Microcavity Laser Diode Model

3D Rectangular VCSEL

Advantage of Microcavity Model

- Rigorous solution of Maxwell wave equation with no need to separate lateral and longitudinal modes.
- Arbitrary FEM mesh structure.
- PML boundary to define output power.
- Coupling of optical gain and drift-diffusion models to achieve full self-consistency.
- Rigorous multicavity eigenmode solution with multi-wavelength operation.

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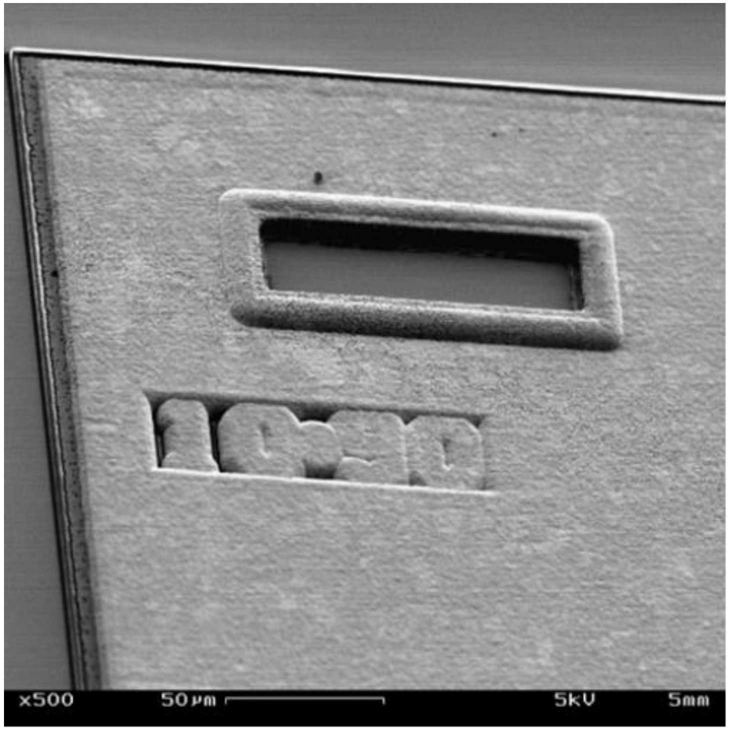
Rectangular VCSEL

- Rectangular VCSEL
  - ✓ Large aspect ratio
    - Improve heat flow
      - Reduce the internal temperature in the active region
      - Reduce carrier losses
    - Homogeneous carrier distribution in QW
  - ✓ Mainly used for high power applications



SEM picture of a top-emitting VCSEL with a rectangular aperture*

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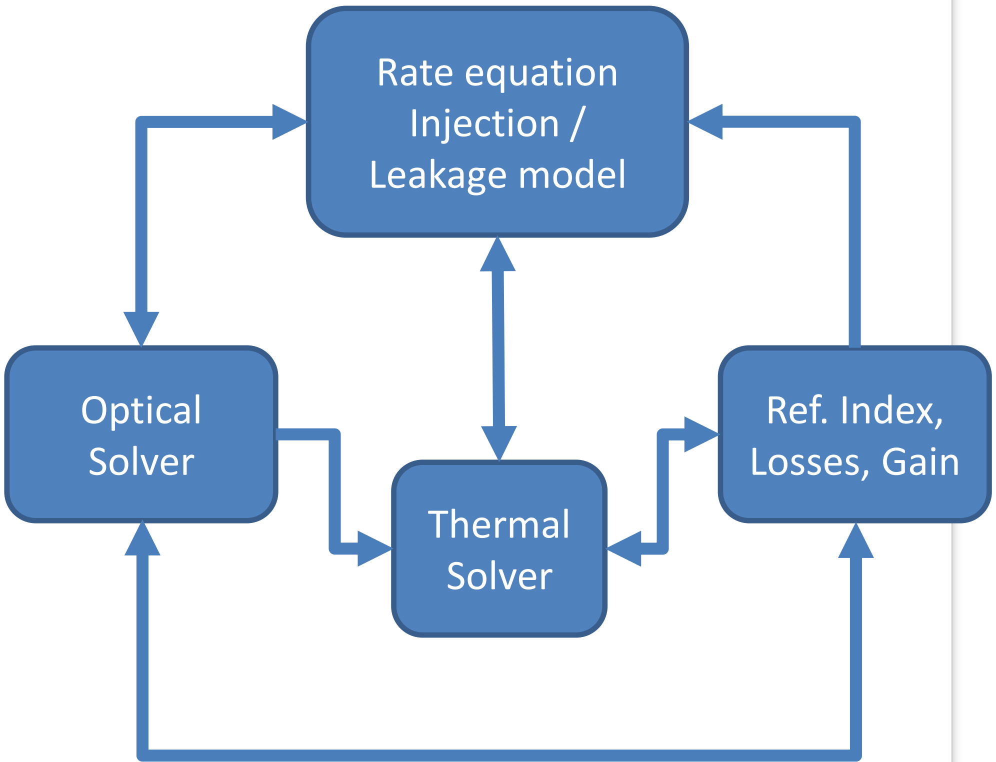
Crosslight PICS3D model for 3D VCSEL

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



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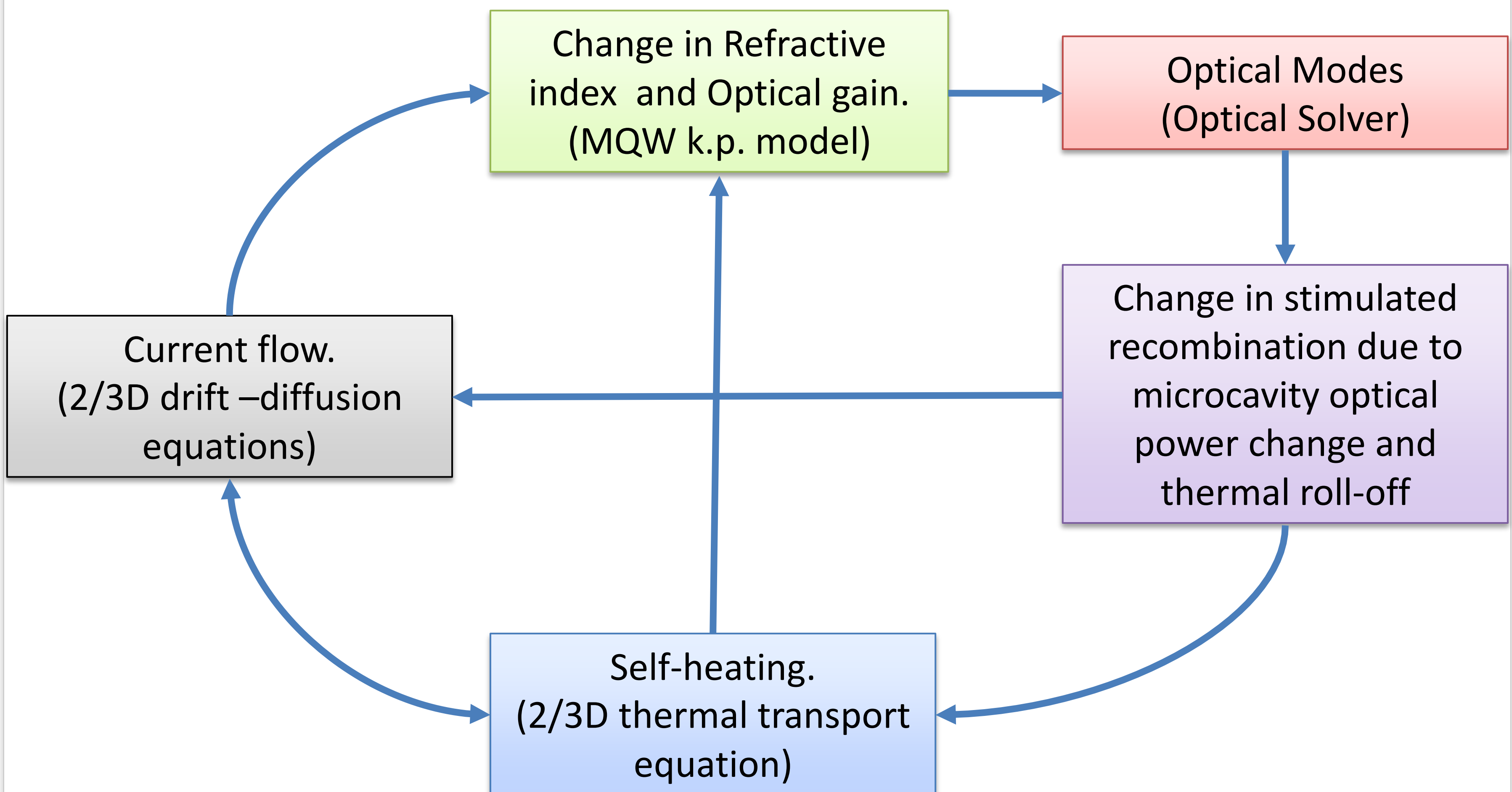
Crosslight PICS3D model for 3D VCSEL

- PICS3D includes quantum mechanical, electrical, thermal and microcavity optical effects.
- Due to their small size, VCSELs have stronger interactions between those models than other optoelectronic devices.

