



Integrated Systems Engineering

Development, Modeling, and Optimization of Microelectronic
Processes, Devices, Circuits, and Systems

Dessis for Optoelectronics

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Overview

- Introduction
- Components of a Laser/LED Simulator
- Highlights of Some Advanced Physics
- Optoelectronics Examples



Introduction to Optoelectronics Simulation in Dessis



History

- **History of electronic simulator**
 - 1993, spinoff from research of Swiss Federal Institute of Technology, ETH, Zurich
 - Became industry standard for modeling CMOS devices, HEMTs, HBTs and high power devices
- **History of laser simulator**
 - 1999, added optics, QW, gain and photon rate modules to the electronic simulator
 - 2000, VCSEL simulation enabled
 - 2002, better gain modeling
 - 2002, photodetector modules added

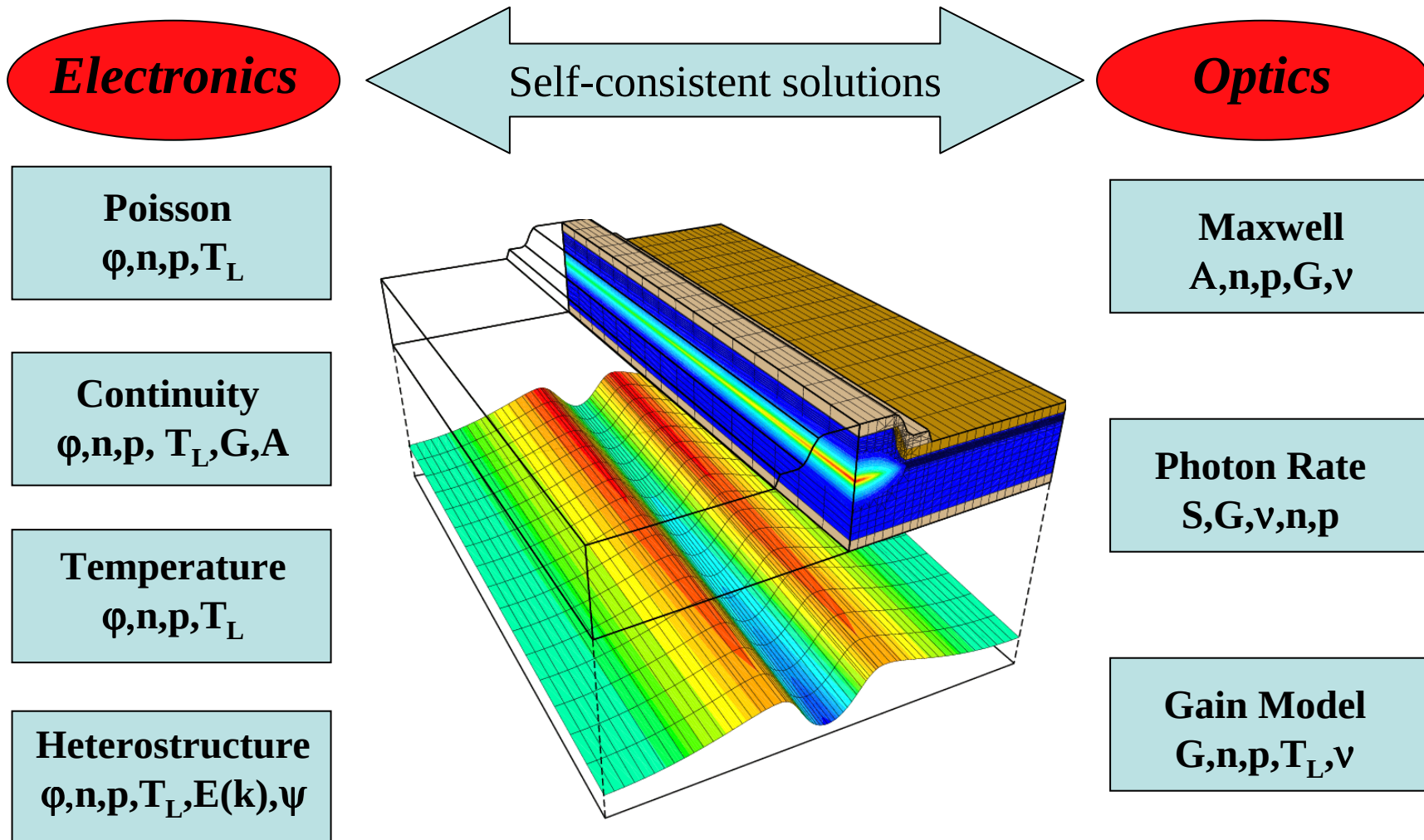


History and Future

- **History of laser/LED simulator**
 - 2003, ray tracing module enabling LED simulation
 - 2004, Full 3D edge emitter simulation
 - 2004, Noise and AC models for lasers
- **The future...research at ETH**
 - Superluminescent LED
 - Tunable lasers
- **The researchers:**

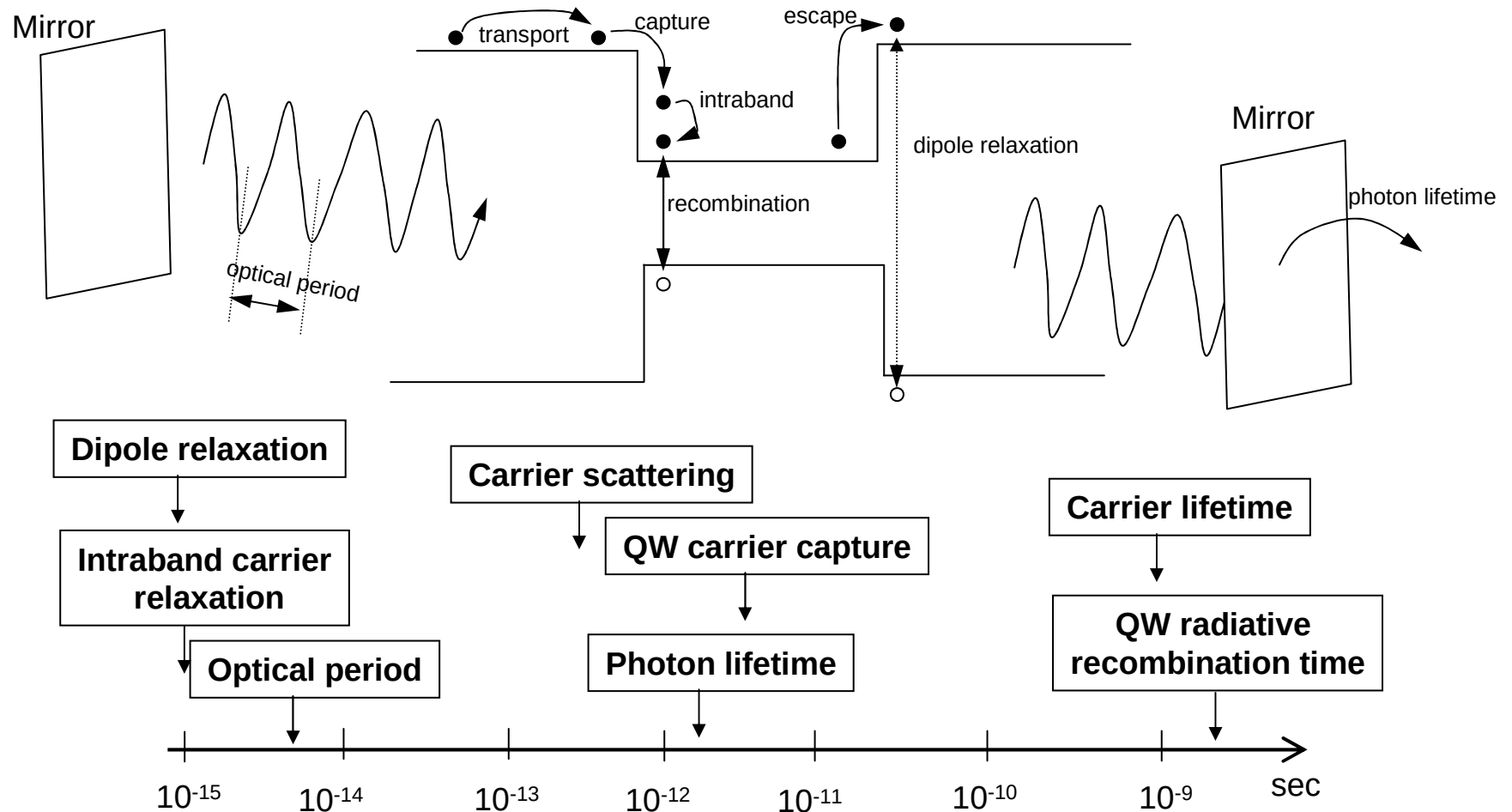
Bernd Witzigmann, Andreas Witzig, Matthias Streiff, Michael Pfeiffer, Lutz Schneider, Stefan Odermatt, Valerio Laino, Prof. Wolfgang Fichtner

Physics-based Optoelectronics TCAD

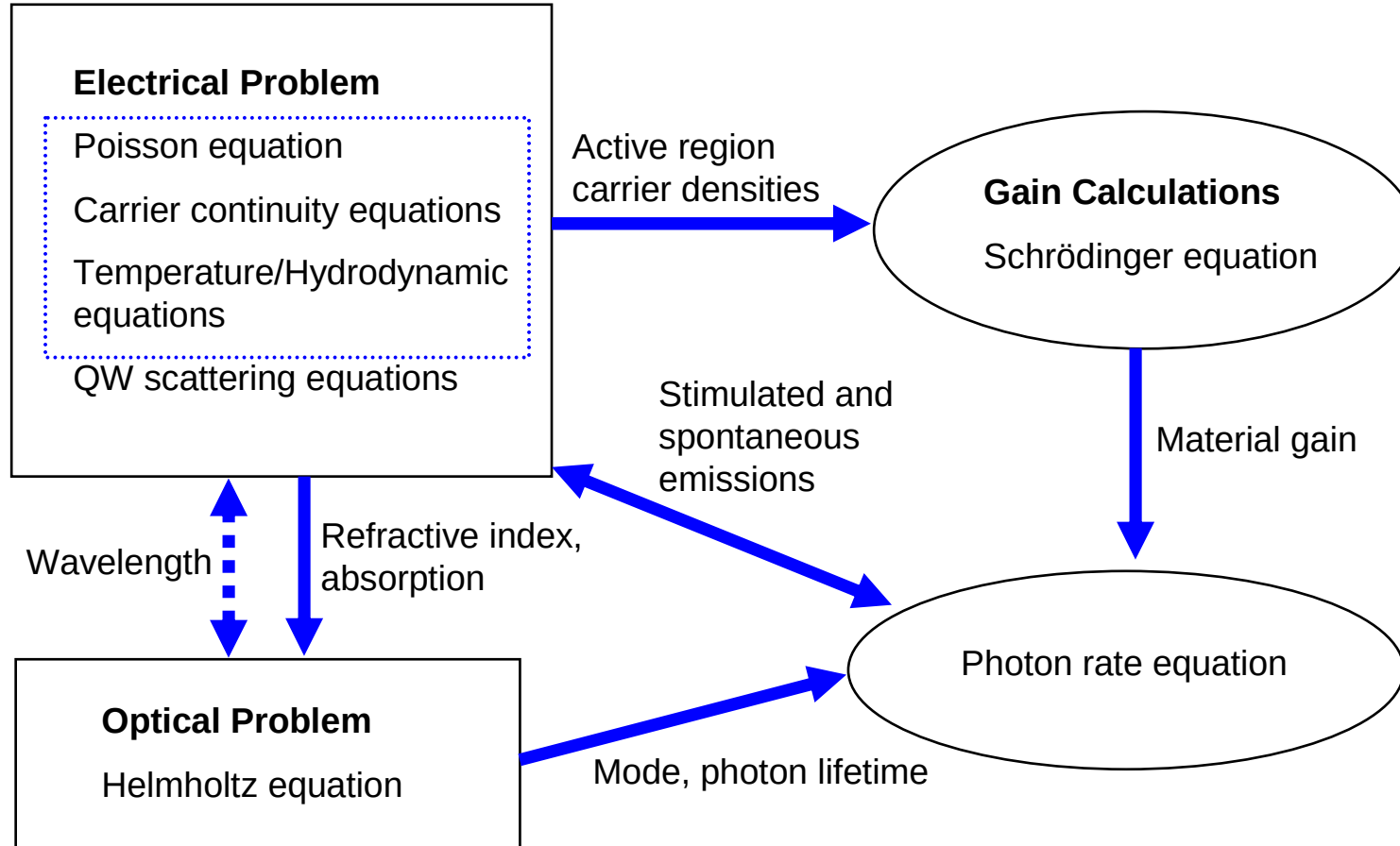


Time Scale

Quantum mechanical treatment of carriers and classical treatment of optics is applied



