
A Three-Dimensional Microscopic Simulation For Vertical Cavity Surface Emitting Lasers

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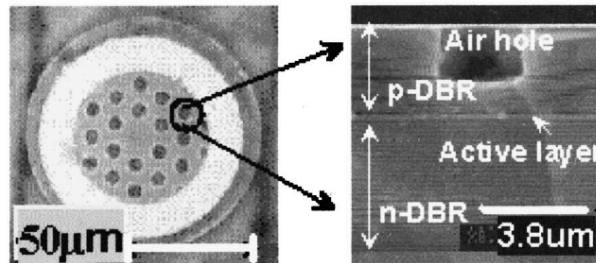
ETH Zürich

Overview

- ❑ Motivation
- ❑ Model Description
- ❑ Simulation Example: Holey VCSEL with Oxide Confinement
- ❑ Device Analysis
- ❑ Conclusion and Outlook

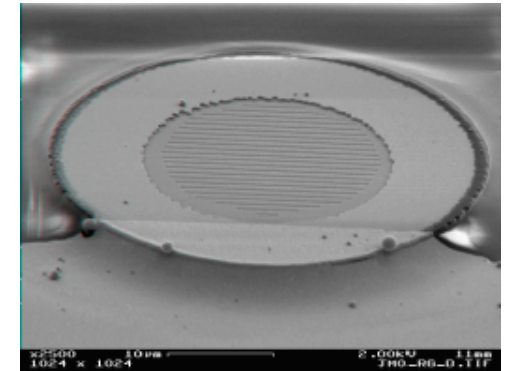
Motivation: 3-D VCSEL Simulation

- ❑ Critical Design Issues for VCSELs:
 - ❑ Single Mode Stability/Power
 - ❑ Temperature Stability AC/DC
 - ❑ Reproducibility/Yield (Polarization Stability etc.)
- ❑ Designers incorporate non-cylindrical features:
 - ❑ Elliptic Mesas
 - ❑ Photonic Crystals
 - ❑ Surface Patterning

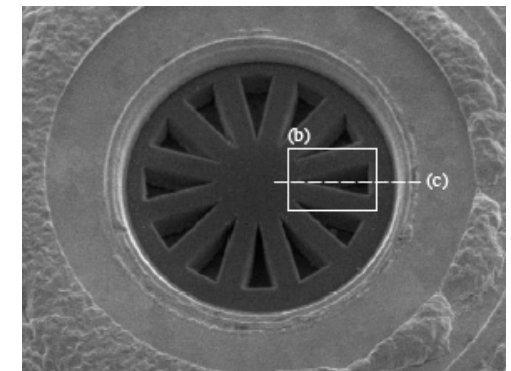


Korea Adv. Inst. Of Science and Tech. 2002

Outlook: High Performance VCSELs will have more complex geometrical features
=> 3-D Features require 3-D Simulation tools



Univ. Ulm 2005



Sony 2005

Simulation Framework

Free Carriers:

$$\nabla \cdot (\epsilon \nabla V) = q(p_{2/3D} - n_{2/3D} + N_D - N_A)$$

$$\nabla \cdot J_n(n_{3D}, V) = q(R_{3D} + C_n)$$

$$\nabla \cdot J_p(p_{3D}, V) = q(R_{3D} + C_p)$$

$$-\nabla \cdot S(T) = H(n_{2/3D}, p_{2/3D})$$

Bound Carriers:

$$(H + V)\psi = E\psi$$

$$C_n - G(n_{2D}, p_{2D}, \omega)S - R_{2D} = 0$$

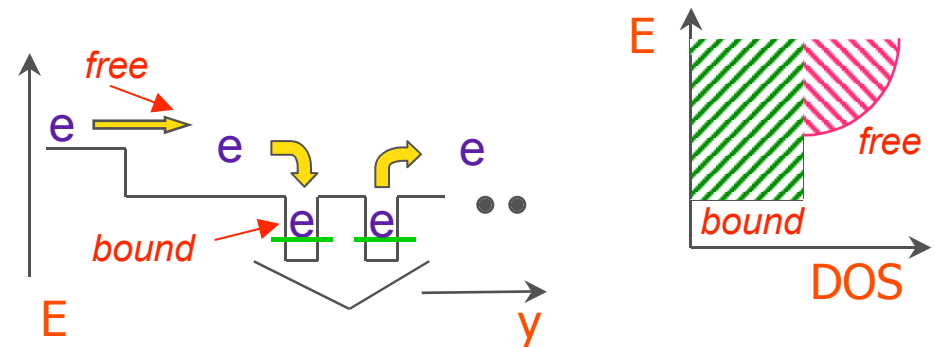
$$C_p - G(n_{2D}, p_{2D}, \omega)S - R_{2D} = 0$$