Crosslight PICS3D model for 3D VCSEL



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Optical Mode Solver

- ❖ Depends on:
  - ✓ The geometry of the structure
  - ✓ Different material parameters
    - Heat and carrier concentration
      - may affect the refractive index
- ❖ Solves for:
  - ✓ Field profile / Intensity / Resonance wavelength
- ❖ Full Vectorial solver
  - ✓ Based on the Finite Difference Frequency Domain FDFD Method
    - Solver optimized for highly accurate results in a reasonable simulation time
  - ✓ To include the effect of material change within the simulation
    - An accurate perturbation model was adapted

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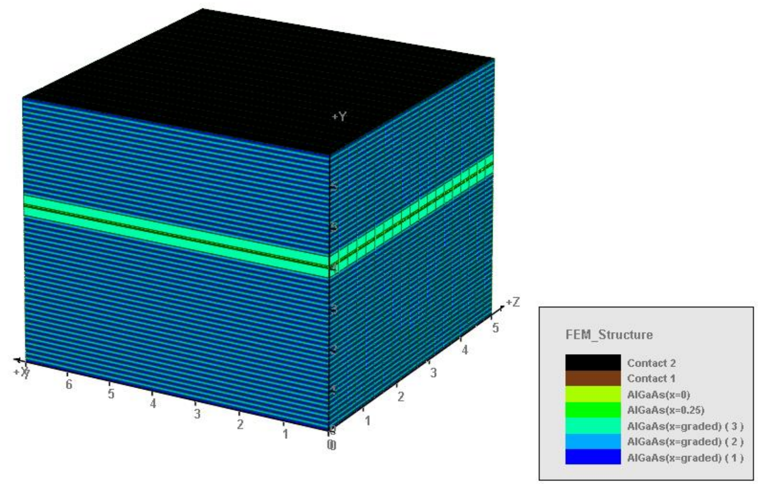
3D VCSEL example

❖ Case01 - Constant Optical Modes

✓ Structure

- Cavity
  - Cavity cross-section
    - » 7 × 5 μm
  - Cavity thickness
    - » 0.521 μm
- DBR Mirror
  - Top Mirror: 19 layers
  - Bottom Mirror: 29 layers



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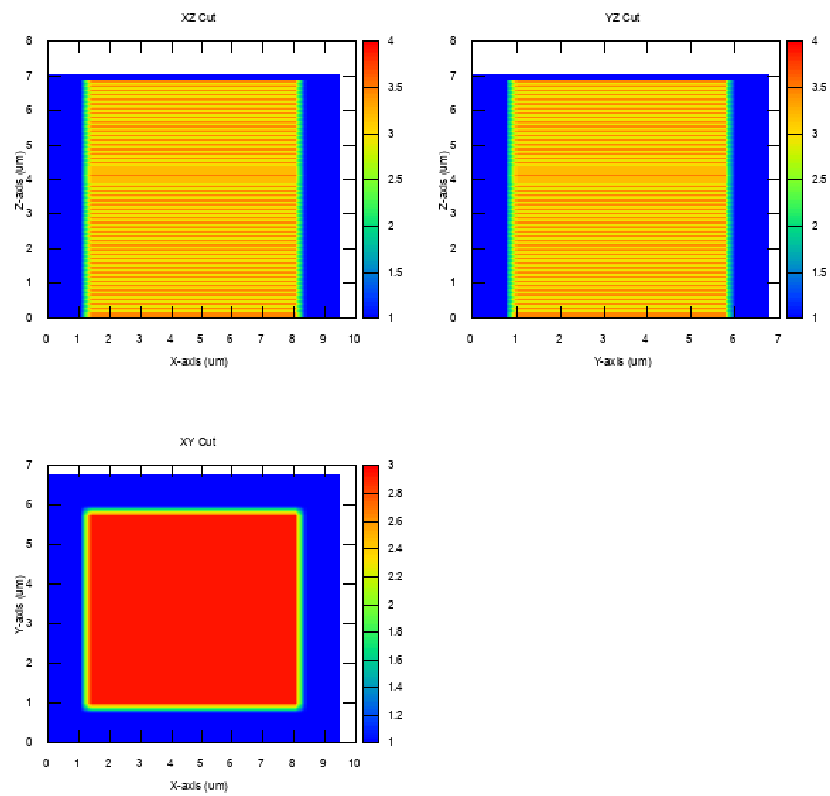
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
    - Cavity
      - – Cavity cross-section
        - » 7 × 5 µm
      - – Cavity thickness
        - » 0.521 µm
    - DBR Mirror
      - – Top Mirror: 19 layers
      - – Bottom Mirror: 29 layers



3D VCSEL example

❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
  - Optical Solver
    - FDFD solver turned on

```
sparse_eigen_solver use_mf=yes
direct_eigen
microcavity_model set_wavelength=0.8370  fdfd_vectorial=yes &&
read_fdfd_only=no
microcavity_exit_above_y=1. power_refl=0.0
```

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3D VCSEL example

❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
  - Optical Solver
    - FDFD solver turned on
  - ***Disable optical mode update***
  - Solve for
    - Mode fields / intensity
    - Mode wavelength (λ_0)
    - Mode wavenumber (K_0)

```
$
newton_par damping_step=1. var_tol=1.e-4 res_tol=1.e-4 &&
max_iter=30 opt_iter=15 stop_iter=10 print_flag=3 &&
update_lateral_mode=no lateral_mode_perturbation=no &&
update_index_change=yes

scan var=voltage_1 value_to=-1.3 print_step=1.3 &&
init_step=0.2 min_step=1.e-5 max_step=0.5
$
scan var=current_1 value_to=8.e-3   &&
init_step=0.25e-3 min_step=10.e-9 max_step=0.5e-3
```

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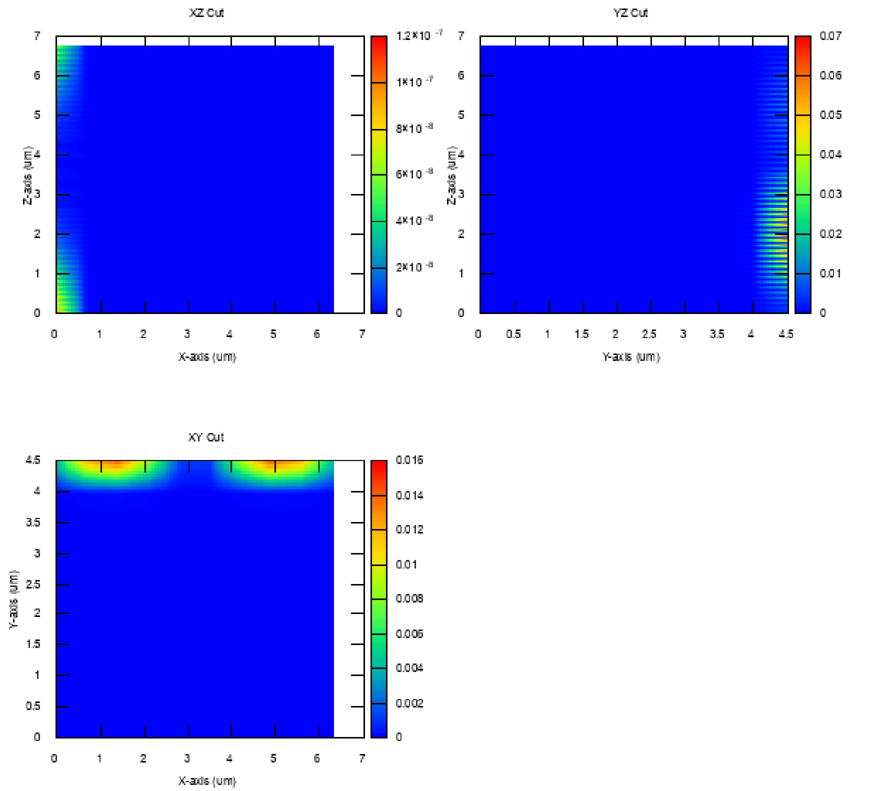
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #01
        - » λ0 = 0.840789 µm
        - » K_0 = 7.47296 +j 0.00986066 rad/µm



