From Microscopic Physics to Advanced Semiconductor Laser Modeling and Simulation

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Semiconductor optoelectronic devices involve complicated interplay of optical, electronic, and thermal processes. These processes span over time scales from microseconds for the thermal process to tens of femtoseconds for optical dephasing and carrier scatterings. In spatial extension, nanometer scale carrier confinement and transport in vertical direction, as well as beam filamentation and carrier diffusion on micrometer scale in the lateral direction are to be treated. In terms of disciplines involved, classical optical propagation and diffraction, thermal diffusion as well as the very frontiers in quantum theory of many-body systems are intertwined in a single event of semiconductor laser operation. Clearly, modeling and simulation of optoelectronic devices deal with a multiple-process system on multiple space and time scales, and pose serious challenge both in terms of model development and numerical computation.

In practical modeling and simulations, however, simplified models based on various approximations or deduced from experiments are very often used. While the advantages of being conceptually and computationally simple are obvious, we need to be aware of the approximations involved and the limit of them. Very often it is helpful to go back to our starting point and to rethink the approximations, under which our simplified equations are derived. Fortunately, the physical processes are understood and described to a large degree at a more fundamental level within the microscopic theory[1,2].

In this presentation, we will show how one can start from physics and the related equations at the microscopic level and derive a set of macroscopic equations that are valid in a wider range of parameters than typical simplified models. Our starting point is the bulk semiconductor parameters including the bulk bandstructure information. Our emphasis will be placed on the treatment of interaction between optical field and electron-hole plasma in a semiconductor host medium, while treating the semiconductor lattice, such as lattice heating and bulk lattice parameters, at the phenomenological level.

The starting equations are based on the Maxwell-Bloch Equations[1,2] describing the motions of laser field and electron-hole plasma and their interactions, but with the following extensions: First the spatial inhomogeneities are included in the distribution functions [3](diagonal elements of the density matrix), so that Boltzmann transport equations for the Wigner type of electron and hole distribution functions result. Second, detailed scattering terms are included to properly account for the lineshape functions. In general, this set of equations have to be accompanied by the Poisson equation. The resulting general set of equations is more appropriately termed “Maxwell-Bloch-Boltzmann-Poisson” equations. Obviously this set of equations in a typical two dimensional real space and its conjugate momentum space for the case of quantum well based devices represents such a formidable computational task that it becomes practically impossible to solve them directly even with today’s high performance computers.

Rather than attempting to solve these equations directly, we try to derive a set of moment equations with respect to momentum space. The resulting moment equations from the Boltzmann equations are the carrier density, carrier momentum, and carrier energy equations. These moment equations now couple to the Maxwell and Poisson equations and close the hierarchy. The k-resolved optical polarization equations are approximated by the effective polarizations, constructed using the microscopically calculated optical susceptibility [4]. This reduced set of equations, even though much simpler than the original equations, consists of partial differential equations with still a few different time scales. In our simulation, we solve these equations directly in space and time using finite difference methods.

The advantages of our approach described above are its bottom-up nature. We start from a few measurable parameters and the microscopic physics with the number of freely adjustable parameters minimized. Our model contains such effects as gain nonlinearity, gain dispersion, plasma heating, many-body effects, nonlinear diffusion, and nonlinear heat conduction. To strike a balance between physical accuracy and computational manageability, we rely heavily on parameterization of quantities that are computed microscopically, such as optical gain and refractive index of the plasma, various diffusion coefficients and the scattering rates. Many of these rates and coefficients are very often treated as constants in the more phenomenological approaches. The effects of variation of these “constants” on laser performance will be discussed. The most notable examples are the gain, index, diffusion coefficients’ variations with carrier densities and temperature.

As example of applying our models to semiconductor laser simulation, the set of equations mentioned above is solved in space and time domains using finite-difference methods for VCSELs [5]. We will show how complicated dynamic mode competition can be described without assuming number and type of transverse modes a priori. Our simulation tool is ideally suited to study the spatial-temporal dynamics under AC modulation and to study the influence of the transverse mode on modulation bandwidth. Furthermore, we will show how the multi-transverse mode dynamics could be explored for ultrafast modulation and switching.

Another interesting example is coupled VCSELs or VCSEL array. We will show that, by coupling two VCSEL together, high frequency (over 40 GHz), narrow-band self-pulsating operation can occur at DC bias. Such high frequency oscillation is accompanied by directional beam switching between two widely separated directions and can be used for ultrafast beams switching in optical network applications.

In summary, we attempted to bridge the gap between the well-developed microscopic theory in the physics community and the phenomenological models very often used in the laser design community by establishing a model that is more extended than the phenomenological approach and contains less free parameters. Parametrization of the microscopically computed quantities allows us to take into accounts of physics at the microscopic level, yet renders the computation manageable. Such an approach, though computationally more expensive than the simplified approaches, allows more accurate description of device physics and should lead to better bottom-up type of design tools for optoelectronic devices, especially with the ever increasing computation power.

Reference:

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