Transport models for quantum cascade lasers

Romain Terazzi, Tobias Gresch, Giacomo Scalari, Marcella Giovannini, Nicolas Hoyler and Jérôme Faist
Institute of Physics, University of Neuchâtel, Neuchâtel, Switzerland
Email: romain.terazzi@unine.ch

***Abstract*—Transport in quantum cascade lasers is investigated in the mid-infrared (7 μm) and far-infrared (80 μm) wavelengths. We focus on a special design - the single-quantum-well - that emphasis the role of coherent transport in the built up of a population inversion. The theoretical predictions are confronted to experimental results, validating the second-order gain model[1] for the mid-infrared and providing faithful lifetimes for the far-infrared through a special feature in the light characteristic. Those models are then considered for optimisation of a two-phonon mid-infrared design and the role of LO-phonon scattering in the intra-subband electron distribution is further investigated.**

***Index Terms*—Quantum cascade laser, Transport simulation, Mid-infrared, Far-infrared, Bloch gain, Resonant tunneling**

I. INTRODUCTION

THE transport in quantum cascade lasers has been intensively considered in many theoretical frameworks. While the very first models used rate equations only to described a few laser states driven by an external current density, the interest for a complete -*ab initio*- simulation scheme that may allow to design and optimize a laser by computing[2] has rapidly grown. But due to the design agility of quantum cascade lasers, the mechanism the electron transport is relying on is very different from a design type to another. Except for general models found in Green's functions formalism[3], the main physical phenomena ruling the transport need to be identified first and the model construct on their basis. Here, we emphasis on a case of study with the particular single-quantum-well design. We present two structures, the one in the mid-infrared (7 μm) and the other in the far-inrared (80 μm).

II. MODEL FOR RESONANT TUNNELING AND SCATTERING

In both structures coherent transport is crucial in the built up of a population inversion between the laser states. In the single-quantum-well design, which is essentially a quantum well with the laser states coupled to an injector region -a superlattice-, both the injection and the extraction of carriers proceed by resonant tunnelling[4], [5] which requires to draw a model in a density matrix formalism, that accounts both for scattering and coherent tunnelling.

For coherent mechanisms between injector and active well regions, the heterostructure period is split into sub-periods in order to work in a tight-binding basis, while rate equations describe the relaxation of carriers inside the sub-periods.

This approach is found very efficient for the mid-infrared structures where the relaxation times can be estimated quite precisely with LO-phonon, LA-phonon, interface roughness and alloy scattering. For the far-infrared structures, the computation of the lifetimes is more difficult, at low temperatures especially. Fortunately, special features of the single-quantum-well design in the light characteristic, allow to extract those relaxation times from measurements.

III. INVESTIGATED DESIGNS AND SAMPLES

In the mid-infrared, we present a sample (N258) where lasing is based on Bloch gain[6]. The active period is shown in Fig.1c. The transport is simulated with resonant tunnelling implemented at the injection and extraction barriers, while the relaxation of carriers is done by scattering between all the states in the injection/active region. As this sample is known to exhibit a special gain curve, measurements and simulations of the spectral gain are presented. The temperature dependance of the threshold current and the gain are also discussed.

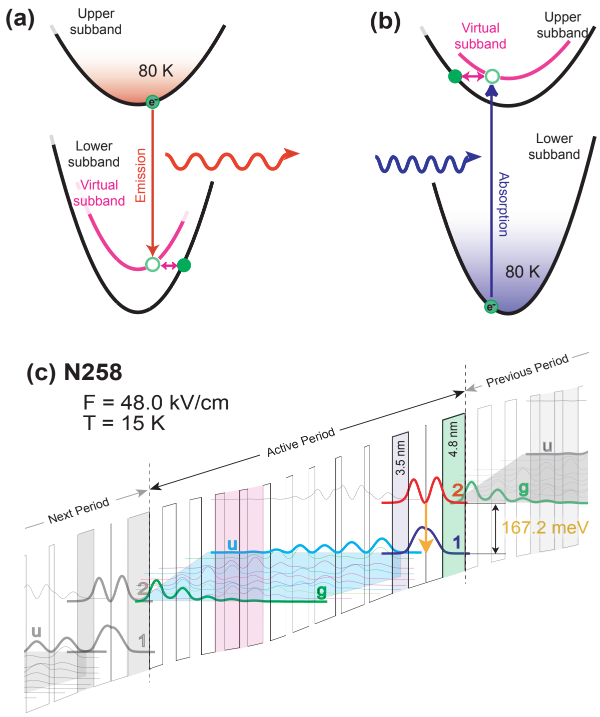

Fig. 1. (a,b) Bloch gain mechanism between a pair of subbands. (c) N258 active period shown at injection resonance.

In the far-infrared (Fig.2), sample N471 has shown a very clear signature of resonant tunnelling in the light characteristic (Fig.3), as the laser stops before the negative differential regime is reached. We attribute this behaviour to a bottleneck of the extraction from the lower laser state as, with increasing bias, the extraction doublet is disaligned. The importance of the dephasing time is also emphasised.