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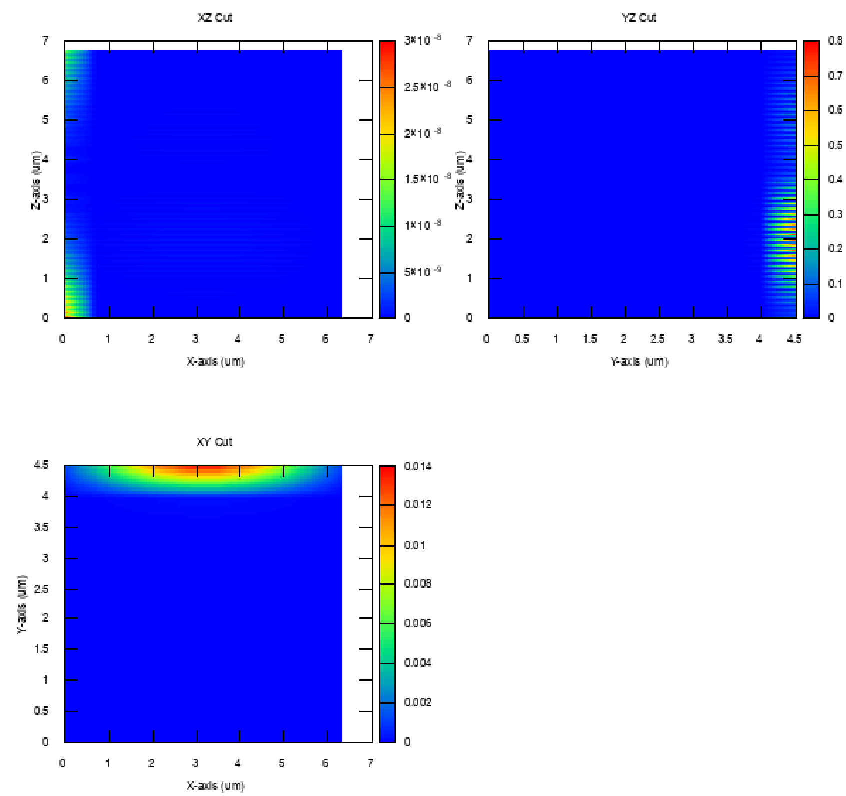
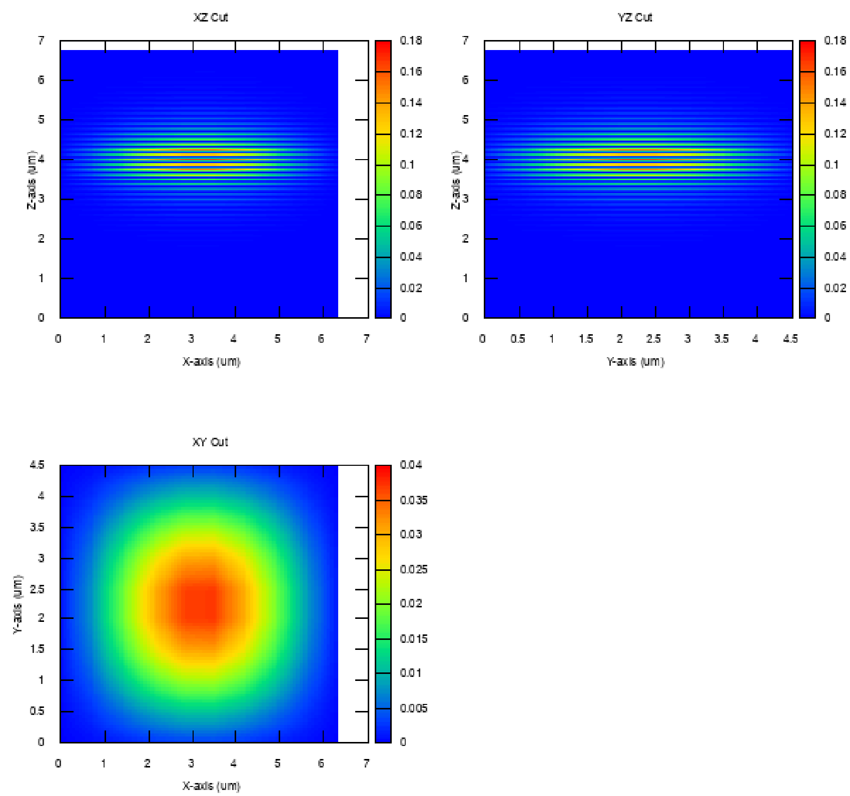
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #02
        - » $\lambda0 = 0.840460$ µm
        - » $K_0 = 7.47589 + j\ 0.00984171$ rad/µm



3D VCSEL example

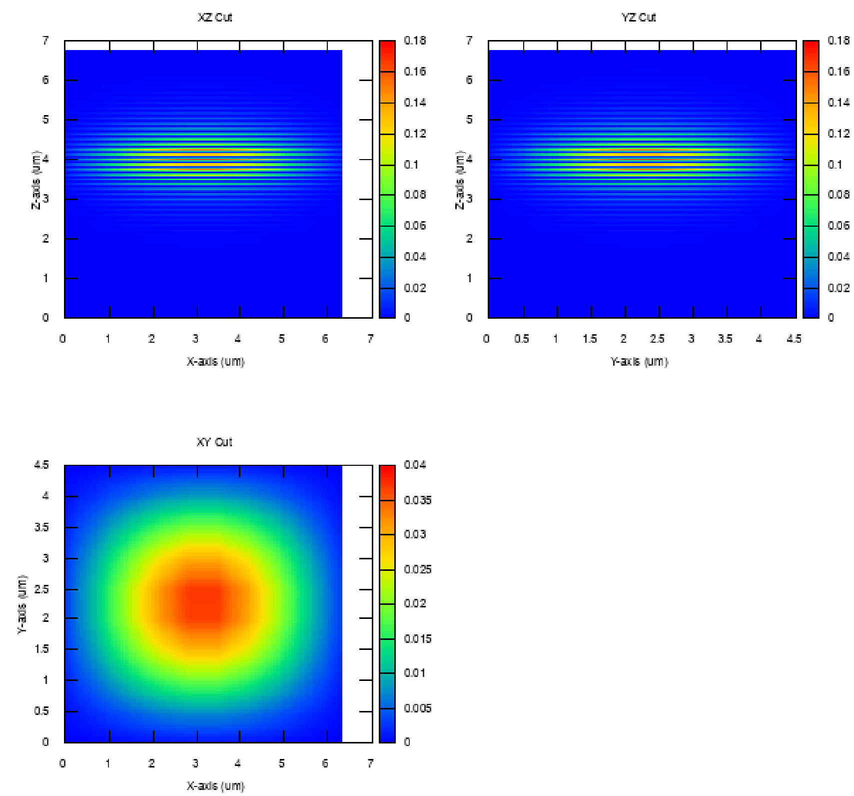
- **Case01 - Constant Optical Modes**
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #03
        - » λ0 = 0.838219 µm
        - » K_0 = 7.49587 +j 0.000153683 rad/µm



3D VCSEL example

❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results
  - Optical Modes
    - Mode #04
      - » λ0 = 0.838192 µm
      - » K_0 = 7.49612 +j 0.000154576 rad/µm



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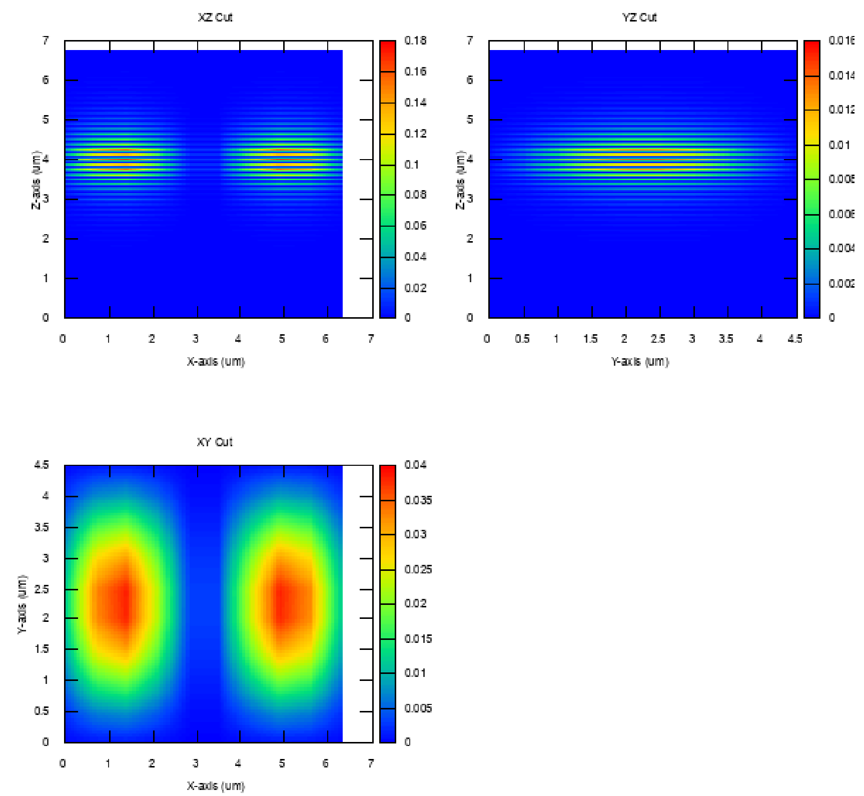
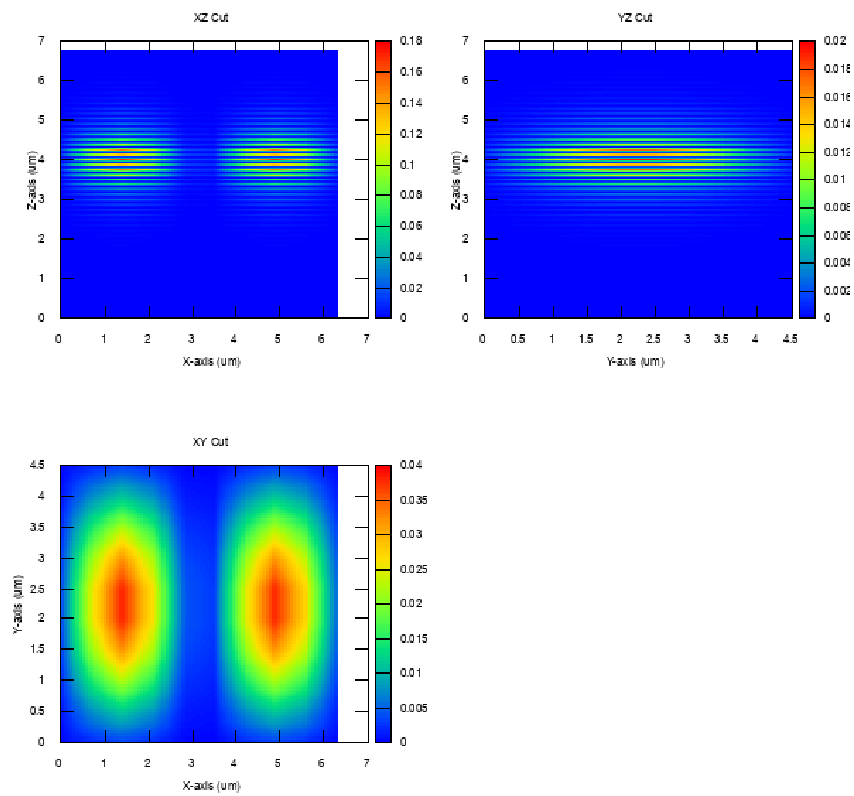
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #05
        - » λ0 = 0.837845 μm
        - » K_0 = 7.49922 +j 0.000153200 rad/μm



