen several different model classes starting from phenomenological multi-level rate equation or master equation models [1,2] up to very rigorous approaches in the frame of Maxwell-Bloch equations, where most of the basic physics have been included [3,4]. The first class of simple models offers the advantage of fast computational speed and allows a basic understanding of the device performance. The second class offers a very good understanding of the device physics but unfortunately it requires huge computational efforts making difficult the design of complex multi-section devices. The Finite Difference Travelling Wave (FDTW) approach is located in between these two extremes: it is based on a phenomenological rate-equation model for representing the carrier dynamics and on TW equations for the electric field. The model can therefore simulate the electric field dynamics over a quite large frequency bandwidth (few THz) as well as the effect of the distribution of the electric field along the longitudinal direction of the device. The TW approach was indeed used by us in the past for the simulations of several multi-section QW devices such as self-pulsating DFB lasers [5] and mode-locked lasers [6]. The crucial point of the TW approach is the inclusion of the gain and refractive index dispersion. In the QW case this problem was solved with various approaches such as numerical temporal filtering, spatial digital filtering or including polarization equations. The correct representation of the gain/refractive index dispersion and dynamics is even more crucial in the QD case: for example when we want to include the broad gain spectrum due to Ground State (GS) and Excited State (ES) emission of QD-SLDS and SOAs [7,8] or when we simulate the chirp of directly modulated QD lasers [9]. Dealing with chirp and phase dynamics the correct representation of refractive index dispersion is imperative since the “alpha”-factor has failed in the QD case.

This talk will present the FDTW approach applied to a large variety of devices based on InAs/GaAs QDs emitting at 1.3 µm: QD-SLDs [7], QD-SOAs [8], QD FP lasers [7], index coupled DFB lasers [9] and mode-locked lasers with saturable absorber [10]. The FDTW model has also been fundamental to validate other more simple and fast models such as the DDE [11].

The spatio-temporal evolution of the complex electric field is described by:

$$\frac{1}{v_{g0}}\frac{\partial E^{\pm}}{\partial t} \pm \frac{\partial E^{\pm}}{\partial z} = -j\frac{\omega_0}{2c\eta\varepsilon_0}\Gamma_{xy}P^{\pm}(z,t) - \frac{\alpha_i}{2}E^{\pm}(z,t) + S^{\pm}(z,t) \qquad (1)$$

where $E^{\pm}$ are the slowly varying forward/backward components of the electric field, $P^{\pm}(z,t)$ the slowly varying components of the macroscopic polarization and $S^{\pm}$ the spontaneous emission noise source. In our approach $P^{\pm}(z,t)$ is the sum of the contribution from each sub-group of QDs of the inhomogenous ensemble; where the sub-groups are groups of QDs with the same size. Assuming that the carrier occupation of the QD states changes on a time scale slower than the dephasing time of the interband transition, we can rewrite the polarization term of eq.(1) as:

$$-j\frac{\omega_0}{2c\eta\varepsilon_0}\Gamma_{xy}P^{\pm}(z,t) = \sum_{i=1}^{N}\sum_{m=GS,ES_1} g^0_{im}\left(\rho^e_{im}(z,t) + \rho^h_{im}(z,t) - 1\right)\int_{-\infty}^{t}\Gamma e^{j\Delta\omega_{im}(t-\tau)}e^{-\Gamma(t-\tau)}E^{\pm}(z,\tau)d\tau \qquad (2)$$

Equations (1) and (2), coupled with electron and hole multi-population rate equations, are then solved self-consistently with a finite difference scheme [9,10]. In the laser section with index grating the TW equations are numerically solved with a slit-step algorithm. In the cases that requires a very small numerical time step (about 10 fs), we have applied the fast algorithm proposed in [12] for the bulk/QW case.

In the following figures we present some application examples to the case of QD-SLDs (Fig.1), QD-SOAs (Fig.2) and QD-DFBs (Fig.3).

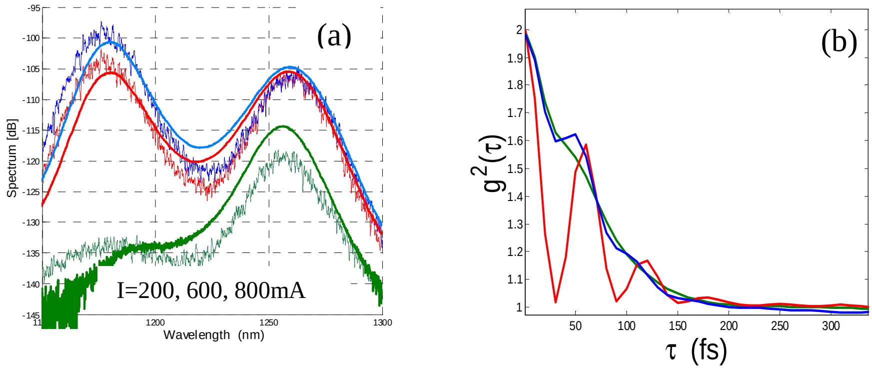

Fig. 1 (a) Calculated QD-SLD amplified spontaneous emission spectrum (solid line) compared with the experiments (dashed line); (b) corresponding calculated second order coherence function $g^2(\tau)$.