Coupling between Electronics & Optics



Optoelectronics Applications

- **Benchmark Applications**

- 2D Edge Emitting Lasers (bulk, QW, Fabry-Perot, simple DFB)
- 3D Edge Emitting Lasers (with varied grating and sectional design)
- VCSELs (including gain guiding and thermal lensing effects)
- Light Emitting Diodes (LED), 2D & 3D
- Photo detectors (PD, APD, MSM)
- Imaging, CMOS Sensors, CCD, Solar cells



Components of a Laser/LED Simulator



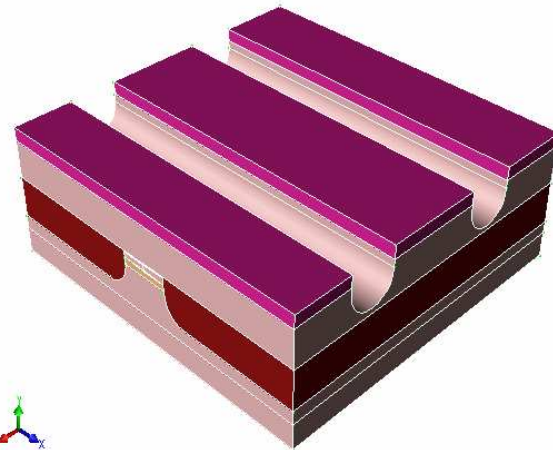
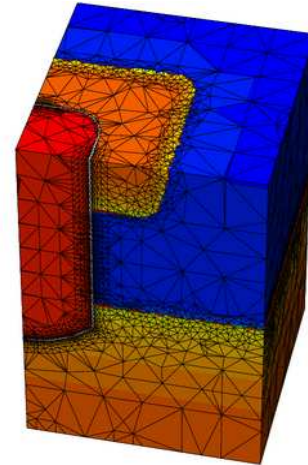
Components of a Laser Simulator

- Representation and Material Database
- Electronic Solver
- Optical Solver
- Quantum Well Transport
- Gain Calculations
- Coupling Everything



Representation of the Problem

- **Devise**, new and versatile editor that enables user to draw 2D and 3D geometries and intersections easily.
- Finite Box Integration method applied to every node of the mesh.



Material Database

- All III-V compounds used in lasers and LEDs
- Binary, ternary, quaternary compounds with default set of parameters
- Users can change any parameter and define the properties of a new material
- A PMI (Physical Model Interface) allows the user to implement functions for certain parameters, e.g. refractive index, bandgap narrowing, etc.



Electronic Solver

- **Poisson, Continuity, Thermodynamic and Hydrodynamic equations**
- Different mobility models
- Ionization, quantization, traps, tunneling models
- Different recombination-generation models
- Degradation, radiation models
- Noise and fluctuation analysis
- Monte Carlo used to tune strained CMOS parameters



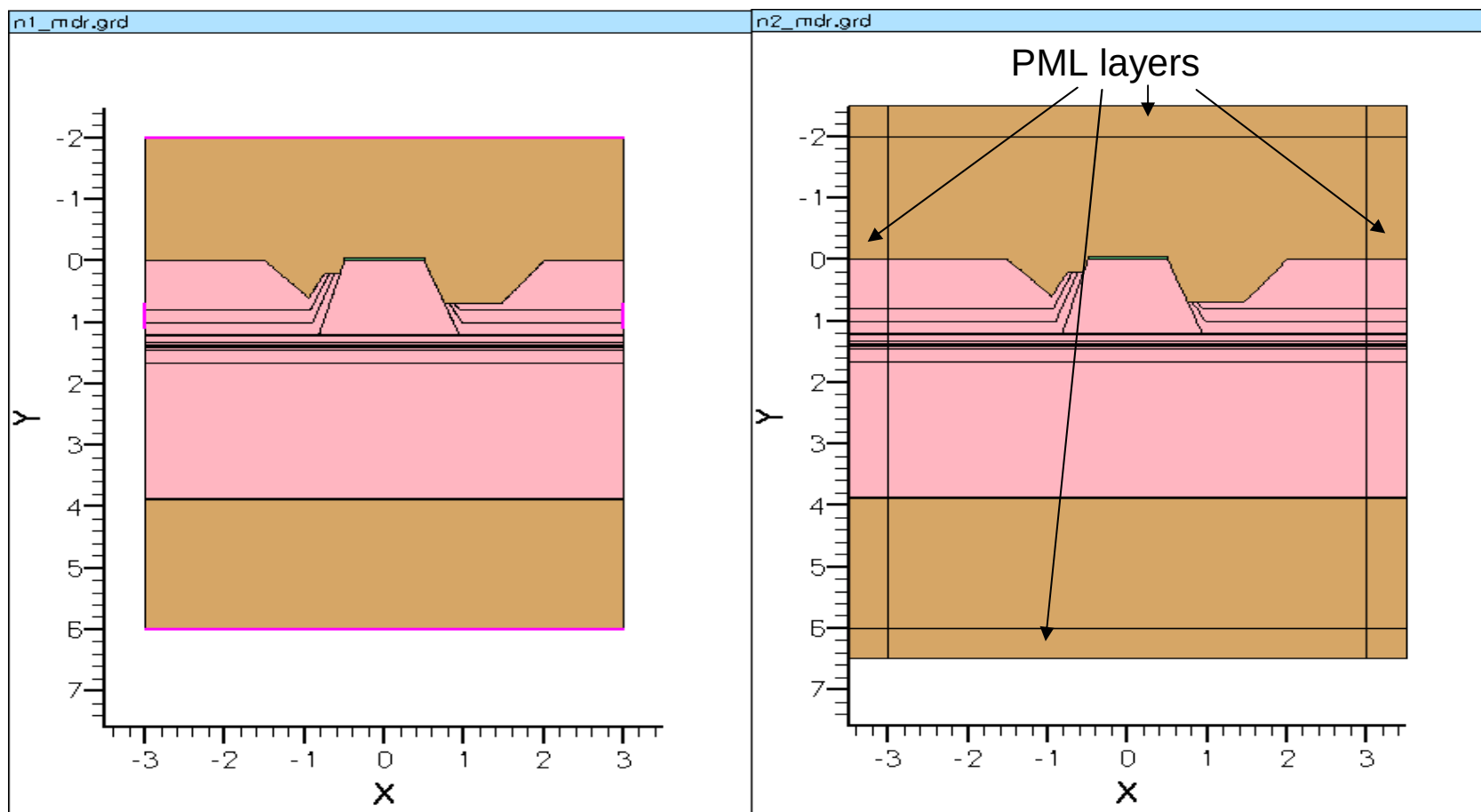
Optical Solvers - Laser

Waveguide problem : Helmholtz equation

Cavity problem : Wave equation

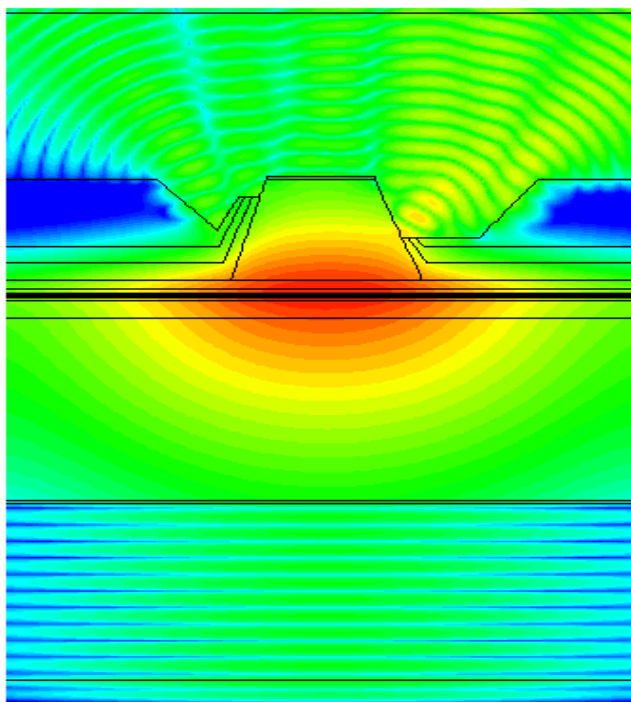
- **Finite element method (FEM)**
(both waveguide & cavity problems, scalar & vectorial)
- **Perfectly Matched Layer (PML)**
(to simulate radiative boundary conditions)
- **Standalone Optical Solver**
(to optimize mode shape and wavelength)

Optical Solvers - PML



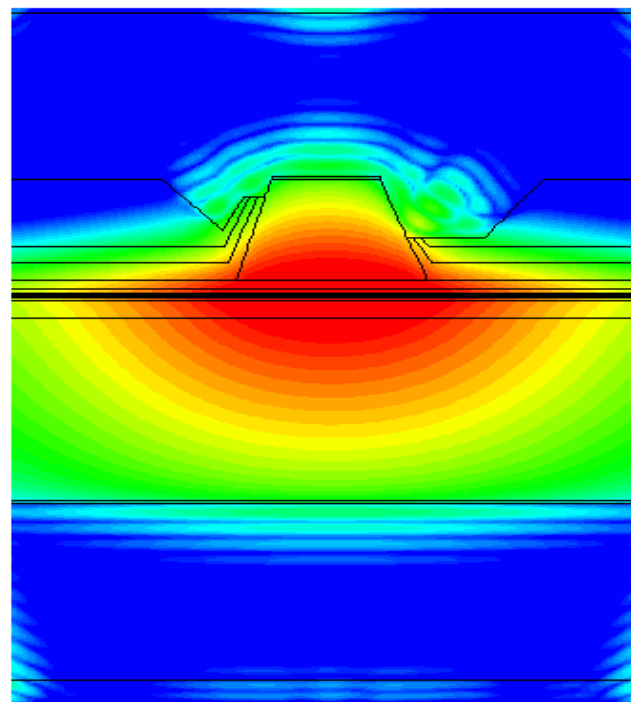
Optical Solvers - PML

zero absorption in GaAs



loss -14.0 [dB/cm]

5e6 1/cm absorption in GaAs

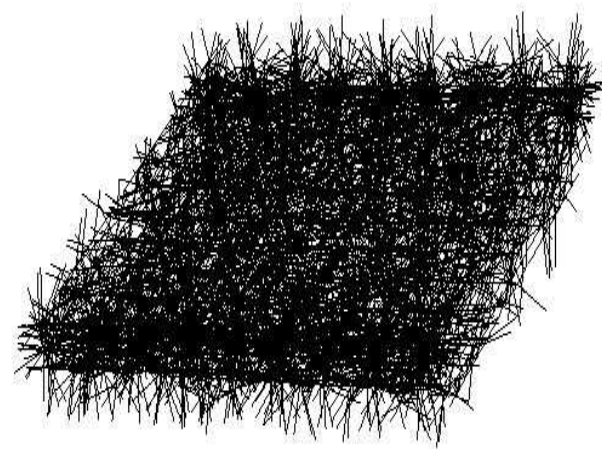
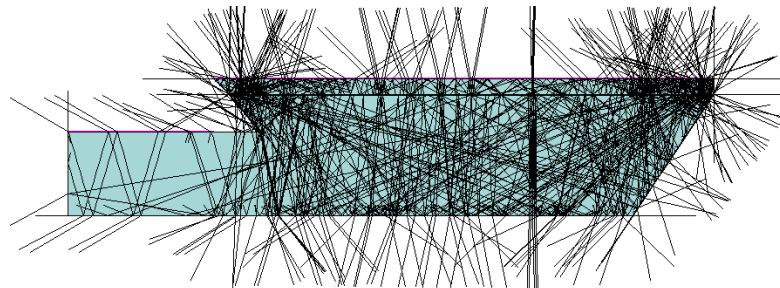


loss 10.58 [dB/cm]

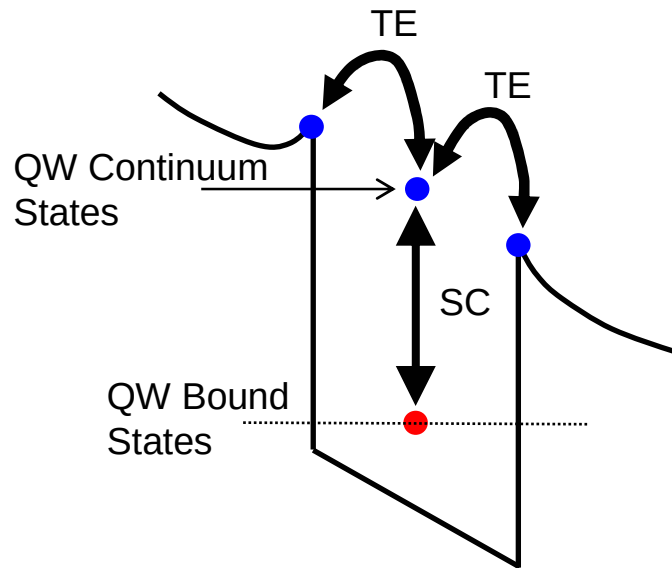
Optical Solvers - LED

LED problem : Wave equation

- Ray Tracing method
(for large structures in the millimeter range)



