

Microcavity Laser Diode Model

3D Rectangular VCSEL



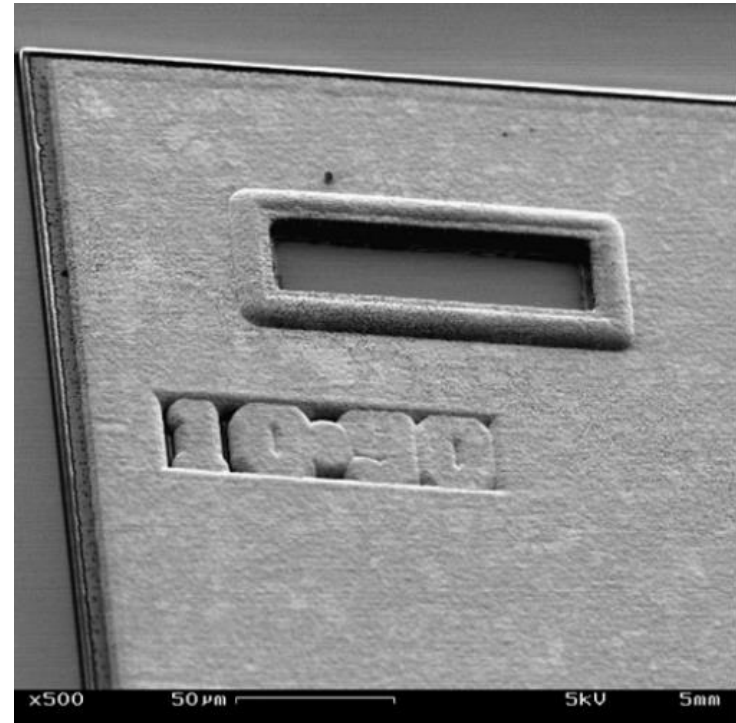
Advantage of Microcavity Model

- ❖ 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.

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*

Crosslight PICS3D model for 3D VCSEL

❖ To analyze the VCSEL accurately, three interrelated problems must be solved

✓ Optical:

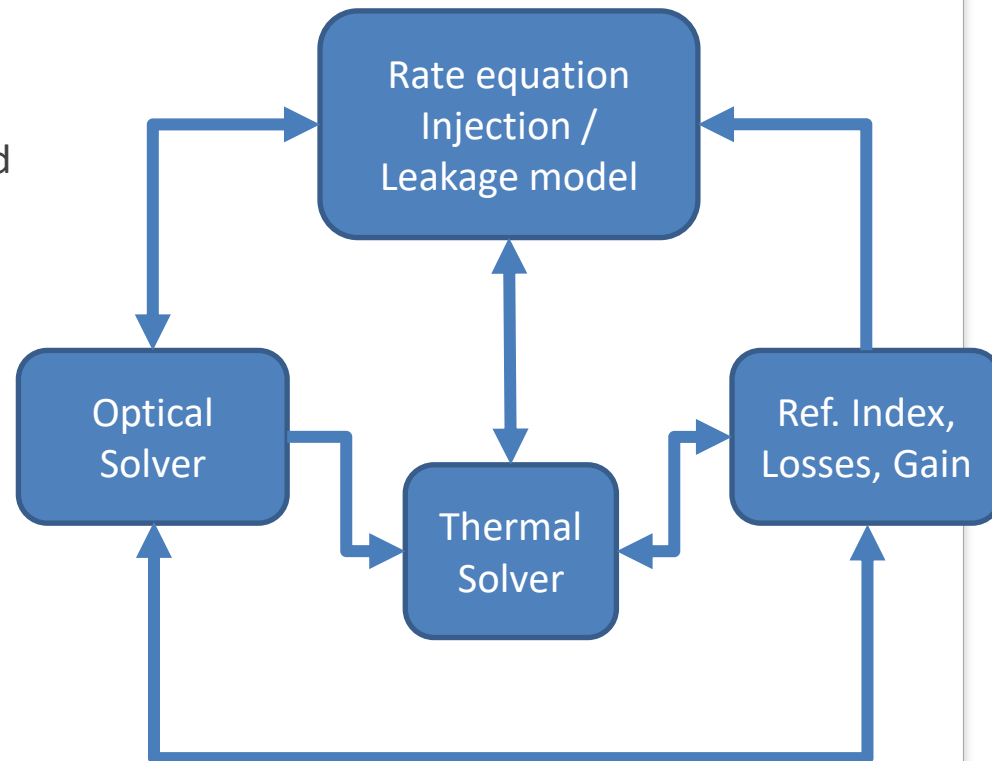
- define modal wavelength / field / intensity

✓ Electrical:

- Carrier injection into the active region
- Joule heating

✓ Thermal:

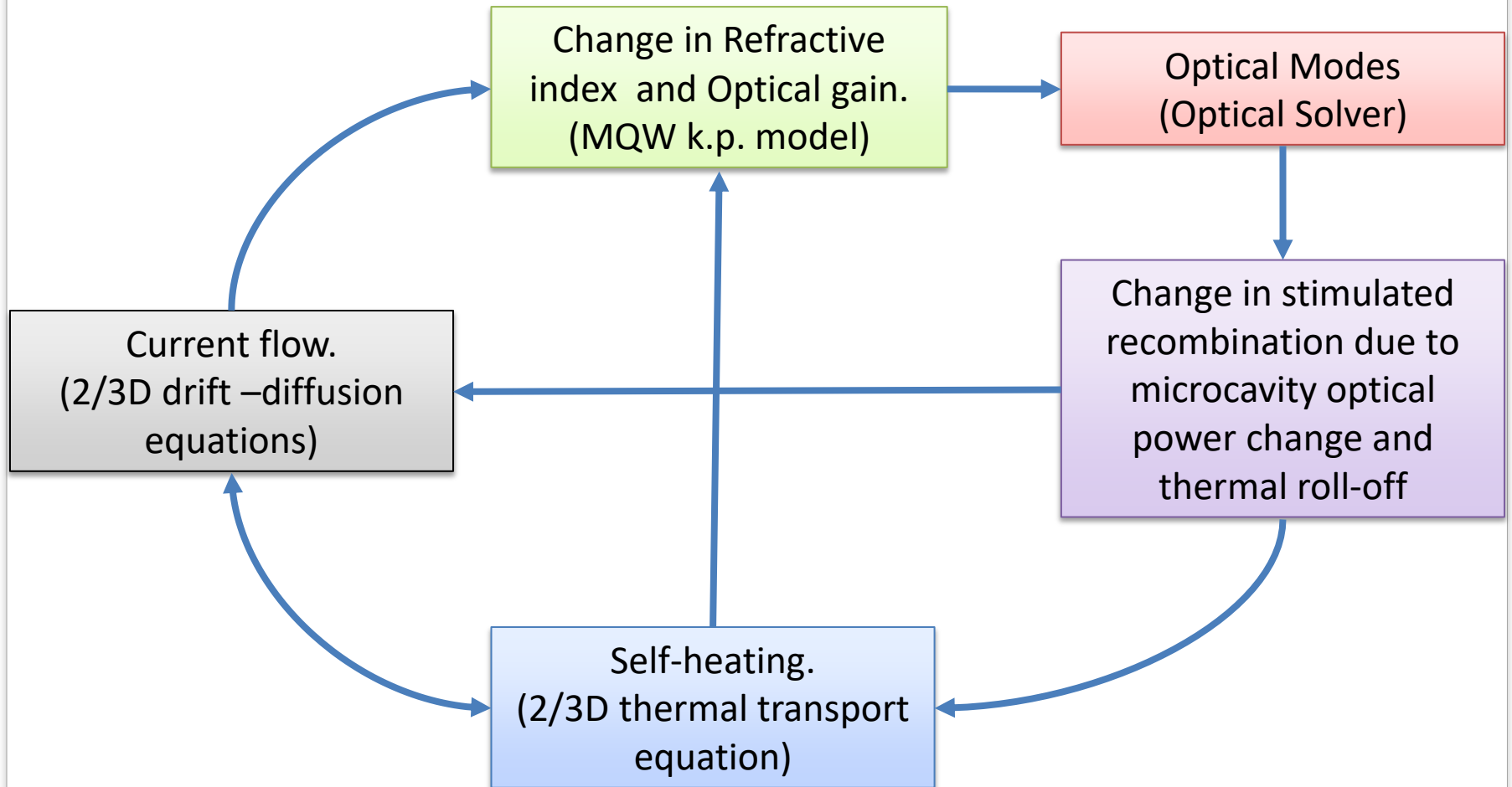
- Temperature change due to
 - Joule heating / non-radiative recombination / free carrier absorption
- Temperature change perturbs the optical and electrical problems



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



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

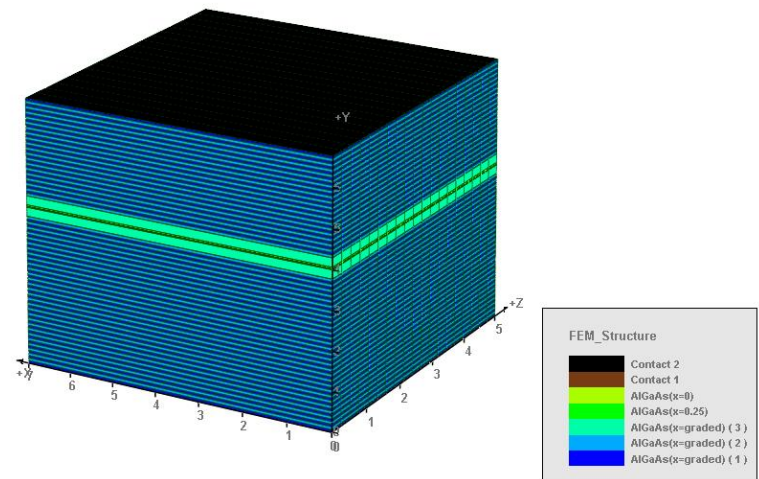
- ✓ Based on the Finite Difference Frequency Domain FDFD Method
 - Solver optimized for highly accurate results in a reasonable simulation time
- ✓ To include the effect of material change within the simulation
 - An accurate perturbation model was adapted