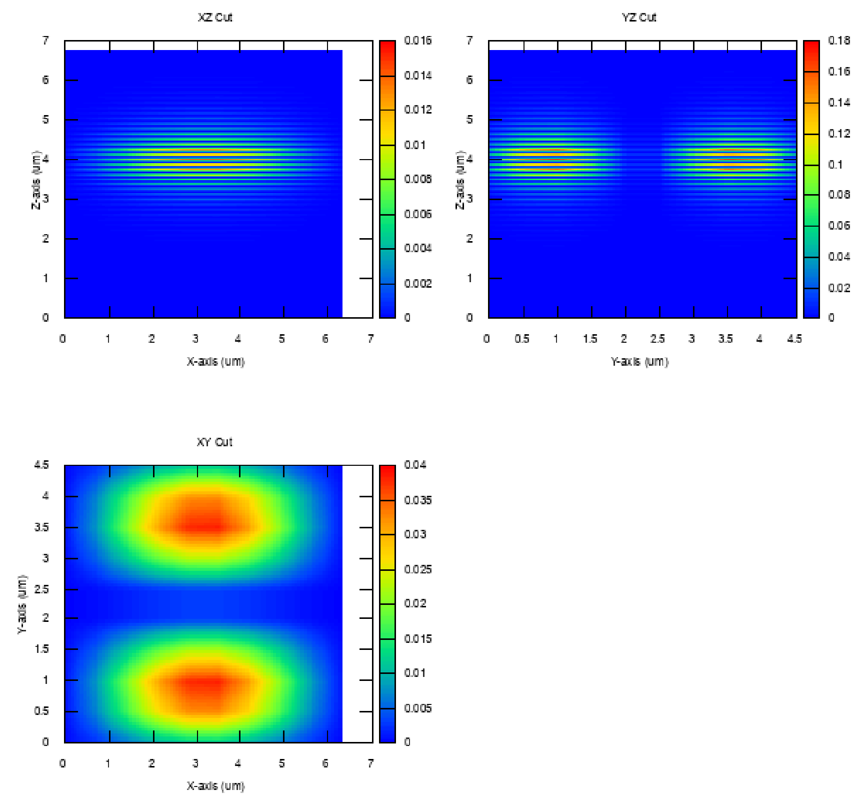
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #06
        - » $\lambda 0 = 0.837792$ µm
        - » $K_0 = 7.49969 + j\ 0.000155149$ rad/µm



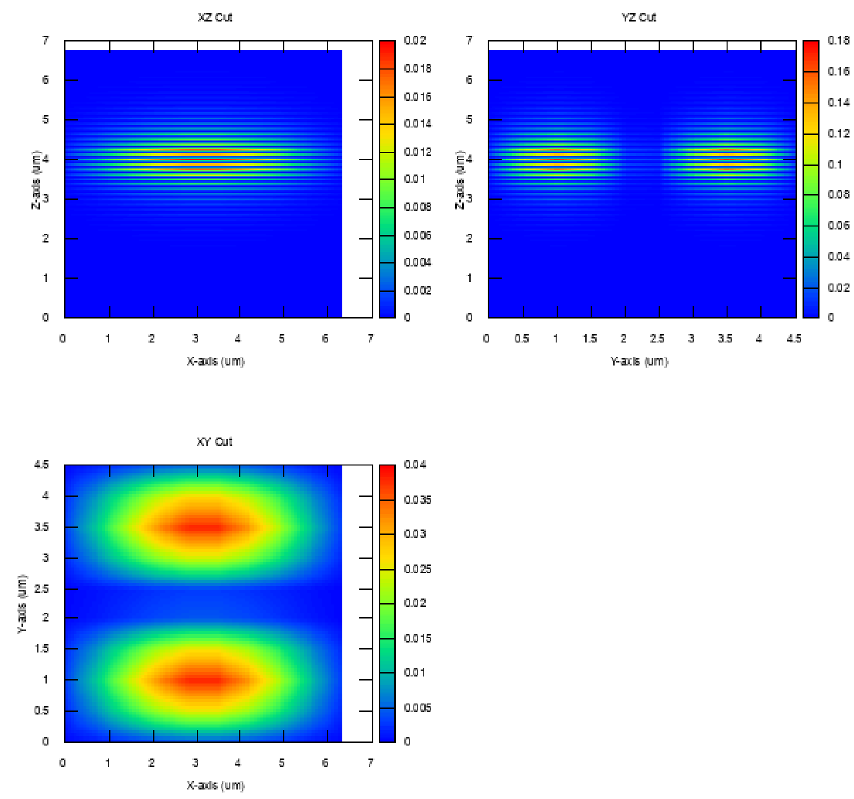
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - – Mode #07
        - » λ0 = 0.837539 µm
        - » K_0 = 7.50196 +j 0.000151303 rad/µm



3D VCSEL example

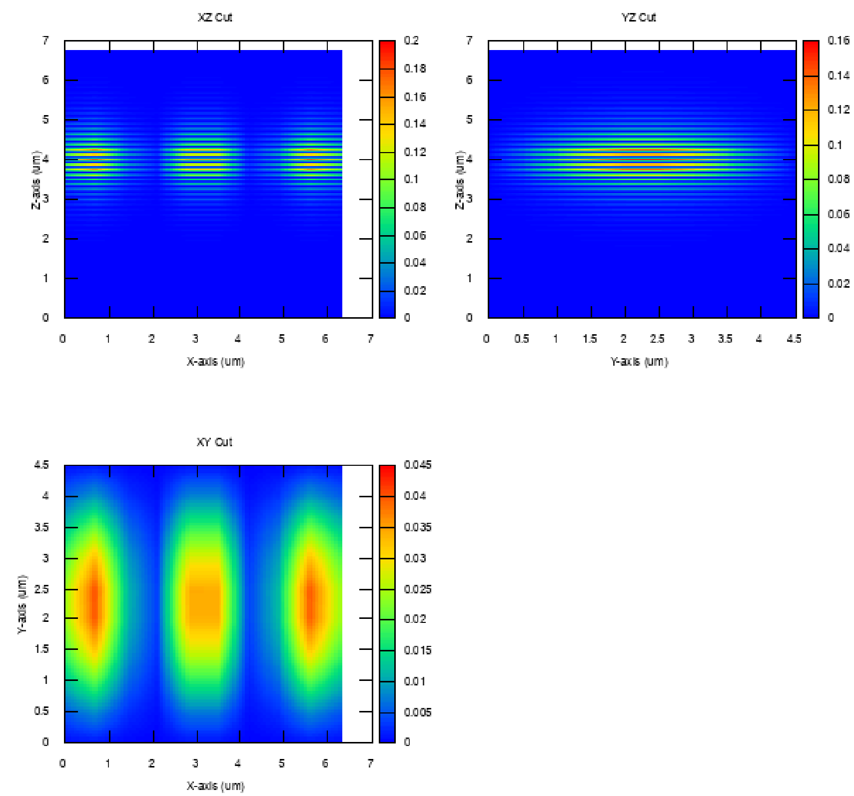
- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - – Mode #08
        - » λ0 = 0.837357 µm
        - » K_0 = 7.50360 +j 0.000157567 rad/µm



3D VCSEL example

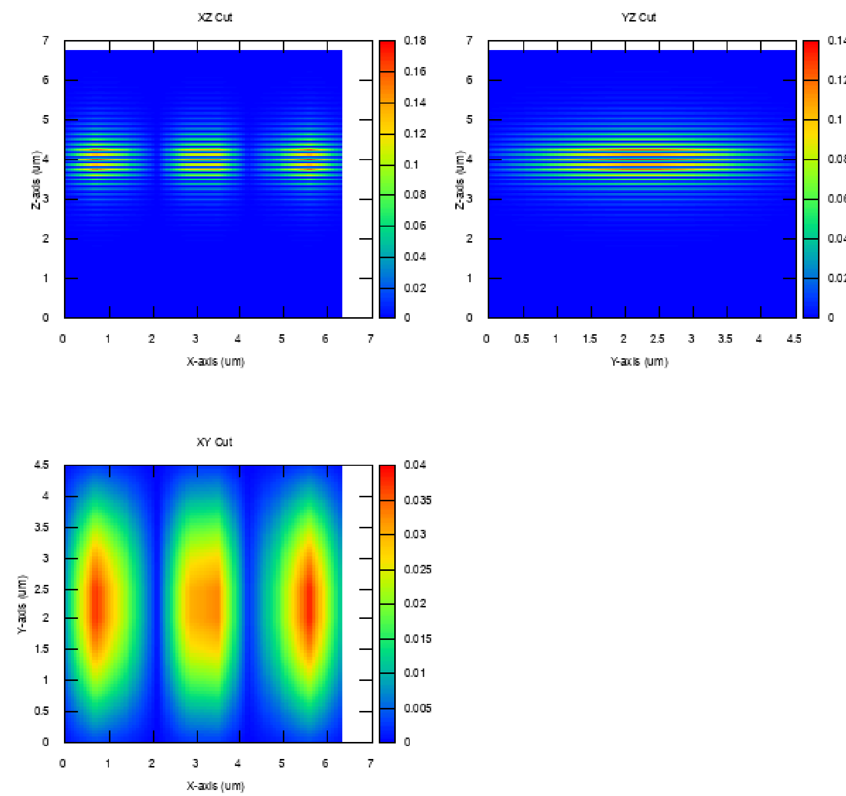
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results
  - Optical Modes
    - Mode #09
      - » λ0 = 0.837299 µm
      - » K_0 = 7.50411 +j 0.000150866 rad/µm



3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #10
        - » λ0 = 0.837127
        - » K_0 = 7.50565 +j 0.000157397 rad/µm



