Numerical Analysis of Gain-Switched Quantum Dot Lasers

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Abstract – **Theoretical analysis of gain-switched quantum dot lasers is done using a multi-population rate equations based model. In particular, we investigate the emission spectrum dependence on both the driving current bias level and on the repetition rate of the pulse train. Results show that these two parameters can be suitably handled to yield only-ground state, only-excited state or even both ground and excited state emission.**

I. INTRODUCTION

Semiconductor quantum dot lasers have attracted a lot of attention in the last few years due to their physical features (e.g., delta function-like density of states and the atom-like energy levels configuration) [1] which make them potentially suitable for a wide range of applications in both continuous-wave (CW) [2] and pulsed mode [3, 4, 5]. In most of the pulsed-mode applications mode-locking is preferred because higher repetition rates are achievable if compared to, for instance, gain-switching technique. However, for applications in which this is not a requirement, gain-switching seems to be better, once its implementation is simpler than mode-locking and q-switching, requiring neither external cavity nor saturable absorber. Indeed, in order to perform gain-switching all one has to do is only to drive the laser active region with a rectangular-shape electrical current, i.e., inject short pulses biased near the threshold current (I_{th}) with height equal to many times I_{th}. The dependence of the parameters of the generated optical pulses on the driving current features as, for instance, the bias level is well-known and were reviewed in [6]; basically the bias condition (i.e. whether the laser is biased exactly on the threshold current or slightly below it) mainly influences the peak power and the full-width at half maximum (FWHM) of the generated pulses [6]. In this work we investigate the dependence of the optical pulses generated from a quantum dot laser on the repetition rate and on the bias condition of the driving electrical current. Simulation results obtained from a rate equations model show how the emission wavelength of the optical pulses depends on the bias and on the repetition rate, allowing for the generation of only-ground state emitting (GS) or only-excited state emitting (ES) pulses.

II. MODEL DESCRIPTION

The results presented in this letter were generated with a simulator based on an excitonic rate equations model, in which is included the effect of the inhomogeneous dot size distribution through a multi-population based description, as done in [7]. The quantum dots of the laser active region are grouped into 45 sup-groups (it implies that dots of different groups have different transition energies, different carrier scattering characteristic times, etc) and they are coupled through the homogeneous optical gain broadening (Lorentzian lineshape) and the wetting layer states. The rate equations for the confined states considered in the formulation - ground state (GS) and the first excited state (ES) – take into account also the effect of the Auger recombination as in the recent description proposed in [8], which considers the recombination processes in the individual dots. In the present formulation we considered 73 optical modes of the Fabry-Perot (FP) cavity, which constitutes one of the main differences compared to the model presented in [7]; the other difference is the inclusion of the Auger recombination rate in the rate equations for carriers in the confined states, which is a subtracting term given by:

$$R^{ES}_{Aug\,n} = \left(\sum_{k=2}^{4} \frac{k!}{(k-2)!\,2!} \frac{\rho_h}{\tau^{ES}_{Aug}} p_{es\,k} \right) \cdot N_{d\,n} \qquad (1)$$

$$R^{GS}_{Aug\,n} = p_{es\,k} \frac{\rho_h}{\tau^{GS}_{Aug}} \cdot N_{d\,n}, \quad k = 2 \qquad (2)$$

$$p_{es\,k} = \frac{\mu!}{(\mu-k)!\,k!} \rho_e^k (1-\rho_e)^{\mu-k}, \quad \mu = \begin{cases} 4, ES \\ 2, GS \end{cases} \qquad (3)$$

In the above equations p_{esk} is the probability of having k occupied states in a total of μ available microstates (ground state has degeneracy equal to 2 and excited state has degeneracy 4), ρ_e (ρ_h) is the mean electron (hole) occupation in the conduction (valence) band (as the model is excitonic $\rho_h = \rho_e$), N_{dn} is the number of quantum dots grouped in the nth sub-group and τ_{Aug} is a characteristic Auger time [8], whose value is about 0.2 – 0.5 ns.

The model was then used to simulate a quantum dot laser in gain-switching regime. Main parameters used in the simulations are listed in Table I.

TABLE I
LASER PARAMETERS

Parameter	Value	Unit
Device length	3	mm
Number of QD layers	6	n.a.
Device width	4	μm
Capture time WL into ES	7	ps
Relaxation time ES into GS	17.5	ps
Auger characteristic time	0.2	ns

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III. RESULTS AND DISCUSSION

In this section we analyze the peak power of the output pulses (defined as the time last to achieve half the maximum power), the full-width at half-maximum of them and the energy ratio of the ES and GS contributions, defined here as the amount of pulse energy due to ES emission divided by the amount of pulse energy due to GS emission and expressed in dB. The results reported refer to the features of the last pulse of a sequence of *N* optical pulses, obtained after 320 ns-long simulations. The electrical pulse width was kept fixed in 2 ns all the time, and the repetition rate was changed from 10 MHz to 200 MHz, with step of 2.5 MHz. We considered two bias scenarios: in the first (thicker lines) the bias level is an under-threshold current level (0.95 I_{th}) and in the second (thinner lines) it is an on-threshold bias (I_{th}). The amplitude of the electrical pulses was chosen to be 2.3 I_{th}.