Photon Modes:

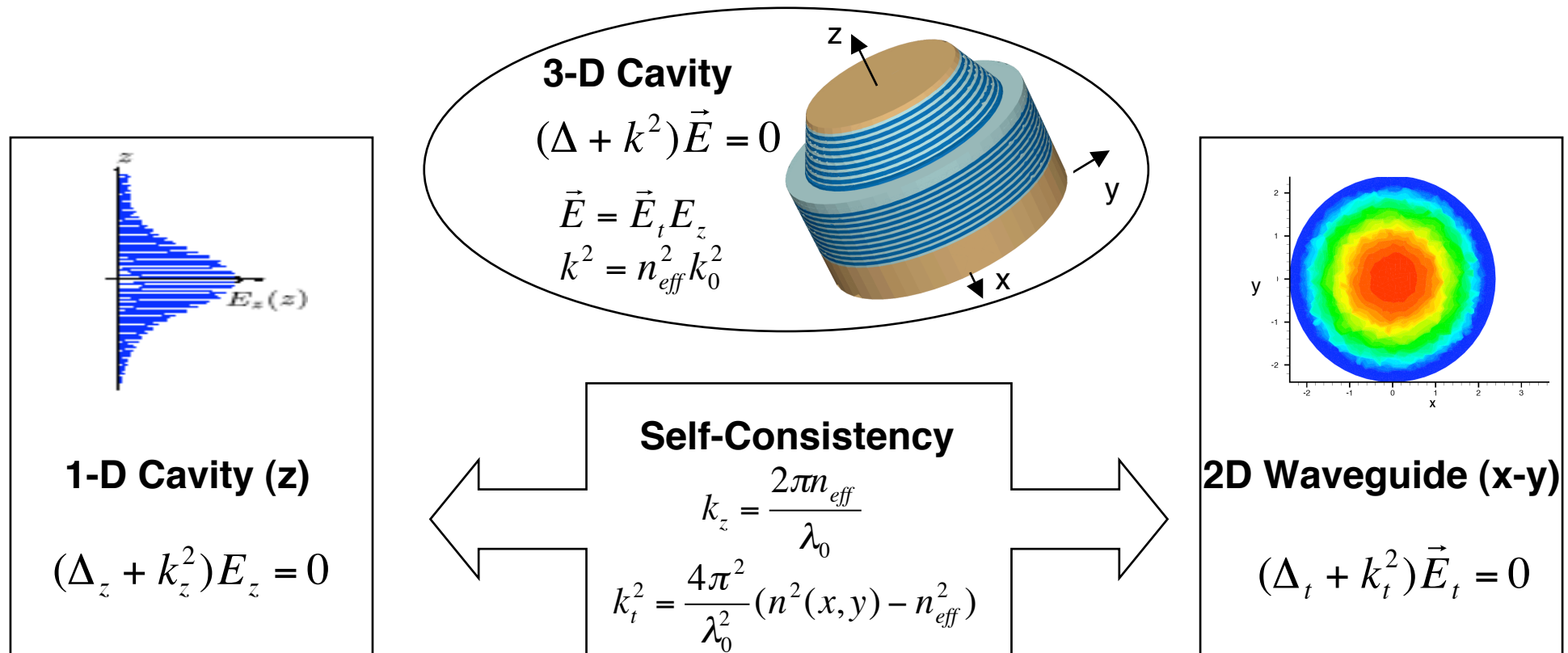
$$(\nabla^2 + \omega^2 \epsilon(n, p)/c^2)\phi = \kappa^2 \phi$$

$$S = \frac{\beta R_{sp}}{\alpha_{mirror} + \alpha_{FCA}(n, p) - G(n_{2D}, p_{2D}, \omega)}$$