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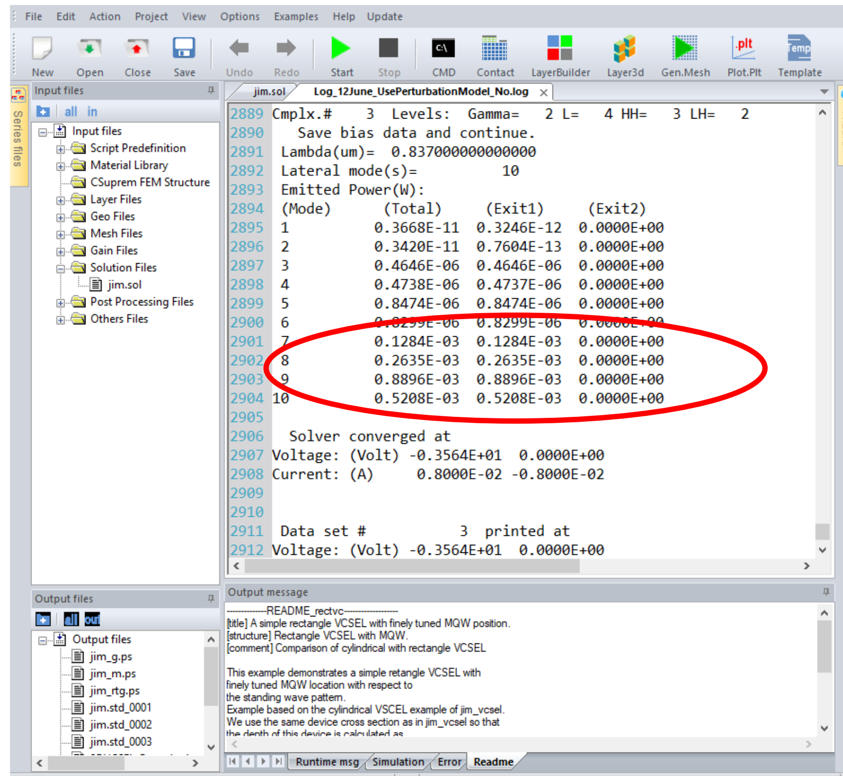
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes



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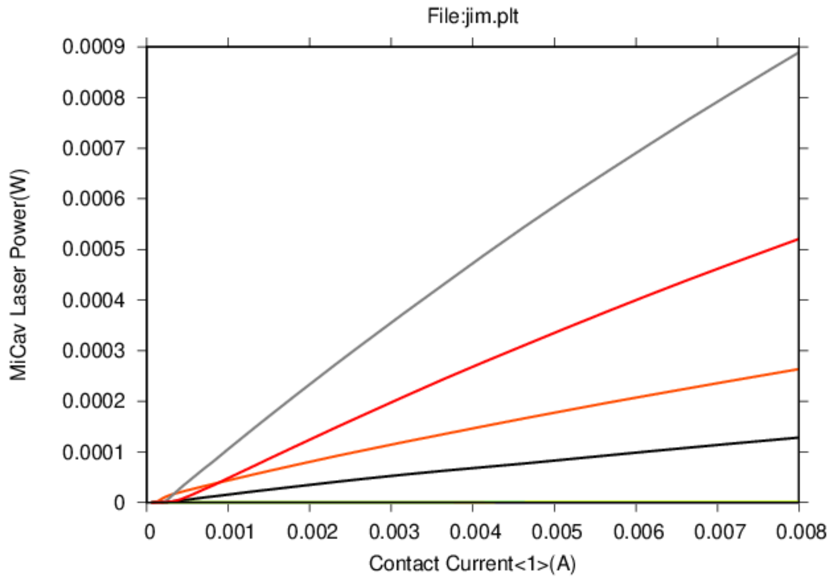
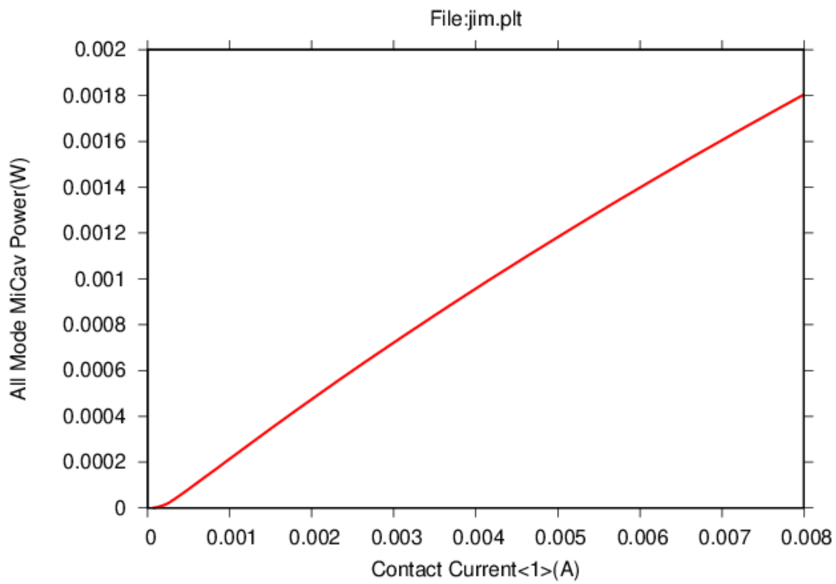
3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes
    - Power
      - All Mode Power



3D VCSEL example

- Case01 - Constant Optical Modes
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes
    - Power
      - All Mode Power



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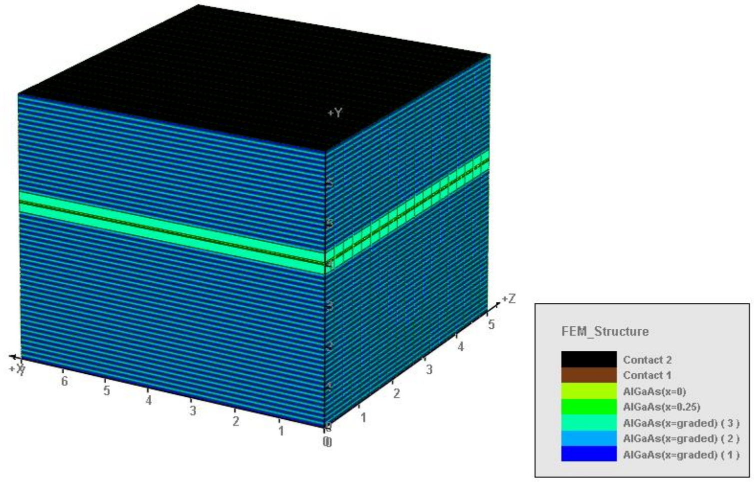
3D VCSEL example

❖ Case02 - Perturbation model

✓ Structure

- Cavity
  - Cavity cross-section
    - » 7 × 5 μm
  - Cavity thickness
    - » 0.521 μm
- DBR Mirror
  - Top Mirror: 19 layers
  - Bottom Mirror: 29 layers



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3D VCSEL example

- Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
    - Optical Solver
      - – FDFD solver turned on

```
sparse_eigen_solver use_mf=yes
direct_eigen
microcavity_model set_wavelength=0.8370  fdfd_vectorial=yes &&
read_fdfd_only=no
microcavity_exit above_y=1. power_refl=0.0
```

3D VCSEL example

❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
  - Optical Solver
    - – FDFD solver turned on
  - ***Enable optical mode update***
    - – ***Using the perturbation model, the optical mode is updated***
  - Solve for
    - – Mode fields / intensity
    - – Mode wavelength (λ_0)
    - – Mode wavenumber (K_0)

```
newton_par damping_step=1. var_tol=1.e-4 res_tol=1.e-4 &&
max_iter=30 opt_iter=15 stop_iter=10 print_flag=3 &&
update_lateral_mode=yes lateral_mode_perturbation=yes &&
update_index_change=yes

scan var=voltage_1 value_to=-1.3 print_step=1.3 &&
init_step=0.2 min_step=1.e-5 max_step=0.5
$
scan var=current_1 value_to=8.e-3   &&
init_step=0.25e-3 min_step=10.e-9 max_step=0.5e-3
```

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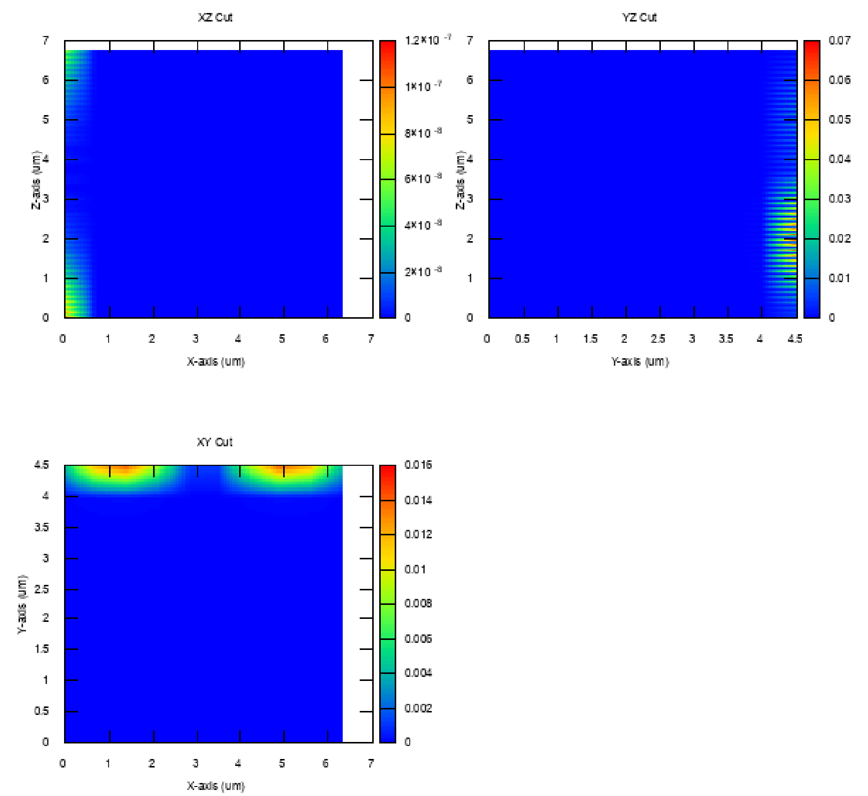
3D VCSEL example

