# Modeling passive mode-locking in InAs quantum dot lasers with tapered gain sections

M. Rossetti*, P. Bardella, T. Xu and I. Montrosset

*Dipartimento di Elettronica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*

Two-section quantum-dot (QD) lasers with a tapered gain section and a straight saturable absorber (SA) section, operating in passive mode locking (ML) regime, have shown improved performances in terms of pulse duration and average output power with respect to corresponding straight lasers [1].

A numerical model of such devices must be able to accurately describe the QD gain and absorption dynamics in the gain and SA section, leading to the onset of the ML regime; as well as the influence of structural parameters such as the number of QD layers, the gain to SA length ratio, the facet reflectivities, and the characteristics of the tapered gain section. In [2] and [3], we proposed two different models that have been applied to the simulation of passive ML in QD straight lasers. In [2], the non-linear dynamics of the field within the laser cavity was computed via the finite-difference solution of one-dimensional time-domain travelling-wave equations; in [3] a model based on delayed differential equations was instead proposed.

In both approaches, the dependence of the electromagnetic field on the transverse coordinates (x,y) was eliminated by assuming a single transverse mode in the waveguide. This assumption is in general not strictly valid in devices with tapered waveguides. To accurately simulate such devices, two-dimensional (2D) numerical models [4] would be in principle required, significantly increasing therefore the computational cost of the simulations and preventing their application on extensive parametric analyses of the ML regimes.

To overcome this problem, we propose a simplified approach based on a 2D static beam-propagation method (BPM) to verify the adiabatic transformation of the amplified field in the cavity and to extract the propagation parameters for the 1D dynamic QD ML laser models proposed in [2],[3]. Using the BPM algorithm, the transverse field profile in each longitudinal section of the laser cavity is computed. From the obtained field distribution, two different z-dependent field confinements factors $\Gamma_y^+(z)$ and $\Gamma_y^-(z)$ for the forward and backward travelling fields are calculated as $\Gamma_y^\pm(z) = \int_{-W(z)/2}^{+W(z)/2} \left|E^\pm(y,z)\right|^2 dy \Big/ \int_{-\infty}^{+\infty} \left|E^\pm(y,z)\right|^2 dy$ where $E^\pm(y,z)$ are the stationary forward and backward travelling fields computed using the BPM and $W(z)$ is the electrode/ridge width. $\Gamma_y^\pm(z)$ are then introduced as input in the numerical models for ML [2],[3], so that in each longitudinal section of the device, the net modal gain is given by $g_{net}^\pm(z,t) = \Gamma_y^\pm(z)\Gamma_x g_{QD}(z,t) - \alpha_i(z)$, where $g_{QD}(z,t)$ is the QD material gain/absorption, $\Gamma_x$ is the field confinement factor in the QD layers along the growth direction (x-axis) and $\alpha_i$ are intrinsic waveguide losses that may be z-dependent. Finally, variation of the electrode width along the longitudinal direction of the cavity, z, is considered in order to properly calculate the number of QDs which are electrically pumped in each longitudinal section.

With this approach, the evolution of the ML regimes as a function of the bias and structural parameters has been evaluated and the ML stability to noise perturbations has been studied, providing useful insights for the design of optimized devices.

[1] M.G. Thompson et al., IEEE JSTQE, 15, 3 (2009);
[2] M. Rossetti et al., IEEE JQE, 47, 2 (2011);
[3] M. Rossetti et al., IEEE JQE (2011), in press;
[4] D. W. Reschner et al., IEEE JQE, 45, 1 (2009);

*Corresp. author: mattia.rossetti@polito.it, Phone: +39-011-090-4208, Fax: +39-011-090-4217