- Electronics Solved in 1-D/2-D/3-D
- Thermionic Emission at Heterointerfaces
- Quantum Wells: Treated as Scattering Centers (Balance of Capture/Escape)
- Drift-Diffusion in Bulk



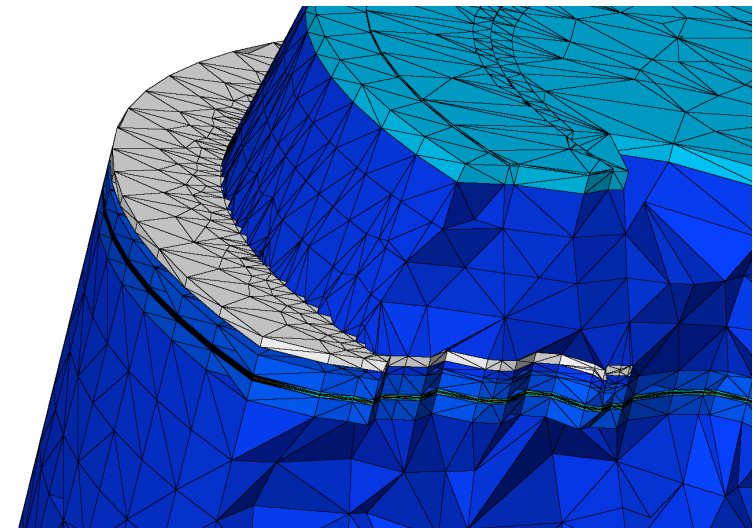
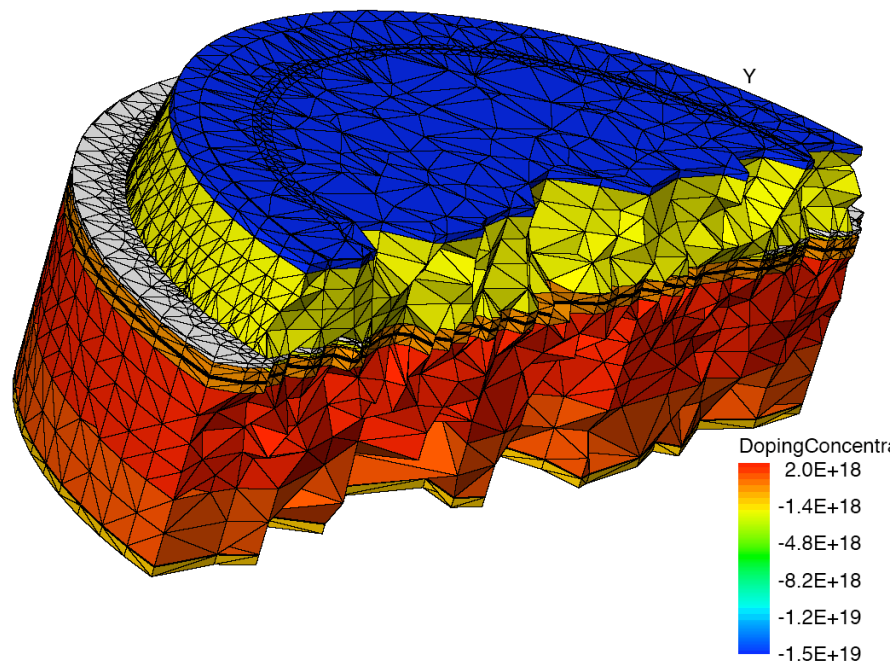
Three-Dimensional Optical Mode Calculation



- “Effective Index Method” (1D Cavity by TMM/2D Waveguide FEM/EIM)
- Iterative Solution gives Eigenvalue & Eigenvector of 3D Cavity