Quantum Well Transport



TE: Thermionic Emission

SC: Carrier Scattering

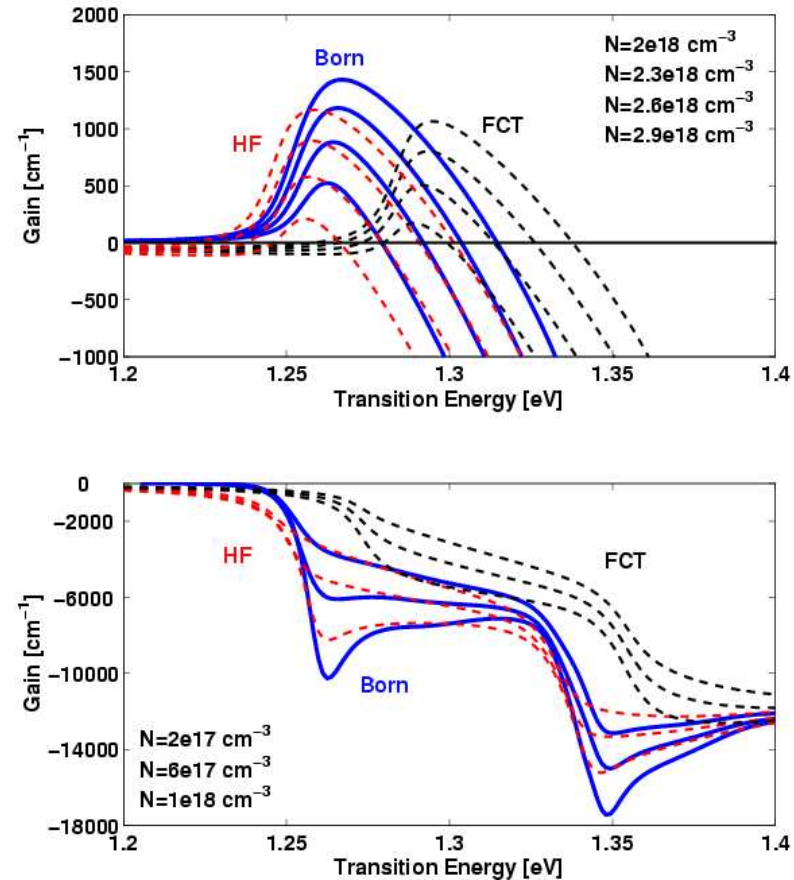
- Capture into QW based on a scattering process
- Separate continuum and bound states carrier continuity equations
- Drift-diffusion transport in the lateral plane of the QW
- Only bound state carriers contribute to the gain calculations

Gain Calculations

- Simple model using rectangular wells
(polarization dependent optical matrix element)
- Advanced model with k.p method (Schrödinger coupled with Poisson)
(zinc blende: 4x4, 6x6 or 8x8. wurtzite: 6x6)
- Bandgap renormalization
- Strain
- Gain broadening models
(Lorentzian, Landsberg, Hyperbolic-cosine)

Gain Calculations

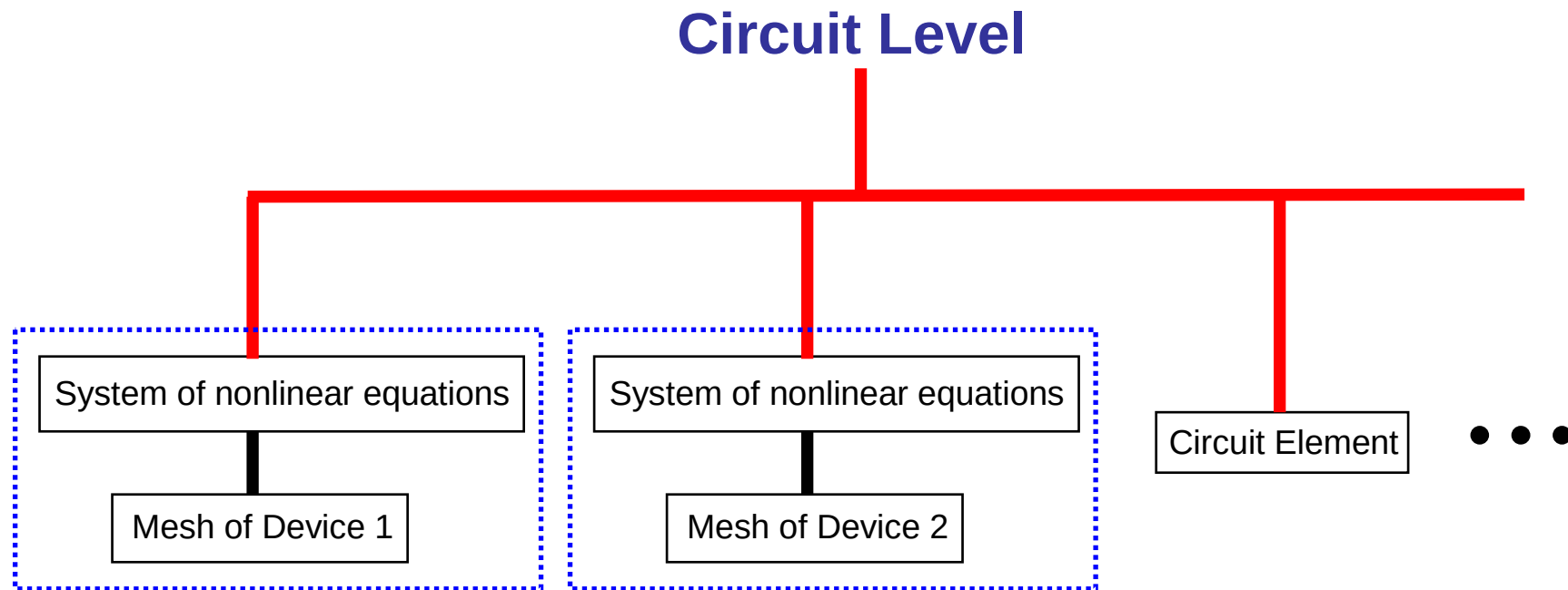
- Gain shift due to many-body effects
(free carrier theory, screened Hartree-Fock, 2nd Born approximation)
- Piezoelectric charge for GaN type QWs



Gain Calculations

- 1D gain modeling
(for initial design and fast tuning)
- PMI for loading in external table of gain values
(possibly from direct measurements)
- Option to output gain tables
(for calibration of gain parameters)
- Output k.p bandstructures and wavefunctions

Coupling Everything



- **Mixed-mode Simulation**
(combining device simulations with circuit elements self-consistently)

Coupling Everything

- Multiple levels and dimensions
(unlimited connectivity)
- Flexible mathematical framework
(add new models easily)
- Solved by Newton and Gummel iterations
- A wide choice of sparse linear and direct solvers
- Enhanced convergence
- Steady state, Transient and AC simulations

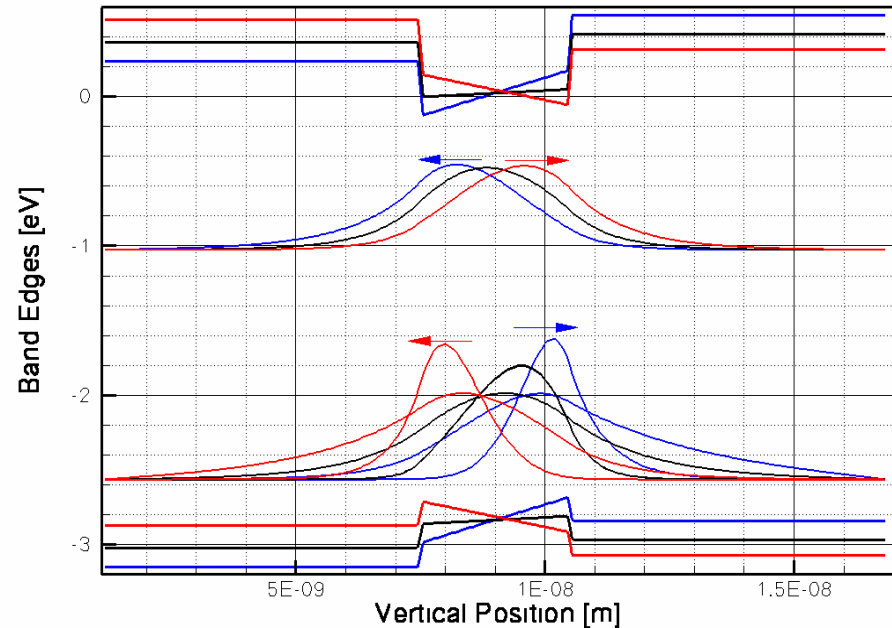


Highlights of Some Advanced Physics



Piezoelectric Field and Screening

- Quantum-confined Stark effect
 - Piezoelectric charge at material interfaces → tilted quantum-well
 - Quantum-well carriers are spatially distributed according to Schrödinger's equation → separation of Electrons and Holes
 - High Quantum-well carrier densities → screening of Piezoelectric charges
- Effect on laser gain
 - Gain reduction due to decreased electron-hole overlap → threshold shift



Band diagram and wave functions for bound carriers. Black: no Piezoelectric charge. Red and blue: positive and negative Piezoelectric charge, respectively.

