Simulating the Modulation Response of VCSEL's with MINILASE

Karl Hess, Yang Liu, Fabiano Oyafuso, and Wei-Choon Ng

Beckman Institute and Coordinated Science Laboratory,
University of Illinois at Urbana-Champaign, Urbana, IL 61801

Vertical cavity surface emitting lasers, particularly VCSEL's with oxide confinement, present a challenge to simulation. The introduction of oxide layers complicates the simulation of electrical properties because of the boundary conditions to electrical current and field and because of the absolute necessity to simulate (at least) in two dimensions. The optical properties require simulation in three dimensions with complex dielectric function and open cavity boundary conditions. Simulation of the modulation response and introduction of time requires the addition of one more dimension and presents therefore problems even for the largest available computational resources.

Rate equation models are numerically tractable but cannot do justice to the requirements of simulating the modulation response because they can include nonlinear gain only in a phenomenological way. Without including a phenomenological damping factor ϵ, the response curves overshoot actual data significantly.

MINILASE can simulate nonlinear gain and the modulation response from first principles. We have also developed several simulation tools to simulate the optical properties of oxide confined cavities. In order to make the numerical requirements tractable, we have therefore developed a solver that works with cylindrical coordinates and symmetry and simplifies such three-dimensional problem to a quasi three-dimensional one.

We have developed 2 optical solvers, one based on a Green's function method and the other on a scalar weighted index method. In the Green's function approach, we solve the in-homogeneous Fredholm integral equation of the second kind by expanding the cavity E-field in terms of the eigen-modes of a corresponding homogeneous equation.[1] The oxide and gain regions are discretized and treated as distributed sources. Together with the dyadic Green's function operator for homogeneous multi-layers and the method of moments, we transform the homogeneous equation into a generalized eigenvalue problem. We also use the fact that at near threshold, the gain eigenvalue can be expanded to first order.[1] This allows us to solve the generalized eigenvalue problem at a few frequencies, ω, and thereby compute the resonant frequencies and threshold modal gain. With these eigen-functions, the in-homogeneous Fredholm equation can then be solved to give accurate spontaneous emission rates. If the number of in-homogeneous regions increases, the computation demands can, however, become prohibitively large.

The scalar weighted index method assumes separable scalar field $\phi(x,y,z) = \phi_s(x,y).\phi_z(z)$. This is substituted into the scalar Helmholtz equation to give the transverse- and z- wave equations. First, the z-wave equation is solved for the resonant frequency, and the resonant z-modal field is used to compute weighted indices for the core and cladding regions. These weighted indices are in turn used in the transverse wave equation to compute the transverse wavenumber which is fed back to the z-wave equation. The 2 wave equations are solved alternately and iterated until convergence; typically in less than 10 seconds on a 333 MHz PC. For the oxide-confined VCSELs, the resonant frequencies and transverse field profile in the QW region agree very well with those of the Green's function method. However, the weighted index method does not yield accurate threshold modal gain and photon lifetimes for small oxide aperture VCSELs. For these parameters, we use pre-computed values from the Green's function method.

The electrical solver was adopted from MINILASE II [2] and includes nonlinear gain, hot electron effects, spatial and spectral hole burning etc. To simulate the carrier transports in real space, Poisson's equation and the equations of continuity are solved for both electrons and holes by a Newton iteration in the bulk regions. At the hetero-junctions that separate the bulk materials, we include the thermionic emission formula of Bethe. In the QW region, carriers are partitioned into continuum and bound states with separate quasi-Fermi levels. The carriers in the continuum states are ballistically coupled to those in the SCH regions and to those in the bound states by scattering interactions (both electron-phonon and electron-electron scatterings are taken into consideration). To account for the hot quantum carriers and spectral hole burning effects, QW carrier transport is also simulated in energy space by solving the Boltzmann equation. In addition, an eight-band $k \cdot p$ method, that takes into account band gap re-normalization and Coulomb enhancement effects, is self-consistently incorporated in MINILASE to compute the QW bandstructure and optical matrix elements.

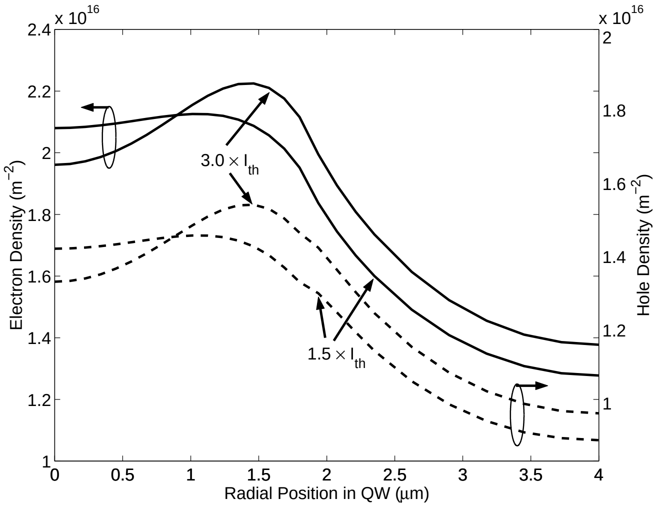

Fig. 1 Spatial hole for electrons (solid lines) and holes (dashed line) in the QW . The bias current is increased from $1.5 \times I_{th}$ to $3.0 \times I_{th}$.

