Numerical and Experimental Characterization of Chirped Quantum Dot-based Semiconductor Optical Amplifiers

Adam F. Forrest and Maria Ana Cataluna
Heriot-Watt University, Edinburgh (UK)

Michel Krakowski
III-V Lab
Campus de Polytechnique, Palaiseau (FR)

Giuseppe Giannuzzi
Politecnico di Bari, Bari (IT)

Paolo Bardella
Politecnico di Torino, Torino (IT)
paolo.bardella@polito.it

***Abstract*—We present a model for the description of the dynamical behavior of Quantum Dot (QD) based Semiconductor Optical Amplifiers (SOAs) under injection of optical pulses. The model uses a Time Domain Traveling Wave (TDTW) approach to describe the optical field in the amplifier, and allows us to consider chirped QD materials by the inclusion of a set of rate equations modeling the occupation probability of the QD confined states in each active layer. The results of the numerical simulations are validated against experimental measurements of a two-contact chirped QD SOA with ground state emissions in the 1200 nm to 1300 nm range. When the single-pass configuration is compared to the double-pass setup, both the numerical simulations and the experimental results show that a clear improvement can be obtained with the latter configuration in terms of output power and signal amplification; for the majority of biasing conditions, the double-pass amplifier presents a gain approximately 3 dB greater than the single-pass without evident saturation of the gain and pulses broadening.**

I. Introduction

Tapered SOAs represent an attractive solution for the amplification of ultrashort pulses: their large active area allows a significant amplification of the input signal, while maintaining a good quality of the output beam thanks to the tapered geometry. These low-cost devices have been used to amplify semiconductor edge-emitting diodes, also operating in optical frequency comb regime [1], operating in pulsed regimes, with peak output powers as high as 9 kW [2].

We describe in this work a model able to predict the dynamic behaviour of QD-based tapered SOAs used to amplify pulsed optical signals in single and double pass configuration into account the presence of chirped materials [3] where the various QD layers present emission peaks centered at different wavelengths in order to maximize the device amplification bandwidth.

II. Numerical model

The model developed for this analysis is based on the TDTW model in [4], extended here to take into account the chirped nature of the QD active material and the feedback introduced by the double pass configuration. The spatio-temporal evolution of the slowly varying forward and backward components $E^{\pm}(t,z)$ of the electrical field around the angular frequency ω_0 are described by the wave equations

$$\frac{1}{v_{\rm g}}\frac{\partial E^{\pm}}{\partial t} \pm \frac{\partial E^{\pm}}{\partial z} = -\frac{\alpha_i^{\pm}}{2}E^{\pm} - j\frac{\omega_0}{2cn_{\rm eff}\varepsilon_0}\Gamma_{\rm xy}^{\pm}P^{\pm} + S_{\rm sp}^{\pm} \quad (1)$$

with $v_{\rm g}$ group velocity, $n_{\rm eff}$ effective index, $P(t,z)$ slowly varying macroscopic polarization, $S_{\rm sp}^{\pm}(t,z)$ noise source associated to the spontaneous emission. In (1), $\alpha_i^{\pm}$ and $\Gamma_{\rm xy}^{\pm}(z)$ indicate the propagation losses and the transverse confinement factor associated to the forward and backward propagating fields, estimated with 2D simulations based on the beam propagation method; these quantities can be different for the forward and backward propagating field in tapered layouts [5]. The boundary conditions for (1) read

$$E^{+}(t,0) = r_0 E^{-}(t,0) + \sqrt{1-r_0^2}E_{\rm inj}(t) \quad (2)$$

$$E^{-}(t,L) = r_L E^{+}(t,L) + (1-r_L^2)r_{\rm ext}E^{+}(t-\tau_{\rm ext},L) \quad (3)$$

with L device length, r_0 and r_L spurious reflectivities at the SOA facets in $z=0$ and $z=L$, $E_{\rm inj}$ externally injected optical field. The feedback term in (3) is included only in the double pass configuration, with $r_{\rm ext}$ and $\tau_{\rm ext}$ describing the external mirror reflectivity and the external cavity propagation delay, respectively. In order to properly model the optical and electrical properties of the QD material, the QD ensemble is divided into $N_{\rm p}$ populations, having existence probability G_p, regrouping the dots having similar transition energies, and a set of Multi-Populations Rate-Equations (MPREs) is introduced, taking into account relaxation and escape processes occurring between the QD wetting layer, the two excited states (ES_1 and ES_2) and the ground state (GS), together with radiative and non radiative recombination processes in the three confined states. To take into account the chirped nature of the QD active material, an independent set of MPRE is solved for each group $g=1,\ldots,N_{\rm g}$ of QD layers with similar optical characteristics; we assume that the driving current distributes uniformly injected across all the layers.

The macroscopic polarization terms $P^{\pm}$ are proportional to

$$P^{\pm} \propto \sum_{g=1}^{N_{\rm g}} n^g \sum_{p=1}^{N_{\rm p}} G_p \sum_{\substack{s={\rm GS},\\ {\rm ES1,\,ES2}}} \mu_s A_s (2\rho_{spg}-1) I_{spg}^{\pm}$$

with n^g number of QD layers in group g, μ_i confined state degeneracy, A_m coefficient containing the interband transition element for the transition s=ES_2, ES_1, GS, ρ_{sgp} occupation probability, and $I^{\pm}(z,t)_{spg}$ filtered electrical field defined as

$$I^{\pm}_{spg}(z,t) = \int_{-\infty}^{t} \Gamma \mathrm{e}^{j(\omega_{spg}-\omega_0)(t-\tau)} \mathrm{e}^{-\Gamma(t-\tau)} E^{\pm}(z,\tau) \mathrm{d}\tau$$

with Γ inverse of the dephasing time of the interband transition and ω_{spg} central emission wavelength of the confined state s of population p of layer group g. The above mentioned differential equations were numerically integrated using a finite differences scheme with 15 fs time step.

