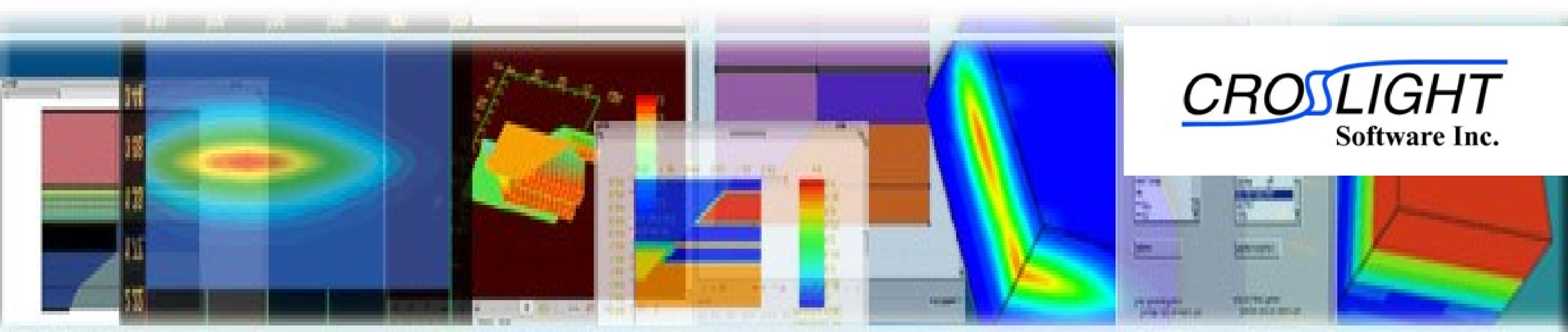


CROSSLIGHT
Software Inc.

Lighting up the Semiconductor World…

Vectorial Microcavity Model

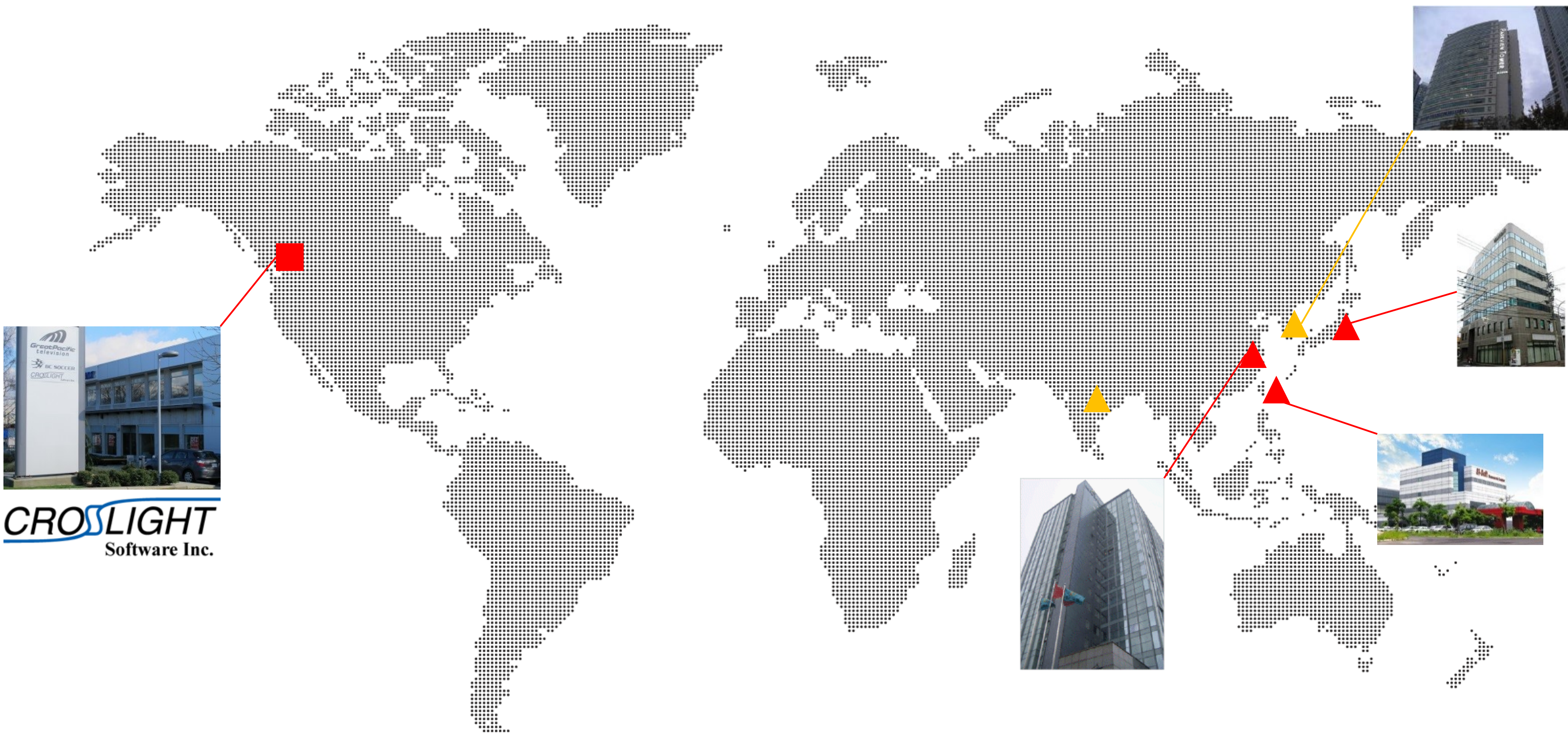
for VCSEL Devices

A Canadian company with ***20*** *years of history*

The world's ***first*** *commercial TCAD for laser diode*

The world's ***No.1*** *provider of optics and photonics TCAD*

The world's ***most advanced*** *stacked planes 3D TCAD*



Agenda

- VCSEL modeling in Crosslight PICS3D
- Optical Mode Solver
- VCSEL Example
  - Reference VCSEL
  - Surface Relief VCSEL
  - Analysis of Surface Relief & Oxide Confinement Width
- Mesh Limitations & Future Work

Agenda

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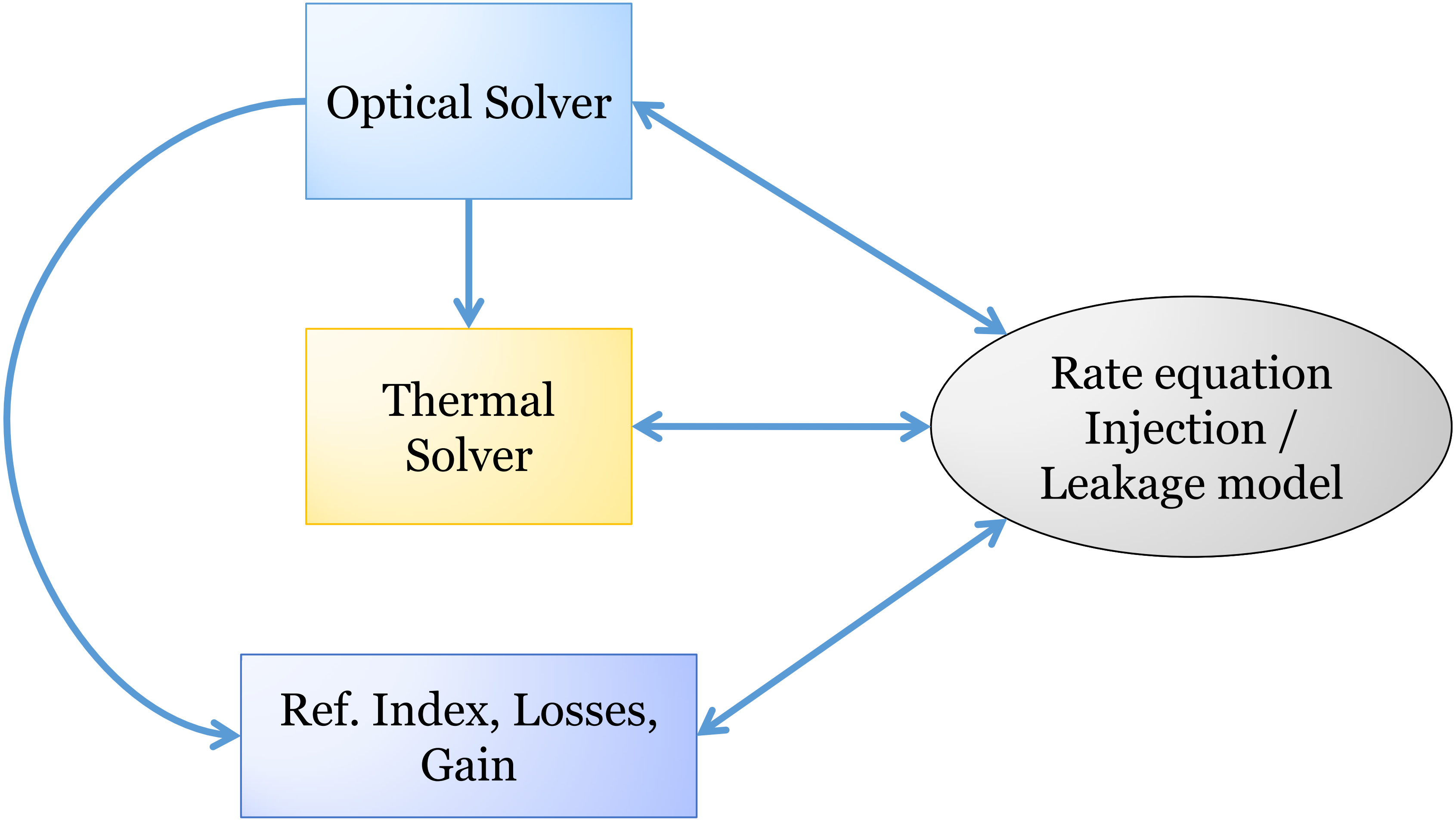
VCSEL modeling in Crosslight PICS3D

- To analyze the VCSEL accurately, three interrelated problems must be solved
  1. Optical:
     - define modal wavelength / field / intensity
  2. Electrical:
     - Carrier injection into active region
     - Joule heating
  3. Thermal:
     - Temperature change due to
       - Joule heating, non-radiative recombination, free carrier absorption & other effects
     - Temperature change perturbs the optical and electrical problems