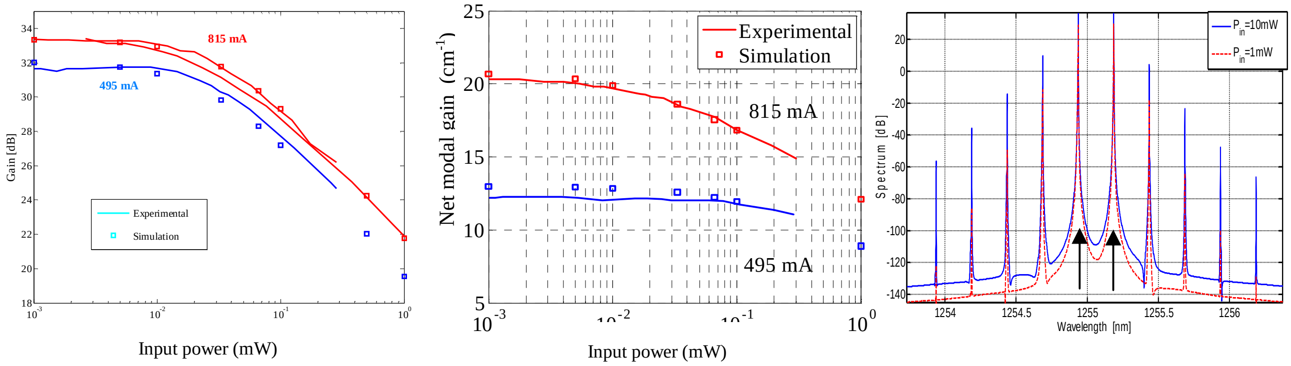

Fig. 2 Calculated chip gain of 4mm QD-SOA for input signal on (a) GS and (b) ES and comparison with experiment and (c) simulated FWM products in 1 mm SOA (the arrows indicate the two input signals).

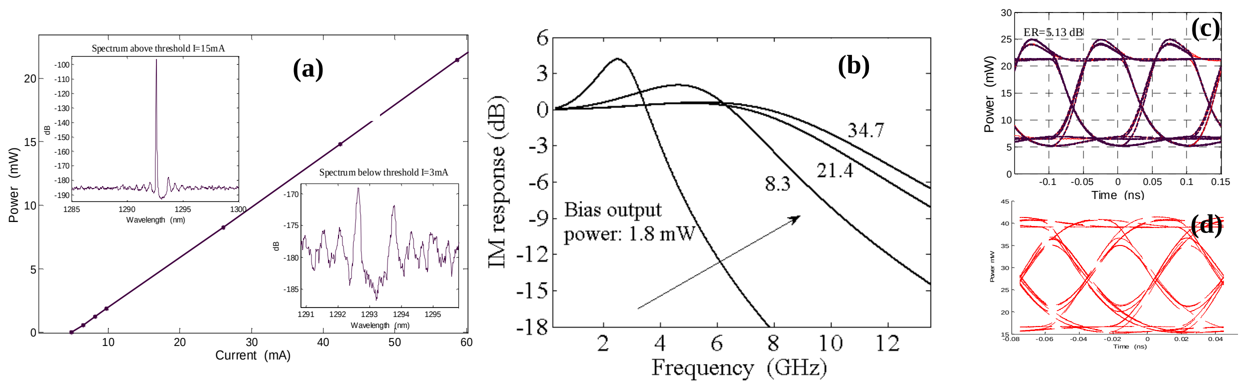

Fig. 3 Calculated QD-DFB (a) L-I characteristics and output spectra; (b) intensity modulation response and eye-diagram with (c) 10Gb/s and (d) 25Gb/s large signal modulation.

References

[1] M. Grundman et al. Phys. Rev. B 55, 9740–9745(1997)
[2] M. Sugawara et al., Phys. Rev. B 61, 7595–7603 (2000)
[3] M. van del Poel et al., JQE 41, 1115-1123, (2005)
[4] W.W. Chow et al., JQE 41, 495-504, (2005)
[5] A. Vizzino et al., JQE 38, 1581-1586, (2002)
[6] F. Pittoni et al., JSTQE 7, 280-286, (2001)
[7] M. Gioannini et al., CLEO-EU, CB-3.2, (2013)
[8] M. Gioannini et al., NUSOD 2011, pp. 171-172 ,(2011)
[9] M. Gioannini et al., JSTQE 17, pp. 1318-1326, (2011)
[10] M. Rossetti et. al, JQE 47, 139-150 (2011)
[11] M. Rossetti et. al, JQE 47, 569-576 (2011)
[12] J.Javaloyes, Opt. Expr **20**, 8496-8502 (2012)