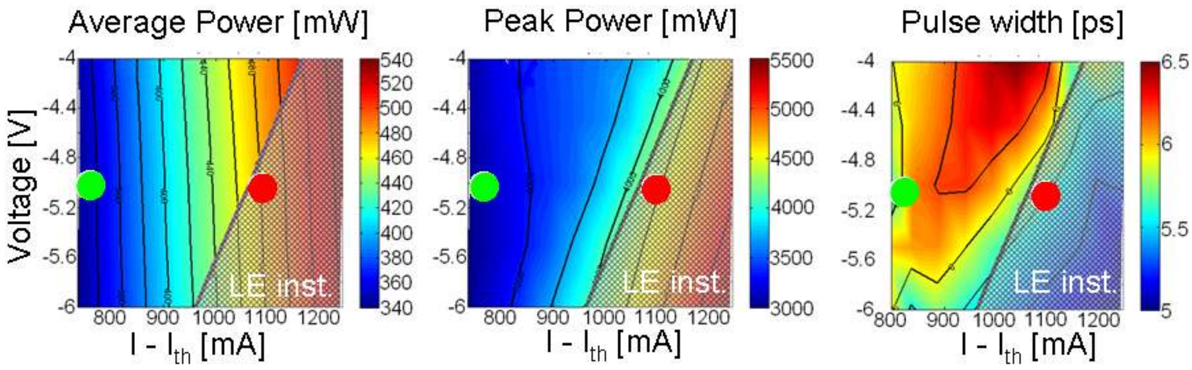


Fig. 1. Mode-locking in a tapered QD ML laser with 5 QD layers, 2.5 mm total length, a 360 μm long and 14 μm wide SA section and a 2.14 mm tapered gain section with 2° full angle. Evolution of average power, peak power and pulse width as a function of the voltage applied to the saturable absorber section and the current above threshold applied to the gain section. Region of unstable mode-locking due to an instability to noise perturbation at the pulse leading edge (LE inst.) is highlighted. Green and red markers show stable and unstable mode-locking conditions highlighted in Fig. 2.

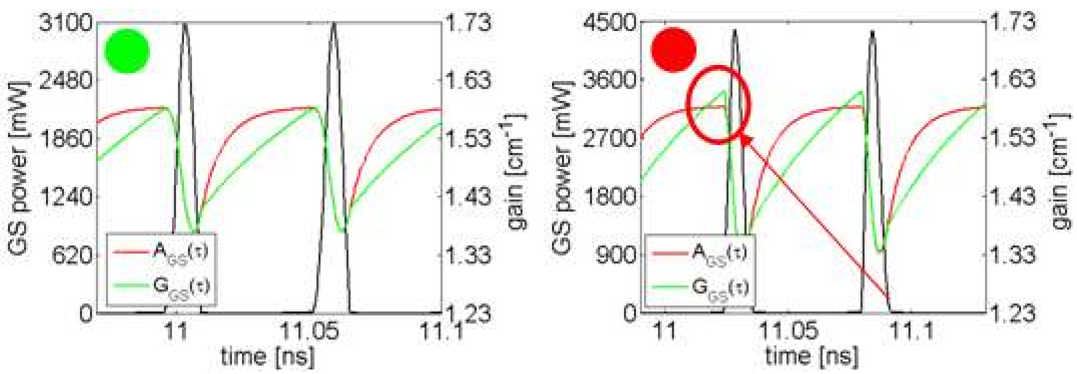


Fig. 2. Dynamics of the pulse amplification, $G_{GS}(\tau)$ (green), and overall saturable and non saturable losses, $A_{GS}(\tau)$ (red), at the QD ground-state wavelength, experienced by the pulse during a single round trip in the cavity. The pulse time trace (black) is also shown. Left: condition corresponding to a perfectly stable mode-locking regime obtained at V=5V and $I-I_{th}$ = 700 mA (green marker in Fig. 1). Right: condition corresponding to V=5 V and $I-I_{th}$ = 1100 mA; a region of net gain $G_{GS}(\tau)>A_{GS}(\tau)$ at the pulse leading edge starts to appear (red circle and arrow), being the main cause for instabilities to noise perturbations (red marker in Fig. 1)

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