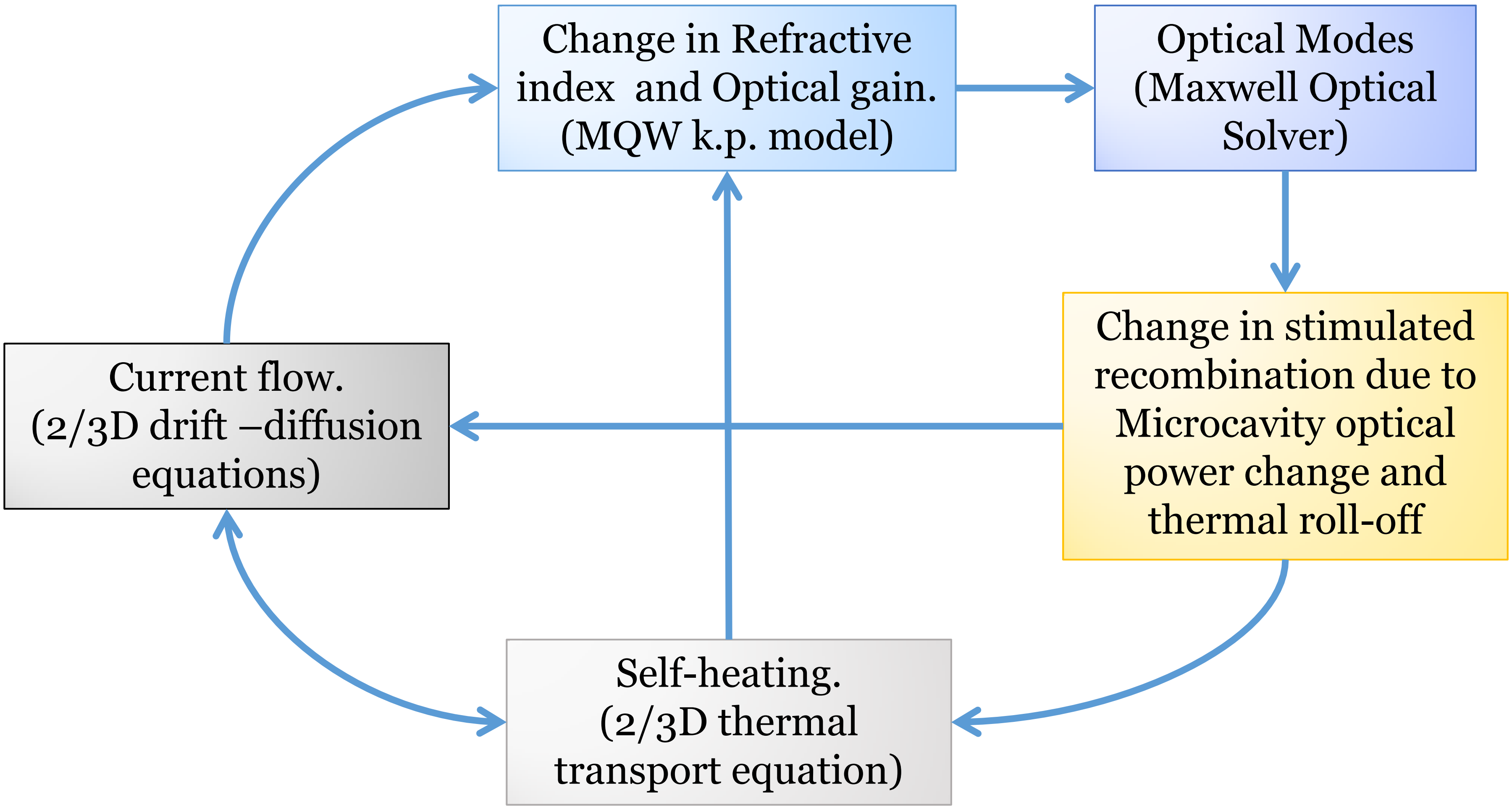
VCSEL modeling in Crosslight PICS3D



VCSEL modeling in Crosslight PICS3D

- PICS3D VCSEL simulation requires electrical, thermal, quantum mechanical and microcavity optical effects, with stronger mutual interactions than for any other optoelectronic devices.

VCSEL modeling in Crosslight PICS3D



Agenda

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Optical Mode Solver

- Depends on:
  - Geometry of the structure
  - Different material parameters
    - Heat and carrier concentration
      - may affect refractive index
- Solves for:
  - Field profile / Resonance wavelength / Threshold gain
- Available solvers:
  - Scalar solvers:
    - Good for first-order mode, not accurate for higher-order modes
  - Vectorial solvers
    - Calculate fundamental and higher-order modes, mode competition allows dominant mode to emerge.

Optical Mode Solver

- Crosslight PICS3D microcavity model:
  - Full Vectorial Solver implemented using Frequency-Domain Finite Difference (FDFD) method.
  - Since the VCSEL is a layer-based structure, mesh can be implemented using a Yee grid
  - Current version of solver:
    - Single mesh plane only
    - Analytical dependence on ϕ rotation angle

Optical Mode Solver

- Crosslight PICS3D full Vectorial Solver
  - Based on Maxwell's equations
  - Includes all the field polarizations
    - TE/TM mode
    - HE modes
  - Accurately calculates for:
    - Fundamental and higher-order modes.
    - Small structure dimensions
    - Modal parameters (ex. threshold gain)

Optical Mode Solver

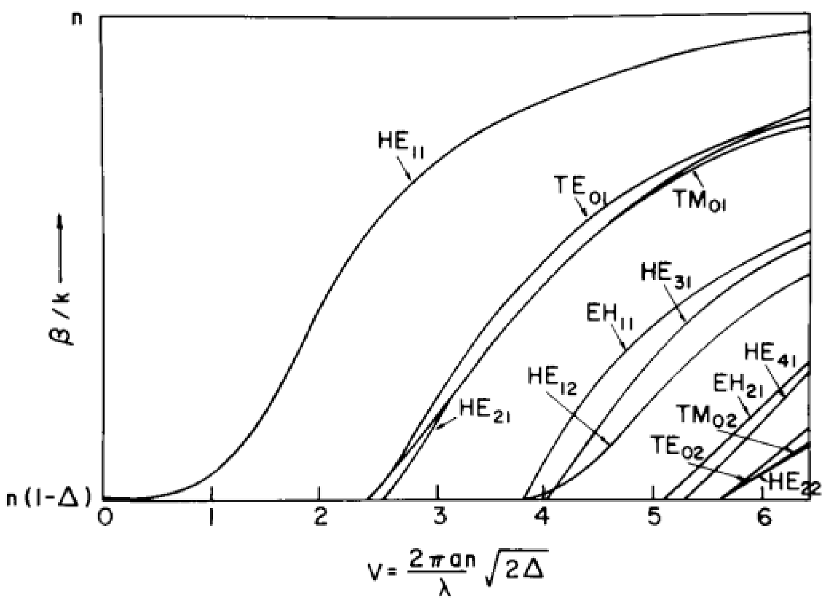
- Field components of each set of mode solutions:
  - TE modes in $E_r, \mathrm{E_z}, \mathrm{H}_\phi$ only, no ϕ dependence.
  - TM modes in $H_r, H_\mathrm{z}, E_\phi$ only, no ϕ dependence.
  - HE modes with all 6 vector field components involved; ϕ dependence in $e^{jn\phi}, n \geq 1$
  - Note that ALL of these modes have the electric field parallel to the quantum well plane so for the purposes of optical gain calculations, ALL of these modes would be considered TE.

Optical Mode Solver

Linearly Polarized (LP) Modes

- Some of the full vectorial modes (TE/TM/HE) are quasi-degenerate so it is common to add them together to form LP modes
  - $LP_{0x} = HE1x$
  - LP_{1x} :
    - $LP_{1x} = HE_{2x} + TM_x$
    - $LP_{1x} = HE_{2x} + TE_x$

Modes of Step index fiber



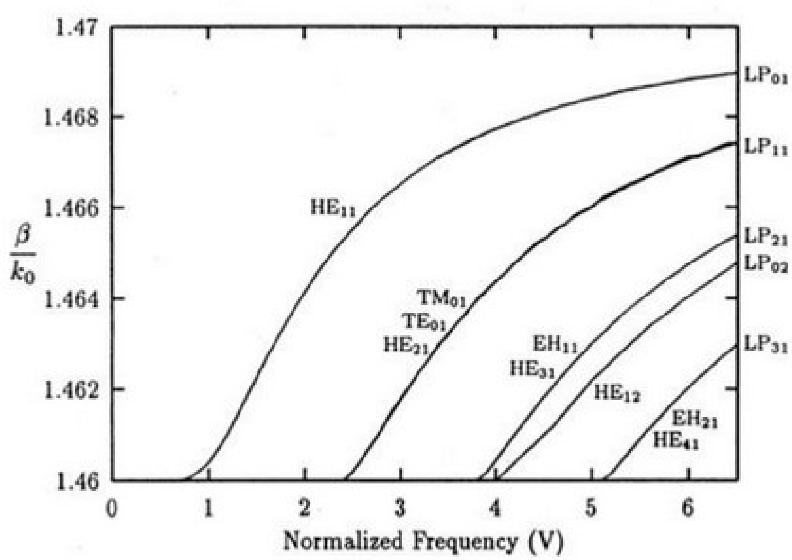
Ref: Michael Barnoski,
"Fundamentals of Optical Fiber Communications", Academic Press, 1981

Optical Mode Solver

Linearly Polarized (LP) Modes

- We therefore expect some difference in the laser power output using the set of pure full vectorial modes (TE/TM/HE) and the set of simplified LP modes.

Modes of Step index fiber



Ref: Michael Barnoski,
"Fundamentals of Optical Fiber Communications", Academic Press, 1981

Optical Mode Solver

- Crosslight PICS3D micro-cavity model features
  - User can define which set of optical modes to use:
    - Full vectorial (TE/TM/HE) modes
    - LP modes
  - Mode Label
    - In both the LP and full vectorial methods, a mode labeling scheme is implemented to help the user identify the optical modes.