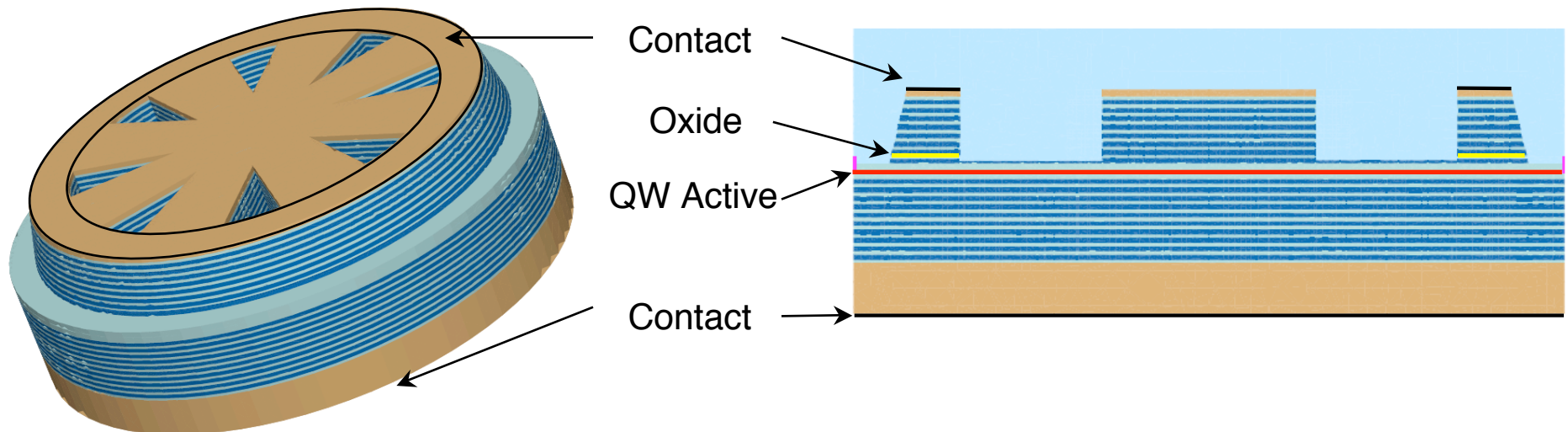
Modeling Aspects

- Unstructured, Tetrahedral Delaunay 3-D Mesh
- Refinement for Nano-Structures
- Script-based Commercial Solid Modeling Tool (dev_ISE)
- Example: SQW VCSEL, 6 μ m mesa diameter, Oxide Aperture: 203,000 Elements, 67,000 Vertices



Example: 750nm Oxide Confined VCSEL

- Single Quantum-Well GaAs/AlGaAs
- AlGaAs Distributed Bragg Reflectors
- Oxide Aperture with 6 μm diameter, Mesa top Ring Contact
- 2 Geometries: Standard Mesa and Holey Mesa
- Holey Geometry: inner (outer) diameter 3 μm (7 μm), opening 30°