3D VCSEL example

❖ Case01 - Constant Optical Modes

✓ Structure

- Cavity
 - Cavity cross-section
 - » $7 \times 5 \mu\text{m}$
 - Cavity thickness
 - » $0.521 \mu\text{m}$
- DBR Mirror
 - Top Mirror: 19 layers
 - Bottom Mirror: 29 layers

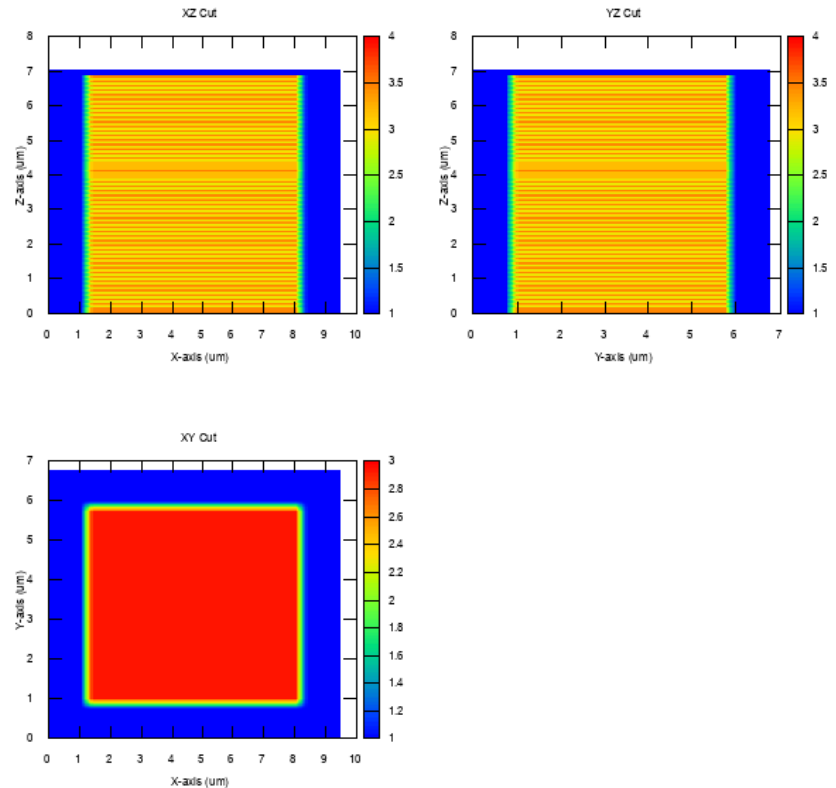


3D VCSEL example

❖ Case01 - Constant Optical Modes

✓ Structure

- Cavity
 - Cavity cross-section
 - » $7 \times 5 \mu\text{m}$
 - Cavity thickness
 - » $0.521 \mu\text{m}$
- 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

```
15  
16 sparse_eigen_solver use_mf=yes  
17 direct_eigen  
18 microcavity_model set_wavelength=0.8370 fdfd_vectorial=yes &&  
19 read_fdfd_only=no  
20 microcavity_exit_above v=1. power_refl=0.0  
21
```

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)

```
48 >  
49 newton_par damping_step=1. var_tol=1.e-4 res_tol=1.e-4 &&  
50 max_iter=30 opt_iter=15 stop_iter=10 print_flag=3 &&  
51 update_lateral_mode=no lateral_mode_perturbation=no &&  
52 update_index_change=yes  
53  
54 scan var=voltage_1 value_to=-1.3 print_step=1.3 &&  
55 init_step=0.2 min_step=1.e-5 max_step=0.5  
56 $  
57 scan var=current_1 value_to=8.e-3 &&  
58 init_step=0.25e-3 min_step=10.e-9 max_step=0.5e-3
```

3D VCSEL example

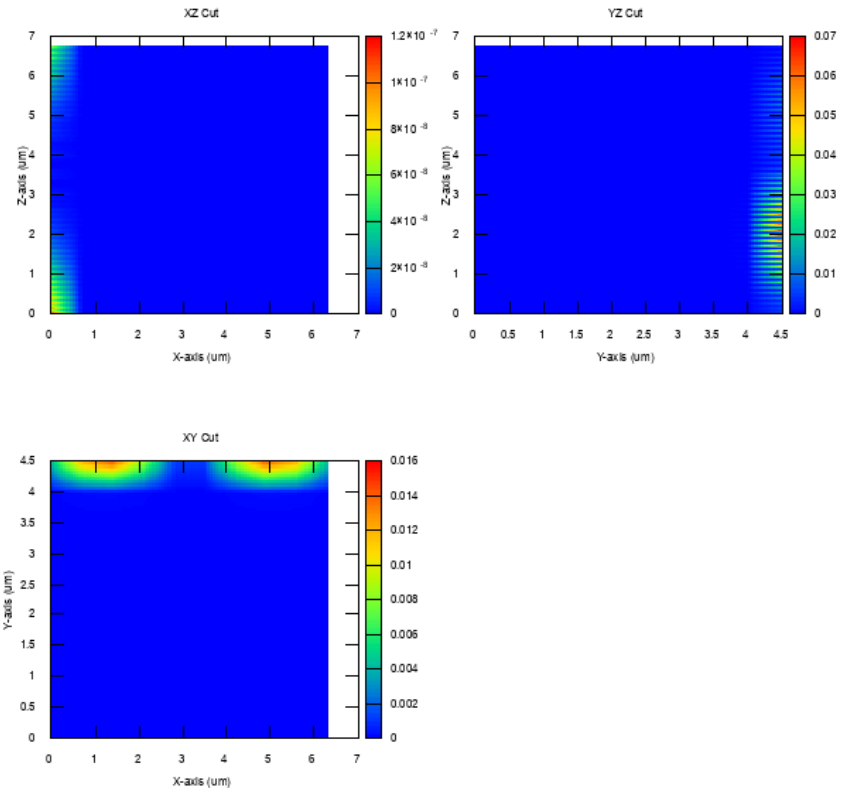
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #01

- » $\lambda_0 = 0.840789 \mu\text{m}$
 - » $K_0 = 7.47296 + j$
 0.00986066
 $\text{rad}/\mu\text{m}$



3D VCSEL example

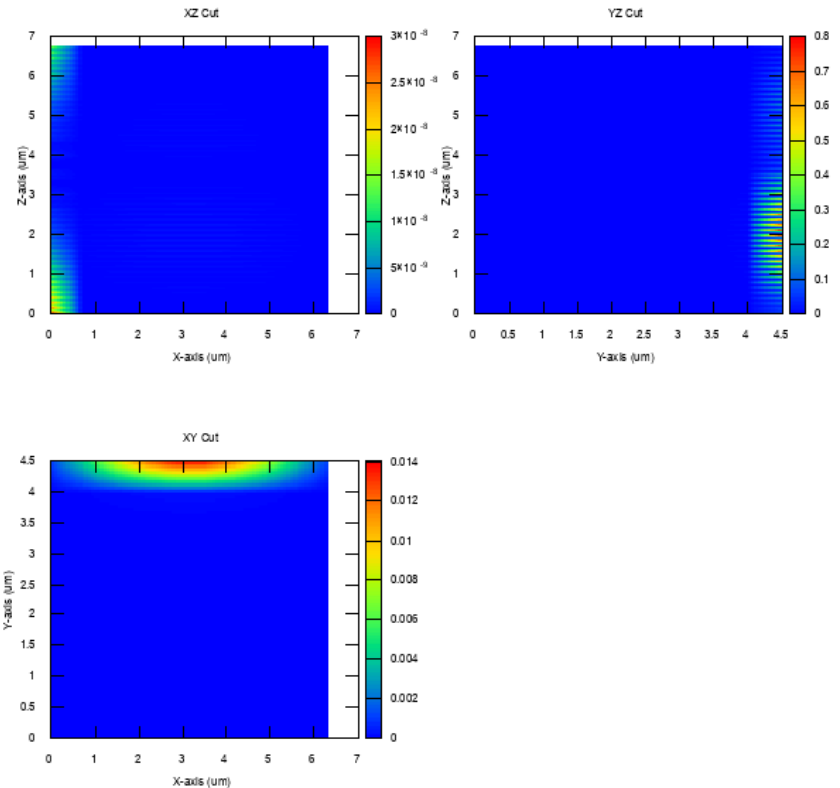
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #02

- » $\lambda_0 = 0.840460 \mu\text{m}$
 - » $K_0 = 7.47589 + j$
 0.00984171
 $\text{rad}/\mu\text{m}$