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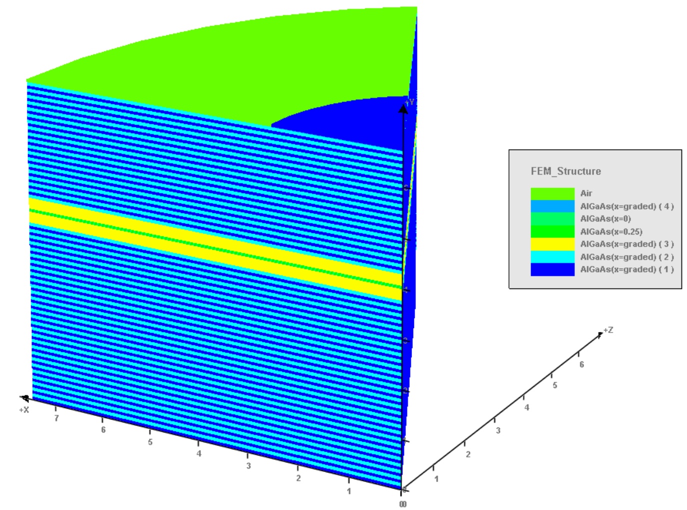
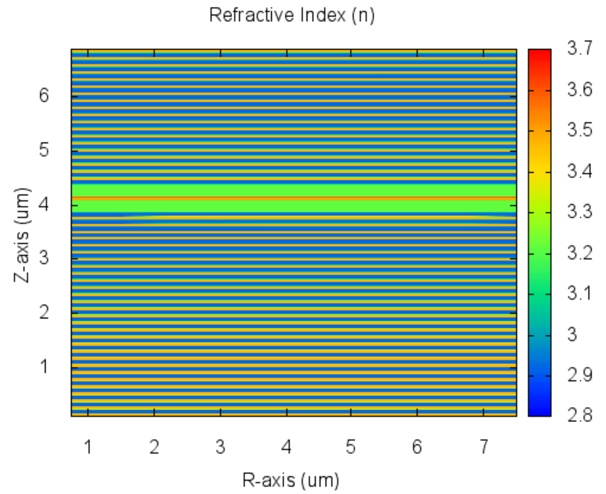
VCSEL Example

Structure

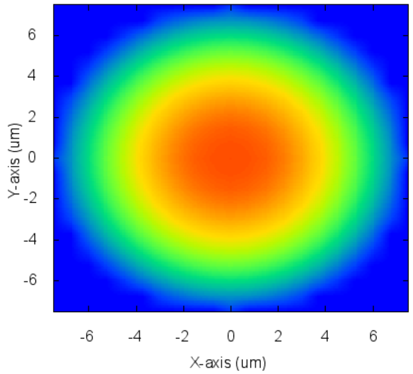
- DBR Mirror
  - Top : 18 DBR layers
  - Bottom : 29 DBR layers
- Cavity
  - Optical Cavity thickness : 0.5μm
  - Active layer thickness : 60nm



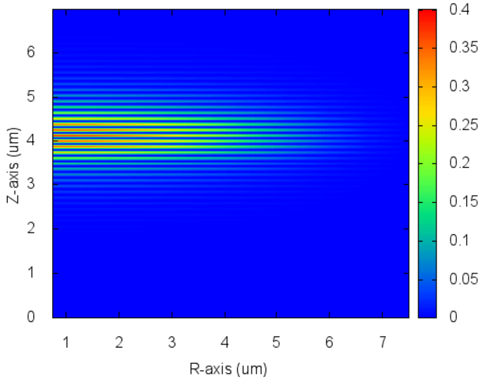


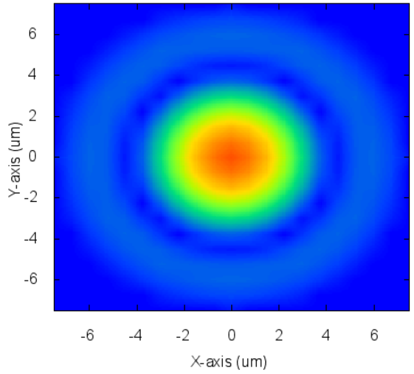
VCSEL Example

- Optical Mode
  - Full vectorial mode
    - HE11
    - HE12
    - TE01
    - TE02

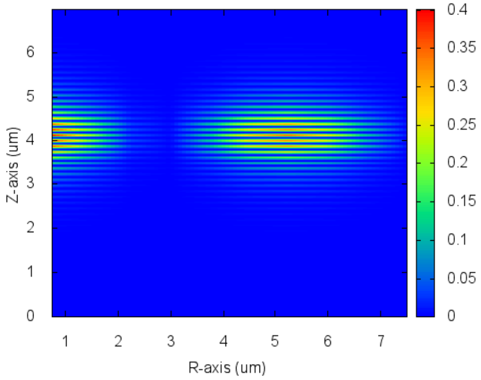


HE_{11}





HE_{12}

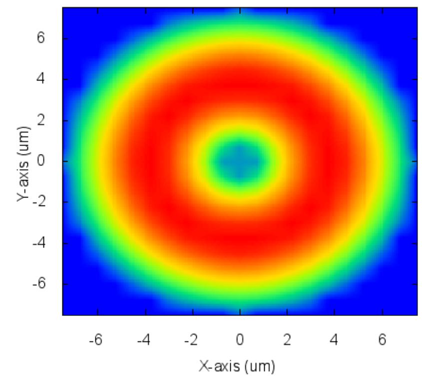


Top View

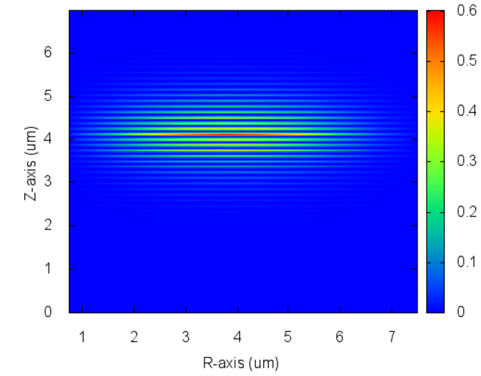
Side View

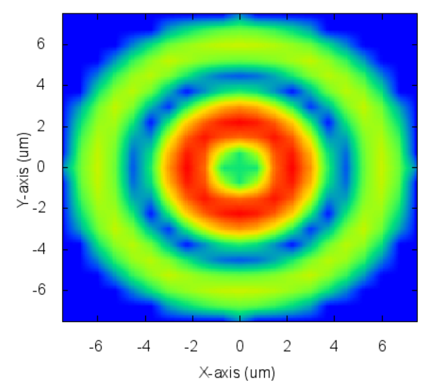
VCSEL Example

- Optical Mode
  - Full vectorial mode
    - HE11
    - HE12
    - TE01
    - TE02