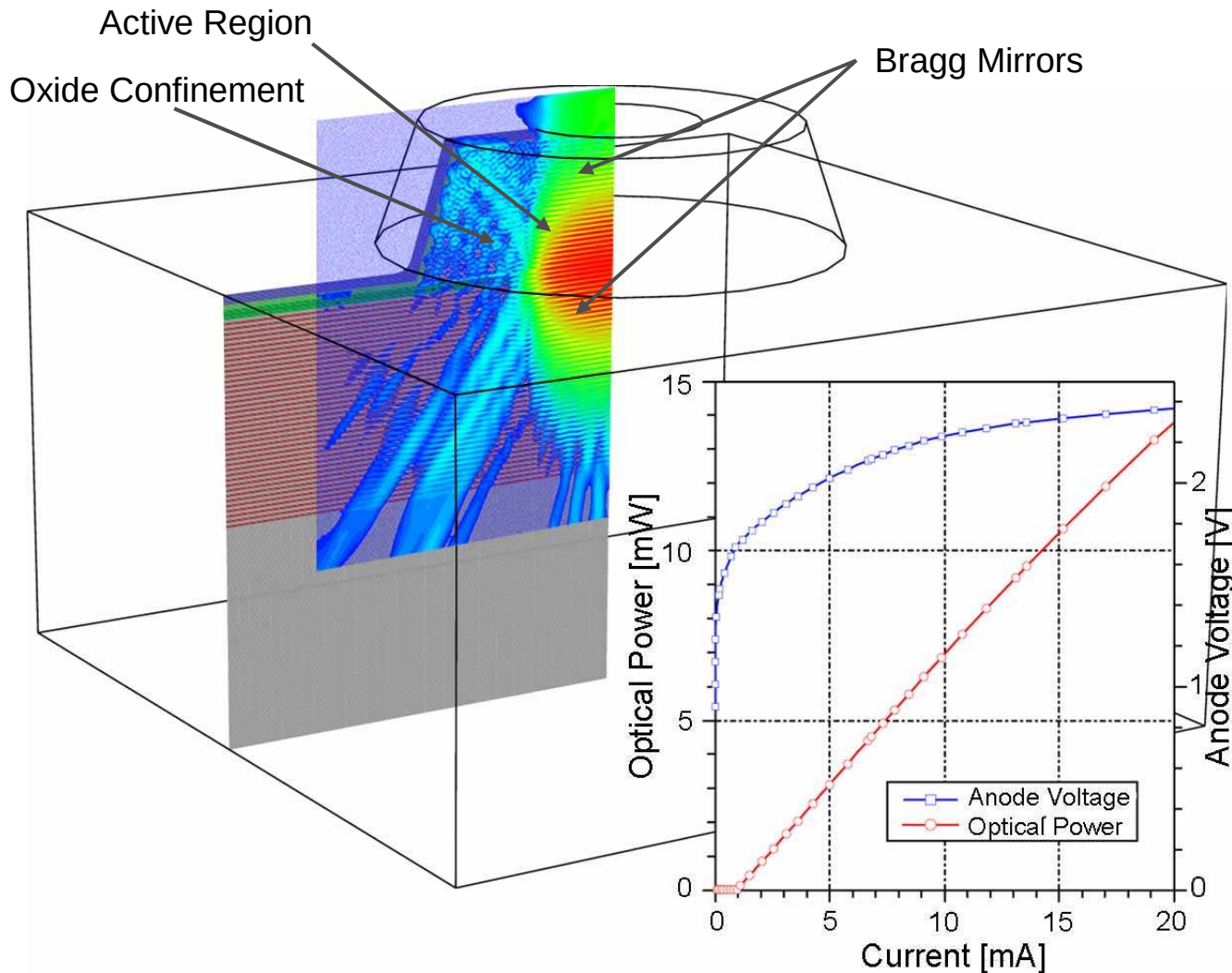
Optoelectronic Examples



AlGaAs/GaAs MQW etched mesa VCSEL simulation



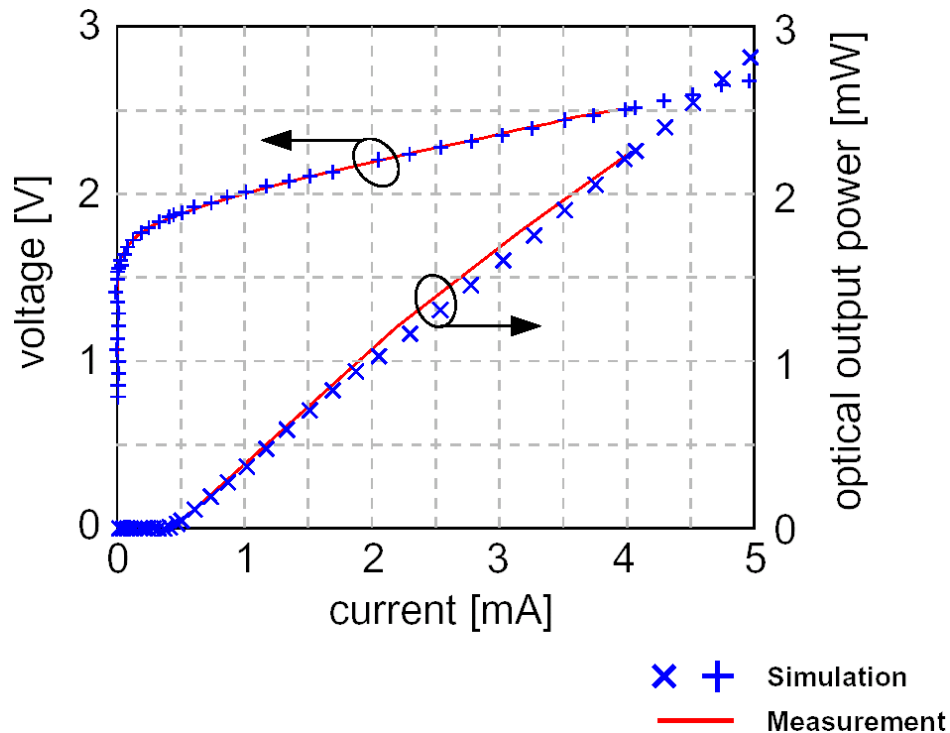
Optoelectronics: VCSEL Simulation



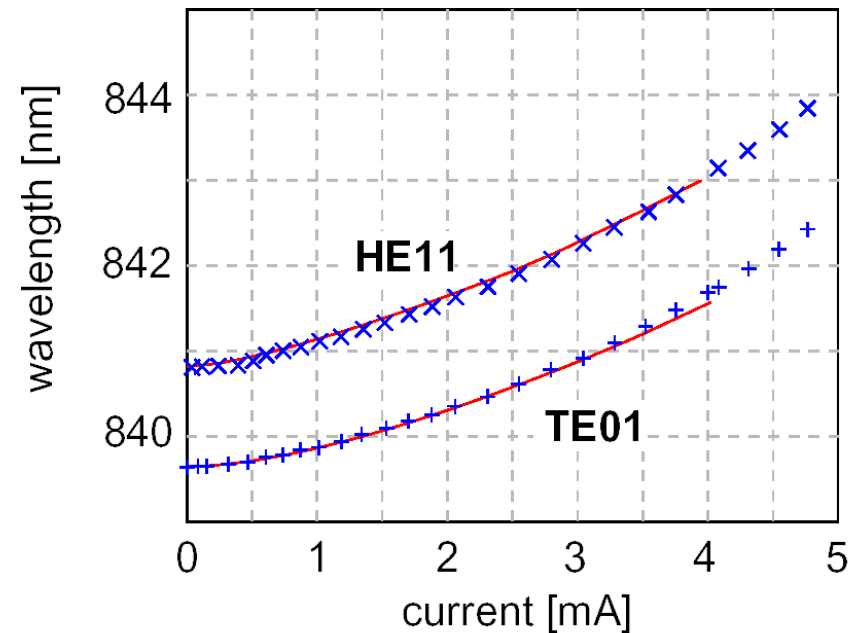
- Simulation of Vertical-Cavity Surface-Emitting Laser (VCSEL)
- Finite-Element Type Full-Vectorial Optical Mode Solver
- Rigorous Simulation of Diffraction Loss and Radiating Waves
- Simulation includes Spatial Hole Burning and Thermal Lensing

VCSEL: Comparison to Measurements

Output Characteristics

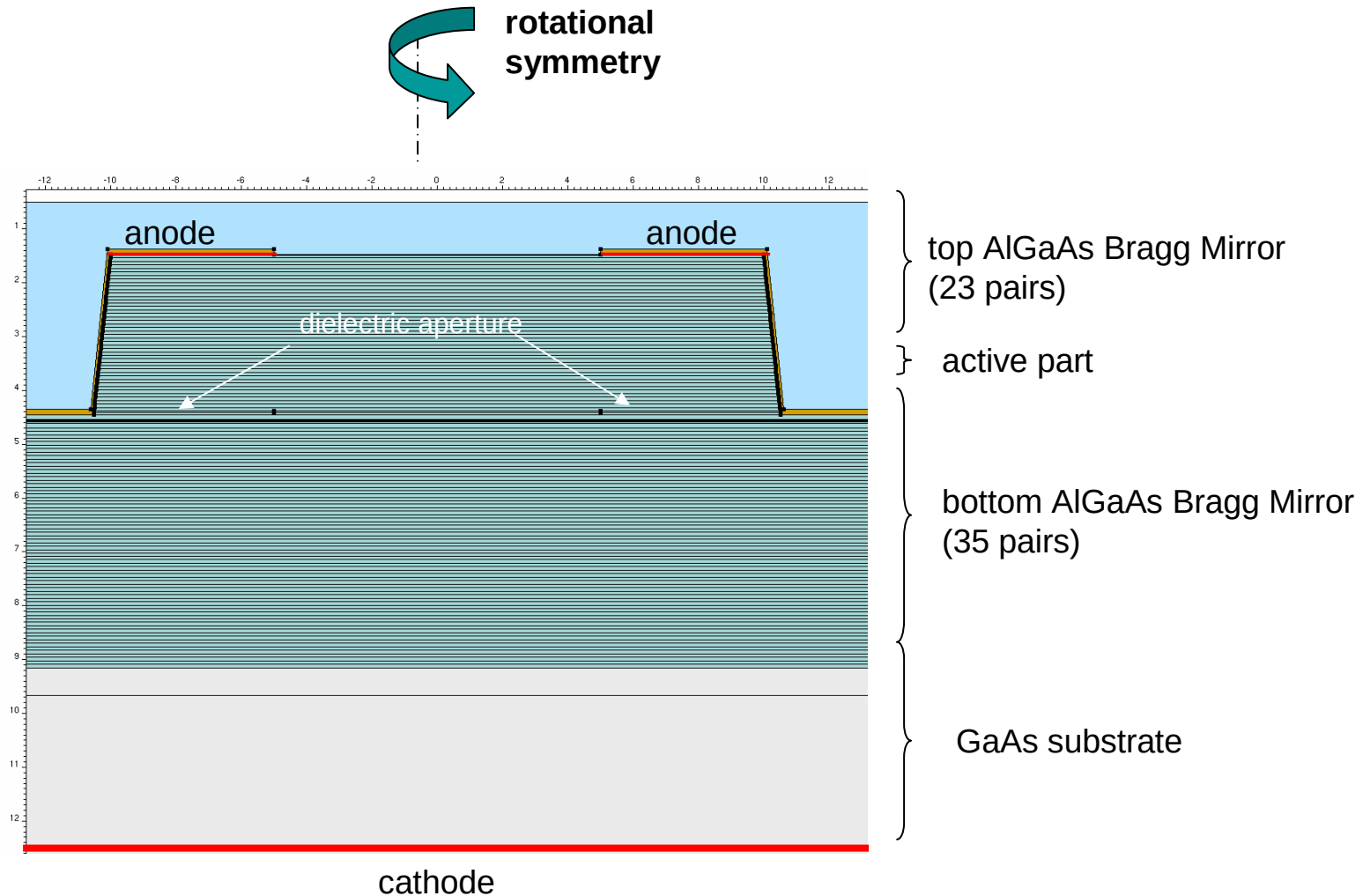


Wavelength Tuning (includes self-heating and thermal lensing)



Reference: M. Streiff, A. Witzig, M. Pfeiffer, P. Royo, W. Fichtner: "A Comprehensive VCSEL Device Simulator", IEEE Journal of Selected Topics in Quantum Electronics, vol. 9, no. 3, May/June 2003

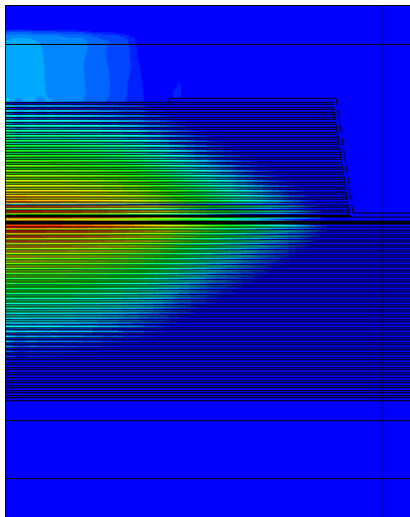
AlGaAs/GaAs MQW VCSEL



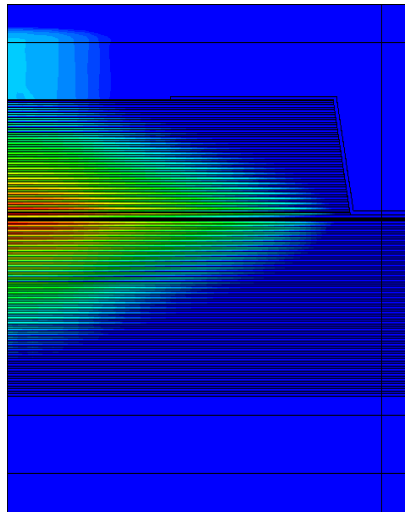
AlGaAs/GaAs MQW VCSEL

Optical field distribution (HE11 mode) inside VCSEL structures for different structure geometries

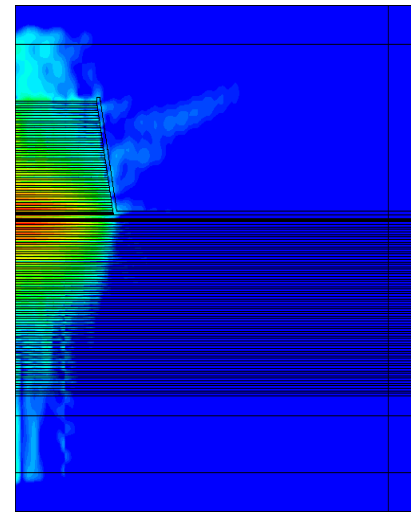
$R_{out}=10\mu m$, $R_{in}=5\mu m$,
 $R_{conf}=5\mu m$