3D VCSEL example

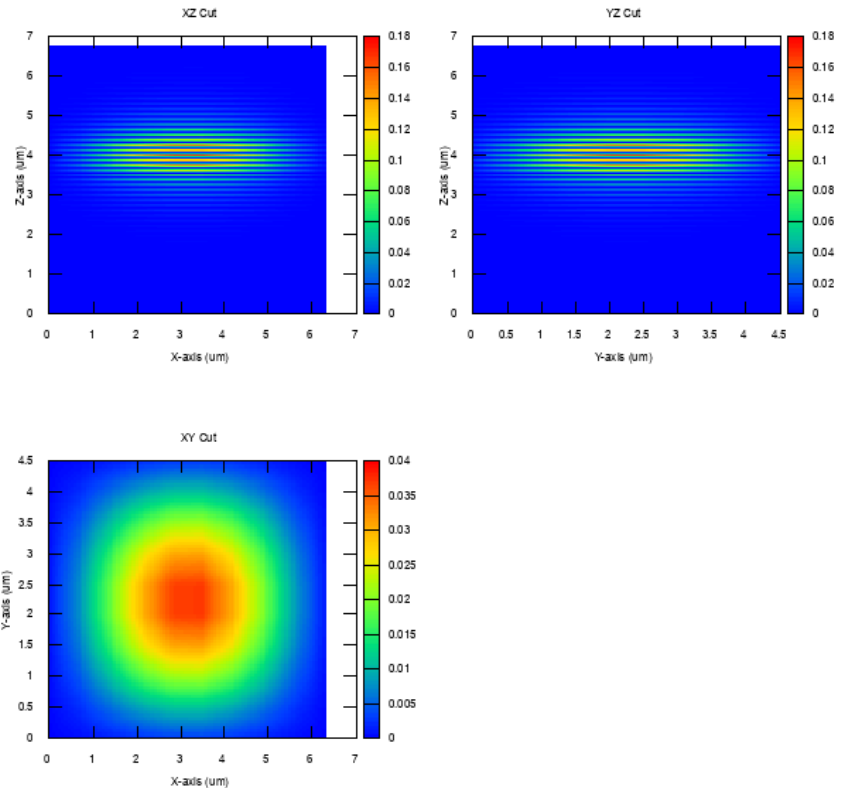
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #03

- » $\lambda_0 = 0.838219 \mu\text{m}$
 - » $K_0 = 7.49587 + j0.000153683 \text{ rad}/\mu\text{m}$



3D VCSEL example

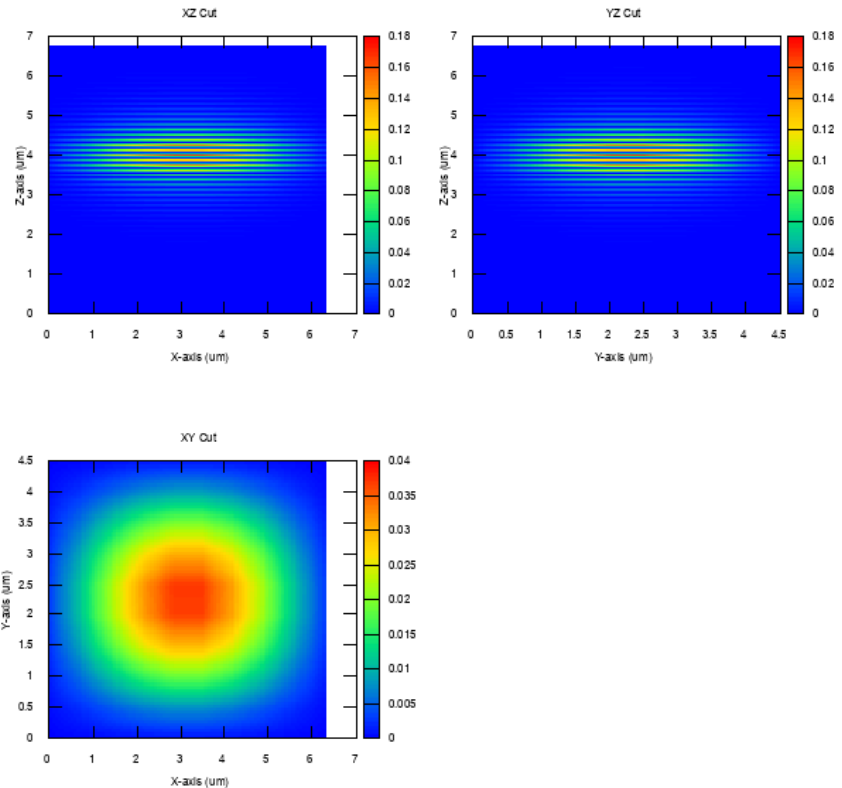
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #04

- » $\lambda_0 = 0.838192 \mu\text{m}$
 - » $K_0 = 7.49612 + j0.000154576 \text{ rad}/\mu\text{m}$



3D VCSEL example

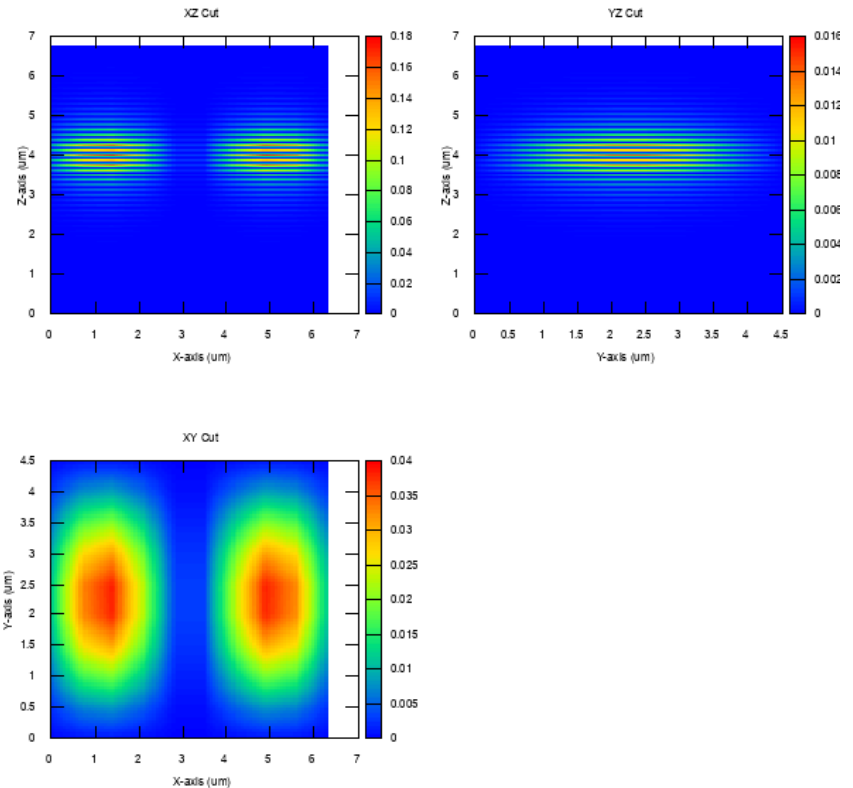
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #05

- » $\lambda_0 = 0.837845 \mu\text{m}$
 - » $K_0 = 7.49922 + j0.000153200 \text{ rad}/\mu\text{m}$



3D VCSEL example

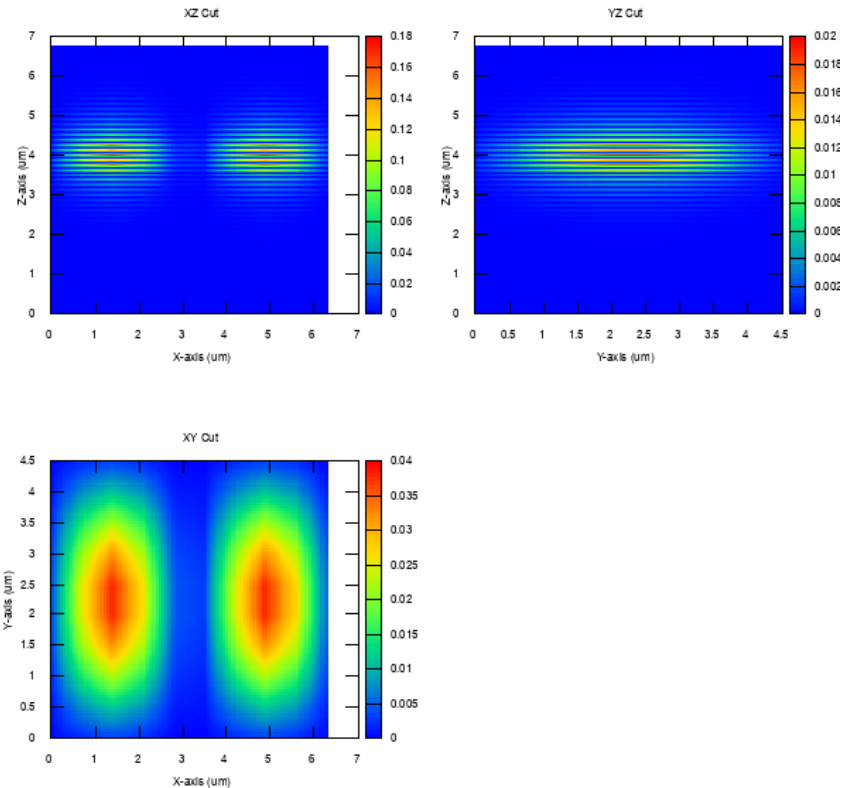
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #06

- » $\lambda_0 = 0.837792 \mu\text{m}$
 - » $K_0 = 7.49969 + j0.000155149 \text{ rad}/\mu\text{m}$