- **Case02 - Perturbation model**
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #01
        - » λ0 = 0.840789 μm
        - » K0 = 7.04730 +j 0.00984850 rad/μm



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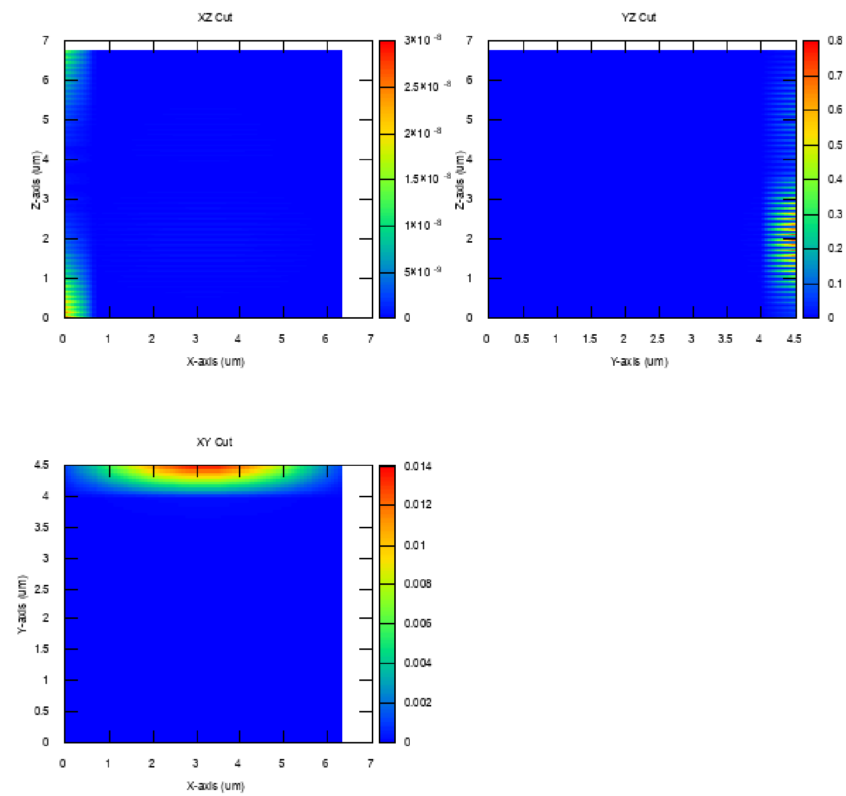
3D VCSEL example

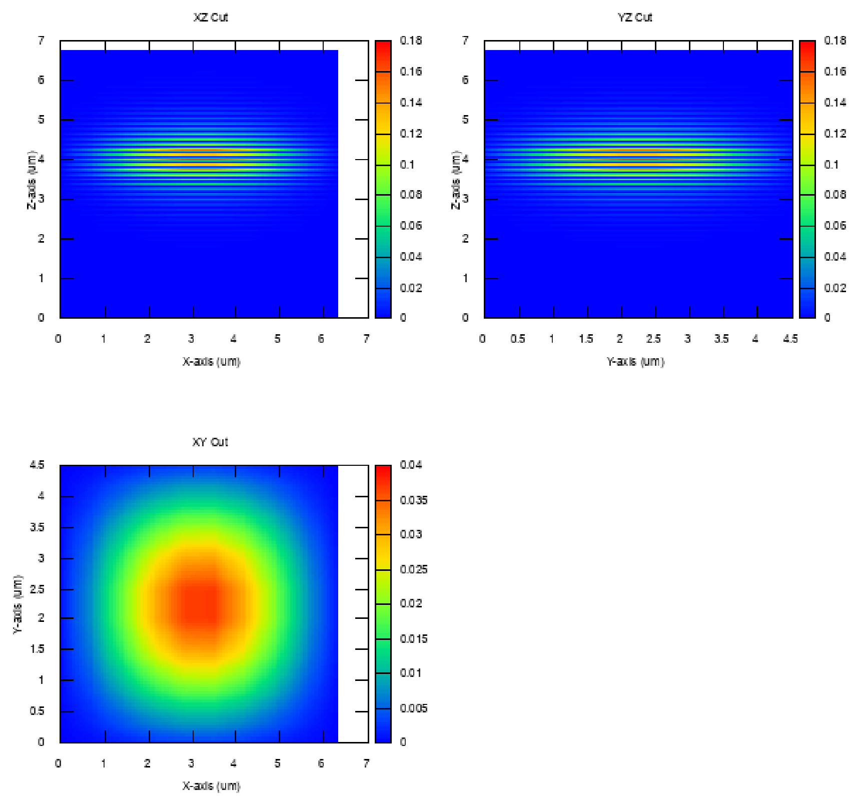
- Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #02
        - » $\lambda 0$ = 0.840460 µm
        - » K0 = 7.04759 +j 0.00982955 rad/µm



3D VCSEL example

❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results
  - Optical Modes
    - Mode #03
      - » λ0 = 0.838220 µm
      - » K0 = 7.04959 -j 0.00132957 rad/µm



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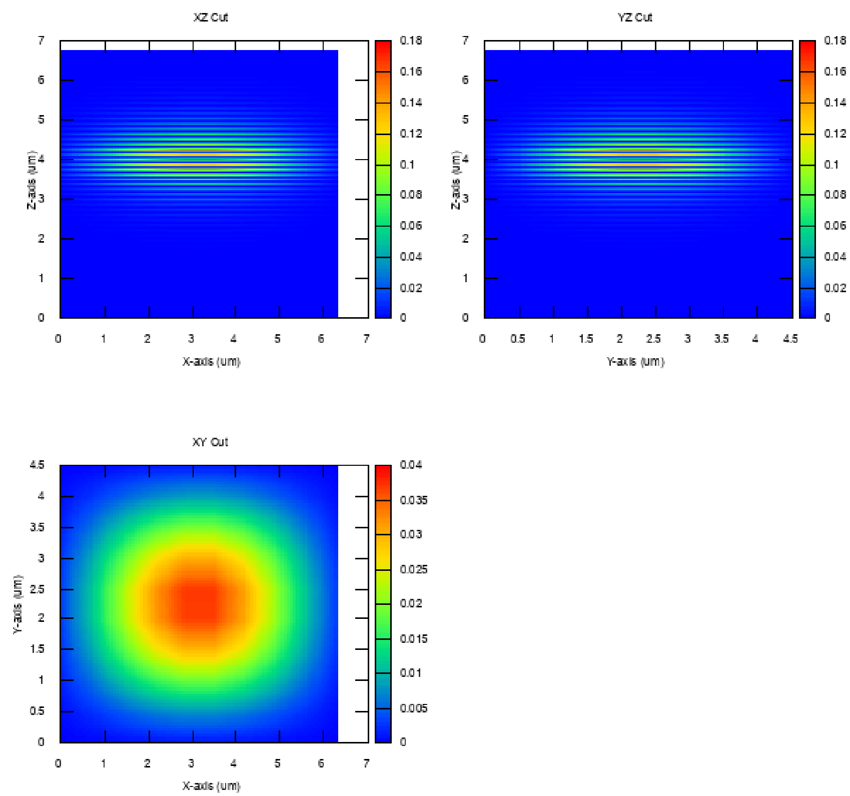
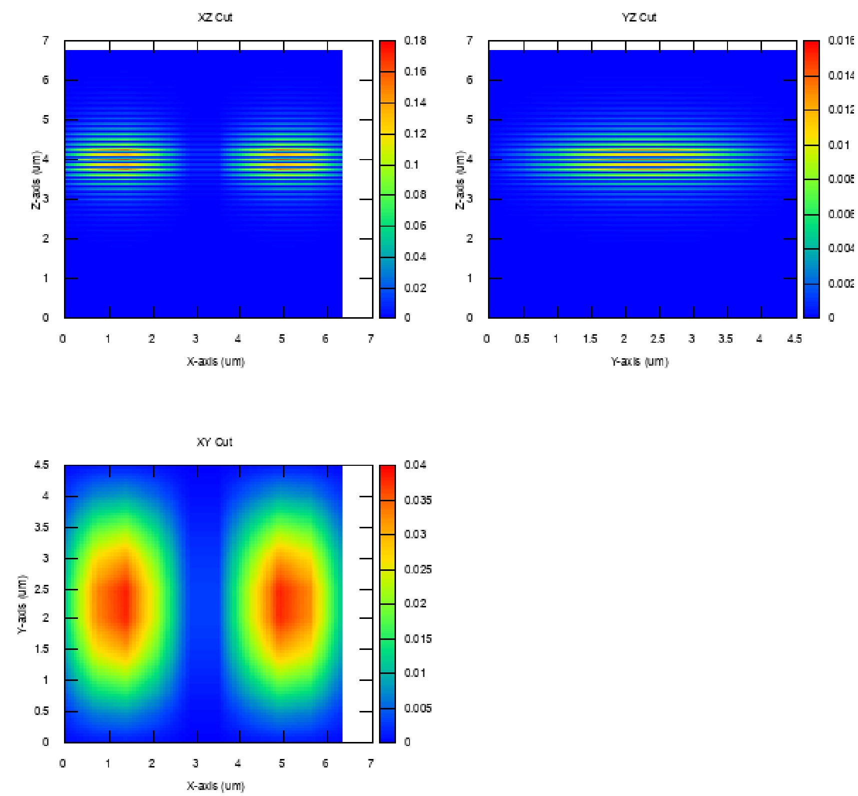
3D VCSEL example

- Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #04
        - » λ0 = 0.838193 µm
        - » K0 = 7.04961 -j 0.00132773 rad/µm



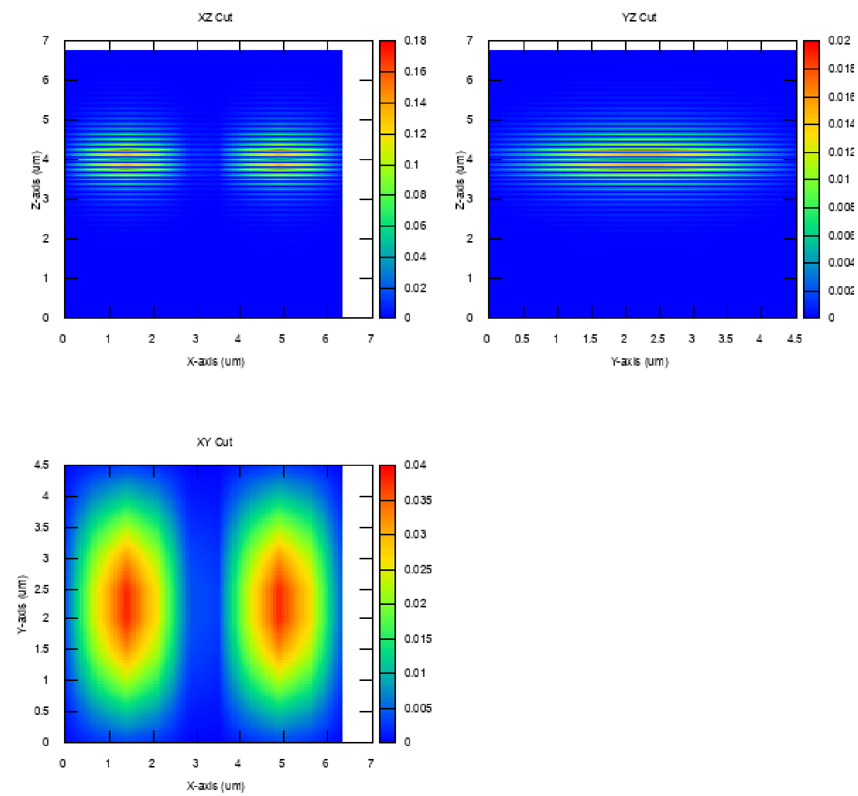
3D VCSEL example

- ❖ Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - – Mode #05
        - » λ0 = 0.837846 µm
        - » K0 = 7.04992 -j 0.00133038 rad/µm



3D VCSEL example

- **Case02 - Perturbation model**
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #06
        - » λ0 = 0.837793 µm
        - » K0 = 7.04997 -j 0.00132645 rad/µm



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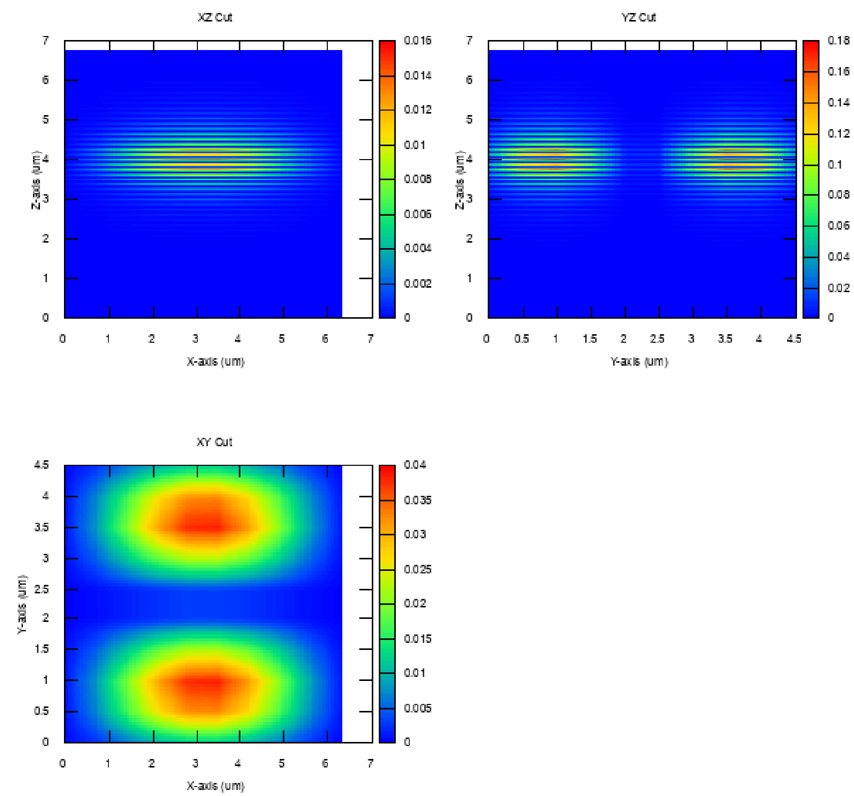
3D VCSEL example

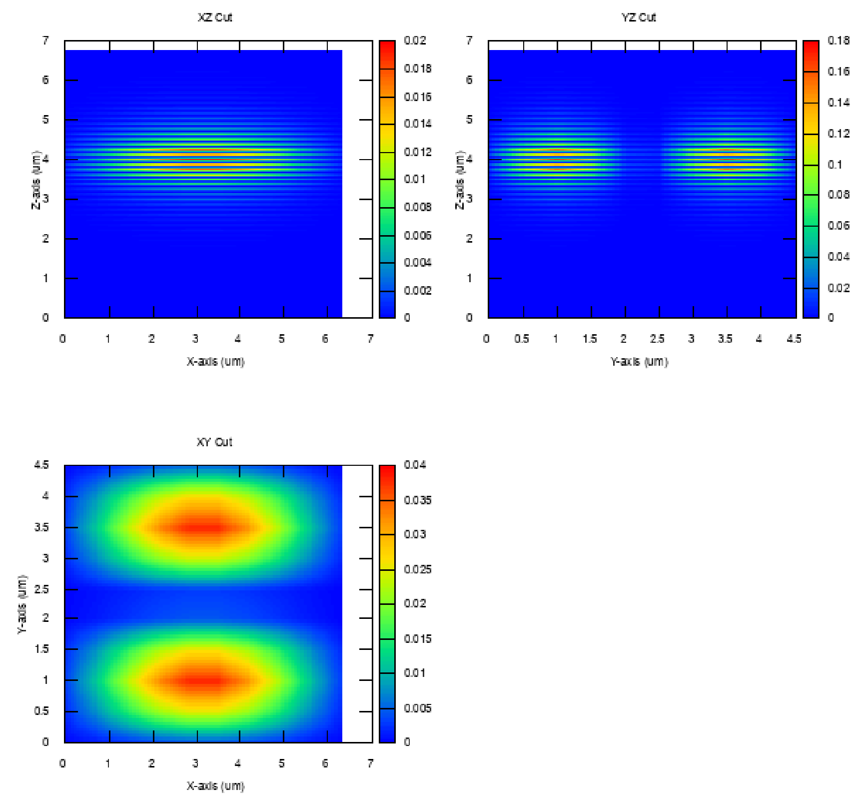
- **Case02 - Perturbation model**
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #07
        - » λ0 = 0.837540 µm
        - » K0 = 7.05019 -j 0.00133426 rad/µm



3D VCSEL example

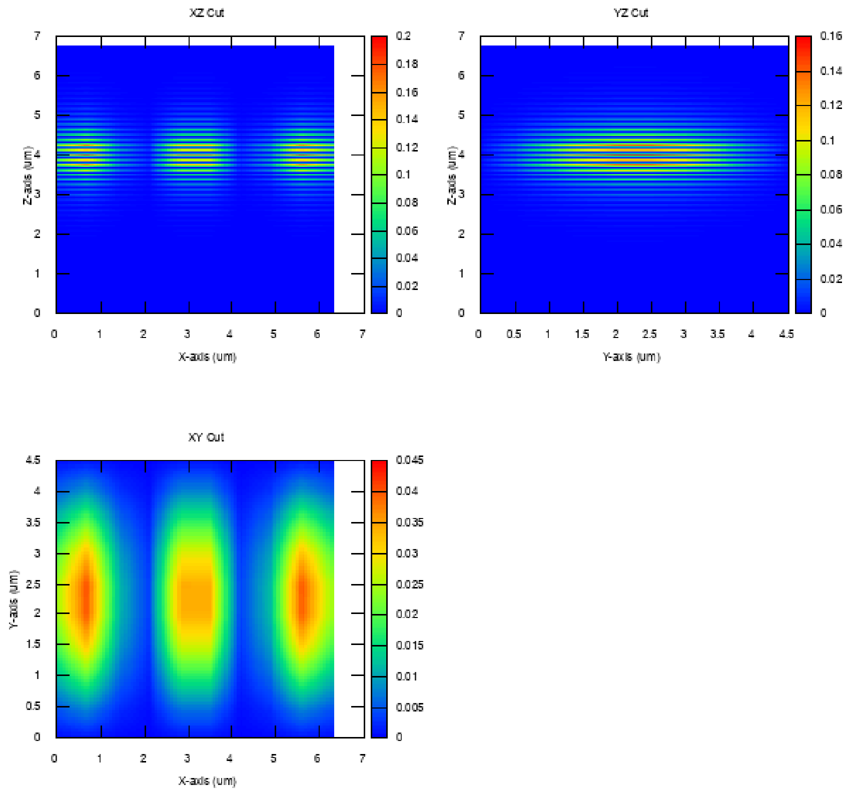
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results
  - Optical Modes
    - Mode #08
      - » $\lambda0$ = 0.837356 µm
      - » K0 = 7.05036 -j 0.00132144 rad/µm