III. Device Description and Experimental Setup

The seed pulses for this investigation were produced by a two-section passively mode-locked QD laser diode. The biasing conditions of the seed laser were kept constant to produce a stable train of mode-locked pulses having a repetition rate of 5 GHz, a central emission wavelength of 1258 nm, a pulse duration of 2.3 ps and an average optical power of 2.5 mW. The tapered SOA used in this work was grown by Innolume GmbH and subsequently processed by III-V Lab [3]. The SOA had a total length of 6 mm and was comprised of a short straight ridge segment, with a width of 14 µm, followed by two distinct tapered segments which culminated in a tapered facet with a width of 110 µm. The edge of the waveguide was defined by a shallow etched ridge which introduced a slight index guiding effect. An isolation trench was etched 1.875 mm from the narrow rear facet to define two electrically isolated contacts which could be biased independently by CW constant current diode drivers. The SOA had an active region that was composed of ten layers of chirped InAs QDs divided into three groups with three different target GS emission wavelengths of 1211 nm (3 layers), 1243 nm (3 layers) and 1285 nm (4 layers). The SOA was mounted at an angle of 7° with respect to its facets, which were anti-reflection coated.

The SOA was tested in both the standard single-pass setup, with seed pulses coupled into the narrow facet of the SOA, amplified over a single pass and then output from the tapered facet, and double pass configuration, where seed pulses were input and output coupled from the tapered facet of SOA having been reflected at the narrow facet and amplified over two passes through the device [6]. A complete review of this experimental investigation is proposed in [3].

IV. Results Overview

Figure 1 shows the good agreement between experimental and simulated input/output optical gain for the SOA in single and double pass configuration. The results are obtained tuning both the front facet and the rear facet currents. In the simulations, the input optical signal was represented by a train of Gaussian pulses reproducing the experimental trace generated by the seed laser. The advantage of the double pass configuration in terms of gain is evident, but the range of driving currents is experimentally more limited, due to the feedback of ASE resulting in laser emission; this detrimental effect was experimental reduced including a long-pass filter in the external cavity, allowing to extend the range of operation of the SOA. The pulse durations shown in Fig. 2 for various driving conditions were obtained using this optimized configuration; the simulations results are in qualitative agreement with the experimental findings.

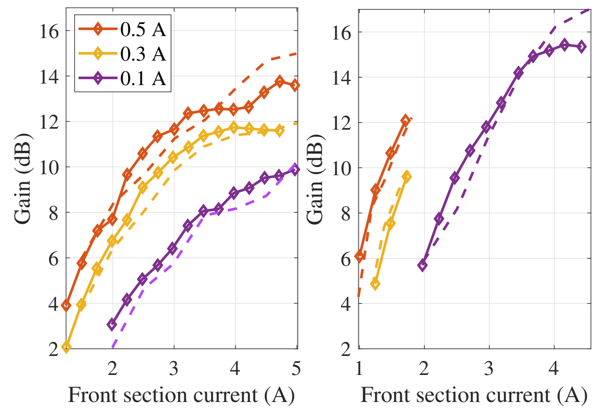

Fig. 1. SOA input/output gain as a function of the front section current for three values of the rear section current, for the single pass (left) and double pass (right) configurations. Experiments: continuous line; simulations: dashed lines.

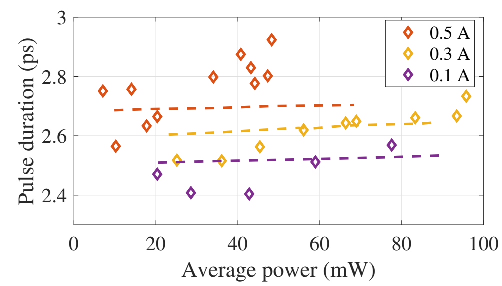

Fig. 2. Pulse duration in the double pass configuration as a function of the output pulses average power and the rear rection current. Experiments: markers; simulations: dashed lines.

V. Conclusion

We presented a TDTW model able to reproduce the behavior of QD based SOA with chirped active material, used to amplify pulsed optical signal with GHz repetition rate. The model has been validated against the experimental results obtained from the characterization of a 6 mm long SOA with 10 QD layers and GS emission centered at three different wavelengths. The results show an agreement between simulation and experiments in terms of SOA optical gain and output pulse widths.

References

[1] F. C. Cruz, et al., *Opt. Lett.*, vol. 31, no. 9, pp. 1337–1339, May 2006.
[2] S. Kono, et al., *Opt. Express*, vol. 25, no. 13, pp. 14 926–14 934, 2017.
[3] A. F. Forrest, et al., *Opt. Express*, vol. 27, no. 21, pp. 30 752–30 762, Oct 2019.
[4] M. Rossetti, et al., *IEEE J. Quantum Electron.*, vol. 47, no. 2, pp. 139–150, 2011.
[5] A. F. Forrest, et al., *Opt. Express*, vol. 28, no. 2, pp. 846–859, Jan 2020.
[6] S. Riecke, et al., *Applied Physics B*, vol. 98, no. 2, pp. 295–299, 2010.