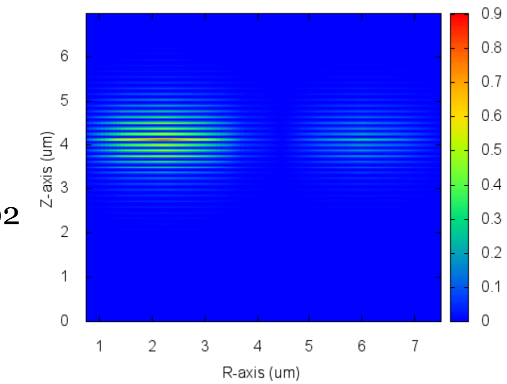


TE_{01}





TE_{02}



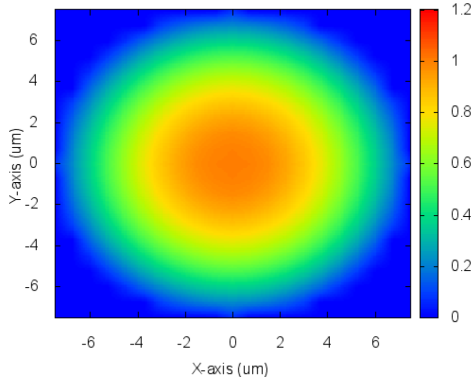
Top View

Side View

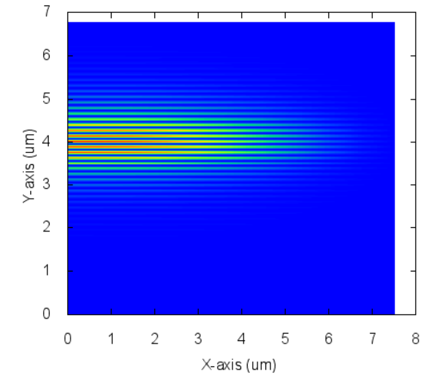
VCSEL Example

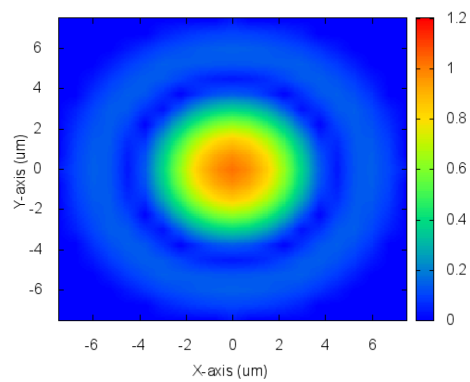
Optical Mode

- LP Modes
  - LP01
  - LP11
  - LP02
  - LP12

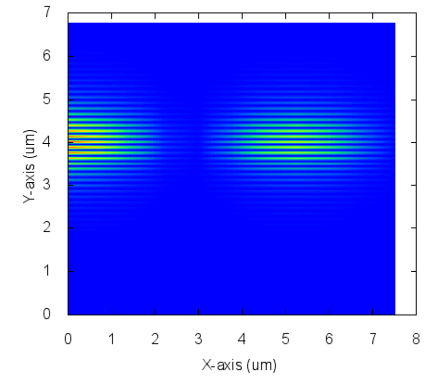


LP$_{01}$





LP$_{02}$

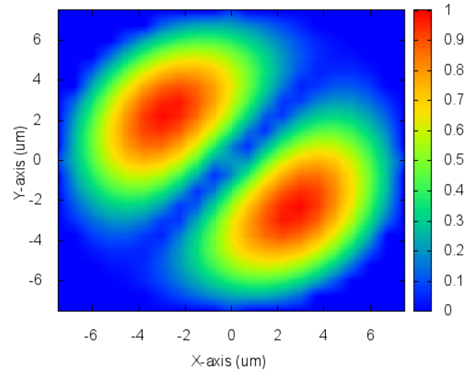


Top View

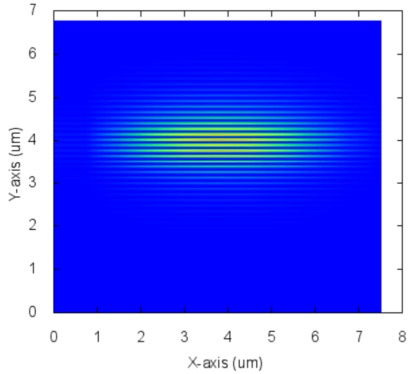
Side View

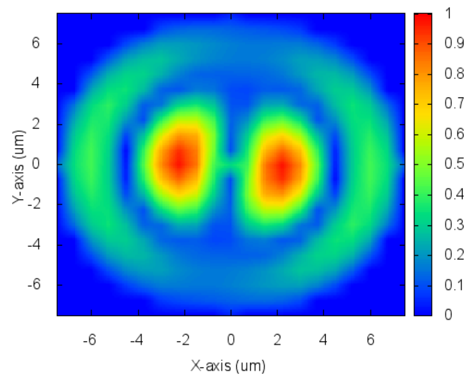
VCSEL Example

- Optical Mode
  - LP Modes
    - LP01
    - LP11
    - LP02
    - LP12

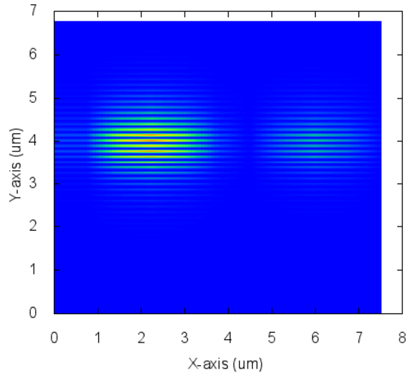


LP_{11}





LP_{12}



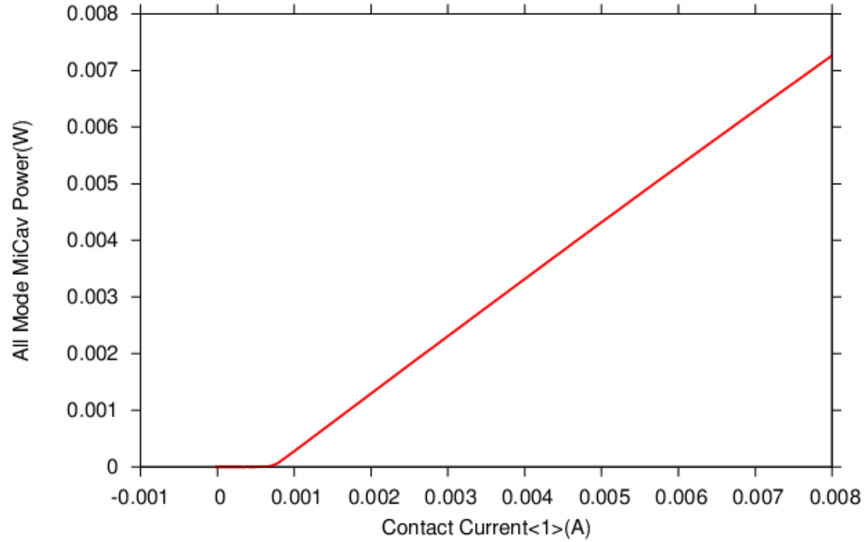
Top View

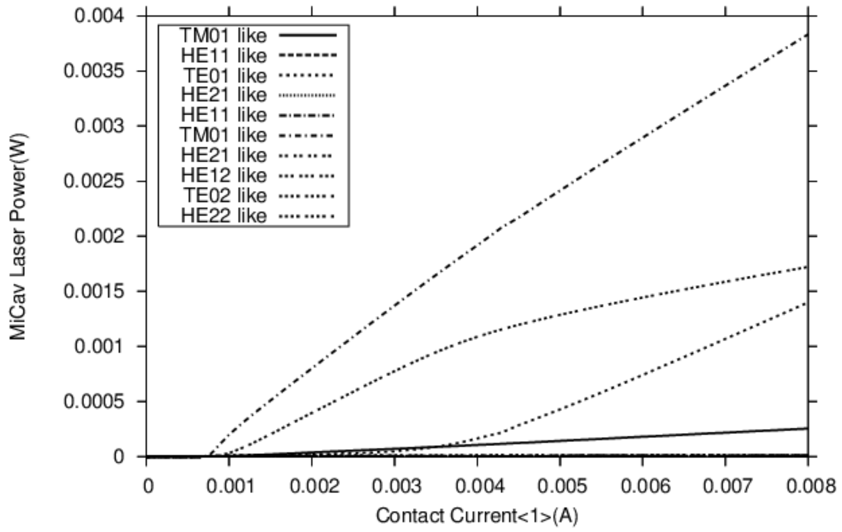
Side View

VCSEL Example

Laser Power Analysis

- Full vectorial mode (TE/TM/HE)
  - All Mode Laser Power
  - Modal Laser Power

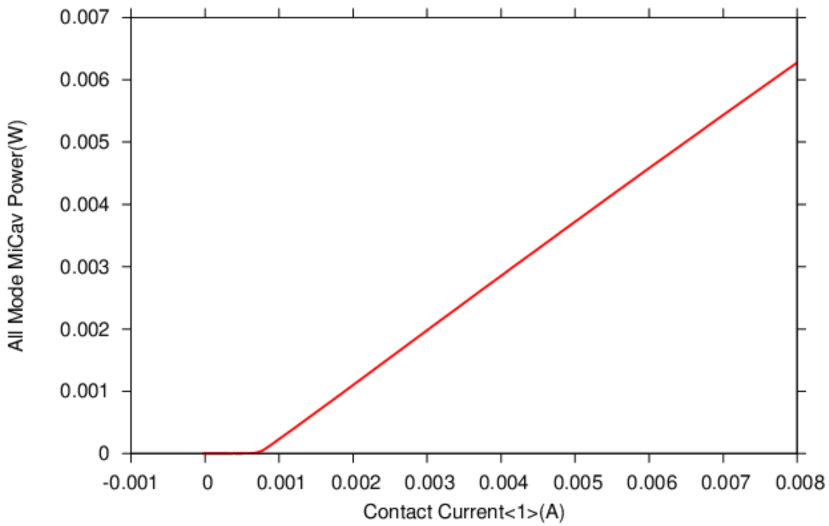


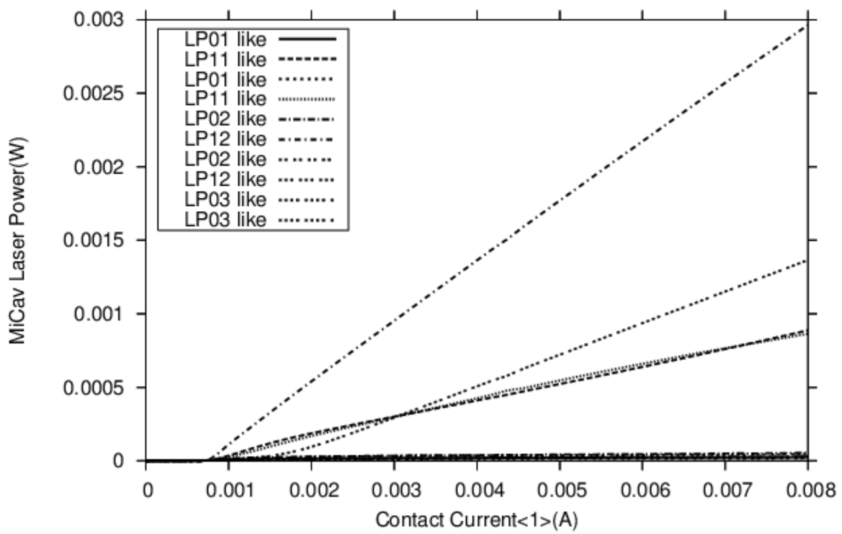


VCSEL Example

Laser Power Analysis

- LP Modes
  - All Mode Laser Power
  - Modal Laser Power





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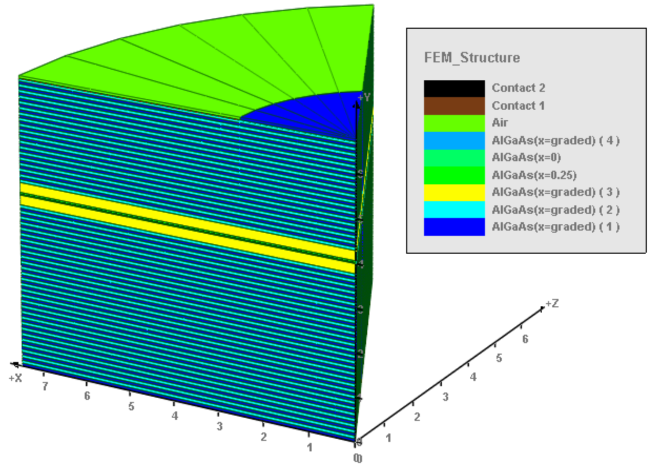
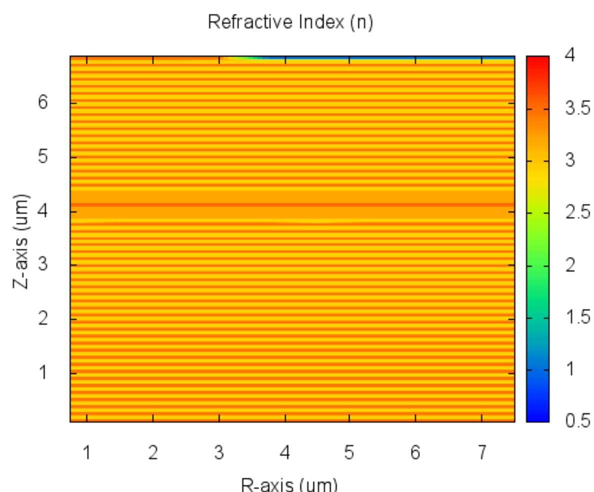
SR-VCSEL Example

Structure

- DBR Mirror
  - Top : 18 DBR layers
  - Bottom : 29 DBR layers
- Cavity
  - Optical Cavity thickness : 0.5μm
  - Active layer thickness : 60nm

