Ultra-fast VCSEL cavity simulations using paraxial eigenmode expansions[§]

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By employing a radiation expansion into cavity eigenmodes we avoid the requirement of spatially resolving the cavity on a fine mesh, and run much faster without the time consuming finite differencing in space. Our method relies on identification of accurate, analytic solutions for cavity eigenmodes. Obtaining such modes has been complicated in the past by the structural complexity of VCSEL cavities, and in particular the lack of lateral confinement. By using a paraxial mode expansion in Gauss-Laguerre (GL) modes we include all mechanisms of radiation escape (a) lateral diffraction (b) edge-clipping due to finite DBR diameter (c) wide angle scattering due to small features (oxide aperture, mesa edges). Earlier application of cylindrical waveguide modes, index-guided[1] or metal boundary, fails to address such losses; the lateral Poynting flux for any such representation (scalar or vectorial) is zero. Cumbersome superpositions including the continuum of unguided ("radiating") fiber modes must be involved [2]-[3] for that purpose.

In the PREVEU (Paraxial Radiation Eigenmodes for VCSEL Emulation) model [4]-[5], the cavity round-trip S-matrix is obtained analytically using a paraxial mode expansion with the mode waist as free parameter. No longitudinal index-averaging, or separable approximations, are assumed. DBRs are modeled by equivalent hard mirrors, located at the effective phase penetration and the effective diffraction lengths, respectively, for standing wave condition and reflected wavefront computation. Wavefront "clipping" due to finite mirror radius, and gain guiding due to finite gain area, are evaluated analytically in terms of non-diagonal S-matricies. In treating apertures, losses from wide angle scattering outside the paraxial propagation cone are computed, applying the Born approximation to the fully EM scattering theory. The aperture-induced phase-shift is computed using Schrodinger perturbation theory. Wave propagation between gain, aperture and mirror elements is modeled by the uniform medium paraxial propagator, yielding simply a rescaling of the paraxial beam parameters with distance traveled. Finally, the diffracted, deformed wavefront is projected into the original, obtaining the analytic expression for the round trip matrix in terms of current aperture, mode waist and cavity Fresnel number. It is shown that over a wide parameter range, cavity eigenmodes are represented *by pure* GL modes of optimized waist. Maximization of the round trip amplification factor in respect to the mode waist yields the mode structure analytically.

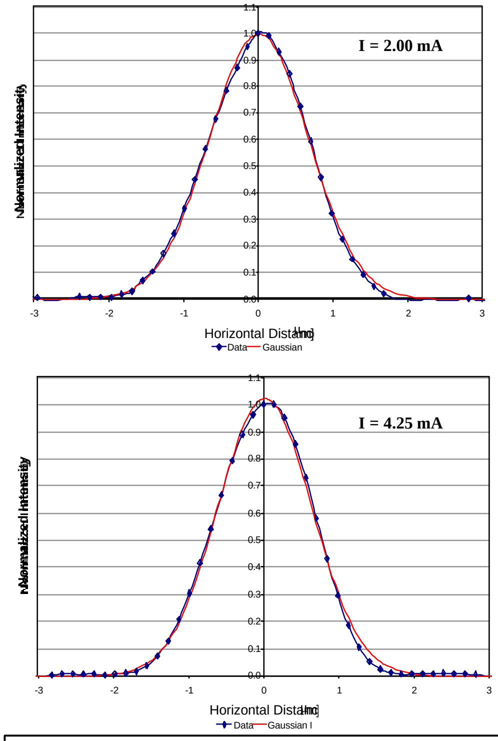

Fig. 1: Best-fitting Gaussian w=1.31 µm vs. NF intensity exp. data (points). Theoretical value w = 1.26 µm.

We compared our predicted mode structure against near field and far field measurements for various VCSELs. Figure 1 shows excellent agreement between theory and near-field profile measurements on a 780 nm, 6 m etched mesa device. Figure 2 compares the computed vs.

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measured waist-to-aperture ratio, as a function of aperture size and placement, for 980 nm USC oxide-confined VCSELs[6]. Incidentally, index-guided models yield a rather constant w/a ratio. Using our model as a design tool for the parametric cavity behavior we found that (a) generic VCSEL behavior, such as frequency blue shifting, and ncreasing modal round trip losses follows self-consistently from the dependence of a/w on the aperture a, (b) *diffraction and scattering losses dominate at small apertures,* causing the observed increase in threshold current density and differentiation in modal losses (c) the correct behavior regarding the aperture location in the standing wave pattern is obtained: systematically *lower threshold current occurs for node (null) aperture placement*. The threshold current density vs. aperture predictions are compared with experiment in Fig. 3. By fully including scattering and diffraction losses, that are essential in explaining the behavior in Fig. 3, our code yields systematically higher threshold current than most of the codes we compared against[7]

Execution time for obtaining the first 20 modes using PREVEU is less than 100 msec on a Pentium 500 equivalent. The dynamical integration of the rate equations using multi-mode expansion is performed by FLASH (Fast Lasing Algorithm for Semiconductor Heterostructures). Steady-state usually takes only few secs on a Pentium 500 equivalent.

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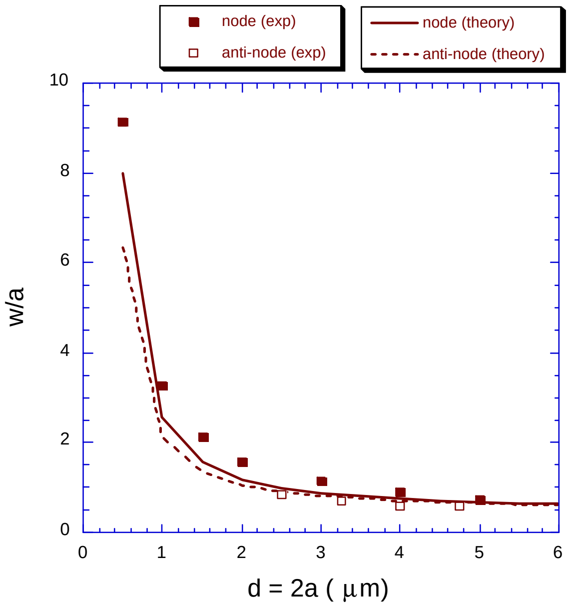

Fig. 2 1/e^2 waist-to-radius ratio vs. aperture diameter 2a

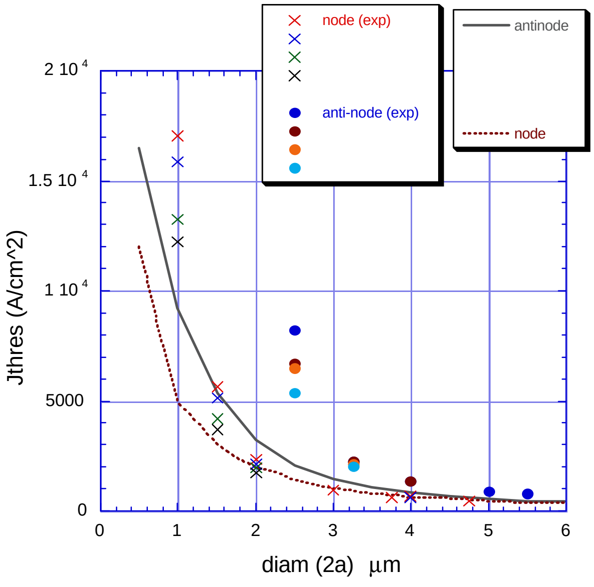

Fig. 3 Threshold current density vs. aperture diameter 2a