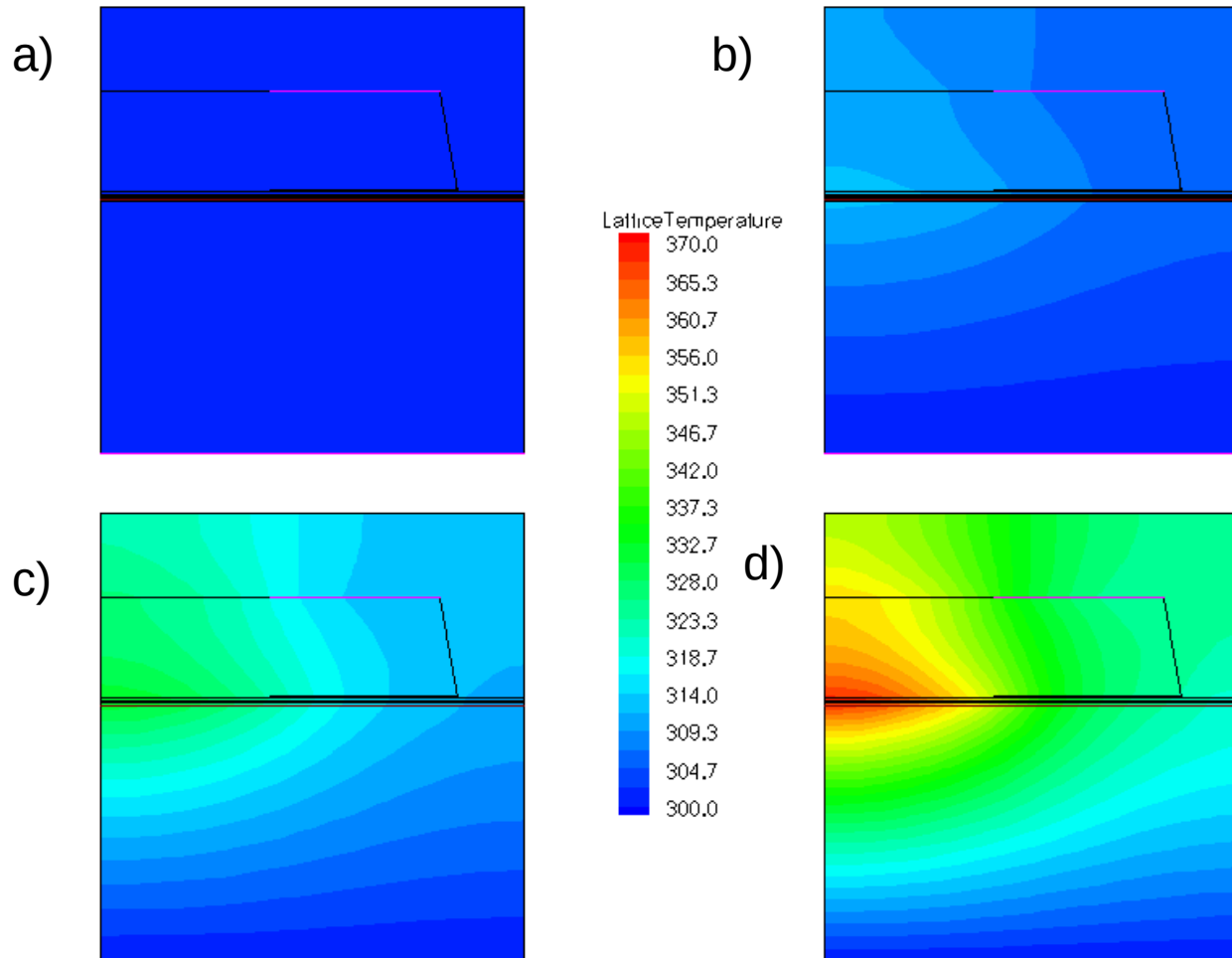
$R_{out}=10\mu m$, $R_{in}=5\mu m$,
 $R_{conf}=2.5\mu m$



$R_{out}=5\mu m$, $R_{in}=2.5\mu m$,
 $R_{conf}=1.5\mu m$

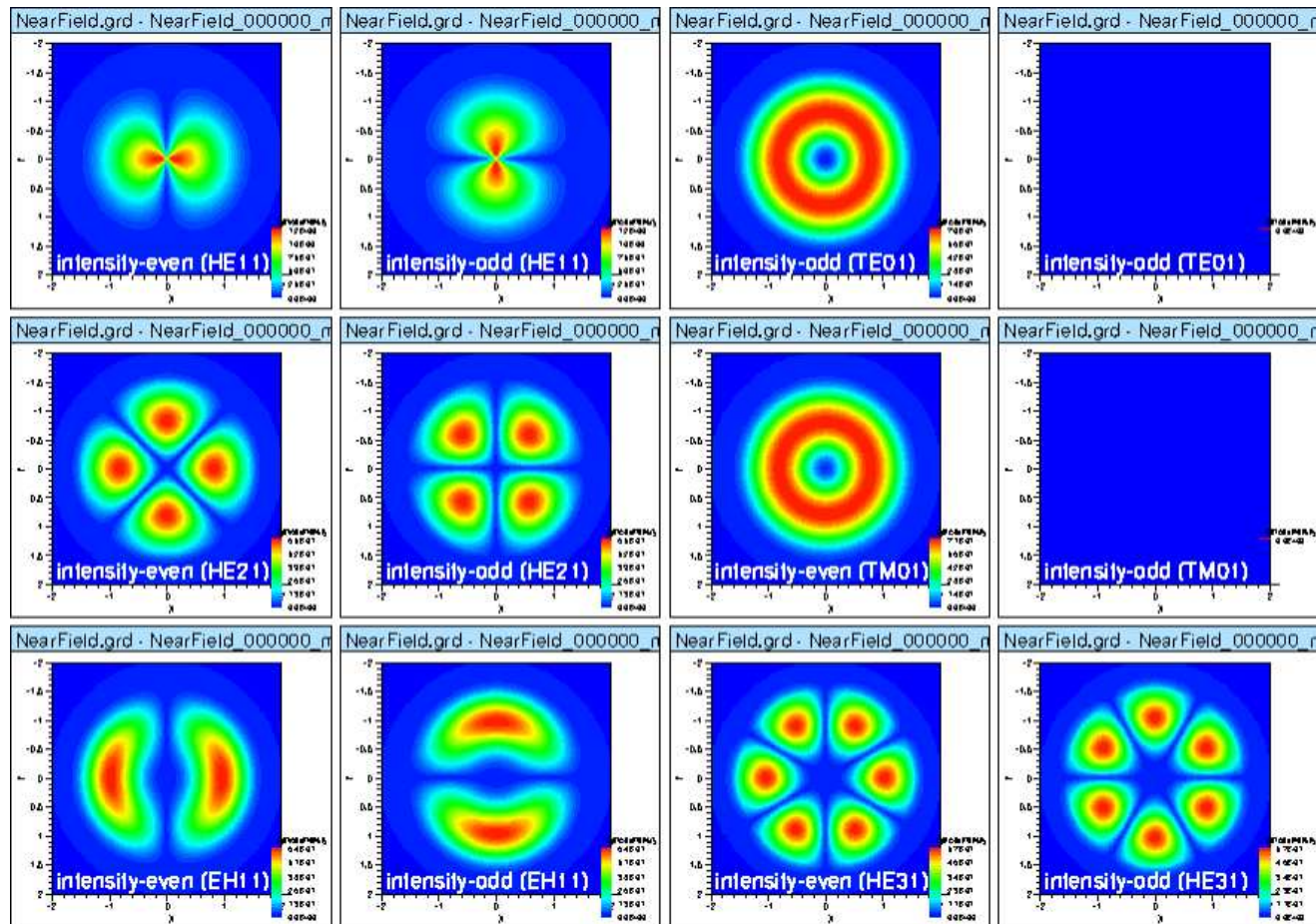


AlGaAs/GaAs MQW VCSEL



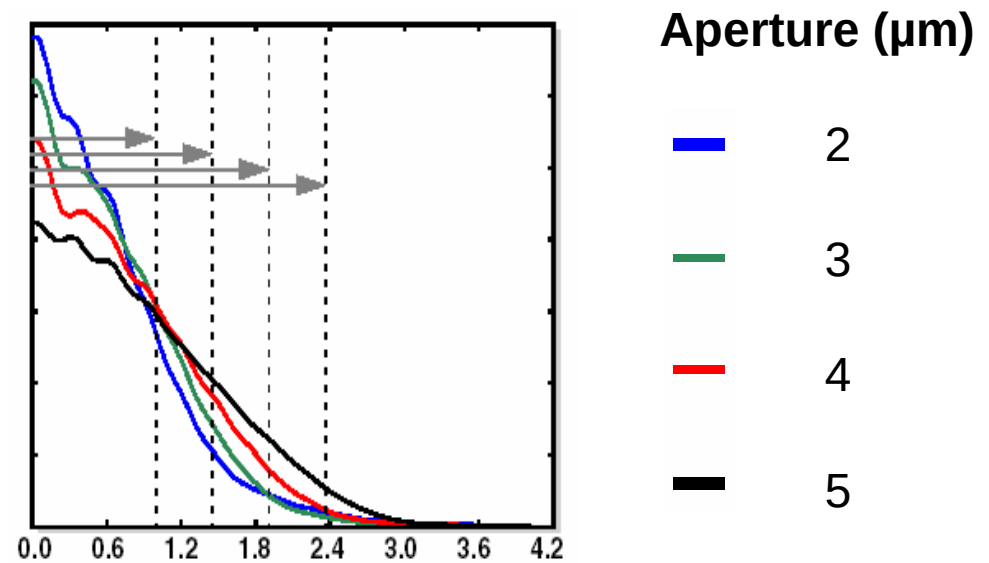
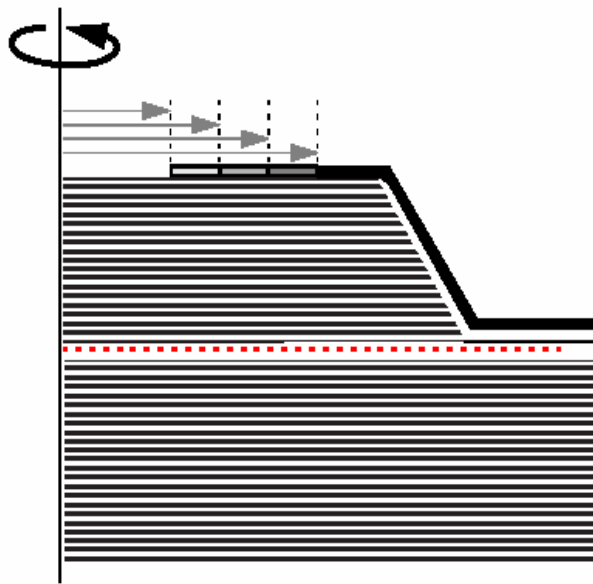
Lattice temperature distribution inside VCSEL taken at $V_a=1.3$ V (a), 1.8V (b), 1.9V (c), and 2V (d) bias points

VCSEL Near-Field Patterns



VCSELs

Typical VCSEL simulation task: Aperture optimization



Device optimization for:

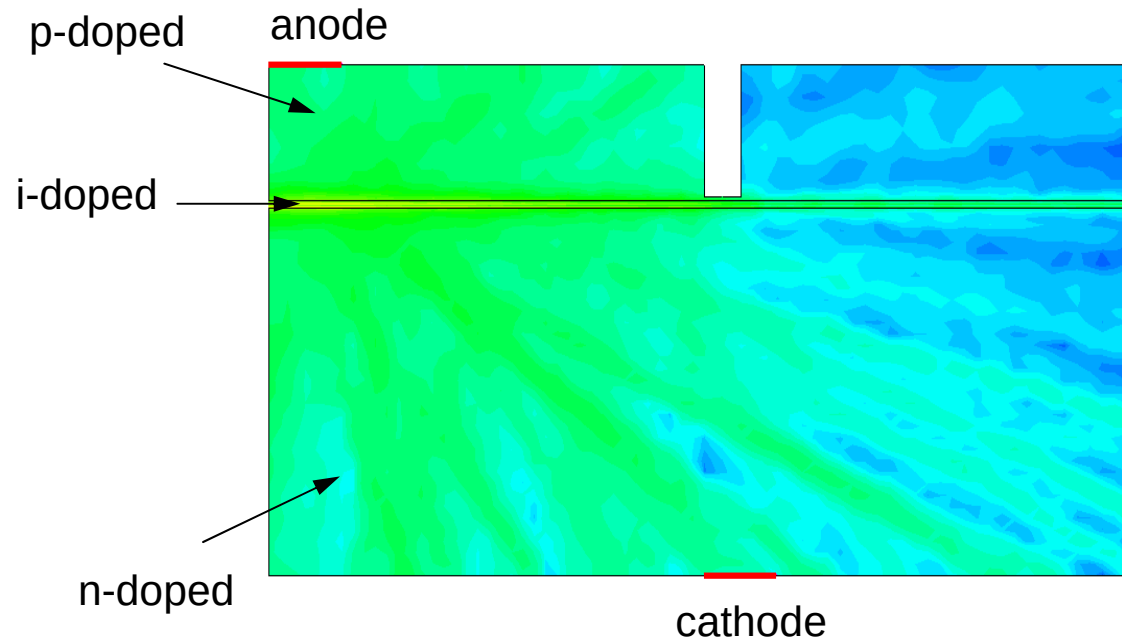
- Mode discrimination
- High Output power
- Good Fiber coupling