3D VCSEL example

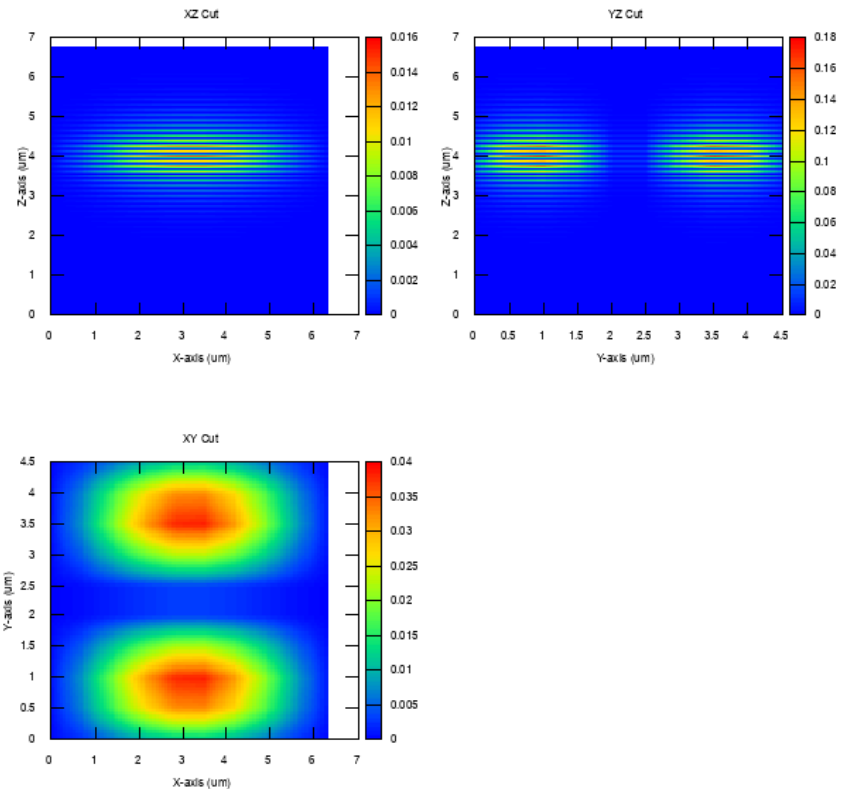
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #07

- » $\lambda_0 = 0.837539 \mu\text{m}$
 - » $K_0 = 7.50196 + j0.000151303 \text{ rad}/\mu\text{m}$



3D VCSEL example

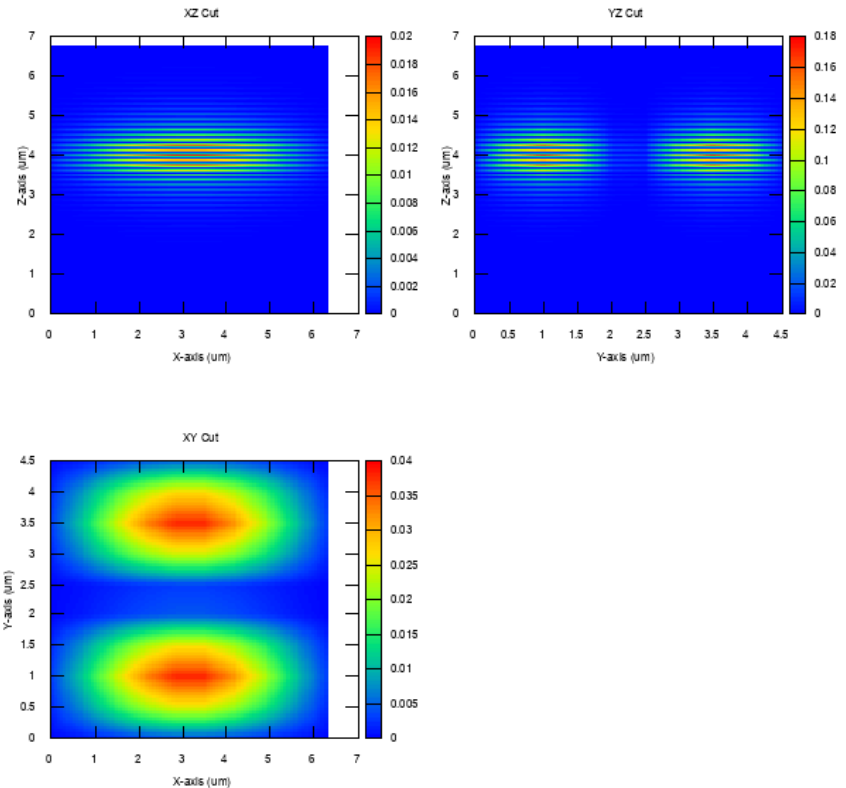
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #08

- » $\lambda_0 = 0.837357 \mu\text{m}$
 - » $K_0 = 7.50360 + j0.000157567 \text{ rad}/\mu\text{m}$



3D VCSEL example

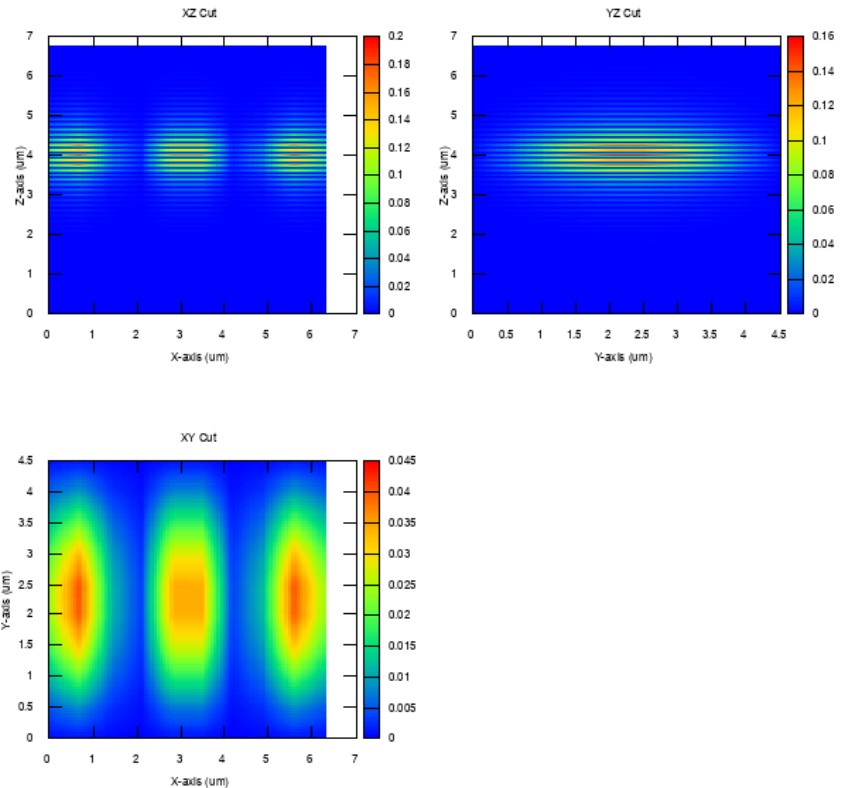
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #09

- » $\lambda_0 = 0.837299 \mu\text{m}$
 - » $K_0 = 7.50411 + j0.000150866 \text{ rad}/\mu\text{m}$



