Simulation and Design of Quantum-Dot Lasers Operating in Dual-wavelength Passive Mode-locking Regime

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***Abstract*— Simultaneous pulse generation from ground state and excited state transitions in a two-section quantum-dot laser is studied via a finite-difference travelling-wave model; design rules to obtain stable dual-wavelength mode-locking regime over a wide range of bias current and voltage are proposed.**

Quantum-dot laser; passive mode-locking; two-state lasing; finite-difference travelling-wave model;

I. INTRODUCTION

Passively mode-locked (ML) two-section lasers based on self-assembled InAs quantum-dots (QD) have shown an impressive potential for the generation of picosecond and sub-picosecond pulses thanks to their ultrafast absorption recovery, high differential absorption, low frequency chirp and large gain spectral bandwidth. The possibility to generate picosecond pulses involving either ground state (GS) or excited state (ES) interband transitions has been demonstrated and the switching between these two regimes has been obtained by simply changing the voltage applied to the saturable absorber (SA) section or the injected current supplied to the gain section [1]. Moreover self-pulsating regimes involving simultaneous GS and ES lasing have been studied both experimentally and theoretically [2][3].

Recently, operating regimes characterized by the coexistence of stable GS and ES mode-locked pulses have been demonstrated in QD lasers emitting around 1.3 µm [4][5]. In [4], such a dual wavelength mode-locking (DW ML) regime is achieved over a small range of currents in the gain section. At low currents, GS mode-locking occurs. Increasing the current up to about three times the GS threshold, ES emission takes place and DW ML is achieved. Increasing further the current however, ES lasing dominates and GS lasing tends to disappear.

Breuer et al. [5] recently observed the DW ML regime in a differently designed laser characterized by a significant wavelength chirp between the QD layers: contrary to [4], at low currents, ML pulses from the ES transition are observed, already for a SA bias of 0 V (short circuit). Increasing the gain current up to about 1.25 times the ES threshold, the GS lasing is achieved and the DW ML regime can be found over a wide range of applied currents. Clear indication of the simultaneity of GS and ES ML pulses in the DW ML regime is confirmed by four-wave-mixing (FWM) in the baseband of the radio-frequency spectrum.

In this paper we present a numerical study of the DW ML regime in a two-section QD laser using a finite-difference time-domain (FDTD) model [6][7]. Starting from the results shown in [5], we propose simple design rules for the simultaneous generation of ML pulses from both GS and ES transitions in a two-section QD laser.

II. FINITE-DIFFERENCE TIME-DOMAIN MODEL

We implemented a finite-difference time-domain travelling-wave model for the simulation of passive mode-locking in QD lasers. As described in [6][7], the propagation equations, describing the field evolution along the laser cavity at both GS and ES characteristic transition wavelengths, are solved in time domain via a finite-difference approach. The optical response of the QD active layers is introduced in the propagation equations through proper polarization terms. This terms provide the coupling between the field equations and a set of rate equations describing the population dynamics within the QD states, carrier capture and escape processes in and out the quantum well (QW) states and the carrier dynamics in the three-dimensional states of the separate-confinement heterostructure (SCH). The dependence of the population dynamics to the applied voltage in the QD system belonging to the SA section is then properly taken into account through voltage dependent thermionic escape rates and tunneling rates, affecting the SA absorption recovery.

Additional effects such as the inhomogeneous gain broadening induced by the QD size fluctuations, the related gain and refractive index dispersion and self phase modulation (SPM) have been introduced in the numerical model via a proper description of the polarization terms in the field equations, implemented using a set of infinite impulse response (IIR) numerical filters. Since their numerical implementation significantly increases the computational cost of the simulations due to the requirements on the integration time step, such effects were at first neglected in order to perform a systematic study of the role played by QD material and device parameters on the ML regime. Performing final simulations

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taking such effects into account, we found that the main features of the studied ML regimes were preserved, revealing that, in the simulated structures, they only give rise to higher order corrections on the steady-state ML regime.

III. SIMULATION RESULTS AND DISCUSSION

In order to obtain a stable DW ML regime over a wide range of bias conditions in a two-section QD laser, we propose, following the results presented in [5], to consider a QD laser structure in which the maximum net modal gain achievable at the GS wavelength is slightly smaller, at ES threshold, than the overall losses in the laser cavity i.e. the sum of the mirror losses, intrinsic waveguide losses and saturable losses in the SA section. In order to satisfy this condition, one must therefore carefully design both the laser cavity (cavity length, facet reflectivities, intrinsic waveguide losses) as well as the properties of the QD active medium.

