Modeling of Quantum Cascade Laser Sources with Giant Optical Nonlinearities

C. Jirauschek
Institute for Nanoelectronics, Technische Universität München, Arcisstr. 21, D-80333 München, Germany
e-mail: jirauschek@tum.de

INTRODUCTION

The quantum cascade laser (QCL) is an extremely versatile light source, employing artificially engineered optical transitions in the conduction band of a semiconductor nanostructure. By careful design of the active region, the optical gain characteristics can be custom-tailored for the envisaged application over a wide range of the mid-infrared (MIR) and terahertz (THz) spectral region. Recently, the possibility to additionally integrate giant artificial nonlinearities into the gain medium has been exploited for various innovative applications, including THz difference frequency generation (DFG) at room temperature [1,2] and QCL-based frequency combs [3,4].

The further development of such advanced QCL sources requires careful modeling, providing an improved understanding of the carrier-light interaction and allowing for systematic design optimization. These devices combine aspects from various areas such as nanoelectronics, nonlinear photonics, and plasmonics, which must be adequately considered in state of the art simulation tools. This can be achieved by an integrated multi-domain modeling approach, taking into account the electron transport in the active region and optical field propagation in the resonator on an equal footing. In the following, we discuss the application of such simulation approaches to QCL-based DFG structures and frequency combs.

SIMULATION

Conventional THz QCLs only work at cryogenic temperatures. A promising alternative is THz DFG, which uses an active region design supporting two MIR lasing modes at frequencies f_1 and f_2 and featuring a second order optical nonlinearity. Frequency mixing gives rise to an additional field component at f_1-f_2, enabling QCL-based THz generation at room temperature. The nonlinear susceptibility can be computed using EMC [5]. By coupling the carrier transport to optical simulations as illustrated in Fig. 1, a self-consistent modeling scheme for THz DFG structures is obtained. This approach has been applied to an experimental device [2]. Figure 2 shows the simulated MIR and THz powers as a function of lattice temperature, along with available experimental data at 300 K [2]. Good agreement between theory and experiment is observed. Furthermore, the results indicate that the temperature degradation of the THz power can be mainly ascribed to the decrease in MIR powers. On the other hand, the optical nonlinearity is temperature insensitive, and also depends only moderately on the applied bias (see Fig. 3).

Besides frequency conversion, giant optical nonlinearities are used to induce coupling between the longitudinal modes, which is exploited for the generation of picosecond pulses [6] and frequency combs [3,4]. To describe the underlying coherent nonlinear optical phenomena, Maxwell-Bloch equations are commonly employed [6,7], which however contain unknown parameters such as scattering rates. These are often estimated from experimental data or used for fitting. In our approach, these quantities are extracted from EMC simulations, resulting in a self-consistent modeling approach. In Fig. 4, the simulated spectral intensity is shown for a THz QCL frequency comb source [4]. The spectrum features equidistant comb lines over an extended spectral range and is split into two lobes, as also observed in experiment [4].

In conclusion, multi-domain simulation approaches combining EMC with advanced models for the nonlinear optical effects provide a powerful tool for the modeling of innovative QCL sources using giant optical nonlinearities.

ACKNOWLEDGMENT

This work was funded by the Heisenberg program of the German Research Foundation (DFG, JI115/4-1).

REFERENCES

[1] M. Belkin et al., *Room temperature terahertz quantum cascade laser source based on intracavity difference-frequency generation*, Appl. Phys. Lett. **92**, 201101 (2008).

[2] Q. Y. Lu et al., *Room temperature single-mode terahertz sources based on intracavity difference-frequency generation in quantum cascade lasers*, Appl. Phys. Lett. **99**, 131106 (2011).

[3] A. Hugi et al., *Mid-infrared frequency comb based on a quantum cascade laser*, Nature **492**, 229 (2012).

[4] D. Burghoff et al., *Terahertz laser frequency combs*, Nature Photon. **8**, 462 (2014).

[5] C. Jirauschek et al., *Monte Carlo study of terahertz difference frequency generation in quantum cascade lasers*, Opt. Express **21**, 6180 (2013).

[6] V.-M. Gkortsas et al., *Dynamics of actively mode-locked quantum cascade lasers*, Opt. Express **18**, 13616 (2010).

[7] C. Jirauschek and T. Kubis, *Modeling techniques for quantum cascade lasers*, Appl. Phys. Rev. **1**, 011307 (2014).