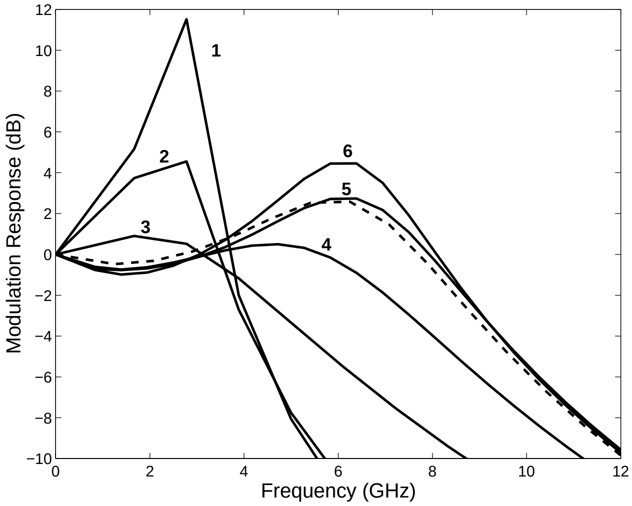

Fig. 2 Solid lines labeled from "1" to "6" show simulated modulation response at bias $I = 2.5 \times I_{th}$ for several QW mobilities; $\mu = \mu_{el} = \mu_{hl} = 10^5$, 5.0, 1.5, 0.5, 0.1, and 10^{-6} $m^2/V \cdot sec$, respectively. For the dashed line, $\mu_{el} = 1.21$ and $\mu_{hl} = 0.04$ $m^2/V \cdot sec$.

In the following we present results of MINILASE simulations for oxide-confined VCSELs with 1.8 μm aperture radius, which experimentally showed a bandwidth > 16 GHz.[3] Fig. 1 gives the 2D carrier distribution inside the QW. As the current bias is increased from $1.5 \times I_{th}$ to $3.0 \times I_{th}$, the stronger stimulated recombination at the central region forms prominent spatial holes for both types of carriers. This "Spatial Hole Burning" effect can cause nontrivial lateral diffusion inside the QW and leads to a new form of diffusion capacitance. To clarify its role on modulation response, modulation responses for artificially high/low carrier mobilities inside QW have been simulated, as shown in the solid lines in Fig. 2. It can be observed that increasing mobilities lead to smaller relaxation frequency and -3dB bandwidth, which can be explained by the more uniform transverse mode that is effectively "seen" by the carriers due to greater lateral diffusion. We also find that competing lateral diffusion and stimulated recombination mechanisms affect spatial hole burning in VCSELs. For very low mobilities, stimulated emission dominates while lateral diffusion rules for the higher mobilities. Either mechanism results in higher relaxation peaks, but the competition of both lowers the peak. The dashed line represents simulated response for mobilities with more realistic values and indicates that in real devices lateral diffusion doesn't affect the relaxation frequency by much but does dampen the relaxation peak. Another interesting result is obtained by simulating the modulation response for VCSELs with graded and ungraded SCH regions. For a long cavity VCSEL, the dynamic response is greatly improved by linear grading for both the relaxation peak and bandwidth. This can be shown to be related to the effects of wasted minority carriers (diffusion capacitance), since similar improvements can be obtained by artificially suppressing the carrier escape from the QW. However, this effect is dependent on cavity thickness and the improvement is no longer observed for shorter cavities.

We acknowledge support of the Office of Naval Research and the Army Research Office.

REFERENCES

1. B. Klein et al., "Self-consistent green's function approach to the analysis of dielectrically apertured vertical-cavity surface-emitting lasers", *Appl. Phys. Lett.*, vol. 73, pp. 3324-6, Dec. 1998.
2. M. Grupen and K. Hess, "Simulation of carrier transport and nonlinearities in quantum-well laser diodes", *IEEE Journal of Quantum Electronics*, vol. 34, pp. 120-140, Jan. 1998.
3. K.L. Lear et al., "High-Frequency Modulation of Oxide-Confined Vertical Cavity Surface Emitting Lasers", *Electron. Lett.*, vol. 32, pp. 457-8, Feb. 1996.