3D VCSEL example

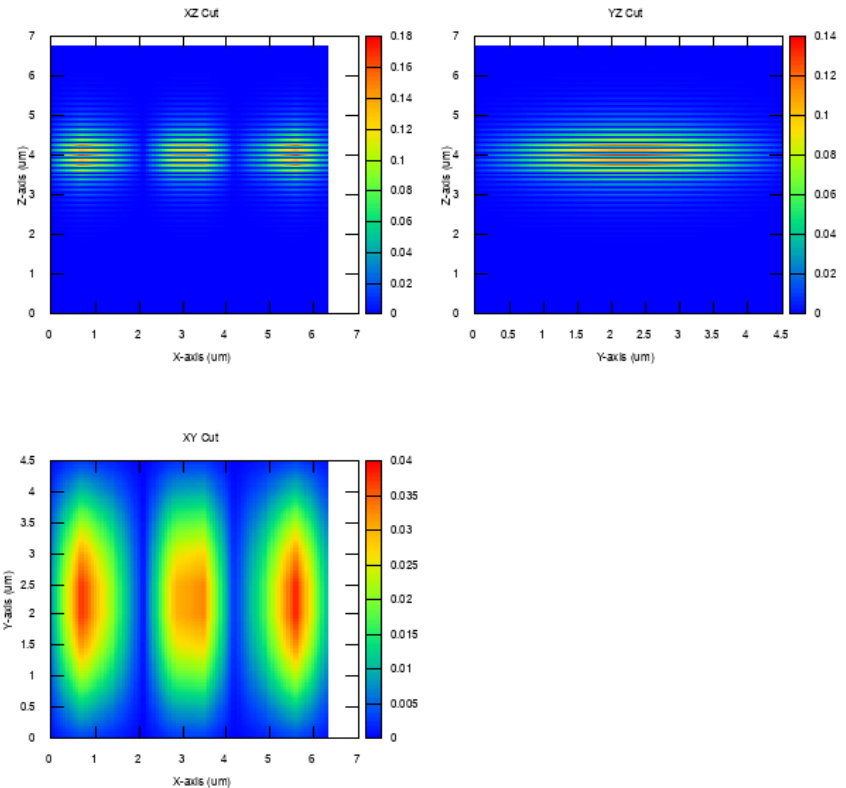
❖ Case01 - Constant Optical Modes

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #10

- » $\lambda_0 = 0.837127$
 - » $K_0 = 7.50565 + j0.000157397$
rad/ μm



3D VCSEL example

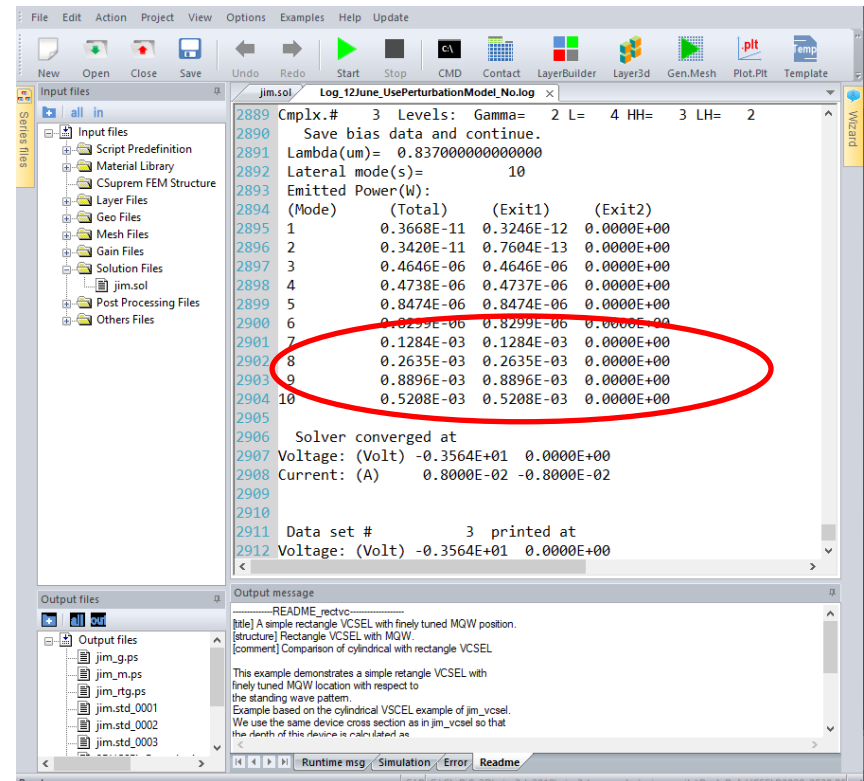
❖ Case01 - Constant Optical Modes

✓ Structure

✓ Analysis

✓ Results

- Optical Modes
- Lasing Modes



```
Log_12June_UsePerturbationModel_No.log
2889 Cmplx.# 3 Levels: Gamma= 2 L= 4 HH= 3 LH= 2
2890 Save bias data and continue.
2891 Lambda(um)= 0.837000000000000
2892 Lateral mode(s)= 10
2893 Emitted Power(W):
2894 (Mode) (Total) (Exit1) (Exit2)
2895 1 0.3668E-11 0.3246E-12 0.0000E+00
2896 2 0.3420E-11 0.7604E-13 0.0000E+00
2897 3 0.4646E-06 0.4646E-06 0.0000E+00
2898 4 0.4738E-06 0.4737E-06 0.0000E+00
2899 5 0.8474E-06 0.8474E-06 0.0000E+00
2900 6 0.8299E-06 0.8299E-06 0.0000E+00
2901 7 0.1284E-03 0.1284E-03 0.0000E+00
2902 8 0.2635E-03 0.2635E-03 0.0000E+00
2903 9 0.8896E-03 0.8896E-03 0.0000E+00
2904 10 0.5208E-03 0.5208E-03 0.0000E+00
2905
2906 Solver converged at
2907 Voltage: (Volt) -0.3564E+01 0.0000E+00
2908 Current: (A) 0.8000E-02 -0.8000E-02
2909
2910
2911 Data set # 3 printed at
2912 Voltage: (Volt) -0.3564E+01 0.0000E+00
```

Output message

```
-----README_rectvc-----
[Title] A simple rectangle VCSEL with finely tuned MQW position.
[Structure] Rectangle VCSEL with MQW.
[Comment] Comparison of cylindrical with rectangle VCSEL.

This example demonstrates a simple rectangle VCSEL with
finely tuned MQW location with respect to
the standing wave pattern.
Example based on the cylindrical VCSEL example of jim_vcsel.
We use the same device cross section as in jim_vcsel so that
the length of this device is calculated as
```

3D VCSEL example

❖ Case01 - Constant Optical Modes

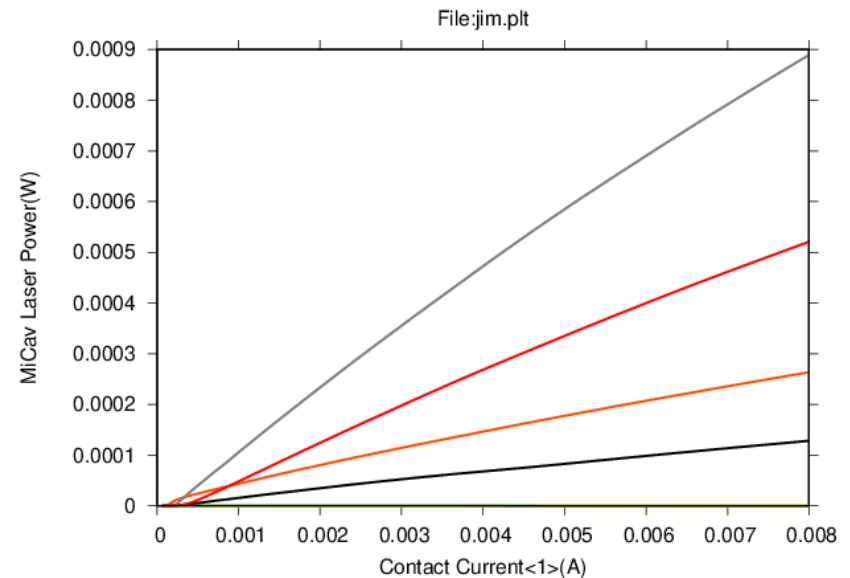
✓ Structure

✓ Analysis

✓ Results

- Optical Modes
- Lasing Modes
- Power

– All Mode Power



3D VCSEL example

❖ Case01 - Constant Optical Modes

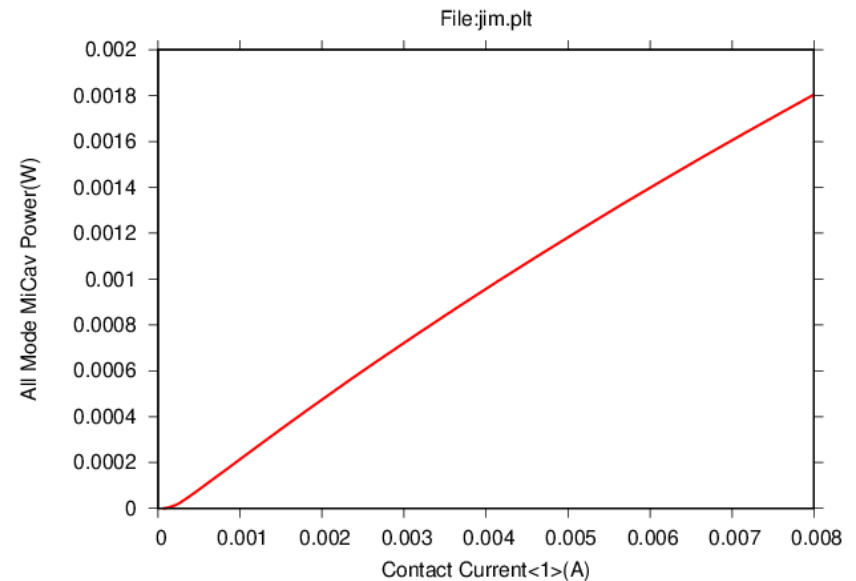
✓ Structure

✓ Analysis

✓ Results

- Optical Modes
- Lasing Modes
- Power

– All Mode Power

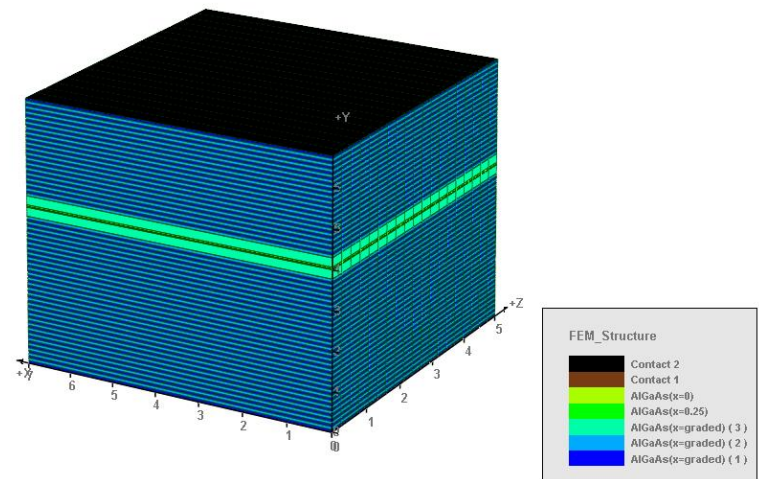


3D VCSEL example

❖ Case02 - Perturbation model

✓ Structure

- Cavity
 - Cavity cross-section
 - » $7 \times 5 \mu\text{m}$
 - Cavity thickness
 - » $0.521 \mu\text{m}$
- DBR Mirror
 - Top Mirror: 19 layers
 - Bottom Mirror: 29 layers



3D VCSEL example

❖ Case02 - Perturbation model

✓ Structure

✓ Analysis

- Optical Solver
 - FDFD solver turned on

```
15  
16 sparse_eigen_solver use mf=yes  
17 direct_eigen  
18 microcavity_model set_wavelength=0.8370 fdfd_vectorial=yes &&  
19 read_fdfd_only=no  
20 microcavity_exit above_y=1. power_ref=0.0  
21
```

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)

```
49 newton_par damping_step=1. var_tol=1.e-4 res_tol=1.e-4 &&  
50 max_iter=30 opt_iter=15 stop_iter=10 print_flag=3 &&  
51 update_lateral_mode=yes lateral_mode_perturbation=yes &&  
52 update_index_change=yes  
53  
54 scan var=voltage_1 value_to=-1.3 print_step=1.3 &&  
55 init_step=0.2 min_step=1.e-5 max_step=0.5  
56 $  
57 scan var=current_1 value_to=8.e-3 &&  
58 init_step=0.25e-3 min_step=10.e-9 max_step=0.5e-3
```