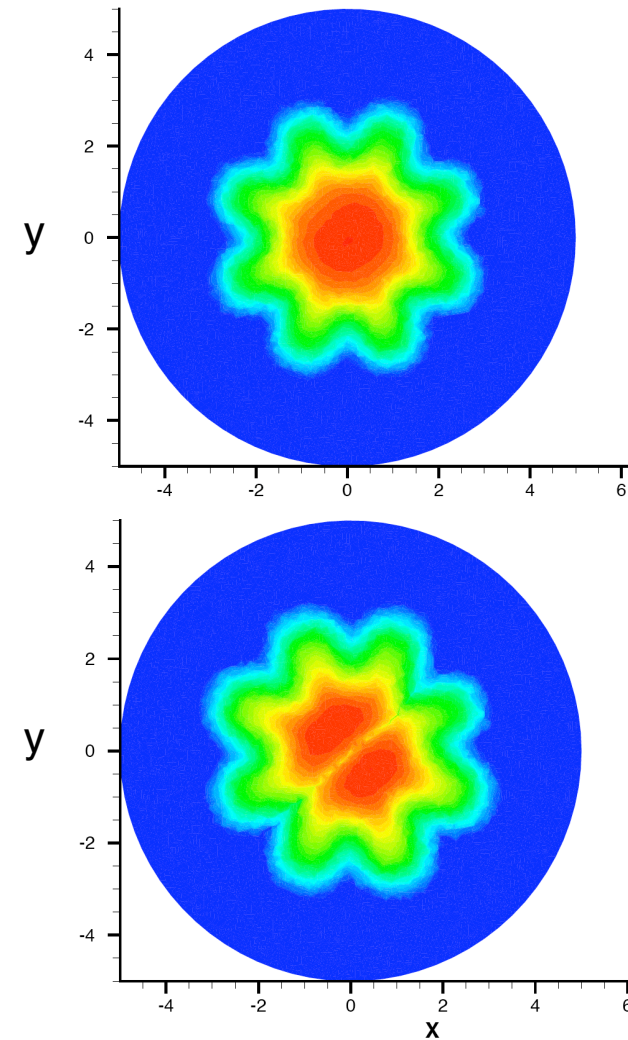
Holey VCSEL: Mode Pattern

- Inverse Cavity Photon Lifetimes from 2-D FEM calculations: [$10^{11}/s$]: LP01 / LP11