As an example, we consider a QD laser with a 3.3 mm total length, a 300 μm SA section, 3 μm ridge width, cleaved facets and intrinsic waveguide losses of 3.5 cm^{-1} as the one described in [5]. We found that a suitable value for the maximum saturated GS net modal gain allowing to satisfy the condition described above is about 8 cm^{-1}. In [5], such a low gain value was experimentally obtained thanks to the wavelength chirp between the different QD layers composing the active structure. Alternative paths however can be successfully followed in order to achieve such a low QD gain without chirping the QD layers, e.g. reducing the number of identical QD layers in the active region or reducing the QD density. Following these last approaches, in the present paper, the proper QD gain is obtained by considering 6 identical QD layers with a low QD surface density of $1.5 \cdot 10^{10}$ cm^{-2}. With this choice of the QD material properties, also the ES peak gain saturates to a low value of about 13 cm^{-1} due to Pauli-blocking effect.

In Fig. 1a, the simulated state-resolved PI characteristics for a 0V biased SA, obtained using the FDTD model is shown: due to the imposed condition on the QD GS gain, ES threshold occurs first at 105 mA. In the range of currents from 105 mA to 135 mA, a stable ES ML regime is obtained. The ES pulse width tends to decrease slightly when the current is increased (Fig. 1b). The low QD saturated ES gain, significantly contributes to achieve a stable ES ML regime. As a matter of fact, in this regime, the ES differential gain in the gain section is significantly reduced compared to standard QD lasers, guaranteeing a gain saturation energy in the gain section much larger than the absorption saturation energy in the SA which is an essential condition to achieve a stable ML regime.

The ES average output power increases with current up to 4 mW. The absorption of the ES power in the SA induces a photon-pumping process in the QD GSs. This process reduces the SA losses at the GS wavelength, so that at 137 mA GS threshold occurs. We found that at the GS threshold, due to the photon pumping process, a 10% reduction of the average GS absorption in the SA with respect to the unsaturated value is obtained proving that this is the main effect leading to GS lasing. Once the GS lasing is obtained, the DW ML regime occurs over a wide range of applied currents.

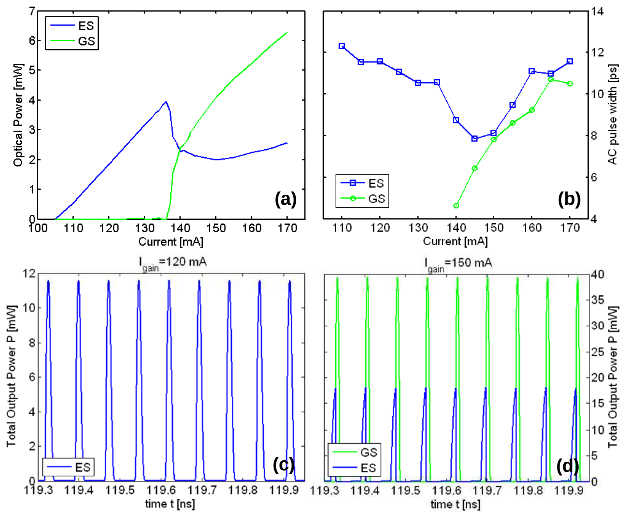

Figure 1. (a) GS and ES average output power versus injected current in the gain section at 0 V SA bias; (b) ML autocorrelation pulse width for GS and ES pulses versus the injected current in the gain section; (c) time trace of ES pulses at 120 mA; (d) time trace of GS and ES ML pulses at 150 mA.

For values of bias current just above the GS threshold, the ES average power is reduced and tends to decrease increasing current. For currents larger than 150 mA however the ES average output power grows up again with current ensuring a large regime where the GS and ES ML pulses coexist. The GS pulse width increases almost linearly with the applied current whereas the ES pulse width approximately follows the behaviour of the ES average power. In Fig. 3d, time traces of GS and ES ML pulses, referring to the DW ML regime at 150 mA, are shown: GS pulses tend to immediately follow the ES ones; this is a consequence of the coupling between the absorption dynamics at GS and ES wavelength respectively, induced by the complex carrier dynamics in the QD SA.

The simulated DW ML regime shows a very good similarity with the experimental results reported in [5], proving that the new proposed design rules represent a alternative method for the realization of QD ML lasers operating in the DW ML regime.

IV. CONCLUSIONS

Starting from the experimental results presented in [5], we simulated a DW ML regime in a two-section QD laser with low gain; a possible route for the new design of passively ML QD laser operating in a DW ML regime was shown.

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