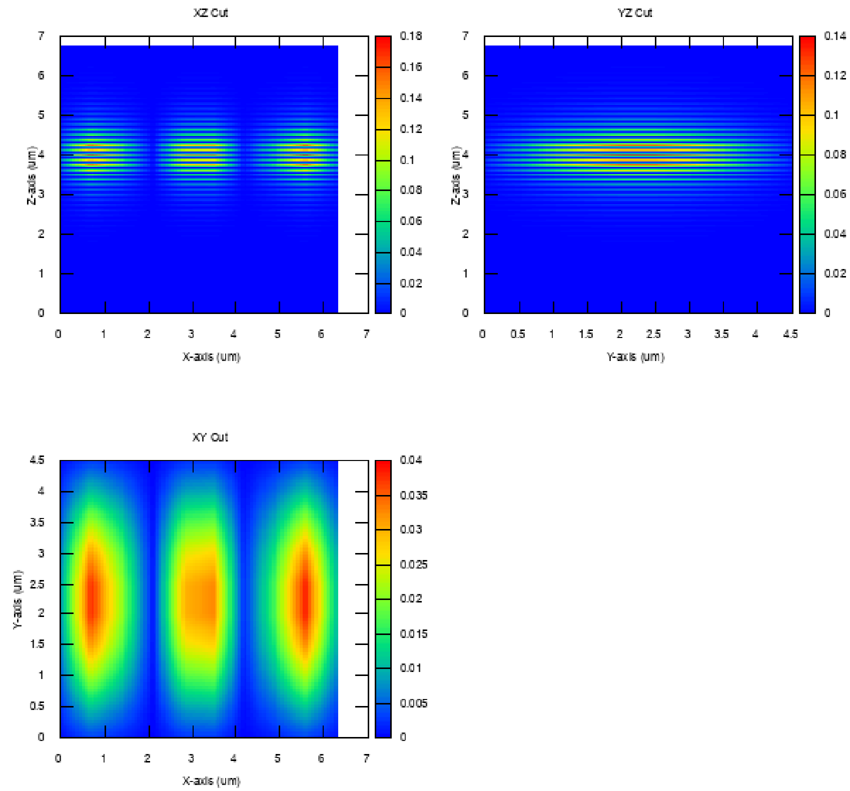
3D VCSEL example

- Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #09
        - » λ0 = 0.837300 μm
        - » K0 = 7.50410 -j 0.00133487 rad/μm



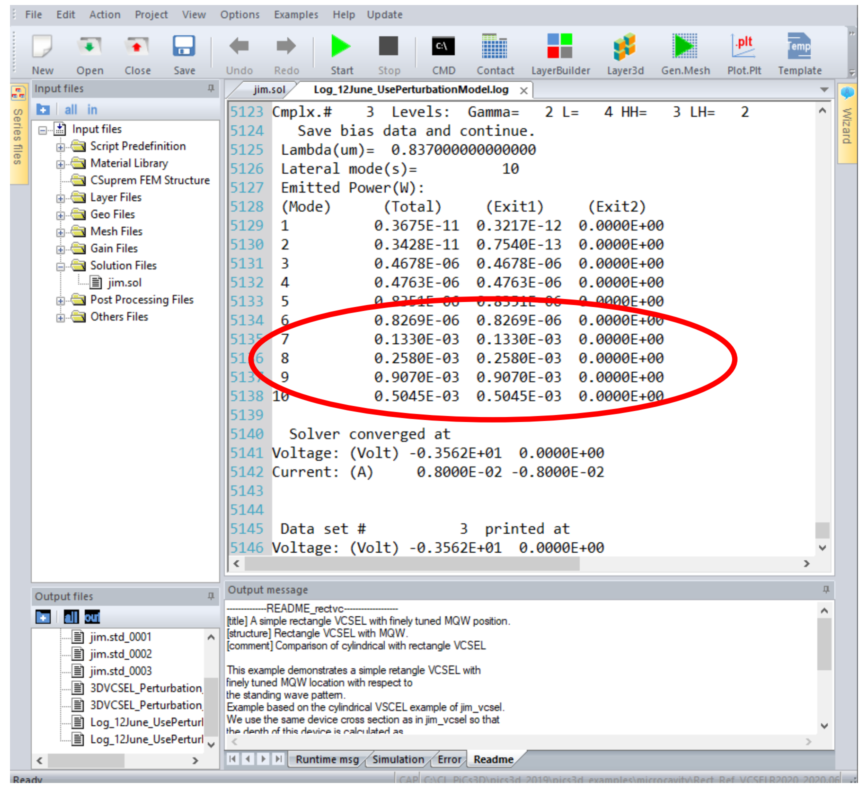
3D VCSEL example

- **Case02 - Perturbation model**
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
      - Mode #10
        - » λ0 = 0.837128
        - » K0 = 7.50564 -j 0.00132175 rad/µm



3D VCSEL example

- ❖ Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes



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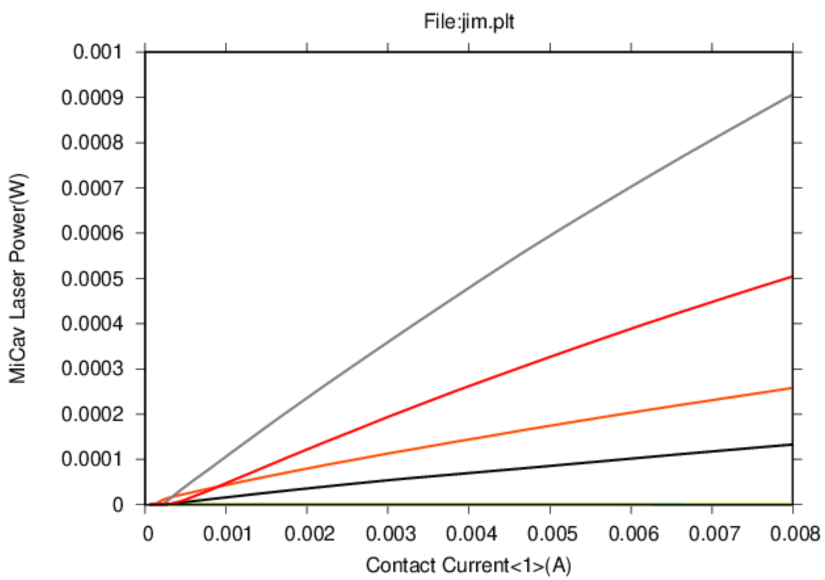
3D VCSEL example

❖ Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes
    - Power
      - – All Mode Power



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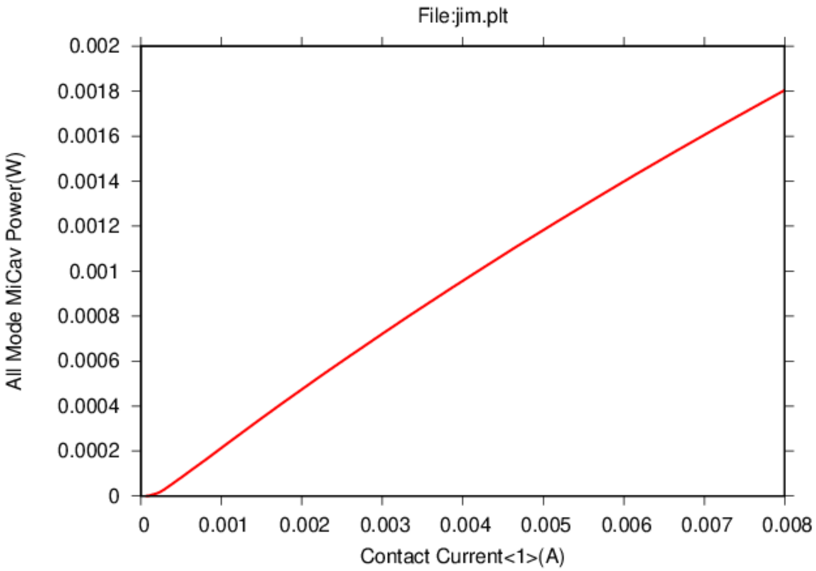
3D VCSEL example

- Case02 - Perturbation model
  - ✓ Structure
  - ✓ Analysis
  - ✓ Results
    - Optical Modes
    - Lasing Modes
    - Power
      - All Mode Power



3D VCSEL example

❖ Notes
- ✓ As the device is pumped, the imaginary part of the refractive index changes compared to initial solution at thermal equilibrium.
- ✓ Net optical gain naturally clamps at threshold.
- ✓ Since the corresponding change in the real part refractive index is small, the perturbation method was used to update the optical fields and resonance wavelengths

	Constant Optical Modes	Update optical mode using Perturbation model
1	0.840789	0.840789
2	0.840460	0.840460
3	0.838219	0.838220
4	0.838192	0.838193
5	0.837845	0.837846
6	0.837792	0.837793
7	0.837539	0.837540
8	0.837357	0.837356
9	0.837299	0.837300
10	0.837127	0.837128

Caveats

- FDFD method relies on a brute force eigenvalue search which means that non-resonant "spurious" modes can be found alongside the modes of interest.
  - Modes sorted in decreasing order of the real part of eigenvalue
  - Wavelength of spurious modes comparable to that of resonant modes
  - Spurious modes will not carry significant power but cannot be easily isolated from resonant modes
- Appropriate care must be taken in selecting the right target wavelength in the mode search in order not to miss the modes of interest in the simulation window.
- Lasing mode for the device is not always the fundamental mode: all modes included in the model will compete for the available gain.