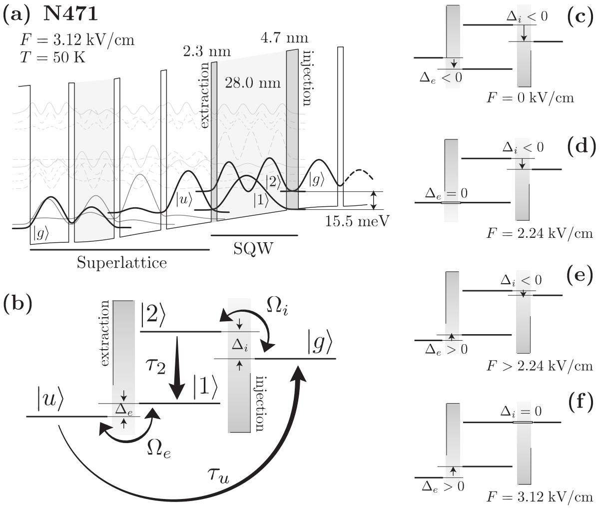

Fig. 2. (a) N471 single-quantum-well design, band structure shown at injection resonance. (b) Four-state density matrix model, with resonant tunnelling at injection and extraction barrier. (c,d,e,f) Injection and extraction doublet configurations for increasing applied bias.

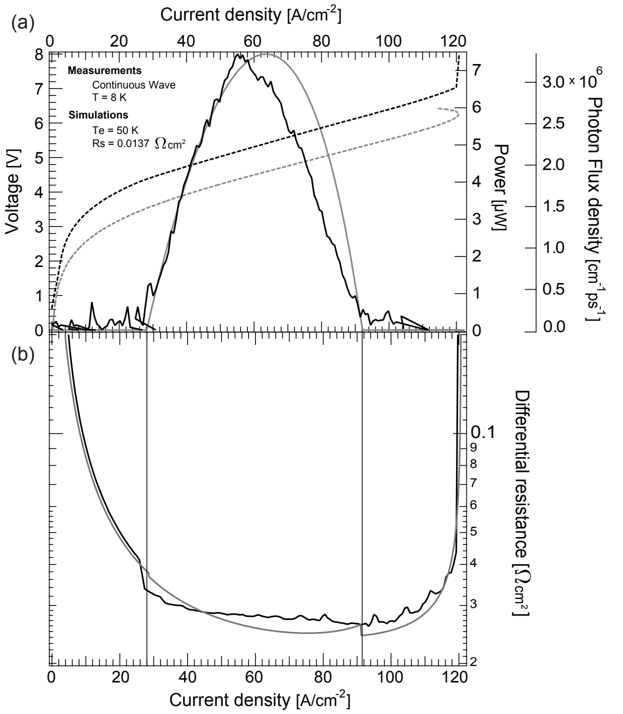

Fig. 3. Characteristics of N471 sample, measurements and simulations. (a) Current-Voltage-Light (b) Differential resistance.

IV. TWO-PHONON DESIGN AND ELECTRON DISTRIBUTION

A complete model is also developed for a two-phonon design in the mid-infrared. This allows to optimise the active region in order to obtain better device performances, as a lower threshold current density with a greater dynamic range.

The electron distribution function in the laser subbands is also computed by sampling the k-space and setting rate equations for the intrasubband LO-phonon transitions.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation and the National Center of Competence in Research, Quantum Photonics.

REFERENCES

[1] H. Willenberg, G. Döhler, and J. Faist, “Intersubband gain in a bloch oscillator and quantum cascade laser,” *Phys. Rev. B*, vol. 67, pp. 085 315–1–085 315–10, 2003.

[2] A. Mircetic, D. Indjin, Z. Ikonic, P. Harrison, and R. Kelsall, “Towards automated design of quantum cascade lasers,” *J. Appl. Phys.*, vol. 97, pp. 084 506–1–084 506–7, 2005.

[3] A. Wacker, “Gain in quantum cascade lasers and superlattices: A quantum transport theory,” *Phys. Rev. B*, vol. 66, pp. 085 326–1–085 326–7, 2002.

[4] R. Kazarinov and R. Suris, “Electric and electromagnetic properties of semiconductors with a superlattice,” *Sov. Phys. Semicond.*, vol. 6, no. 1, pp. 120–131, 1972.

[5] C. Sirtori, F. Capasso, J. Faist, A. Hutchinson, D. Sivco, and A. Cho, “Resonant tunneling in quantum cascade lasers,” *IEEE J. Quantum Electron.*, vol. 34, no. 9, pp. 1722–1729, 1998.

[6] R. Terazzi, T. Gresch, M. Giovannini, N. Hoyler, N. Sekine, and J. Faist, “Bloch gain in quantum cascade lasers,” *Nature Phys.*, in press.