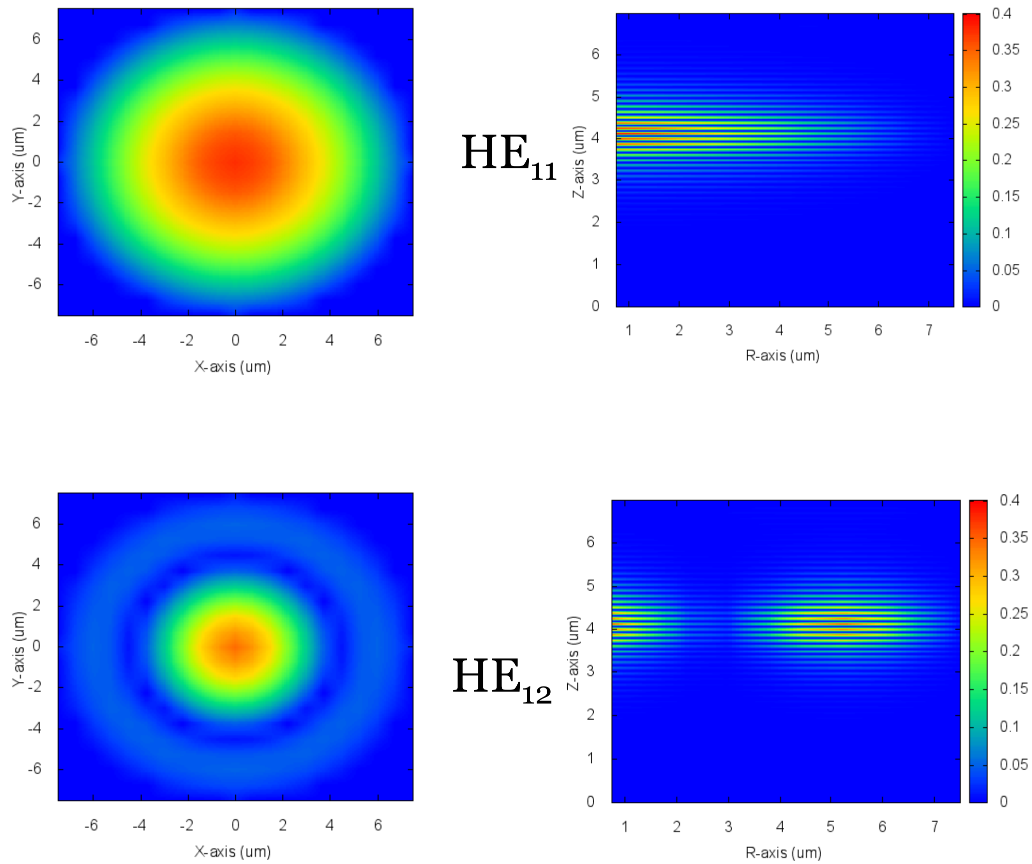




SR-VCSEL Example

Optical Mode

- Full vectorial mode
  - HE11
  - HE12
  - TE01
  - TE02



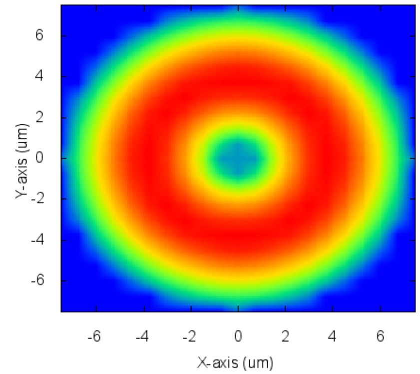
Top View

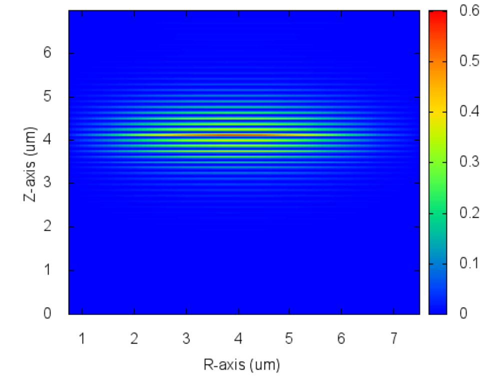
Side View

SR-VCSEL Example

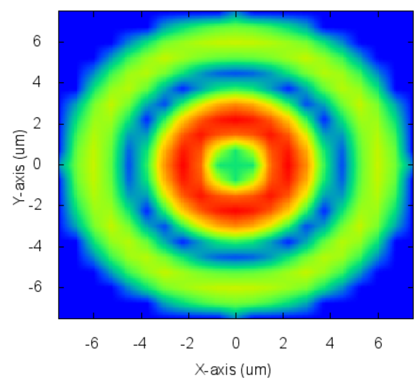
Optical Mode

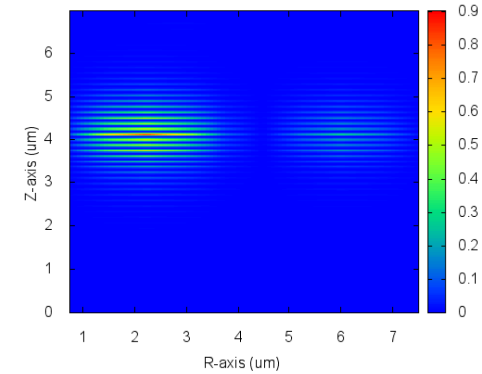
- Full vectorial mode
  - HE11
  - HE12
  - TE01
  - TE02





TE_{01}





TE_{02}

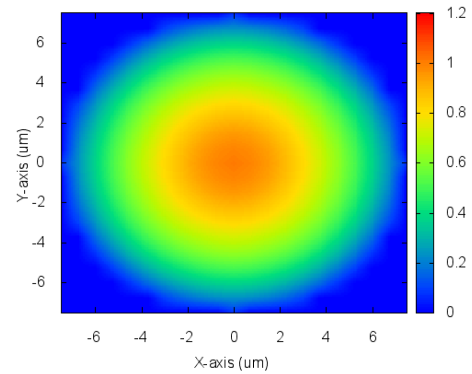
Top View

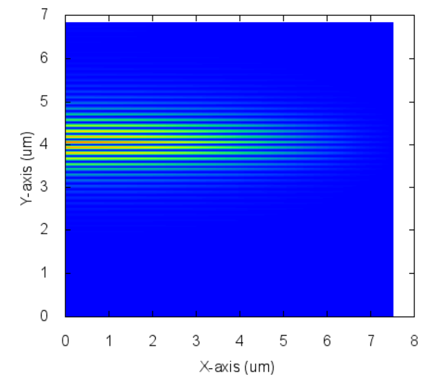
Side View

SR-VCSEL Example

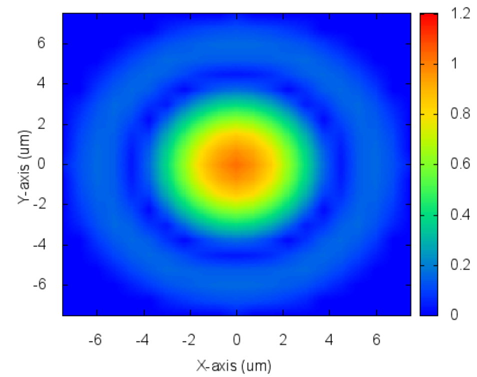
Optical Mode

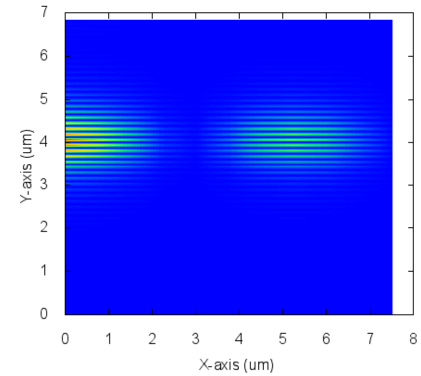
- LP Modes
  - LP01
  - LP11
  - LP02
  - LP12





