Comprehensive Mathematical Modeling and Simulation of Semiconductor Lasers

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Abstract We present a thermodynamic designed self-consistent semiclassical multi-species model for the 3D simulation of semiconductor lasers containing quantum dots, which combines classical drift-diffusion transport and quantum confinement for carriers providing gain for the optical field.

Introduction

Throughout the last years active layers containing quantum dots have been embedded within semiconductor lasers. However, their design is still subject to optimization, depending on the desired applications. In comprehensive modeling one has to cover a close interplay of all such effects like carrier transport, optical waveguiding, population dynamics as well as heating on different spatial and time scales. We give an overview on comprehensive semiclassical modeling of such effects and discuss the most challenging issues.

Electronic Model

The electronic model differs between free-roaming carriers, which can be described in a classical drift-diffusion setting [2], including heating [3], and quantum-confined carriers. This makes up a multi-species model [4]. The bulk carrier transport considers the free electrons and holes completely incoherent in all spatial directions [2].

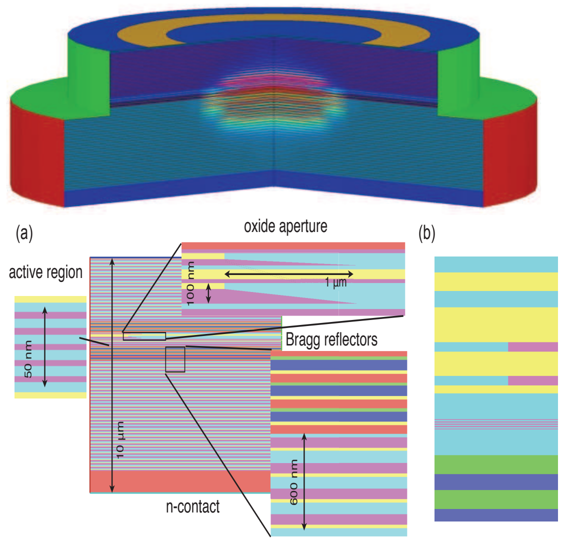

Fig. 1 VCSEL structure with intensity distribution of main optical mode. Bottom: details of material composition.

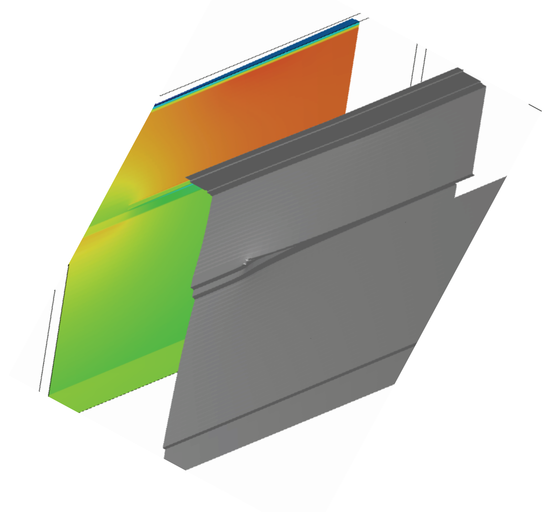

Fig. 2 Potential and carrier distribution along the VCSEL, calculated with WIAS-Oskar3.

The quantum confined carriers, however, are considered completely coherent in the quantized spatial directions, but completely incoherent in the non-quantized directions (wetting layer), where they can still be described by reduced drift-diffusion equations. The population dynamics of localized carrier states in the quantum dots is described by rate equations. The net exchange between the confined and unconfined species is caused by inelastic scattering (Coulomb-effects), modeled by corresponding nonlinear density-dependend scattering rates, which are calculated microscopically [5,6]. The exchange via these nonlinear scattering rates gives rise to new dynamic features, as the strongly damped relaxation oscillations observed in QD lasers [1,6]. The charge distribution of all carriers – confined and unbounded - is in addition globally coupled by the Poisson equation.

Optical Model

We consider the classical macroscopic electromagnetic field of a laser cavity with boundary conditions for outgoing waves. Effects like spontaneous emission are modeled in this setting via Langevin sources. Motivated by the high quality of the VCSEL resonator we decompose the field into modes, which are eigensolutions of a dissipative operator that spatially describes the optical waveguiding. Waveguiding for hot-cavity modes is influenced by the actual carrier distribution that in turn modifies the spatial variation of refractive index and optical gain. The resulting complex eigenfrequencies govern the dynamics of the amplitudes of such instantaneous hot-cavity modes.

Coupling of Electronic and Optical Model

The dynamics of the photon number as well as the modified waveguiding feeds back to the carrier distribution via the stimulated recombination term. This yields in consequence a nonlinearly coupled system for carriers and photons, which has to be treated self-consistently [2,3]. At the very heart of this coupling is the model for the optical gain, which clearly has signatures of the nano-structured active region. The gain itself enters the stimulated recombination rate for the carriers in the active region, as well as the generation rate for the photons of the coherent optical field. The gain model has to be designed for inhomogeneous broadening, caused by the individuality of the quantum dots, as well as for homogeneous broadening caused by Coulomb-effects [4].

Heating

The inclusion of heating effects is essential in VCSELs and high-power lasers. We include them in a thermodynamic consistent way, by starting with a formulation of the free energy for the whole carrier-light system. Taking into account Onsager symmetry relations this approach guarantees at least consistency with the 2nd law of thermodynamics [3].

Conclusions

Comprehensive modeling of quantum dot lasers has to cover a close intimate interplay of a various different effects. Most important effects are carrier transport, optical waveguiding, microscopic population dynamics, and heating, acting on different spatial and temporal scales. The description of QD active regions requires at least a multi-species model, as in our case in terms of rate equations for the wetting-layer – quantum dot population dynamics. We give an overview on comprehensive semiclassical modelling of corresponding devices and discuss the most challenging issues.

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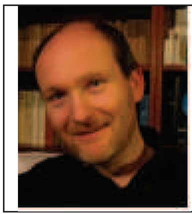

Uwe Bandelow received his Diploma and his PhD degree from HU Berlin in 1991 and 1994, respectively, all in theoretical physics. Since 1996 he is with WIAS Berlin, where he is heading the *Laserdynamics* group since 2005, and where he coordinates the research area *Nano- and Optoelectronics*. Since 2010 he is teaching as a Priv.-Doz. at HU Berlin. U. Bandelow's research interest is in the area of optoelectronic devices and nonlinear optical fibers. He has authored 79 papers in leading technical journals and conferences. He is a member of DPG and O