LED Simulation



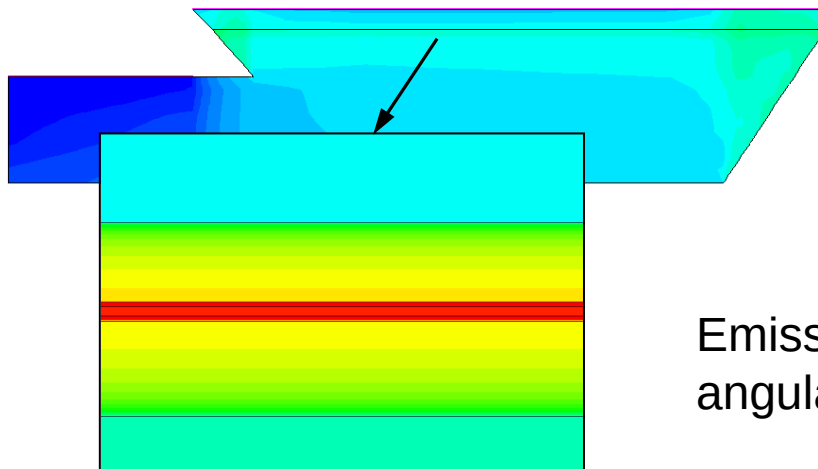
Light Emitting Diodes (LEDs)

Optical intensity distribution inside GaN LED at 2 Volts forward bias condition

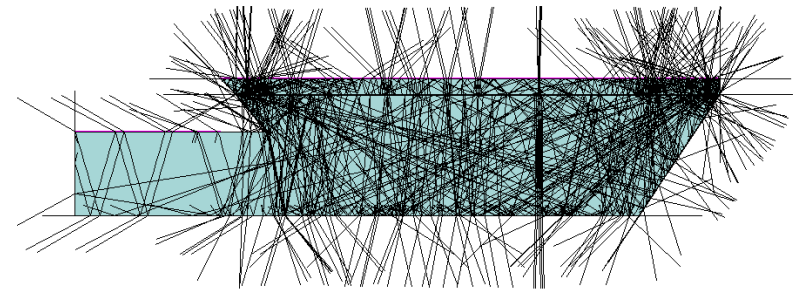


2D MQW AlGaAs/InGaAs LED

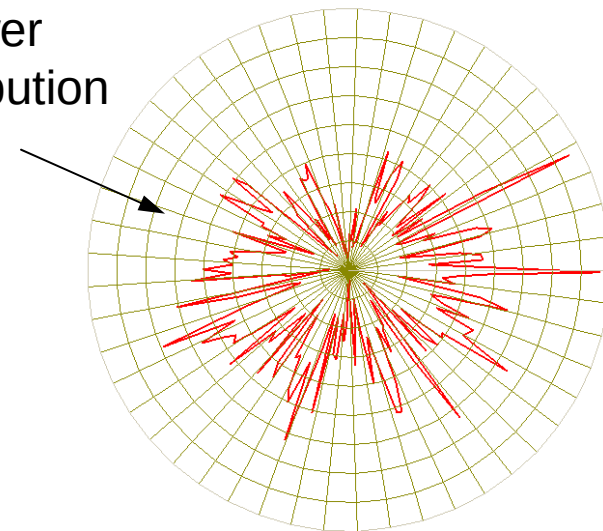
Optical intensity



Ray Trace portrait



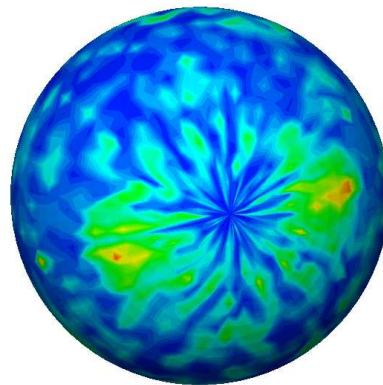
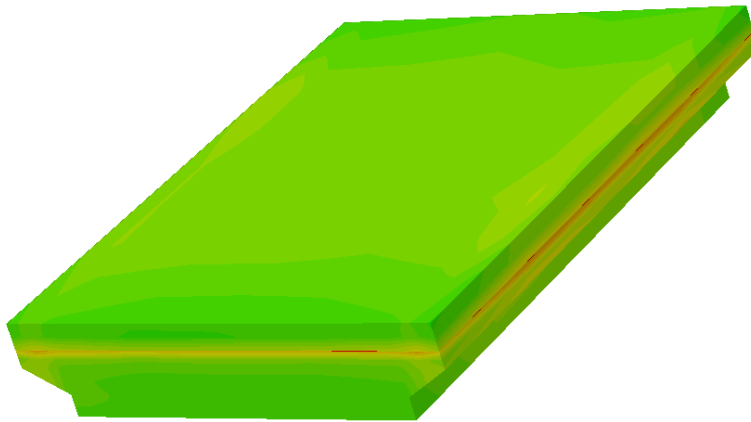
Emission power angular distribution



Spontaneous emission in quantum wells or bulk regions is considered as radiation source

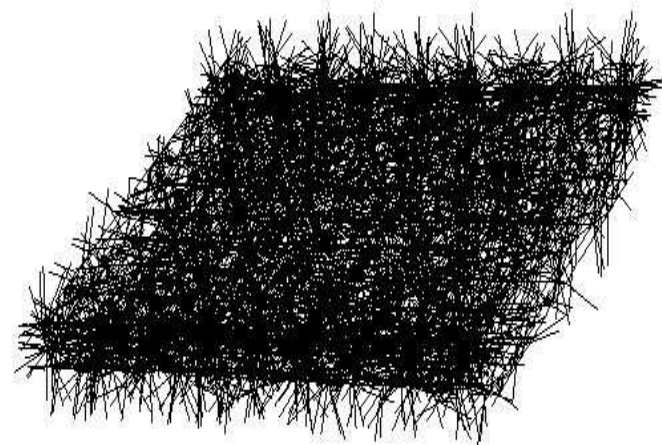
3D MQW AlGaAs/InGaAs LED

Optical intensity



Ray Trace portrait:

- 289 active vertices
- 68 rays per active vertex



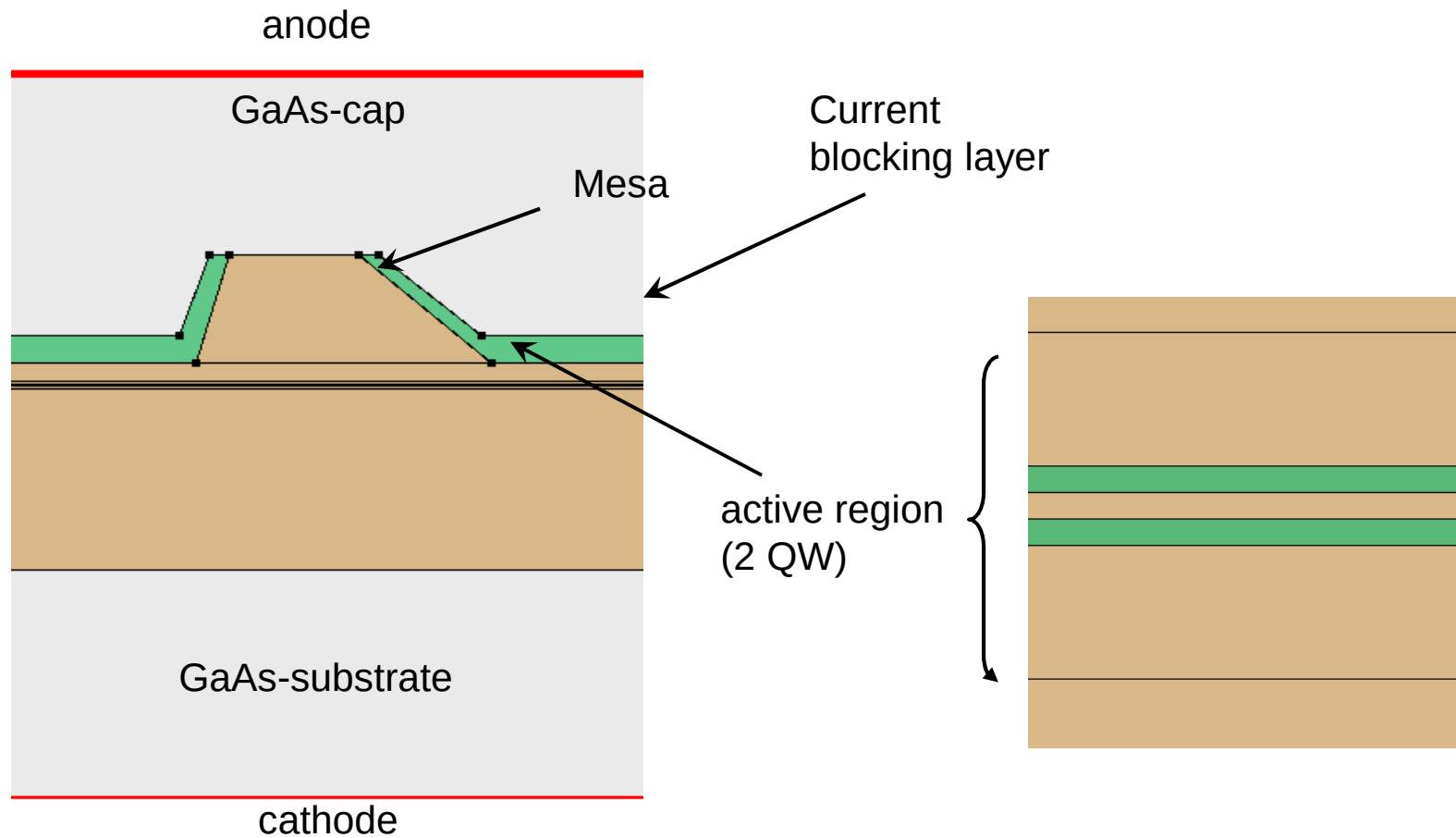
“Far-field” is represented as output intensity projected to the sphere

AlGaInP MQW edge-emitting laser on GaAs substrate



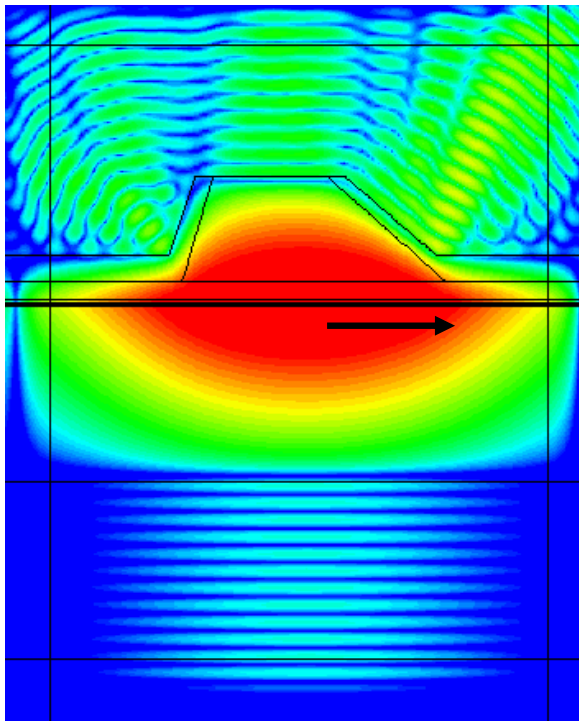
AlGaInP MQW laser (1)

Device structure

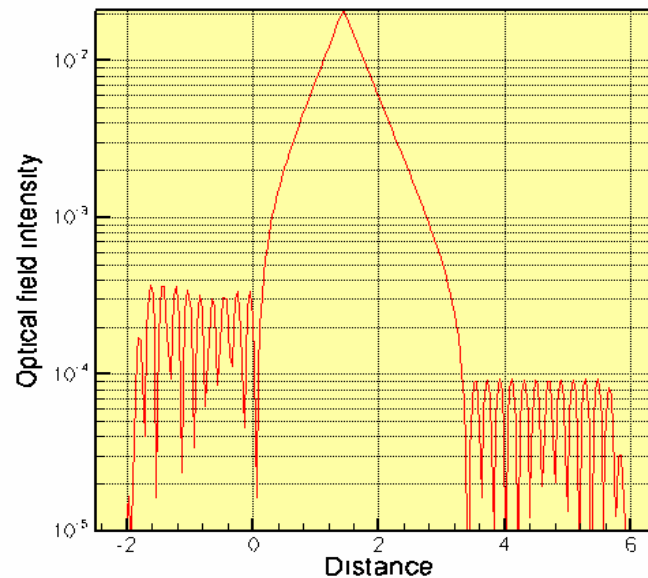


AlGaInP MQW laser (2)

Real part of the complex optical mode intensity obtained by vectorial optical mode solver Lumi. Mode polarization is indicated by vector



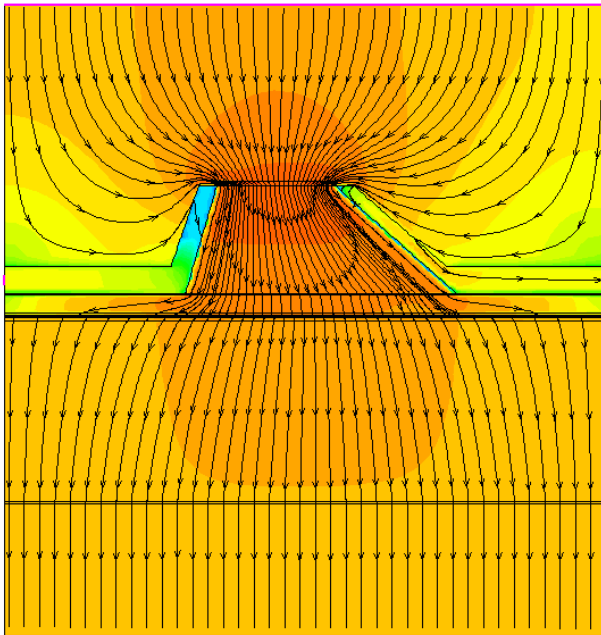
Radiation waves towards the higher refractive index GaAs layers are clearly seen