LP_{01}





LP_{02}

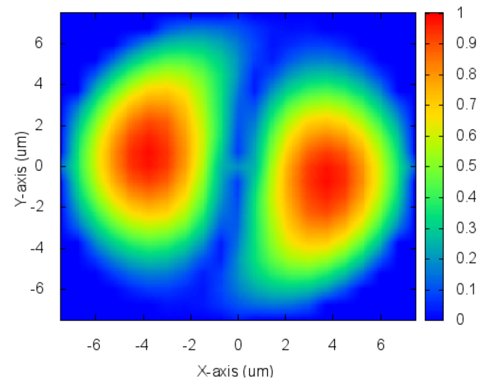
Top View

Side View

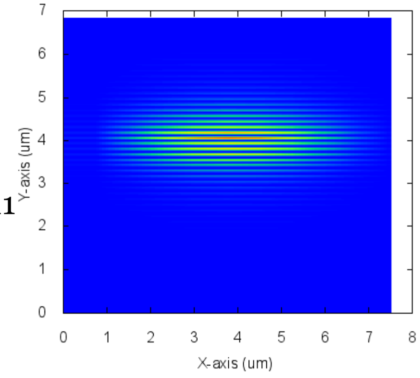
SR-VCSEL Example

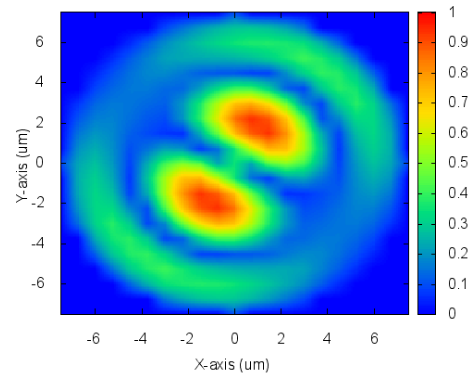
Optical Mode

- LP Modes
  - LP01
  - LP11
  - LP02
  - LP12

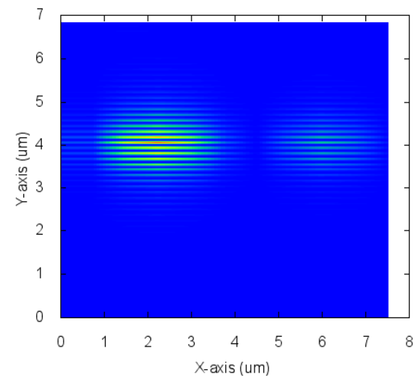


LP$_{11}$





LP$_{12}$



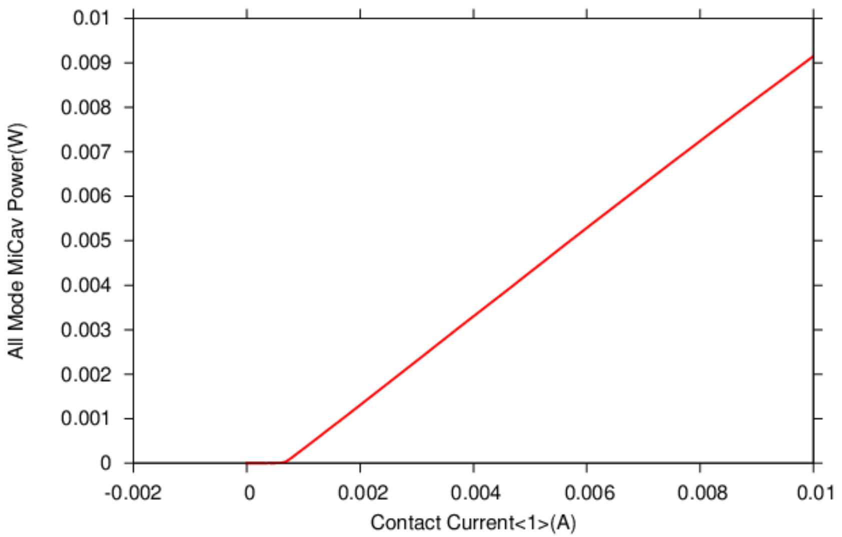
Top View

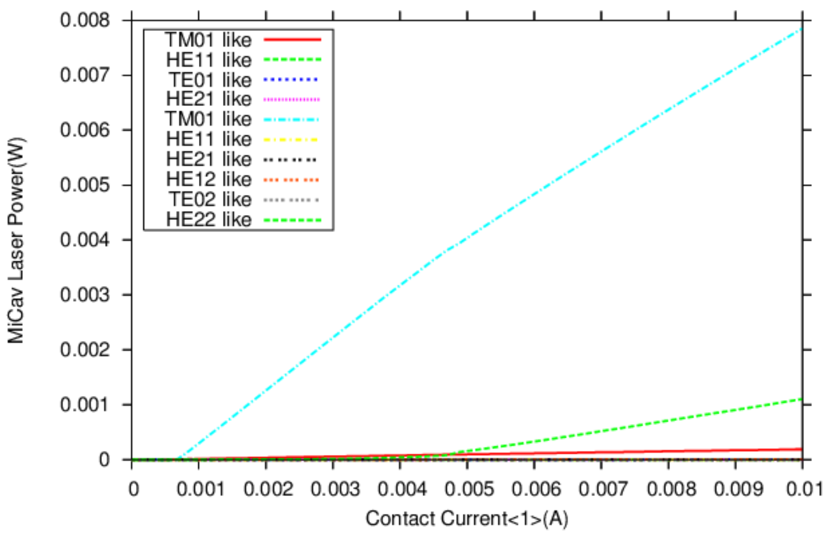
Side View

SR-VCSEL Example

Laser Power Analysis

- TE/TM/HE
  - All Mode Laser Power
  - Modal Laser Power

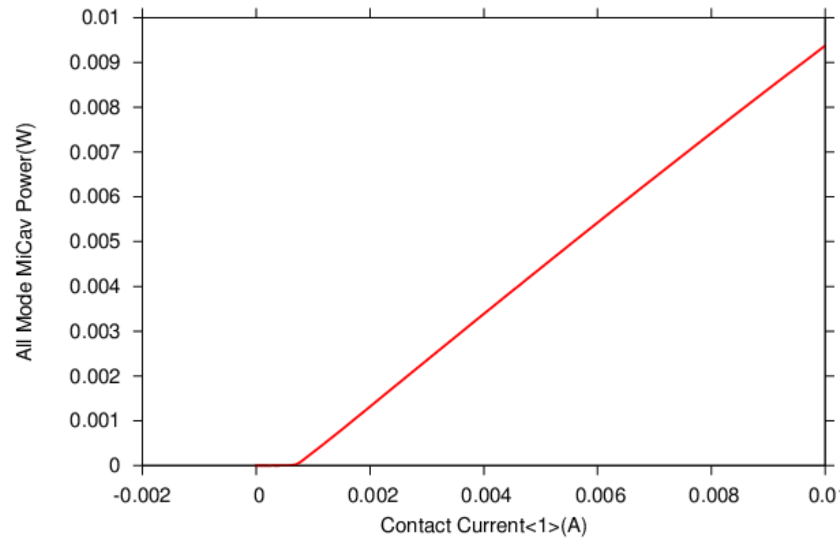


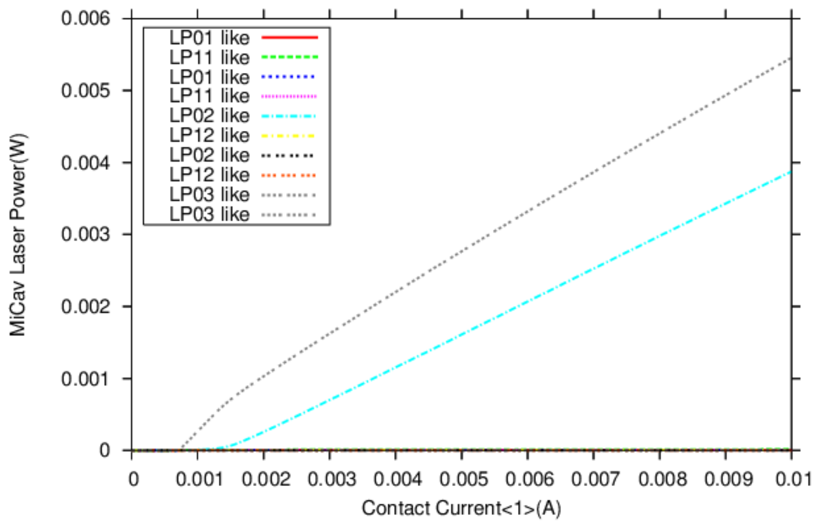


SR-VCSEL Example

Laser Power Analysis

- LP Modes
  - All Mode Laser Power
  - Modal Laser Power

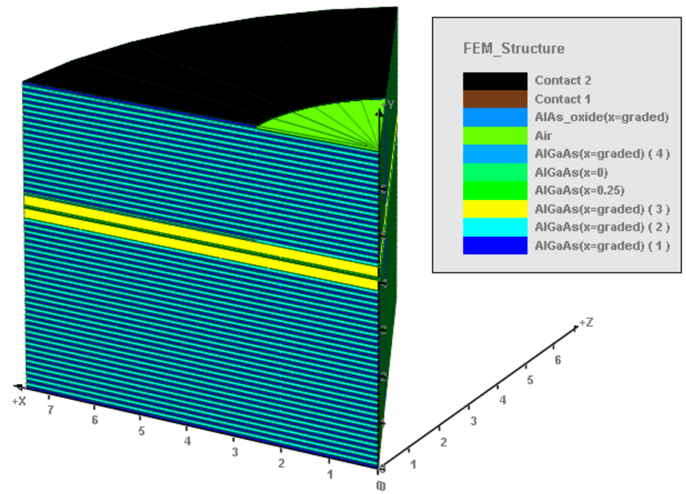


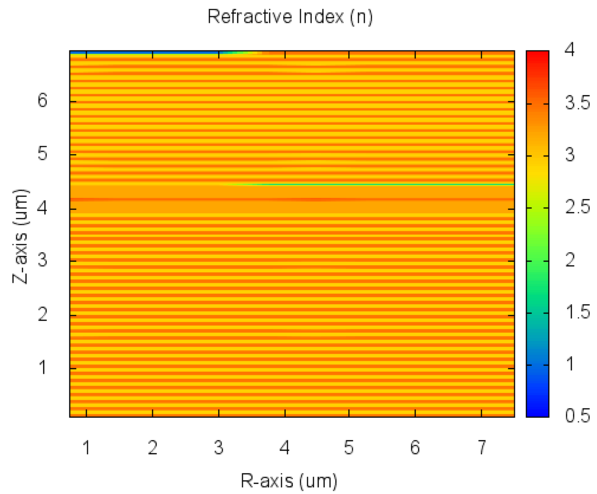


SR-VCSEL with Oxide Example

Structure

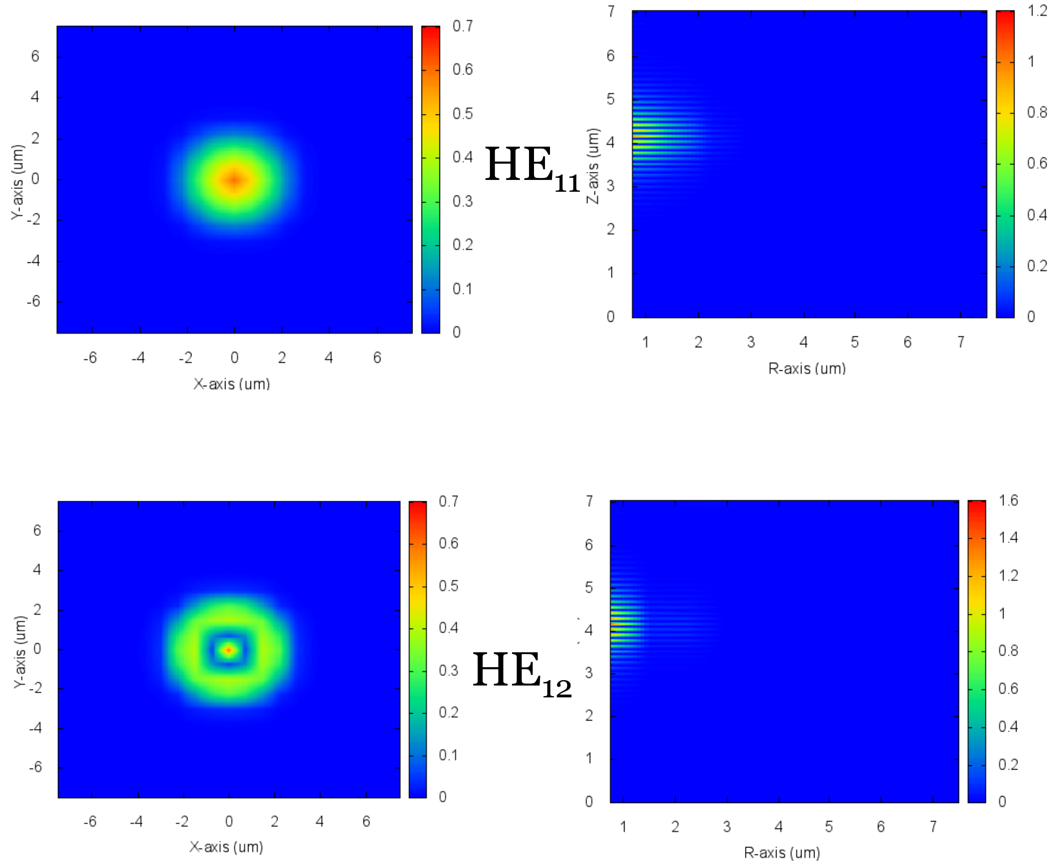
- DBR Mirror
  - Top : 18 DBR layers
  - Bottom : 29 DBR layers
- Cavity
  - Optical Cavity thickness : 0.5µm
  - Active layer thickness : 60nm
- Oxide Layer
  - Adding an oxide layer of thick 30µm





SR-VCSEL with Oxide Example

- Optical Mode
  - Full vectorial mode
    - HE11
    - HE12
    - TE01
    - TE02



