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Analysis of Mode Locking in Quantum Dot Laser Diodes: a Time-Domain Travelling-Wave Approach

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Abstract: We present a review of the most recent techniques for the analysis and the numerical simulation of mode locking in edge emitting and ring Quantum Dot laser diodes, in both single section (spontaneous mode locking) and two-section (active and passive mode locking) configurations.

Keywords: Semiconductor lasers, Quantum Dot, Mode-Locking, Time-Domain Travelling-Wave.

Optical frequency combs (OFCs) realized with semiconductor lasers (SCLs) have attracted a remarkable interest in the last decade as sources for the rapidly growing field of high-data rates optical interconnection [1]. OFCs are also suitable sources for packet-based clock recovery in all-optical communication systems [2]. In addition, comb lines can be mixed on fast photodetectors [3] to generate sub-THz signals for the upcoming 5G wireless networks. Finally, OFCs in the mid-infrared range are used for high precision and high speed spectroscopy based on dual comb techniques [4]. For many of these applications, the generation of pulses is not a requirement, on the contrary a multi-mode optical spectrum with phase-locked modes is the sole requirement.

In this framework, quantum dot (QD) and quantum dash lasers present advantageous properties if compared to Quantum Well based solutions, including fast carrier dynamics, small linewidth enhancement factor, large saturation energies, reduced temperature dependence. These properties make QD materials also promising candidates for short pulse high peak power generation.

In monolithic SCLs, the longitudinal modes can be phase-locked without the need for a saturable absorber or any active optical or electrical modulation. Four-wave-mixing (FWM) has been shown to play a fundamental role in this self mode-locking (SML) mechanism [5, 6] and multi-mode emission is favored by the longitudinal standing wave pattern resulting in a dynamic carrier grating which, in low dimensionality materials, is not washed out by diffusion. SML has been reported for single-section Fabry-Pérot quantum well [7], quantum dash [8], quantum cascade [9], and QD [10] single section lasers. Ultrashort pulses have been reported at the laser output facet [10], or after dispersion compensation by a single mode fiber [11].

Recently [12], we proposed a time-domain traveling-wave (TDTW) model to describe the multi-longitudinal mode dynamics of single-section SCL quantum dot lasers. Such a model provides an insight on the electrical field and carrier distribution in the edge emitting laser cavity, properly considering the inhomogeneous dispersion of the QD sizes, modeled as equivalent dephasing time of the material polarization, and including the sub-wavelength carrier grating trough a set of additional differential equations for the fast (half wavelength scale) varying components of the carrier densities.

The model allowed to properly describe the onset of the self-locking condition in 250 µm and in 1 mm long single section QD lasers, with the consequent reduction of the RIN of the total output field (Fig.1a) and of the single cavity modes, the increase of the optical spectra width, and the narrowing of RF beat note (Fig.1b) and the individual longitudinal optical lines (Fig.1c). These numerical results have been recently validated trough recent experimental measurements that will be discussed during the presentation.

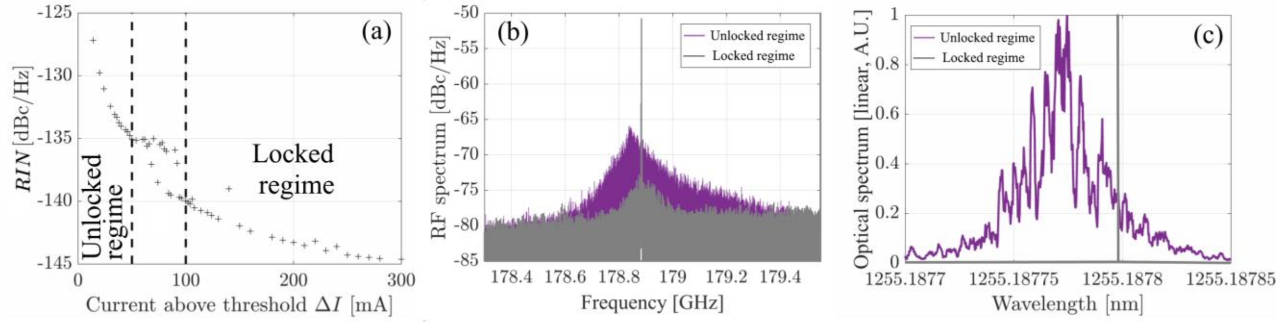

Fig.1. Simulated RIN (a), RF beat note (b), and detail of the optical spectrum (c) for a 250 µm long QD SCL emitting around 1255 nm. From [12].

In the case of QD single section ring lasers, a similar model can be used, with proper simplifications, and a linear stability analysis can be performed in addition to the temporal integration [13]; in particular, when unidirectional ring lasers are considered, the simulations predict the occurrence of SML leading to ultrashort pulses with a terahertz repetition rate via Risken-Nummedal instability of the single mode emission.

While SCLs provide a convenient, simple, compact and economic solution for the generation of optical pulses at high bit rate and OFCs, more conventional two-section ML lasers allow an improved temporal stability of the pulses; a fine tunability of the pulses repetition rate and power is generally also possible [14]. Edge emitting configuration with more than two electrodes and tapered waveguides were recently demonstrated [15].

The TDTW model can be easily adapted to the simulation of these configurations, as far a proper model is included for the description of the reversely biased region acting as saturable absorber [16]. The model has been largely used to design new sources and explain experimental findings, thank also to the possibility to gain a deep knowledge on the internal dynamics of a QD lasers, as shown in the exemplary images in Fig. 2. While this method can accurately predict the complex behavior of QD SCLs [17], the numerical solution of the TDTW model can be resources and time consuming. This drawback could severely limit the application of the TDTW when the device behavior needs to be analyzed as a function of two or more external control currents or voltages. In these cases, the delayed differential equation approach represents a valid alternative for both ring and edge emitting structures, when its multi-section derivation is used [18,19].

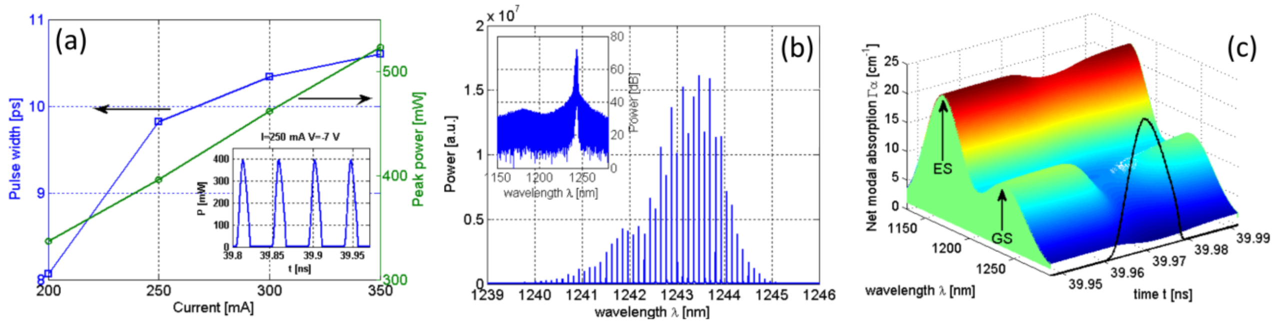

Fig.2. Examples of TDTW simulation of two-section QD 2 mm long edge emitting laser. (a) Pulse width and peak power against bias current in the active section; inset: exemplary time trace. (b) Optical spectrum; inset: enlarged wavelength range. (c) Time evolution of the QD gain spectrum at the device output (GS and ES denote QD ground state and excited state, respectively). From [16].

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