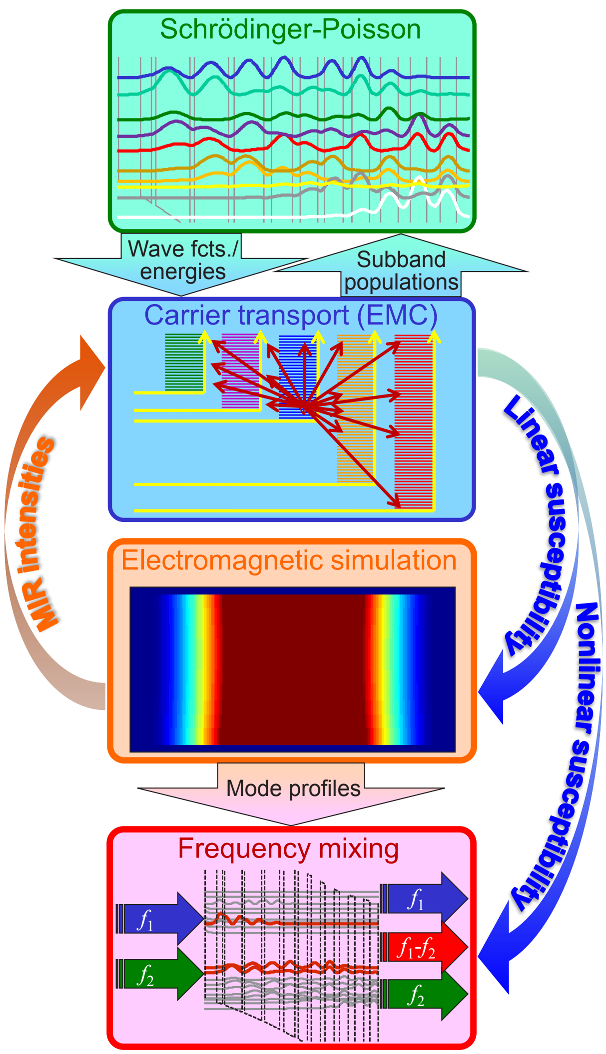

Fig. 1. Schematic illustration of a multi-domain simulation approach for QCL frequency conversion structures.

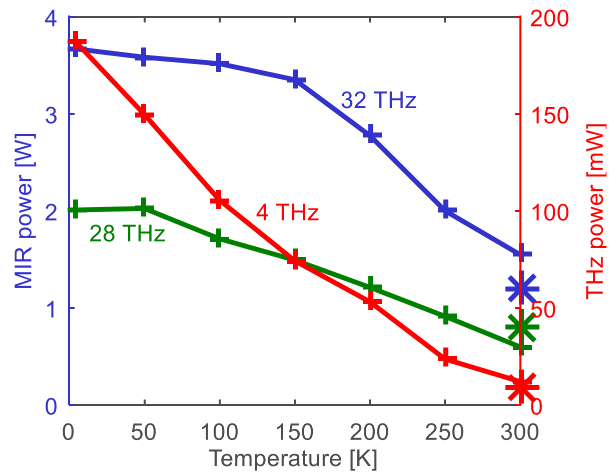

Fig. 2. Simulated MIR and THz powers vs. temperature (solid lines), and available experimental data (asterisks).

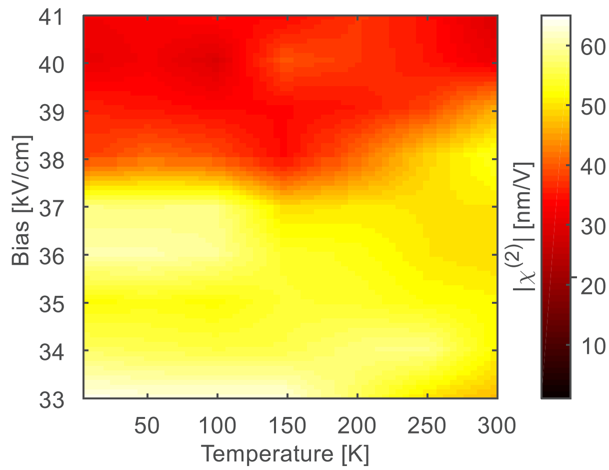

Fig. 3. Nonlinear susceptibility $|\chi^{(2)}|$ as a function of temperature and applied bias.

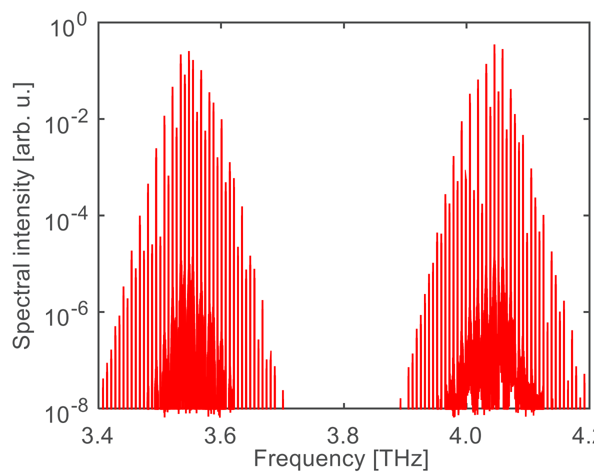

Fig. 4. Simulated optical power spectrum of the QCL frequency comb source in [4].