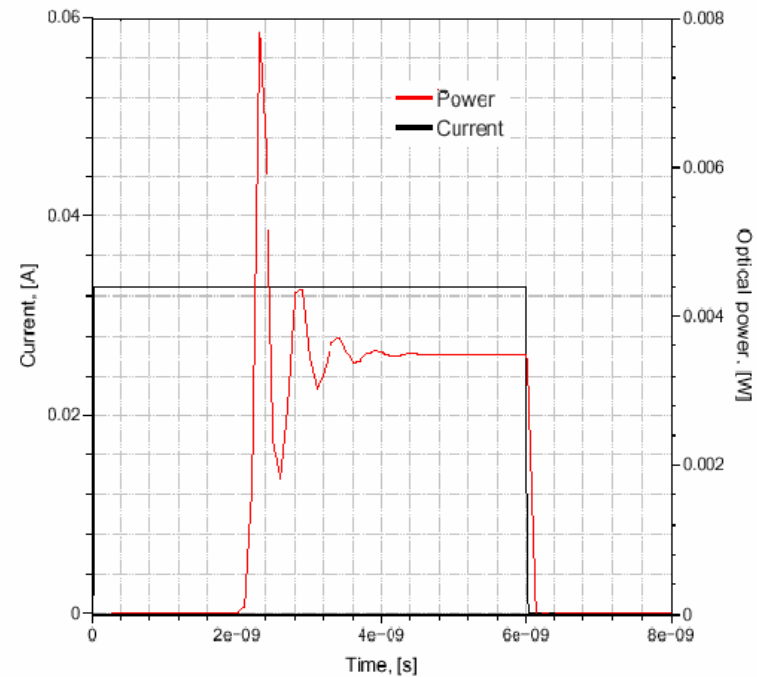
Perfectly Match Layer (PML) approach has been used to apply the absorption boundary condition at the external boundaries

AlGaInP MQW laser (3)

Current confinement above
the lasing threshold



Laser output power transient
response on a current pulse

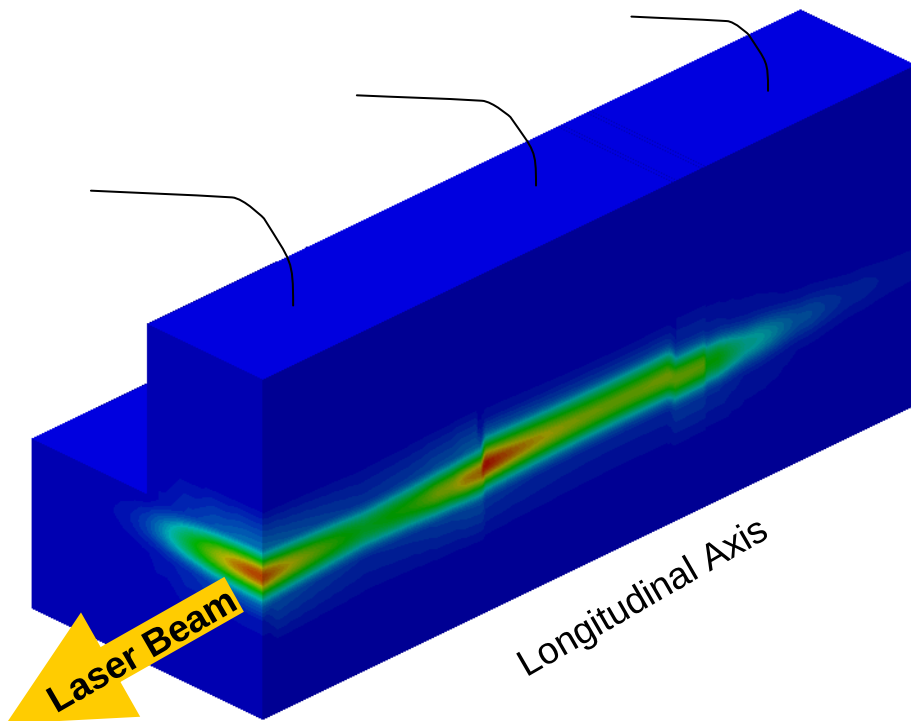


3D Edge Emitting Laser Simulation



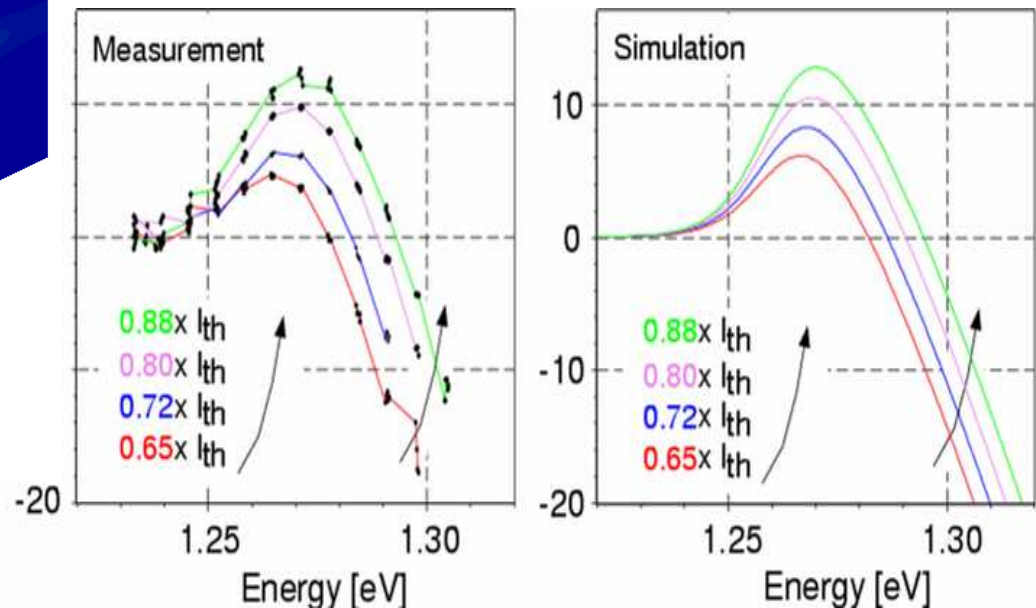
Optoelectronics: Advanced / Future Features

Full 3D Edge-Emitter Laser Simulation
Example: Ridge Waveguide Multi-Section
Sampled-Grating DFB



State-of-the-Art Active Region Models:

- k·p Bandstructure
- Manybody Gain

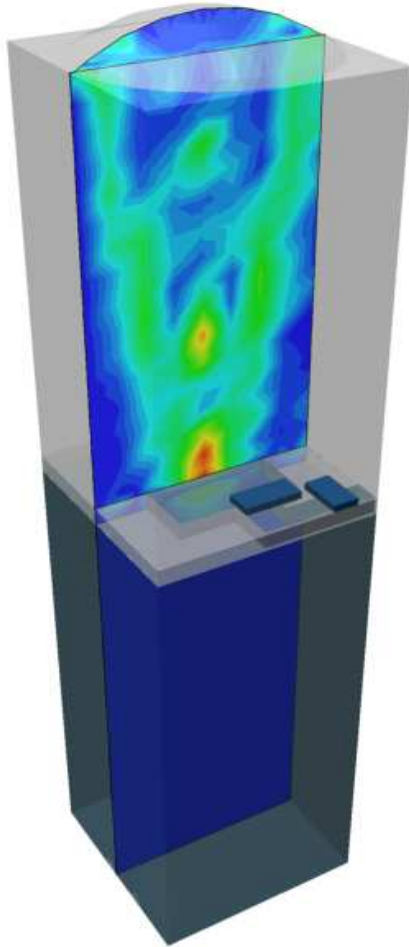


CMOS Sensor



Transient Electric Field

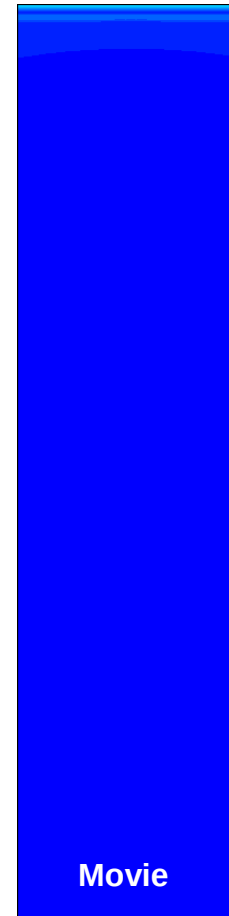
Electric field plotted on DESSIS grid



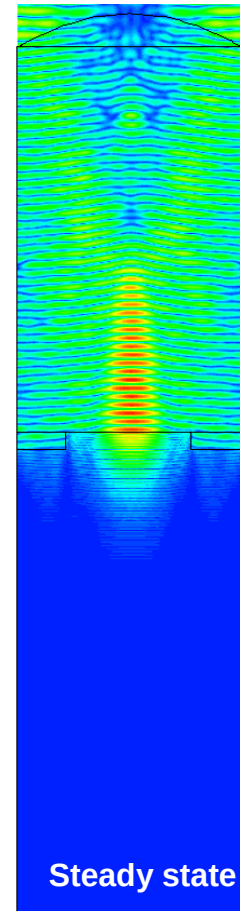
$P = 10 \text{ W/m}^2$
 $\lambda = 500\text{nm}$

The fields are simulated in 3D, but only a cross-section is displayed here.

Electric field plotted on EMLAB grid



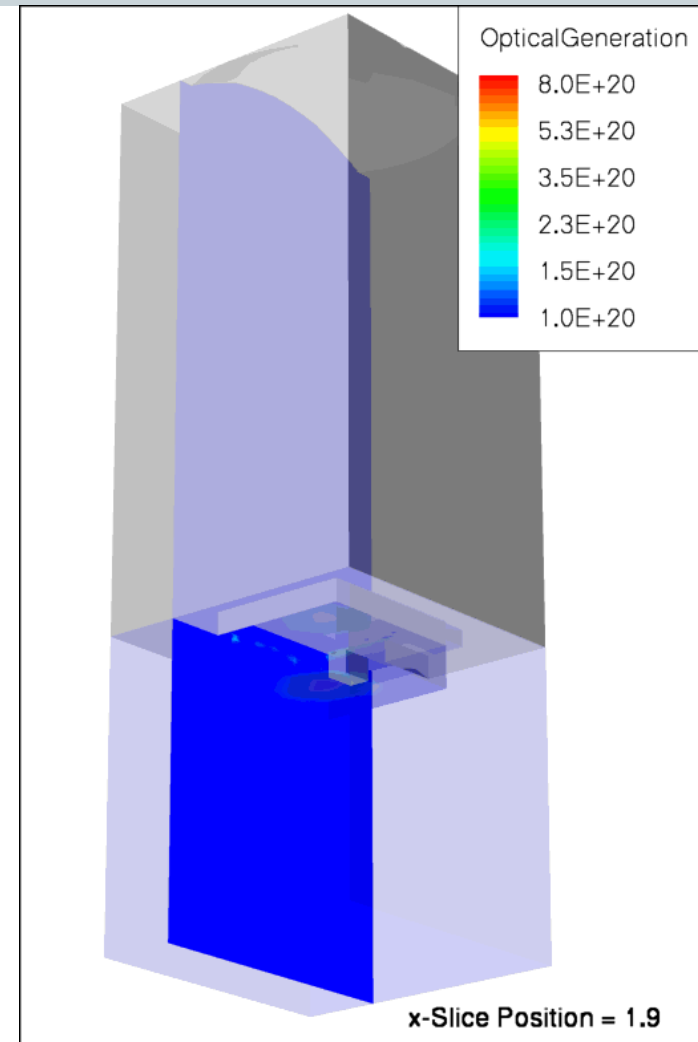
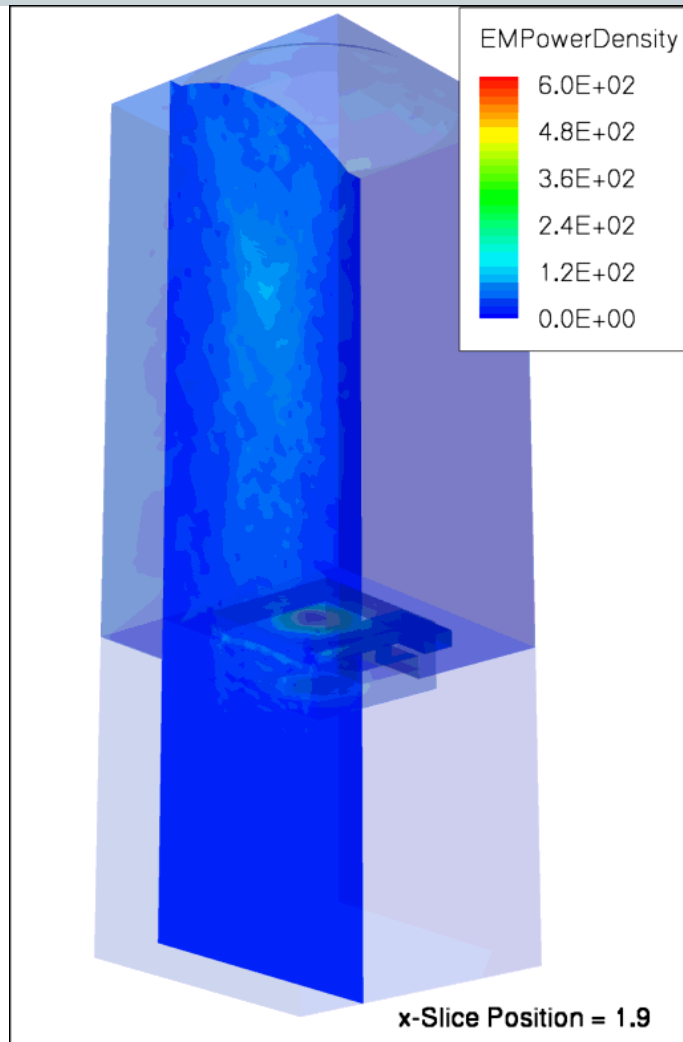
Movie