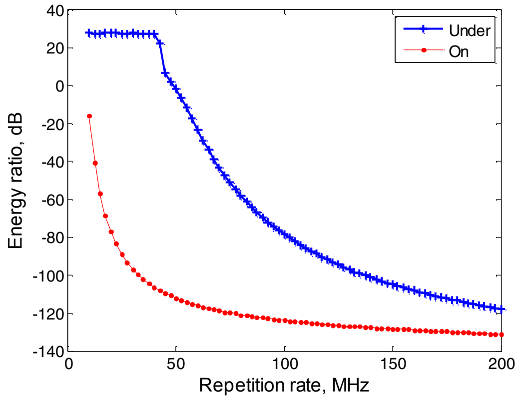

Fig. 1. Energy ratio dependence on the repetition rate for on-threshold (thinner lines) and under-threshold (thicker ones) bias condition.

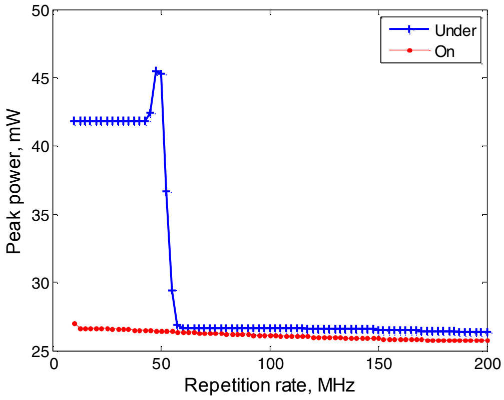

Fig. 2. Peak power dependence on the repetition rate for on-threshold (thinner lines) and under-threshold (thicker ones) bias condition.

Figure 1 shows that for on-threshold bias condition the generated pulses are predominantly due to GS emission in all the considered repetition rate range, but Figures 2 and 3 reveal that in this condition the achievable peak power are rather low (~26mW) and the FWHM are always larger than 400ps. On the other side, working in an under-threshold bias condition reveals three different repetition rate regions (look at thicker lines): I) rates ≤ 40 MHz allow for only-ES emission (Figure 1), higher peak power levels (Figure 2) and shorter optical pulses (Figure 3); II) rates ≥ 57.5 MHz allow for only-GS emission and again low peak power levels and wide pulse-widths; III) 40 < rates < 57.5 MHz allow for both GS- and ES-emission; as a consequence, in region III the highest peak power level is observed (~46mW), after which the ES contribution switches-off and the GS one start to dominate the spectrum.

We associate this particular behavior in the under-threshold bias condition to the carrier density in the excited state level; as the carrier capture rate from the wetting layer into the dot is relatively high, when the current pulse is applied, instantaneously the excited state becomes filled and reaches the population inversion before than the ground state. This phenomenon is not observed in the on-threshold bias condition because, since the bias is I_{th} the GS is already completely filled, and even a low current step would be able to make it to switch-on.

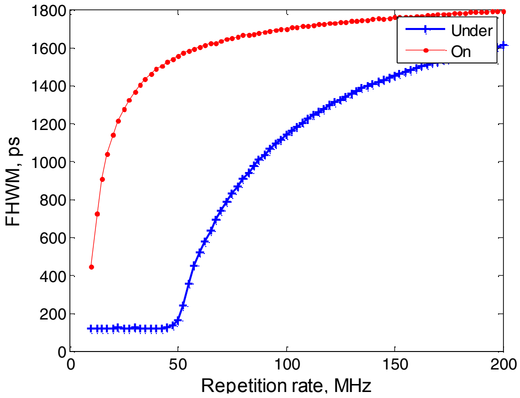

Fig. 3. FWHM dependence on the repetition rate for on-threshold (thinner lines) and under-threshold (thicker ones) bias condition.

IV. CONCLUSIONS

GS/ES emission suppression by controlling the repetition rate and the bias level of the driving current can be properly used to achieve a condition of only-GS emission or only-ES emission. These results show that one can easily use the profile of the driving current to coherently switch the emission wavelength of the generated optical pulses from GS to ES transition energy and vice-versa.

REFERENCES

[1] N. N. Ledentsov et al., “Quantum-dot heterostructure lasers”, *IEEE J. of Sel. Top. in Quant. Electr*. vol. 6, 3, pp. 439-451, 2000.

[2] S. S. Mikhrin *et al* , “High power temperature-insensitive 1.3µm InAs/InGaAs/GaAs quantum dot lasers”, *Semicond. Sci. Technol.* vol. 20, pp. 340-342, 2005.

[3] K. T. Tan et al., “Investigation of high-repetition rate mode-locked quantum dot lasers”, *LEOS Annual Meeting Conference Proceedings*, pp. 826-827, Tucson, October 2003.

[4] D. Klotzkin, R. Jambunathan, K. Kamathm and P. Bhattacharya, “DC, modulation and gain-switched characteristics of self-organized In0.4Ga0.6As/GaAs quantum dot room temperature lasers”, *Digests International Electron Devices Meeting*, pp. 385-388, Washington DC, December 1997.

[5] H. C. Lai, A. Li, K. W. Su, M. L. Ku, Y. F. Chen, and K. F. Huang, "InAs/GaAs quantum-dot saturable absorbers for diode-pumped passively Q-switched Nd-doped 1.3-µm lasers," *Opt. Lett.* vol. 30, pp. 480-482, 2005.

[6] P. Vasil’ev, “Ultrafast diode laser – Fundamentals and Applications”, Artech House, Norwood, 1995.

[7] M. Gioannini, A. Sevega, and I. Montrosset, *Opt. Quantum Electron.* vol. 38, pp. 381-394, 2006.

[8] P. Blood, H. Pask, H. D. Summers, and I. Sandall, *IEEE J. of Quantum Electron*. vol. 43, 12, 2007.