3D VCSEL example

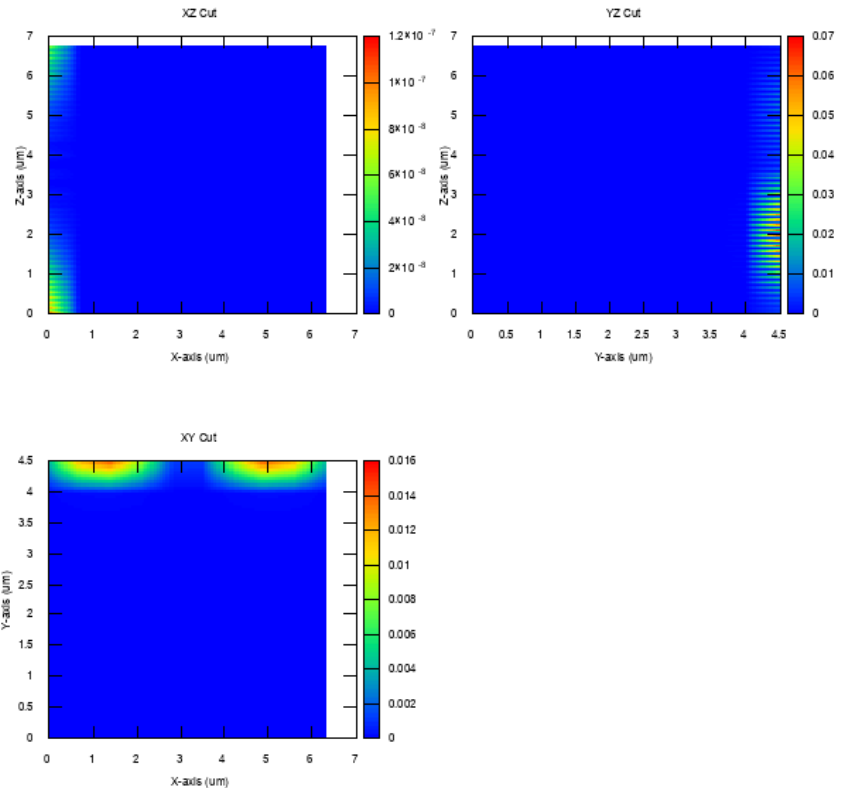
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #01

- » $\lambda_0 = 0.840789 \mu\text{m}$
 - » $K_0 = 7.04730 + j$
 0.00984850
 $\text{rad}/\mu\text{m}$



3D VCSEL example

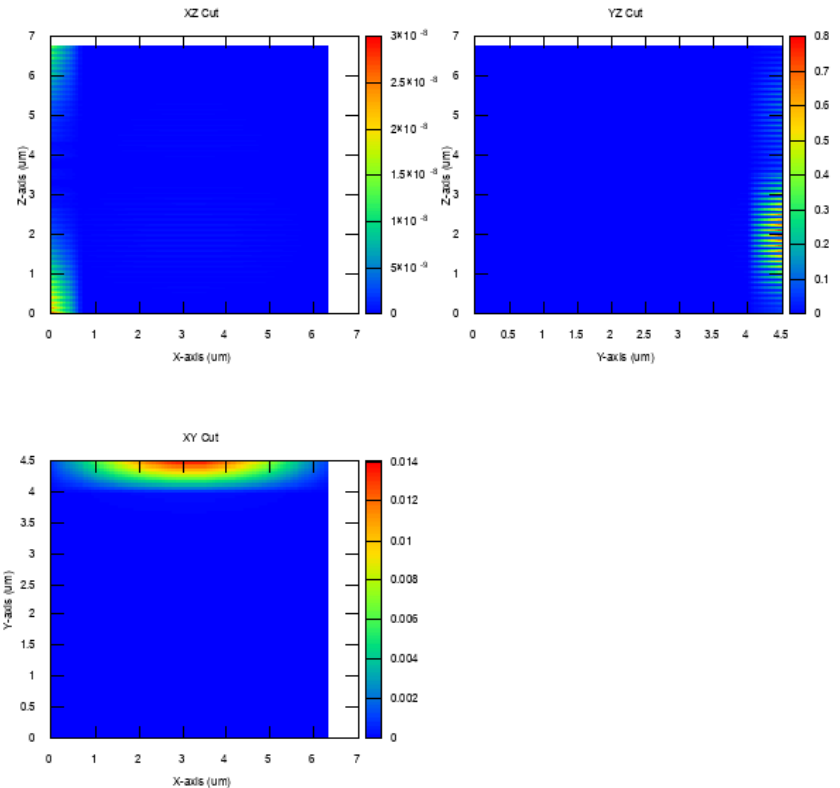
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #02

- » $\lambda_0 = 0.840460 \mu\text{m}$
 - » $K_0 = 7.04759 + j$
 0.00982955
 $\text{rad}/\mu\text{m}$



3D VCSEL example

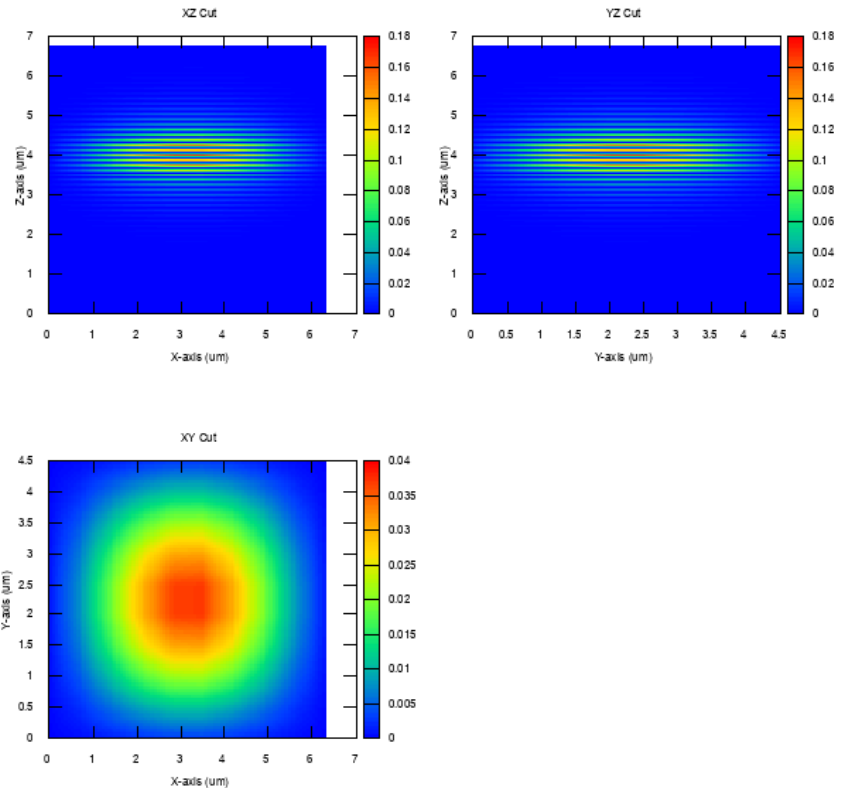
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #03

- » $\lambda_0 = 0.838220 \mu\text{m}$
 - » $K_0 = 7.04959 - j 0.00132957 \text{ rad}/\mu\text{m}$



3D VCSEL example

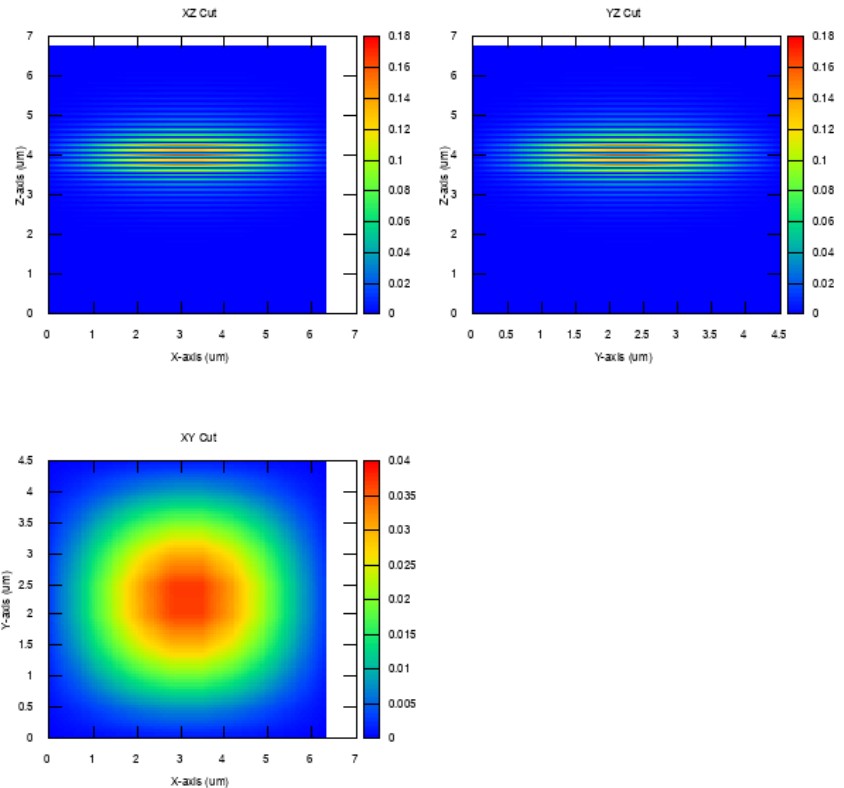
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #04

- » $\lambda_0 = 0.838193 \mu\text{m}$
 - » $K_0 = 7.04961 -j$
 0.00132773
 $\text{rad}/\mu\text{m}$