Steady state

Power Density and Optical Generation (Movies)

$P = 10 \text{ W/m}^2$
 $\lambda = 600\text{nm}$

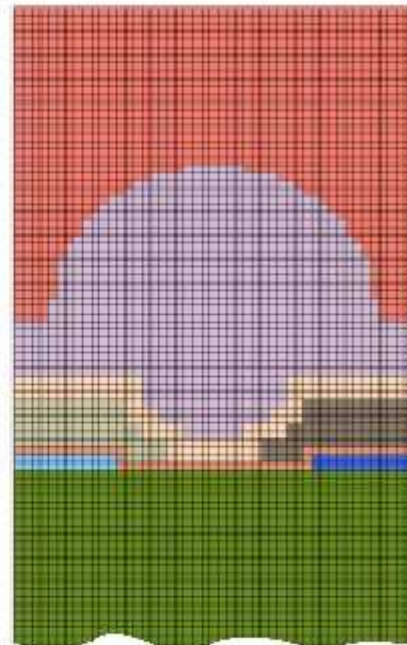
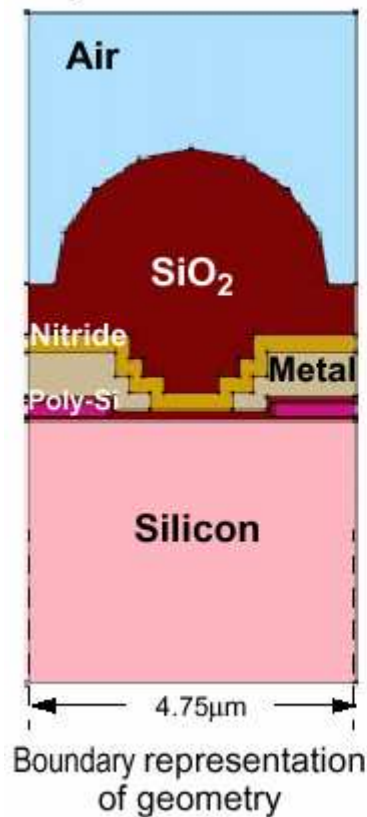


Charged Coupled Device

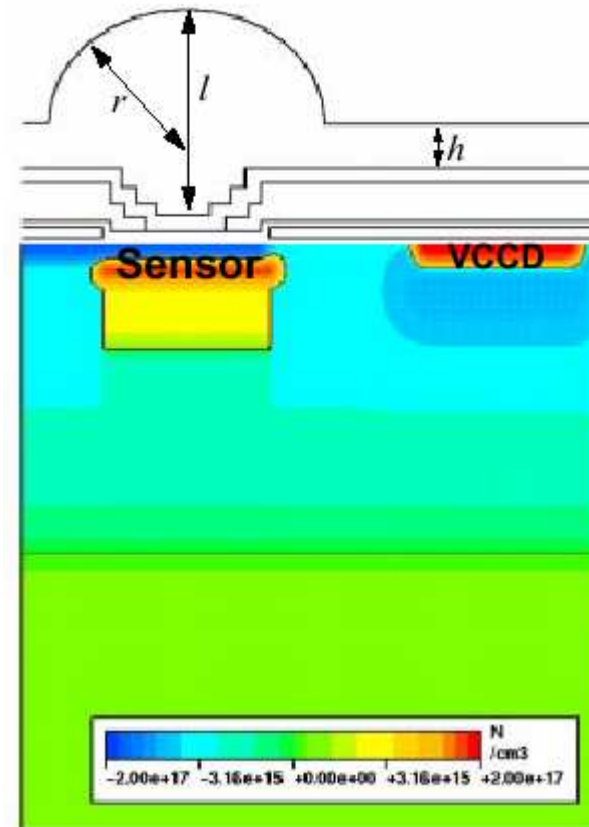


Charge Coupled Device (CCD)

CCD cell geometry

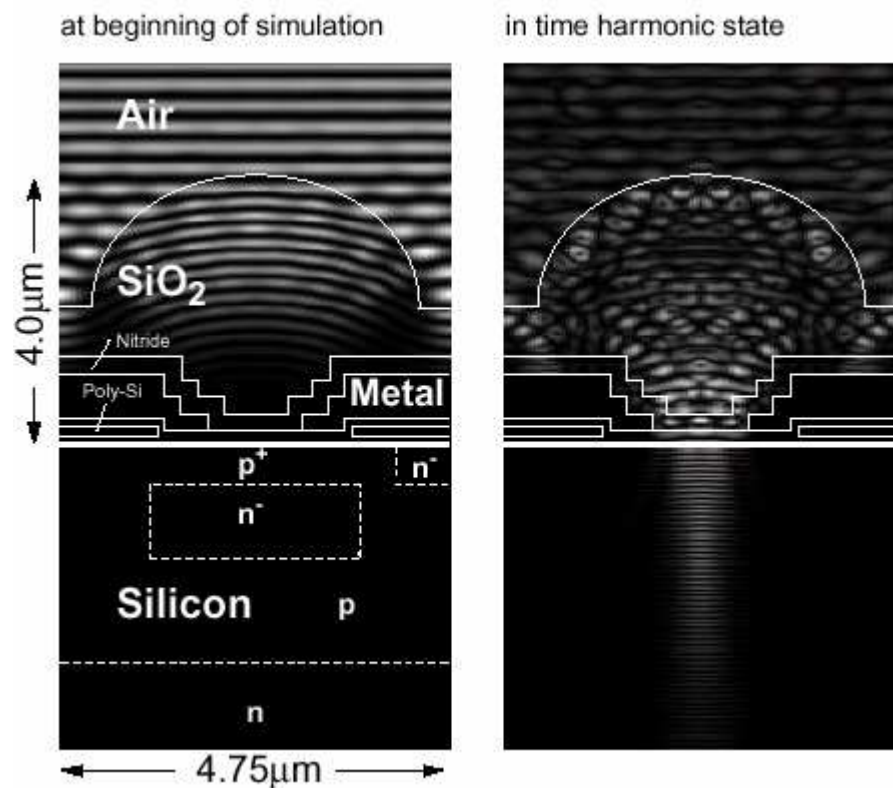


Doping Profile

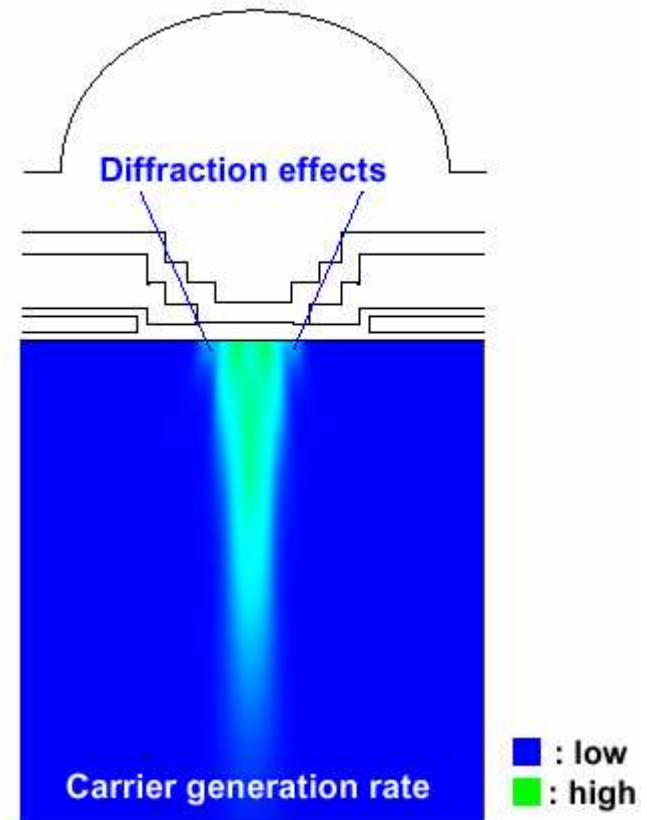


CCD - Simulation Results (EMLAB)

Instantaneous Poynting Field



Carrier Generation Rate

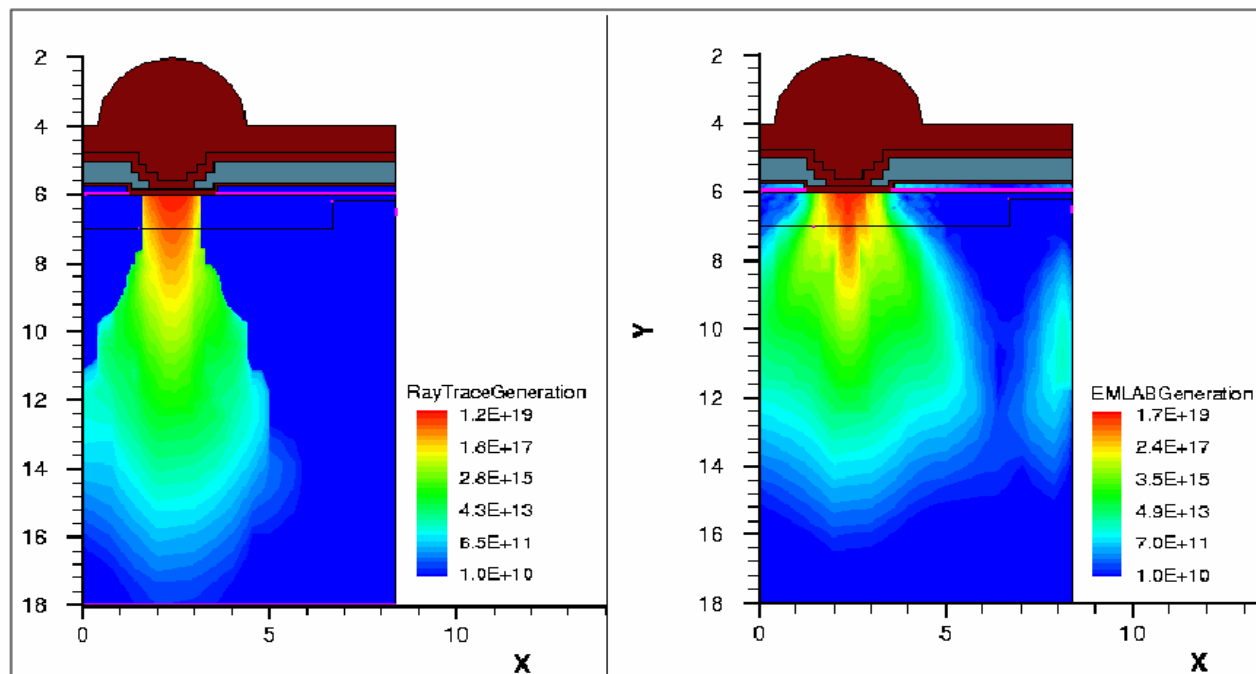


CCD –Ray Tracing vs EMLAB

Ray Tracing

Carrier Generation Rate for $\lambda=0.5 \mu\text{m}$

EMLAB



Both generators predict the similar carrier generation patterns within the certain wavelength range



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