Top View

Side View

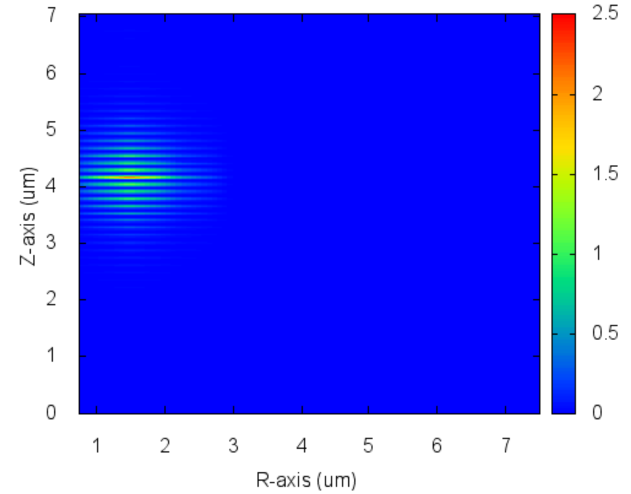
SR-VCSEL with Oxide Example

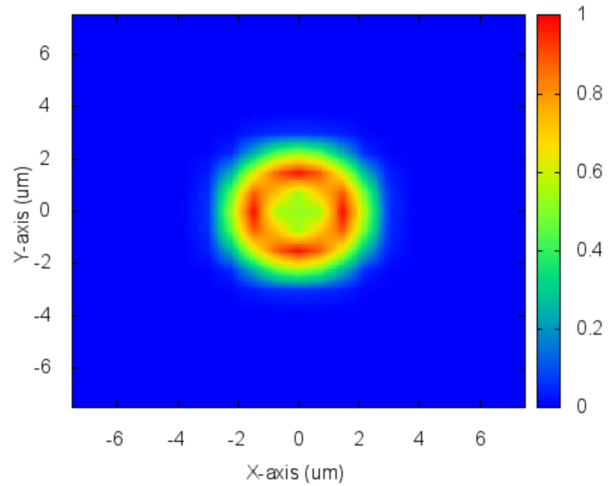
Optical Mode

- Full vectorial mode
  - HE11
  - HE12
  - TE01

TE_{01}

Side View





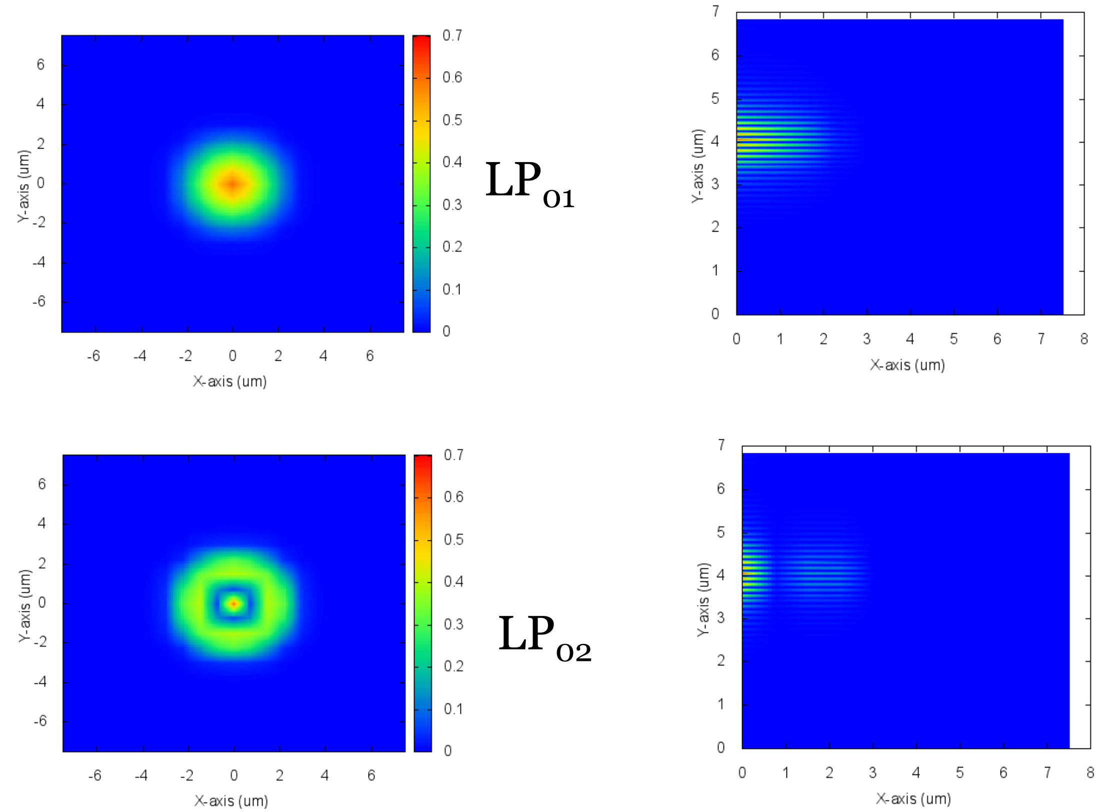
TE_{01}

Top View

SR-VCSEL with Oxide Example

Optical Mode

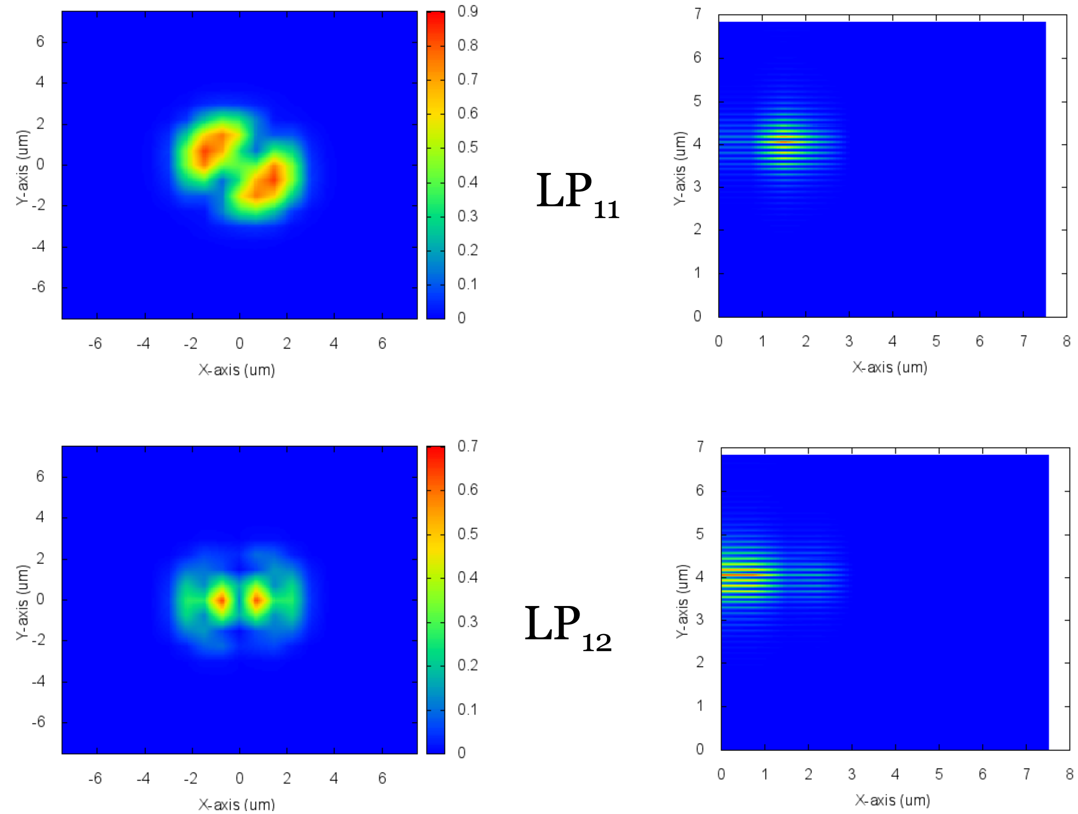
- LP Modes
  - LP01
  - LP11
  - LP02
  - LP12



Top View   Side View

SR-VCSEL with Oxide Example

- Optical Mode
  - LP Modes
    - LP01
    - LP11
    - LP02
    - LP12



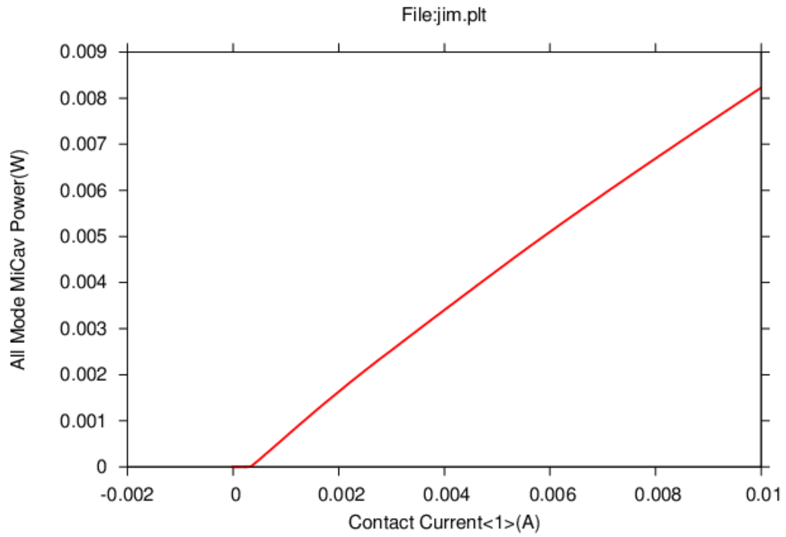
Top View

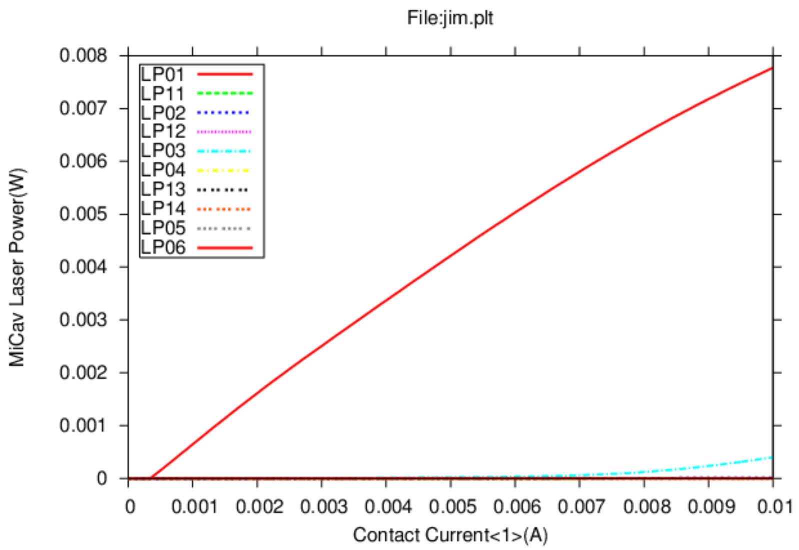
Side View

SR-VCSEL with Oxide Example

Laser Power Analysis

- LP Modes
  - All Mode Laser Power
  - Modal Laser Power





Time Comparison

	LP Modes	Full Vectorial Modes	Scalar Modes
Reference VCSEL	10.5 min	9.0 min	5.5 min
SR VCSEL	14.5 min	13.0 min	8.0 min
SR VCSEL (Oxide)	19.5 min	18.5 min	17.0 min

- Scaling between vectorial/scalar solutions depends on relative weight of mode solver time on total computation; non-linear Newton solver also contributes a significant amount.
- Test machine: Xeon E5-1620 v3 (3.5 GHz), Windows 10, 64 GB RAM