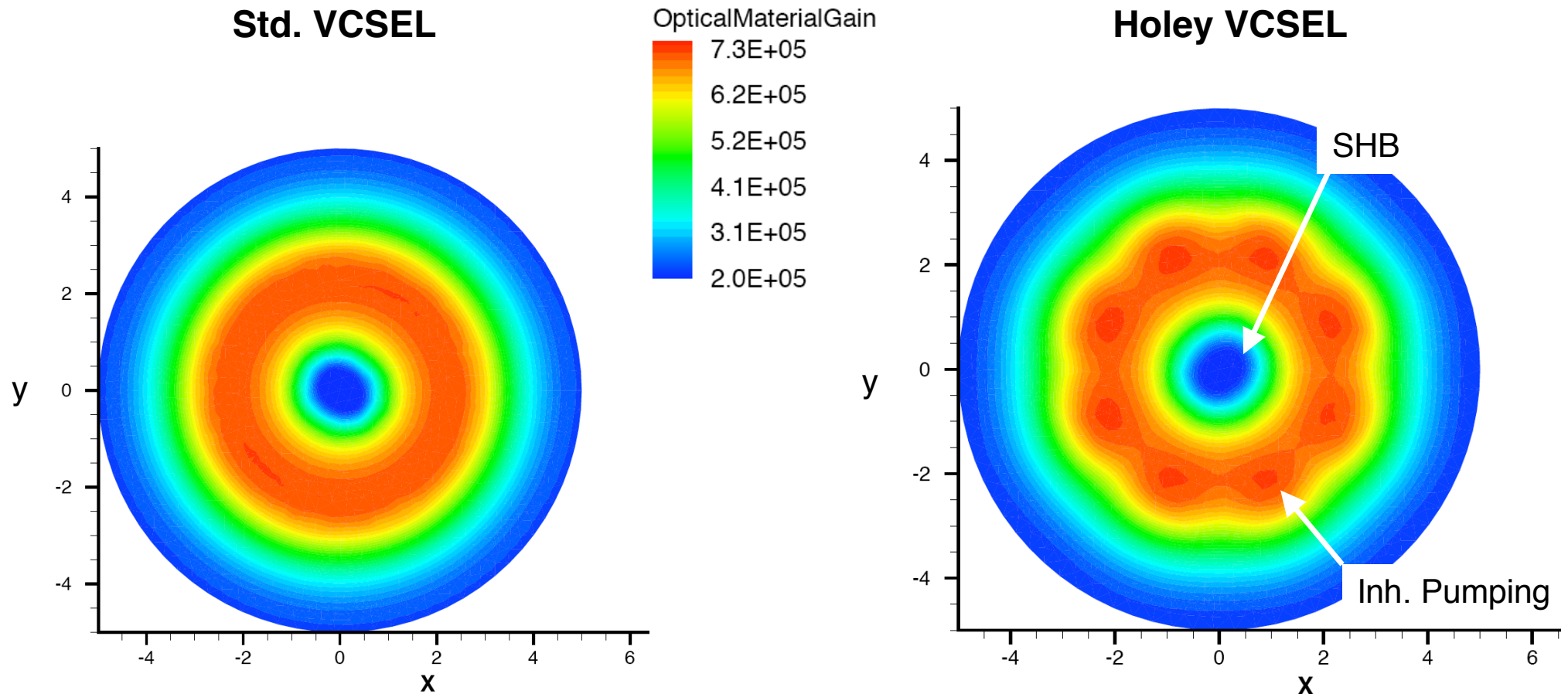
Standard: 4.0 and 4.3

Holey: 4.0 and 6.0

- Floral Mode Pattern in x-y cut through Quantum-Well Plane



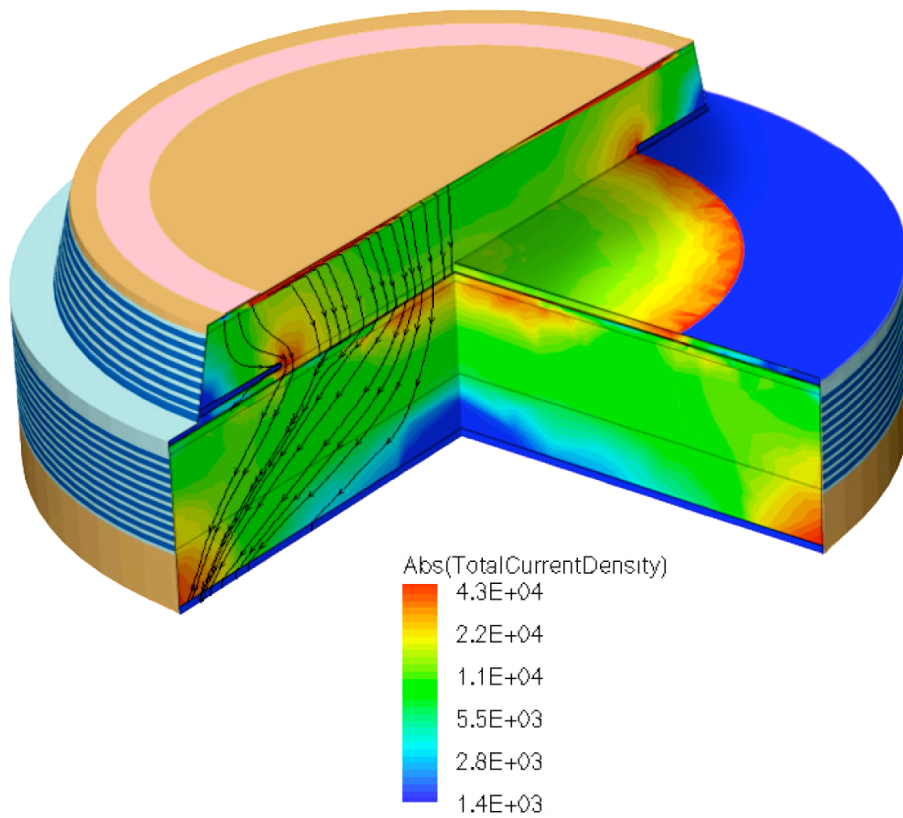
Spatial Hole Burning (SHB)



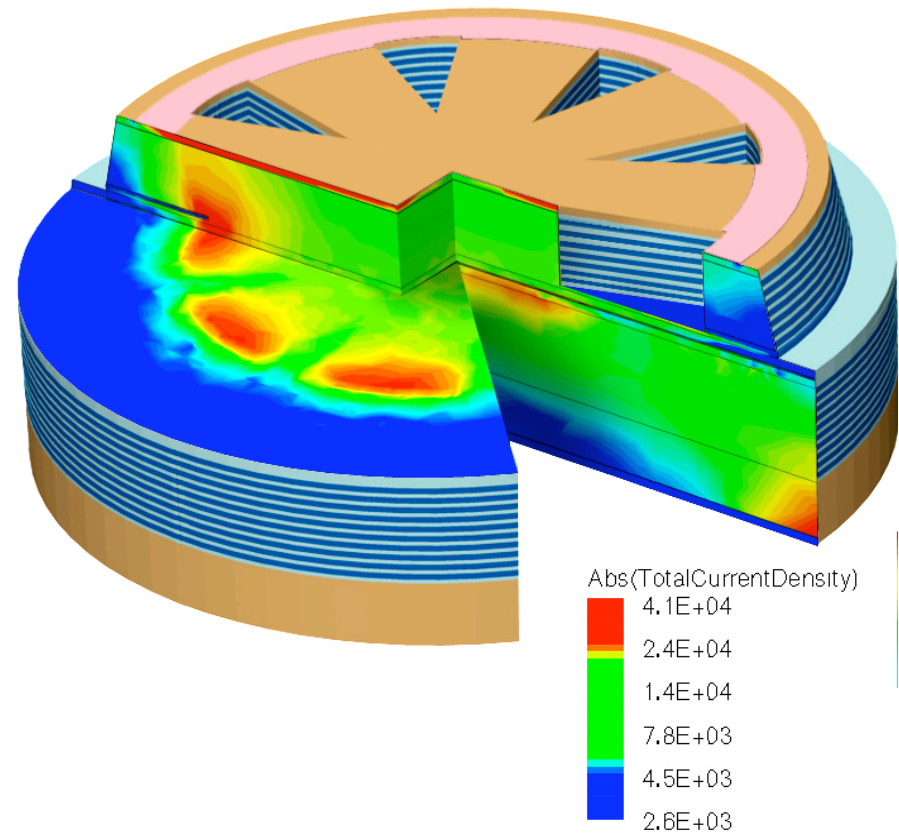
X-Z cut through quantum-well plane at $I = 6$ mA