3D VCSEL example

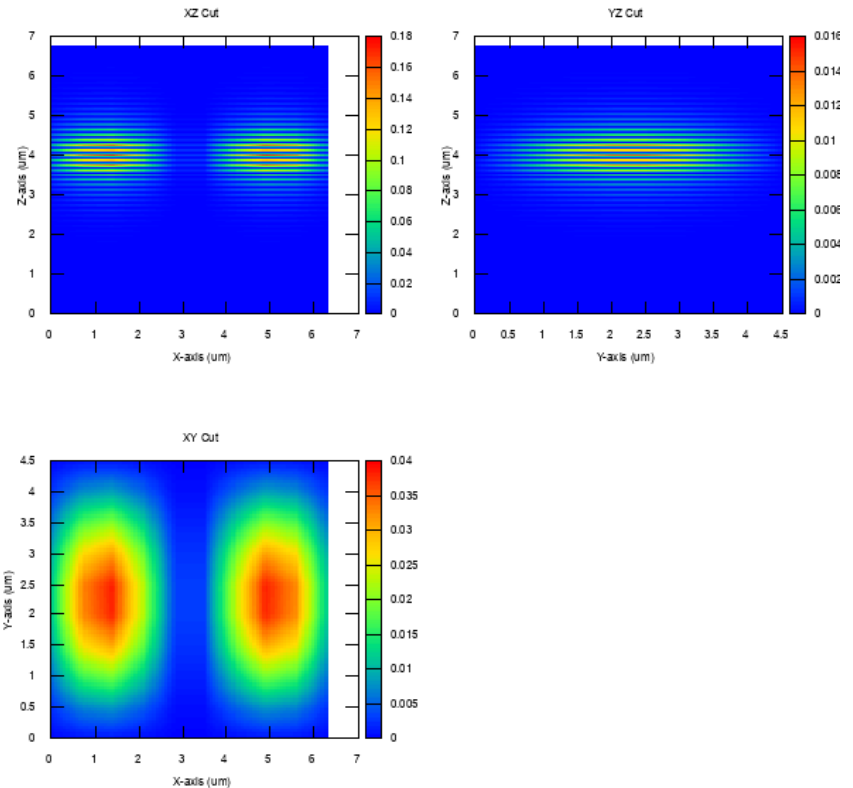
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #05

- » $\lambda_0 = 0.837846 \mu\text{m}$
 - » $K_0 = 7.04992 - j 0.00133038 \text{ rad}/\mu\text{m}$



3D VCSEL example

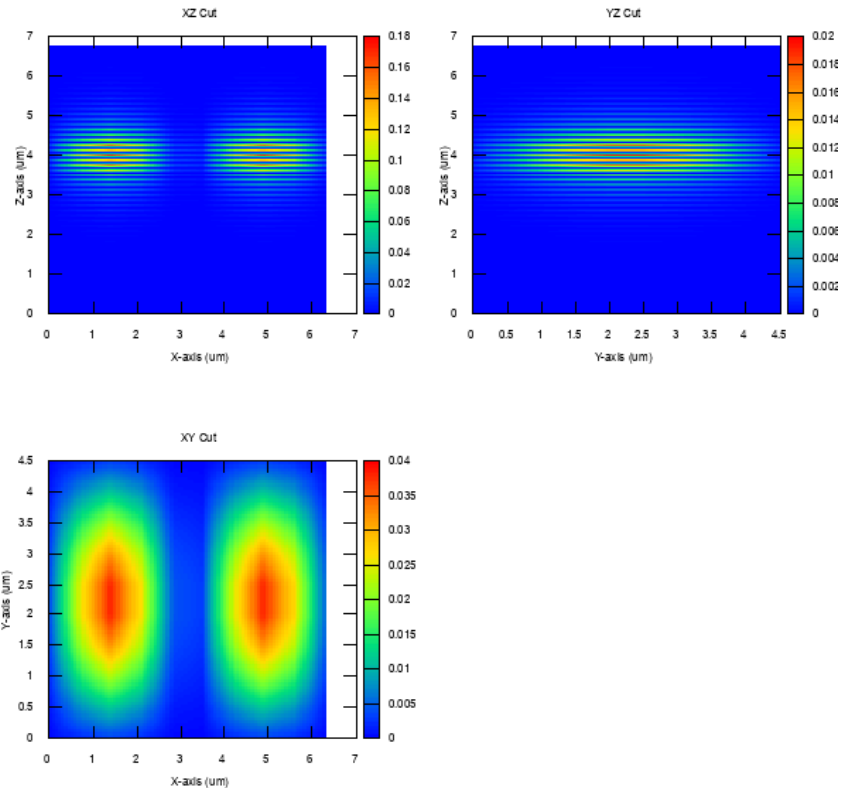
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #06

- » $\lambda_0 = 0.837793 \mu\text{m}$
 - » $K_0 = 7.04997 - j 0.00132645$
rad/ μm



3D VCSEL example

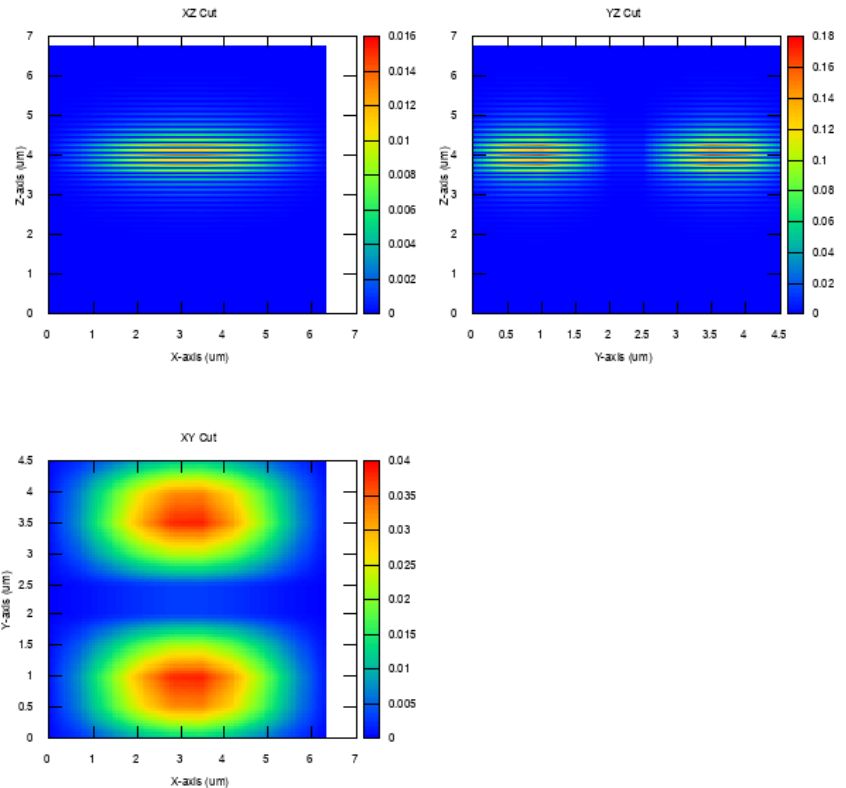
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #07

- » $\lambda_0 = 0.837540 \mu\text{m}$
 - » $K_0 = 7.05019 - j 0.00133426 \text{ rad}/\mu\text{m}$



3D VCSEL example

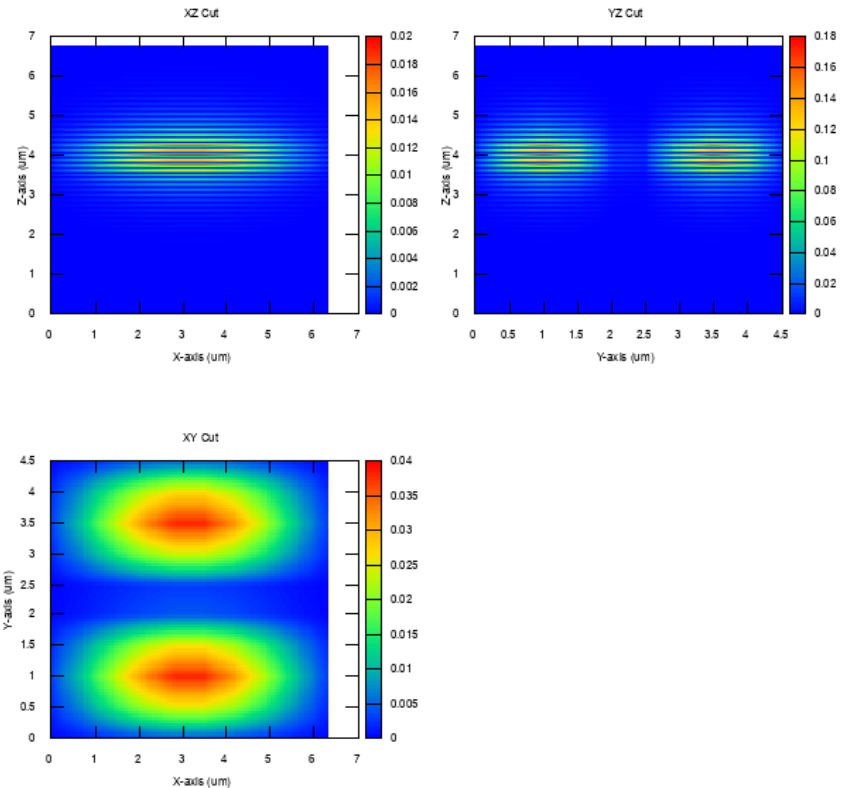
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #08

- » $\lambda_0 = 0.837356 \mu\text{m}$
 - » $K_0 = 7.05036 - j 0.00132144$
rad/ μm



