Modeling of InAs\GaAs QD-SOAs for amplification of ultra-short high power pulses

Mariangela Gioannini*, Mattia Rossetti*, Ivo Montrosset*,
Lukas Drzewietzki†, Grigori Grozman†, Wolfgang Elsäßer† and Igor Krestnikov ‡
* Dipartimento di Elettronica, Politecnico di Torino, Torino, Italy, Email: mariangela.gioannini@polito.it
† Institute of Applied Physics, Technische Universität Darmstadt, Darmstadt, Germany,
Email: lukas.drzewietzki@physik.tu-darmstadt.de
‡ Innolume GmbH, Dortmund, Germany, Email: Igor.Krestnikov@innolume.com

***Abstract*—We present a model for the propagation of very short (hundreds of femtoseconds) high power pulses in QD-SOAs. We analyze the gain and refractive index dynamics after the pulse propagation and we determine how the electron and hole dynamics contribute to the recovery of the gain.**

I. Introduction

Very recent progress in the modeling and realization of high power pulses generated by mode-locked lasers based on InAs/GaAs quantum dot (QD) active material [1], [2] opens new possibilities for biomedical applications. In these applications the peak power of the mode-locked pulses is often not sufficient and the pulses need to be amplified further by a semiconductor optical amplifier (SOA) that may be integrated with the mode-locked laser [3]. Differently from the propagation of telecom pulses in SOAs [4], the SOA is operating in a strong saturation regime due to the high average power of the incoming pulse train. Furthermore, the amplified spontaneous emission (ASE) out of the SOA can couple back in the modelocked laser changing the operating conditions [3]. We have developed a model based on Time Domain Traveling Wave (TDTW) equations for the simulation of various kind of QD lasers [1], [5]. In this contribution we will present the application of the model to the analysis of pulse propagation in QD-SOAs. Respect to other models for QD-SOA [4] we have included: 1) the noise spectrum caused by the spontaneous emission 2) the refractive index change due to inter-band recombination and free carrier absorption. The model is general and can be applied to study the propagation of any kind of pulses, but we will focus only on the propagation of very short and very high power pulses, since this case, to the best of our knowledge, has never been studied in QD-SOAs.

II. Numerical Model

The spatio-temporal dynamics of the field inside the SOA waveguide is computed solving the following equation for the slowly varying mode-amplitude $E(z,t)$:

$$\frac{1}{v_g}\frac{\partial E}{\partial t}+\frac{\partial E}{\partial z}=-\frac{\alpha_i}{2}E(z,t)-j\frac{\omega_0}{c}\Delta\eta_{free}E(z,t)$$
$$-j\frac{\omega_0}{2c\eta}\int_{-\infty}^{t}\chi\left(\left\{\rho_{im}^{eh}(z,t)\right\},t-\tau\right)E(z,\tau)\,d\tau+S(z,t) \quad (1)$$

where v_g is the group velocity, ω_0 is a reference pulsation chosen close to the central frequency of the considered optical pulses, α_i are the internal waveguide losses. $\chi\left(\left\{\rho_{im}^{eh}(z,t)\right\},t\right)$ and $S(z,t)$ represent, respectively, the optical susceptibility and the spontaneous emission noise source of the QD active medium. These two terms account for the interplay between homogeneous and inhomogeneous broadening in the gain, refractive index and spontaneous emission spectra of the self assembled QDs. The convolution product appearing in (1) is described through a series of numerical filters. Both $\chi\left(\left\{\rho_{im}^{eh}(z,t)\right\},t\right)$ and $S(z,t)$ depend on the dynamics of electron and hole occupation probabilities ρ_{im}^{eh} in the QD ground state (GS) and in the excited states. These probabilities are obtained solving a system of several rate equations for the QDs of different size. The rate equations are then coupled with the equation (1) via the stimulated and spontaneous emission rates. In the case of InAs QD grown on GaAs there are usually two excited states in conduction band and several hole states in valence band. To simulate the hole dynamics in valence band we have tested and compared two different approaches: 1) we have considered several rate equations describing the hole dynamics in each of these states with very fast relaxation times (less than 100 fs) from one state down to the adjacent one 2) we have assumed that the holes always thermalize among the confined states due to the fast dynamics and the small separation between the states. The second approach is preferable because it reduces the number of equations to be solved. The two approaches have been compared and the second one results reliable when the pulse width is larger than about 200 fs (as for the case of mode-locked pulses).