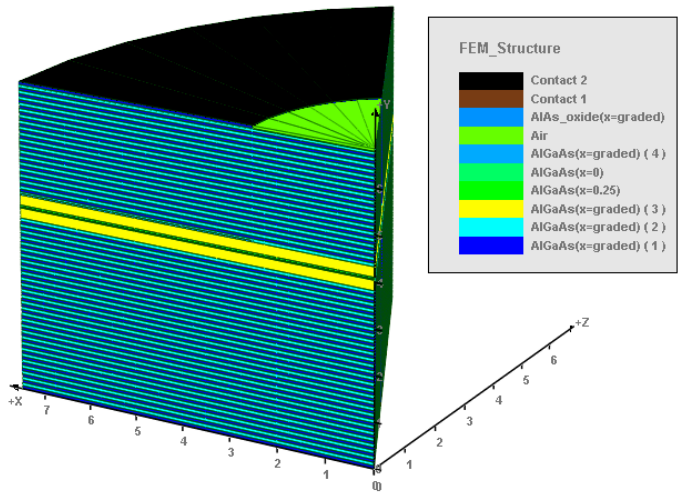
Agenda

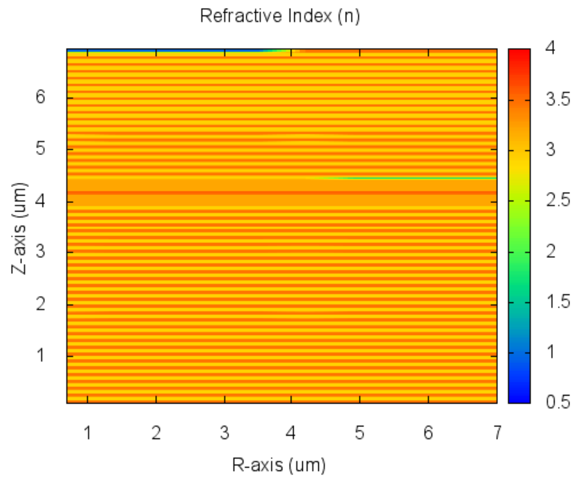
- VCSEL modeling in Crosslight PICS3D
- Optical Mode Solver
- VCSEL Example
  - Reference VCSEL
  - Surface Relief VCSEL
  - Analysis of Surface Relief & Oxide Confinement Width
- Mesh Limitations & Future Work

Analysis of Surface Relief & Oxide Confinement Width

Structure

- DBR Mirror
  - Top : 18 DBR layers
  - Bottom : 29 DBR layers
- Cavity
  - Optical Cavity thickness : 0.5μm
  - Active layer thickness : 60nm
- Oxide Layer
  - Increase radius of the surface relief layer to 3.5μm

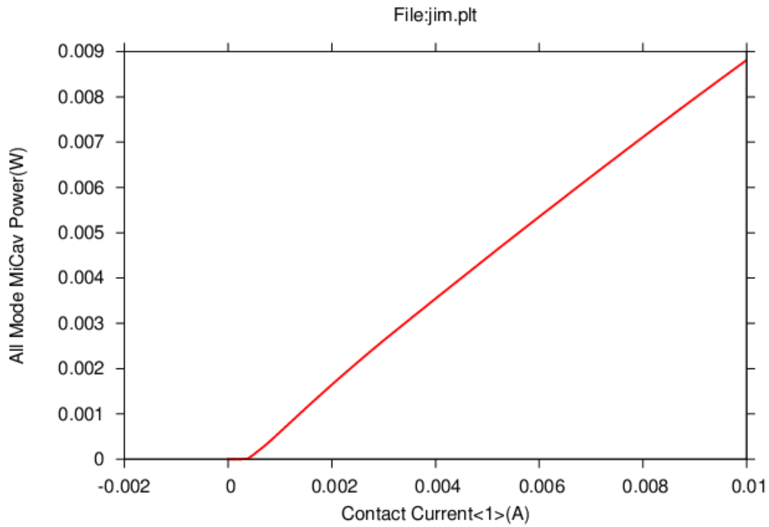


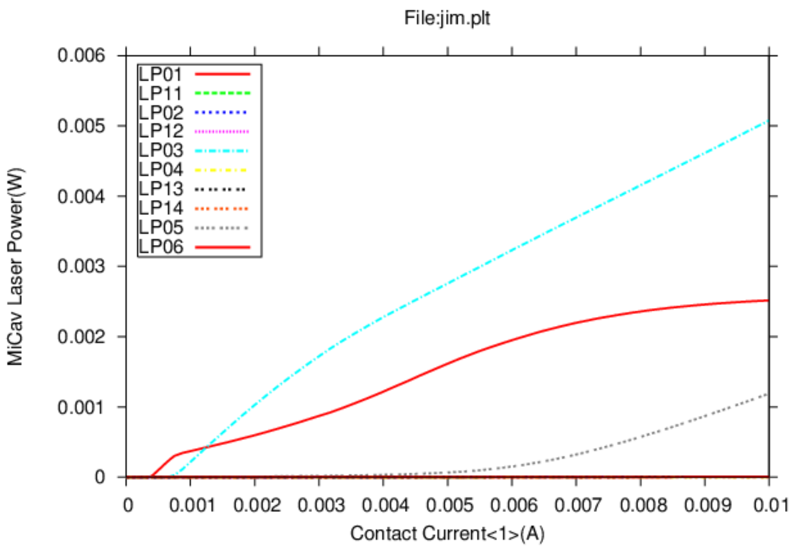


Analysis of Surface Relief & Oxide Confinement Width

Laser Power Analysis

- LP Modes
  - All Mode Laser Power
  - Modal Laser Power

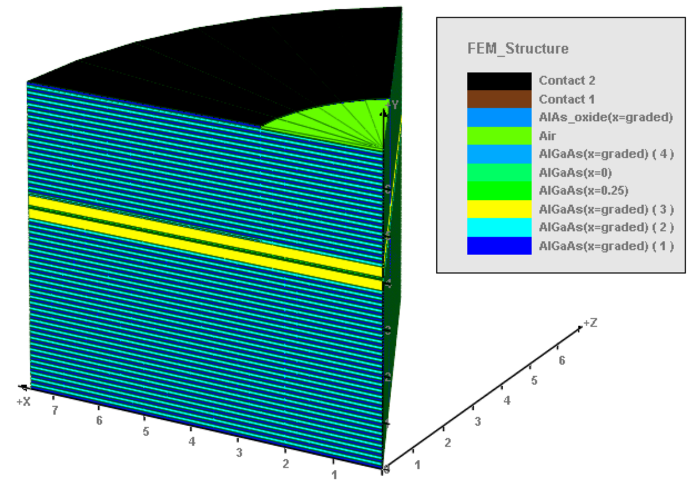


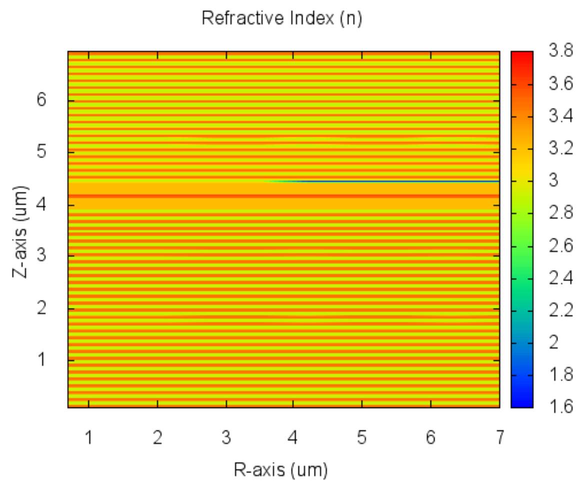


Analysis of Surface Relief & Oxide Confinement Width

Structure

- DBR Mirror
  - Top : 18 DBR layers
  - Bottom : 29 DBR layers
- Cavity
  - Optical Cavity thickness : 0.5μm
  - Active layer thickness : 60nm
- Oxide Layer
  - Remove the surface relief layer

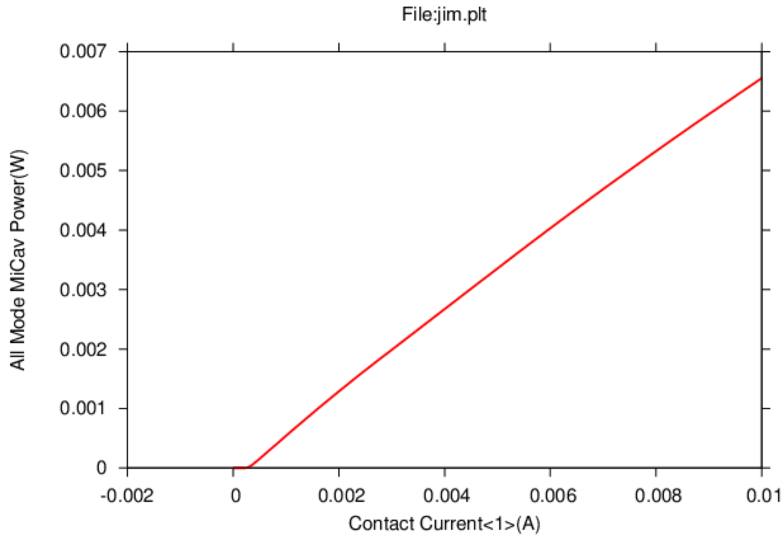


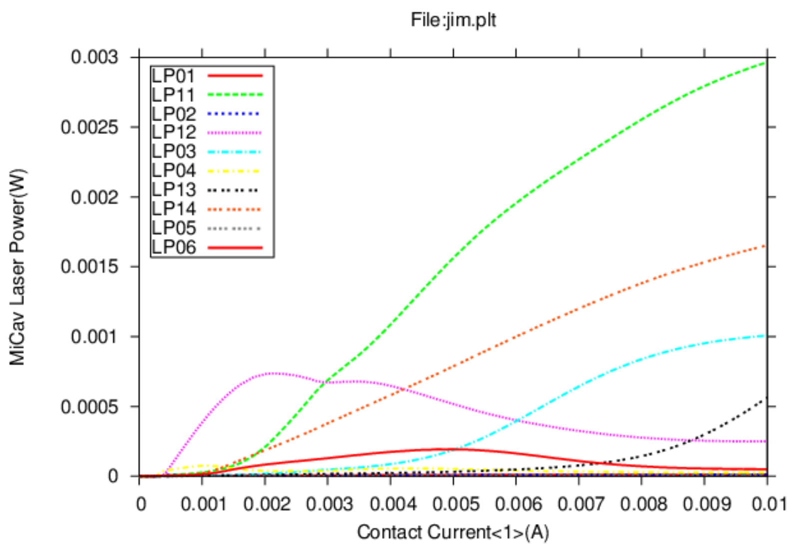


Analysis of Surface Relief & Oxide Confinement Width

Laser Power Analysis

- LP Modes
  - All Mode Laser Power
  - Modal Laser Power





Agenda

- VCSEL modeling in Crosslight PICS3D
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Mesh Limitations & Future Work

- Electrically, the Drift-Diffusion solvers in Crosslight are full 3D, with a FEM volume range dependent on the mesh plane spacing.
  - For default single mesh plane case in cylindrical coordinates, the FEM volume covers the entire $\phi = [0,2\pi]$ range.
- Scalar mode solver is single-plane only (2D). Current version of vectorial mode solver is also single-plane.
  - This implies that ***NO*** information on the phi dependence is currently used and that asymmetric modes are shown for ***plotting purposes only***.

Mesh Limitations & Future Work

- Even structurally-symmetric cylindrical VCSELs that can be optically solved in 2D using an analytical ϕ function require 3D electrical mesh to represent the asymmetry of higher-order modes:
  - Not demonstrated yet: investigate computational requirements & feasibility on conventional desktop platforms.

- Expand vectorial mode solver to full 3D to cover rectangular and structurally non-symmetric cylindrical VCSEL structures.