Coupled Carrier-Field Monte-Carlo Analysis of Mid-IR Quantum Cascade Lasers

A. Mátyás, S. Katz*, S. Söntges, A. Vizbaras*, P. Lugli, M. C. Amann* and C. Jirauschek
Institute for Nanoelectronics, Technische Universität München, Arcistrasse 21, D-80333 München, Germany
*Walter Schottky Institut,
Technische Universität München, Am Coulombwall 3, D-85748 Garching, Germany
e-mail: alparmat@mytum.de

Introduction

Short-injector and injectorless mid-infrared (mid-IR) quantum cascade lasers (QCLs) based on the $In_{0.6}Ga_{0.4}As/In_{0.365}Al_{0.635}As$ material system [1] are analyzed by means of a well-established ensemble Monte-Carlo (EMC) method. Our simulations are based on the Schrödinger-Poisson wave function solutions [2] and include all the relevant scattering mechanisms, namely electron (e)- acoustic and longitudinal optical (LO) phonons including hot phonons, e-e, e-alloy, e-impurity and e-interface roughness scattering [2], [3], [4]. The cavity field is self-consistently included by introducing the photon-induced scattering contributions [4] and adding an optical evolution equation. For the device simulation, only well-established material parameters and the device specifications are used as an input. Due to the extended nature of the wave functions, shown in Fig. 1, the simulation results are sensitive to the interface roughness. The used values were carefully deduced from photoluminescence and current measurements and are consistent with literature.

Discussion

In Fig. 1, the conduction band profile and squared wavefuncions of the investigated short-injector mid-IR QCL are shown. The device contains additional AlAs barriers for reducing the escape of the electrons to the continuum [1]. The $E - J$ and $L - I$ curves of the QCL are shown in Fig. 2 and compared to experiment. In the lasing region, the inclusion of the light field in the simulation is critical to get good agreement with experiment, since the photon-induced current contributes significantly. The simulated $L - I$ curve shows good agreement with experiment; specifically, also the threshold current is reproduced well. Figure 3 shows the simulated unsaturated and saturated spectral gain profile at 60 kV/cm. As expected, gain clamping to the loss occurs once the cavity field is self-consistently included into the simulation [4].

We have presented EMC simulations for mid-IR short-injector quantum cascade lasers, including both the carrier transport and optical cavity field in a fully self-consistent manner. Comparing the $E-J$ and $L - I$ characteristics with experiment, we find qualitative and quantitative agreement. Such coupled simulations provide an improved understanding of the laser operation in QCLs and allow for optimizations with respect of efficency and output power.

Acknowledgment

A. M. and C. J. acknowledge support from the Emmy Noether program of the German Research Foundation (DFG, JI115/1-1).

References

[1] A. Vizbaras, S. Katz, G. Boehm and M. C. Amann, *Short-Injector Quantum Cascade Laser Emitting at 8-μm Wavelength With High Slope Efficiency*, IEEE Photonics Technology Letters **21**, 1384 (2009).

[2] C. Jirauschek, *Accuracy of Transfer Matrix Approaches for Solving the Effective Mass Schrödinger equation*, IEEE Journal of Quantum Electronics **45**, 1059 (2009).

[3] C. Jirauschek and P. Lugli, *Monte-Carlo-based spectral gain analysis for terahertz quantum cascade lasers*, Journal of Applied Physics **105**, 123102 (2009).

[4] C. Jirauschek, *Monte Carlo study of carrier-light coupling in terahertz quantum cascade lasers*, Applied Physics Letters **96**, 011103 (2010).

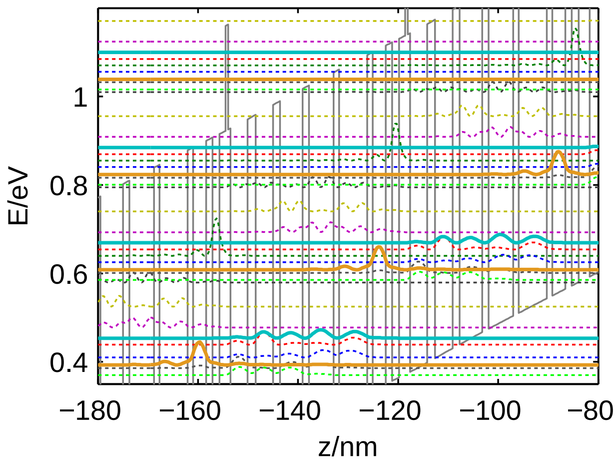

Fig. 1. Conduction band profile and squared wavefunctions for the simulated device from [1], emitting at $8\mu m$. Upper and lower laser levels are marked by bold solid lines.

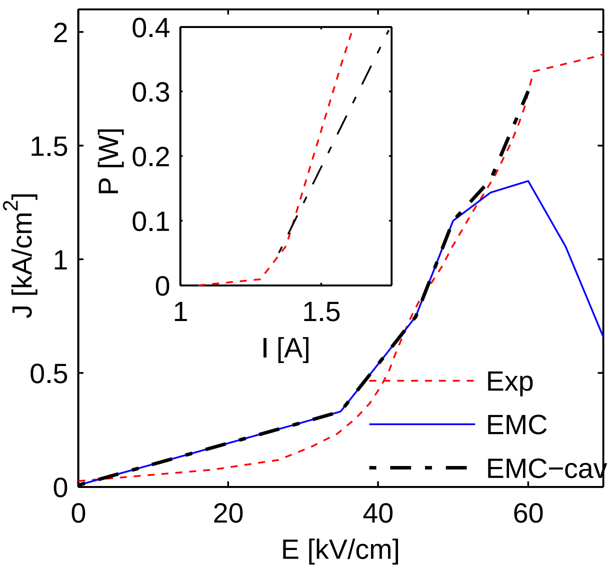

Fig. 2. Electric field−current density $(E-J)$ characteristics as calculated by the EMC method with (dash-dotted line) and without (bold line) lasing included and obtained from experiment (dotted line). In the lasing region, the inclusion of the light field in the simulation is critical to reproduce the experimental result. The inset shows the output light-current $(L-I)$ characteristics, yielding good agreement between simulation and experiment.

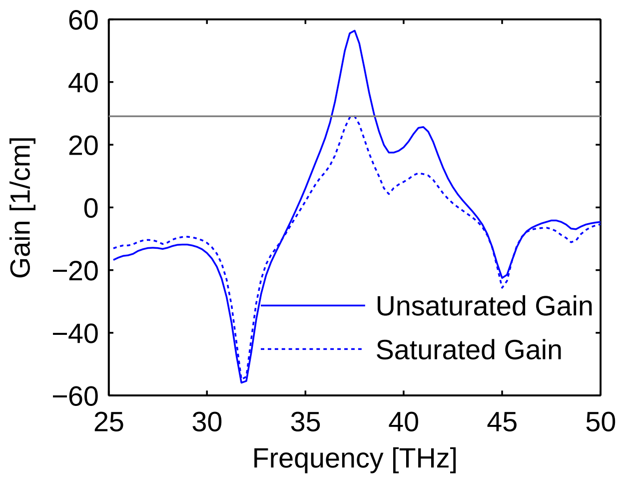

Fig. 3. Unsaturated and saturated spectral gain profile of the simulated QCL. The horizontal line indicates the total cavity loss. Gain saturation and clamping to the loss is obtained if the cavity field is included into the simulation.