III. Numerical results and conclusion

The input parameters for the model were almost taken from the literature and refined to fit the available CW character-

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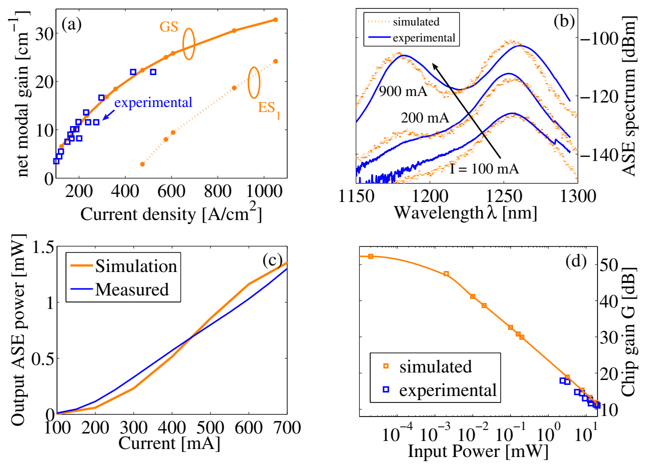

Fig. 1. Measured and simulated CW characteristic of the SOA: (a) net modal gain versus current density; (b) spectra of ASE (c) light-current characteristics of ASE; (d) chip gain versus input power.

istics of the SOA as shown in Fig.1. The SOA consists of 15 InAs\InGaAs DWELL layers separated by 35 nm GaAs barrier; the waveguide is 4 mm long with a ridge width of 5 μm. Fig.1(b) and Fig.1(c) shows the capability of model to correctly include the spontaneous emission and the ASE of the amplifier. Fig.1(d) highlights that the amplifier can provide a very high small signal gain of about 50 dB but with very low input saturation power. In the simulation results that follow we will consider the propagation of pulses with very high average input power (tens of mW), operating in the very strong saturation regime of the curve in Fig.1(d). As a simulation example we report here the results of the amplification of a pulse train at 21 GHz, with pulses of 2.4 W peak power and pulse width of 390 fs. These pulses, reported in [6], are, to our knowledge, the shortest high power pulses obtained with a mode-locked QD laser. In Fig. 2 we compare the input and output pulse from the SOA with overlapped the simulated chirp. We observe a distortion and a broadening of the pulse on the trailing edge with a consequent long tail of the chirp . We have observed that the distortion is caused by the recovery of the gain after the pulse. In Fig. 3 we analyze the gain dynamics, after two pulses, at the wavelength of the peak gain of the GS (center of the pulse spectrum) and of the first ES. The figures show that the gain recovery after the pulses is determined by several effects with different intensities and time scales: 1) the very fast thermalization of the holes leaves a very slight variation of the GS and ES_1 gain in the observed picosecond time scale; 2) the GS gain recovery in the range of about 2 ps is due to the recovery of the electron GS population and it almost dominates the gain dynamics 3) the slower recovery on the time scale of tens of picosecond is due to the slow recovery of electron GS population due to the slower recovery of ES_1 (see Fig. 3b) as well as the slow recovery of the whole hole population in the QD. The magnitude of these slow components are the main limiting factor to the increasing of the repetition rate. Several other

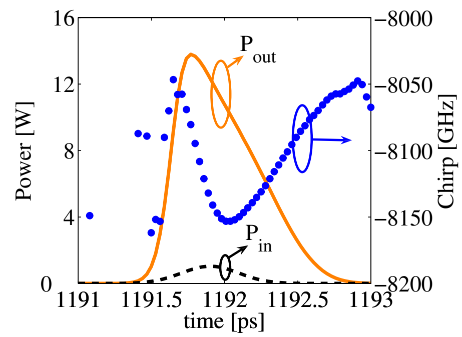

Fig. 2. Output pulse envelope (orange line) and instantaneous frequency variation (blue markers) versus time; dotted black line shows the optical pulse in input to the SOA.

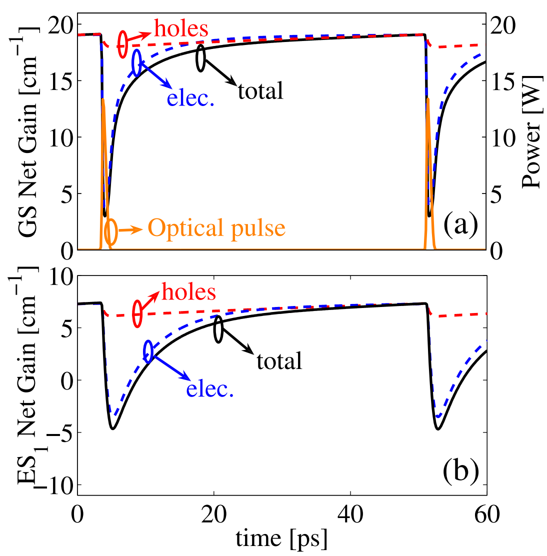

Fig. 3. Dynamics of (a) GS and (b) ES_1 gain after two power pulses; we separate the contributions of electrons and holes to the gain dynamics.

simulations results analyzing the role of electron and hole dynamics will be given at the conference.

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