Current Density

Std. VCSEL



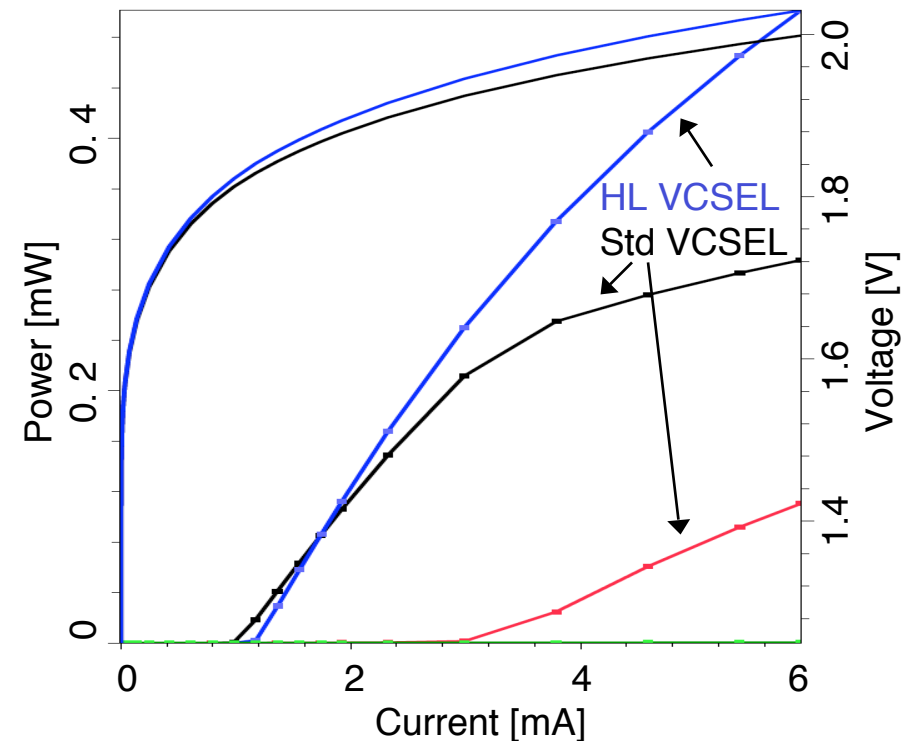
Holey VCSEL



Single Mode Stability

Comparison Holey versus Standard VCSEL:

- ❑ Higher Threshold due to inhomogeneous carrier supply to active
- ❑ Higher Efficiency due to better internal efficiency (lower leakage at oxide)
- ❑ Higher SM Output Power (Increased LP11 Optical Loss)
- ❑ Higher Resistance due to reduced P-Injection Area



Conclusion & Outlook

- ❑ 3-D Microscopic Simulation of VCSELs
- ❑ Optics 2.5-D Separation Approach/Electronics Full 3-D
- ❑ Examples: Standard QW VCSEL with Oxide Aperture and Holey VCSEL with Oxide Aperture
- ❑ Holey VCSEL shows improved SM stability and Power due to:
 - ❑ Optical Losses
 - ❑ Internal Efficiency

Outlook:

- ❑ Full 3-D Optics
- ❑ Inclusion of Many-Body Gain & Calibration to real-world Example

Acknowledgements

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