3D VCSEL example

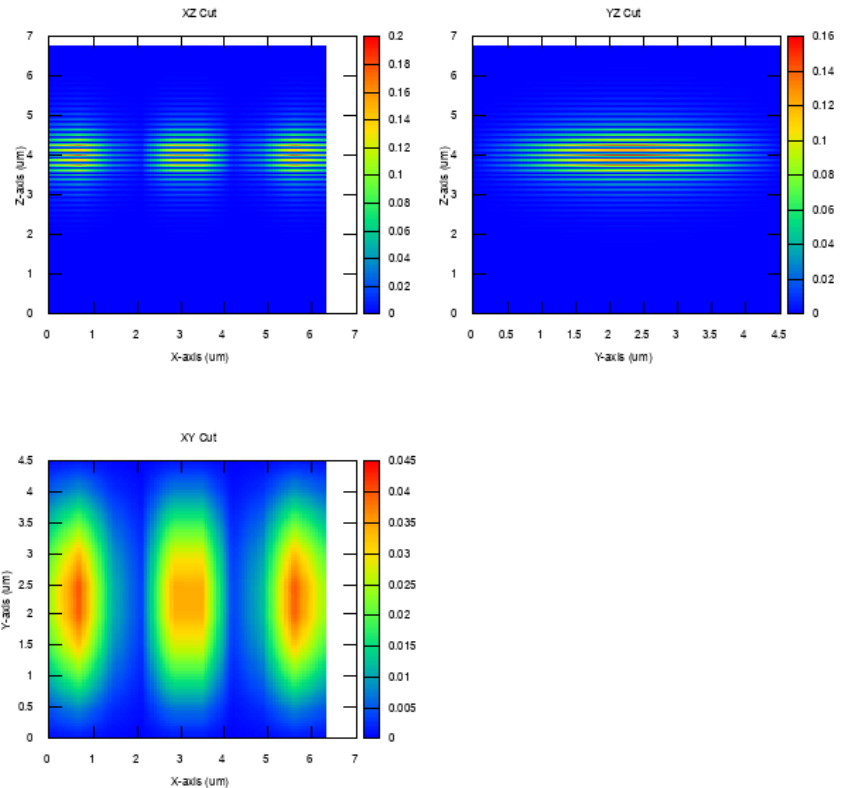
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #09

- » $\lambda_0 = 0.837300 \mu\text{m}$
 - » $K_0 = 7.50410 - j 0.00133487 \text{ rad}/\mu\text{m}$



3D VCSEL example

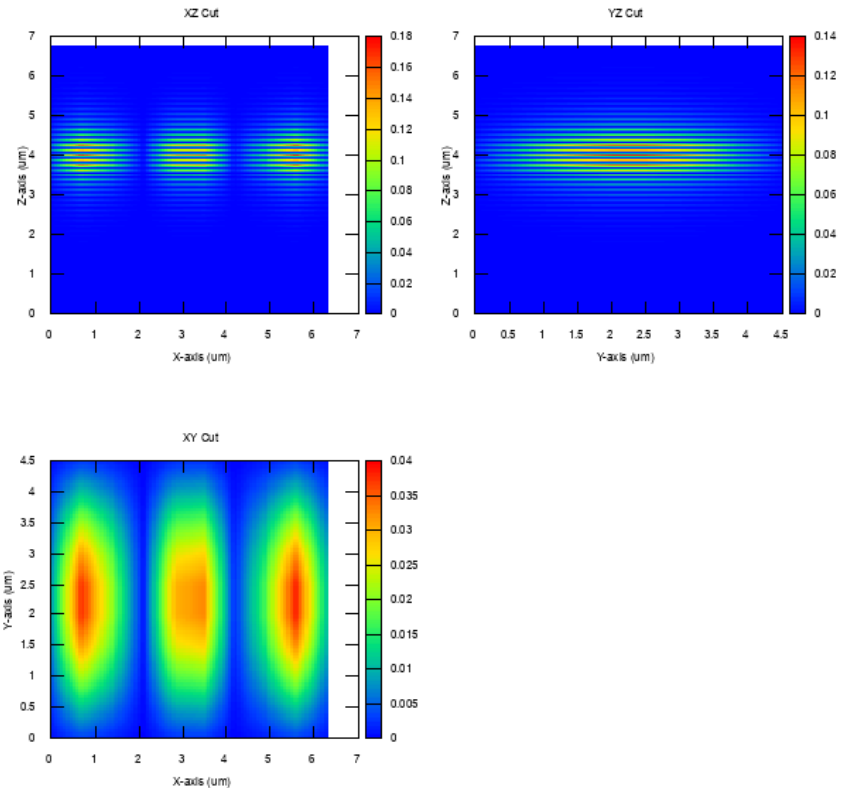
❖ Case02 - Perturbation model

- ✓ Structure
- ✓ Analysis
- ✓ Results

- Optical Modes

- Mode #10

- » $\lambda_0 = 0.837128$
 - » $K_0 = 7.50564 - j$
 0.00132175
 $\text{rad}/\mu\text{m}$



3D VCSEL example

❖ Case02 - Perturbation model

✓ Structure

✓ Analysis

✓ Results

- Optical Modes
- Lasing Modes

```
5123 Cmplx.# 3 Levels: Gamma= 2 L= 4 HH= 3 LH= 2
5124 Save bias data and continue.
5125 Lambda(um)= 0.837000000000000
5126 Lateral mode(s)= 10
5127 Emitted Power(W):
5128 (Mode) (Total) (Exit1) (Exit2)
5129 1 0.3675E-11 0.3217E-12 0.0000E+00
5130 2 0.3428E-11 0.7540E-13 0.0000E+00
5131 3 0.4678E-06 0.4678E-06 0.0000E+00
5132 4 0.4763E-06 0.4763E-06 0.0000E+00
5133 5 0.8269E-06 0.8269E-06 0.0000E+00
5134 6 0.8269E-06 0.8269E-06 0.0000E+00
5135 7 0.1330E-03 0.1330E-03 0.0000E+00
5136 8 0.2580E-03 0.2580E-03 0.0000E+00
5137 9 0.9070E-03 0.9070E-03 0.0000E+00
5138 10 0.5045E-03 0.5045E-03 0.0000E+00
5139
5140 Solver converged at
5141 Voltage: (Volt) -0.3562E+01 0.0000E+00
5142 Current: (A) 0.8000E-02 -0.8000E-02
5143
5144
5145 Data set # 3 printed at
5146 Voltage: (Volt) -0.3562E+01 0.0000E+00
```

3D VCSEL example

❖ Case02 - Perturbation model

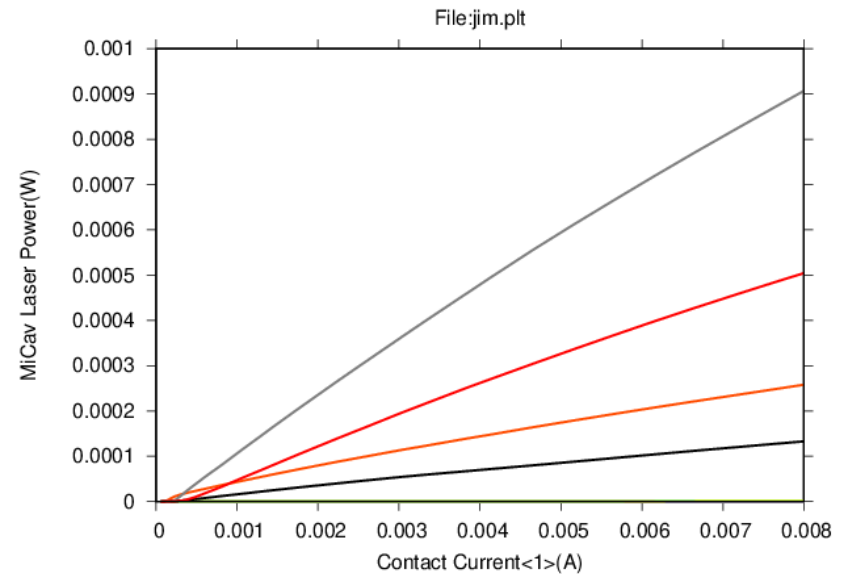
✓ Structure

✓ Analysis

✓ Results

- Optical Modes
- Lasing Modes
- Power

– All Mode Power



3D VCSEL example

❖ Case02 - Perturbation model

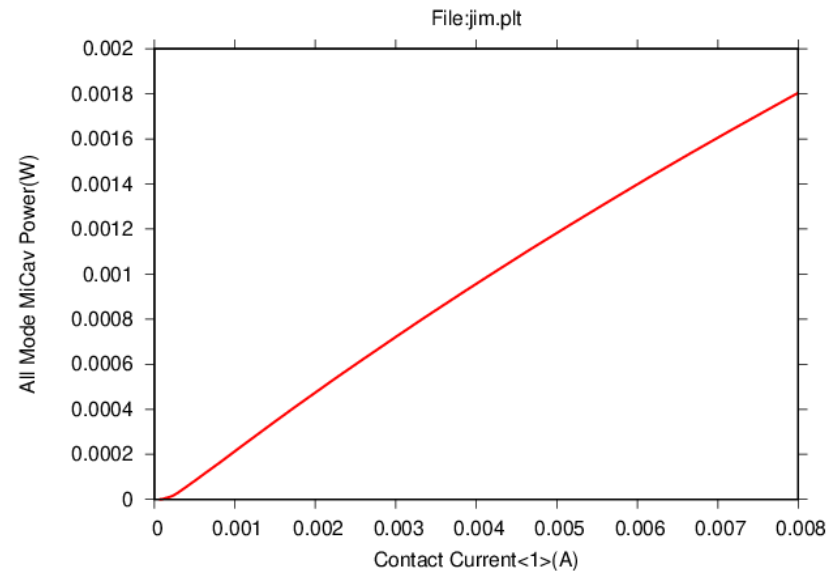
✓ Structure

✓ 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.