Pulse Broadening in Quantum-Dot Mode-Locked Semiconductor Lasers: Simulation, Analysis, and Experiments

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***Abstract*— We consider a mode-locked (ML) quantum-dot (QD) edge-emitting semiconductor laser consisting of a reverse-biased saturable absorber and a forward-biased amplifying section. To describe the dynamics of this laser, we use the traveling wave model taking into account carrier exchange processes between a reservoir and the QDs. A comprehensive parameter study is presented and an analysis of mode-locking pulse broadening with an increase of injection current is performed. The results of our theoretical analysis are supported by experimental data demonstrating a strong pulse asymmetry in a monolithic two-section QD ML laser.**

***Index Terms*— Mode-locking, pulse broadening, quantum dots, saturable absorber, semiconductor laser, trailing edge.**

I. Introduction

SEMICONDUCTOR lasers based on self-assembled quantum dots (QD) [1] attract significant attention due to their improved modulation bandwidth as well as reduced threshold current [2], [3], pulse intensity noise, chirp [4], temperature [5], and feedback sensitivity [6] at telecom wavelengths. The advantages of a QD material can be exploited in multi-section mode-locked (ML) lasers which generate stable high intensity picosecond and even sub-picosecond pulses at high repetition rates [7]–[9].

A realistic modeling of QD lasers should take into account carrier exchange processes between a carrier reservoir (CR) and discrete levels in quantum dots. Recently proposed models based on rate equations for QD lasers operating in a continuous wave (CW) regime [10], [11] and delay differential equations (DDE) [12], [13] for QD ML lasers [14] demonstrate a qualitative agreement with some experimental observations. However, these models either neglect spatial distributions of carriers and electric field amplitudes (rate equations), or assume unidirectional lasing in a ring cavity (DDE models). In order to overcome these limitations, we incorporate the carrier exchange rate equations for a QD material (see, e.g., Refs. [15], [16]) into the traveling wave (TW) laser model [17] that takes into account such important features of a ML laser as spatial non-uniformity of laser parameters and spatio-temporal dynamics of carrier densities as well as counter-propagating complex optical fields.

In this paper we consider a model of a two-section QD ML laser consisting of a reverse biased saturable absorber (SA) and a forward biased amplifying (gain) section, see Fig. 1. We perform a comprehensive numerical study of the operation regimes in this laser, identify the type of dynamical states, and estimate different characteristics of ML pulses, such as repetition rate, pulse width (PW) and shape, etc. Special attention is payed to the ML regime with asymmetric pulses [18], [19], and pulses having a broad trailing edge plateau (TEP) [20]. We show that standard approaches for the estimation of the PW of such kind of strongly asymmetric pulses can either lead to controversial results or fail at all.

According to the results of our simulations, the pulses with a broad TEP can appear in different models of QD ML lasers [20], [21], but they are not typical for models taking into account only ground state occupation probability in QDs [22], [23], or for related models of quantum-well ML lasers [12], [13], [24]. Our theoretical analysis shows that the TEP in QD ML lasers arises mainly due to non-instant carrier transitions between the CR, excited state (ES), and ground state (GS) of the QD. These multiple finite-time transitions slow-down the carrier exchange between the electrically pumped CR and the photon generating GS of QD, act as a filter, and lead to a homogenization of the carrier and photon distributions along the gain section.

Finally, we support our theoretical findings on the strongly asymmetric pulses having a broad TEP with experimental results performed using the QD ML lasers described in Refs. [19], [22], [25], [26]. We demonstrate that broadening of a pulse with growing injection current results mainly from the growth of its trailing edge. We confirm experimentally that very broad ML pulses whose width at their base exceeds one half of the laser cavity round trip time can appear.

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