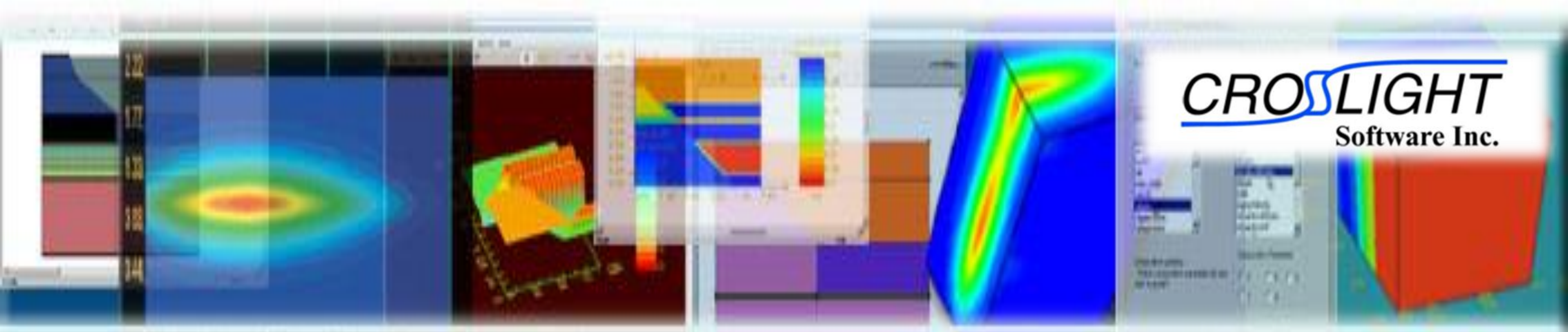


Project conversion to full vectorial VCSEL model

Introduction
VCSEL TMM model

- The optical wave is decoupled into its lateral and longitudinal components, leading to some approximations.
- The longitudinal wave is determined using a 1D transfer matrix (TMM) model.
- The lateral mode (LP) is based on a fiber-like (Bessel) solution or a 1D effective index method in the radial direction.
- Lasing behavior based on the same round-trip gain equation (RTG) as our edge-emitting laser models (phase matching & unity gain).
- Relatively simple with small mesh size & fast computation time.

Introduction
VCSEL microcavity (FDFD) model

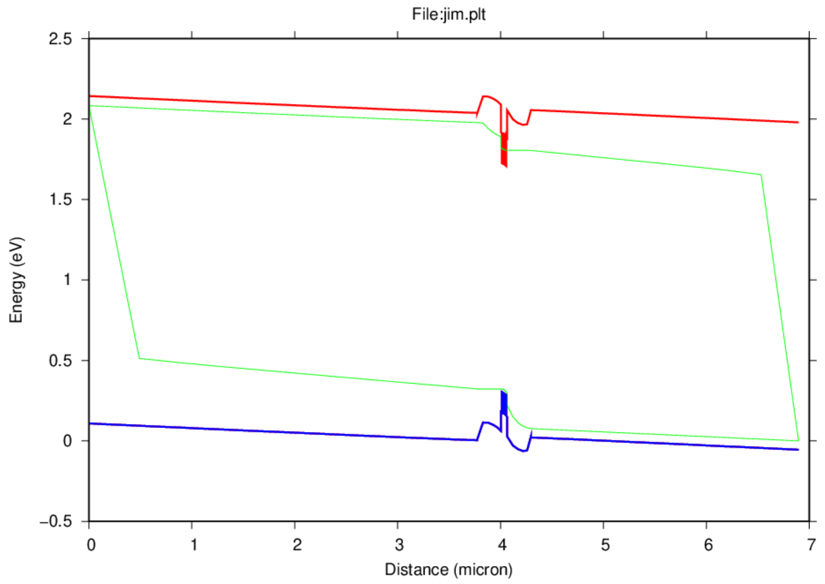
- Full solution of vectorial Maxwell equations to provide a single combined mode for the lateral & longitudinal problems.
- TE/TM/HE modes with fully resolved optical standing wave
- Requires more mesh/computation time than older TMM model

Step 00 – Original Results

- Start from the existing project
  - Make sure the project can run successfully

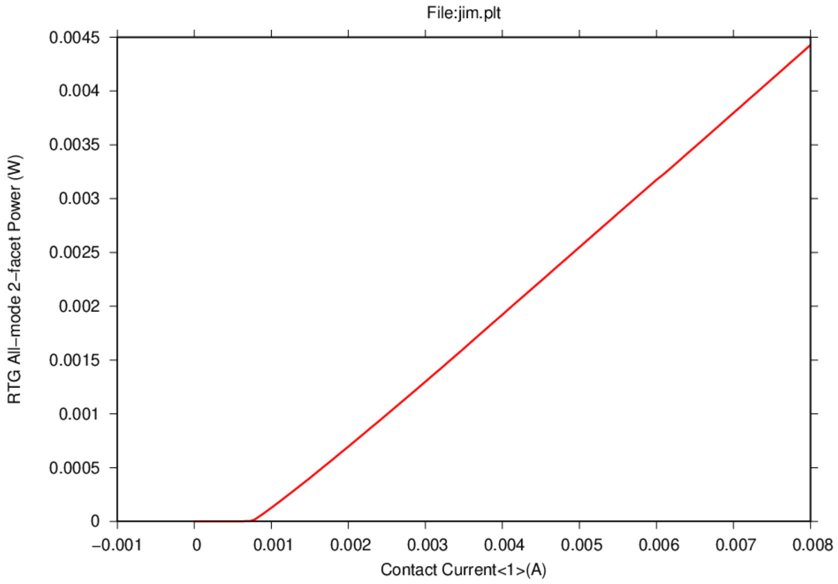
Step 00 – Original Results

- Results
  - Band diagram



Step 00 – Original Results

- Results
  - Lasing power



Step 01 – Input file modifications

- Edit .sol file:
  - Remove all optical models specific to the TMM model: vcsel_model, etc...
  - Remove all references to RTG model: begin_zsol/end_zol, solve_rtg=yes, etc...
  - Adjust all scan commands so that it is a purely electrical problem (i.e. a basic diode)

Step 01 – Input file modifications

- Edit .sol file:
  - Remove vcsel parameters from sol file
  - Ensure electrical behavior for a basic diode is preserved

```
$file:jim.sol
$***********
begin
load_mesh mesh_inf=jim.msh
include file=jim.gain
include file=jim.doping
output sol outf=jim.out
more_output rtgain_scan=yes

$
$ *************************
$ VCSEL parameters:
$
vcsel_model index_core=3.2 index_cladding=1.0 &&
core_radius =7.5  bessel_order=0
sor_par  max_iter=0
init_wave backg_loss=500 init_wavel=0.83  wavel_range=(0.75, 0.90)
cylindrical axis=y
$
parallel_linear_solver solver=mumps mumps_workspace=50
$
newton_par damping_step=5. var_tol=1.e-9 res_tol=1.e-9 &&
max_iter=100 opt_iter=15 stop_iter=50 print_flag=3
$restart
equilibrium
rtgain_phase  density=4.5e24
$stop
```

Step 01 – Input file modifications

- Edit .sol file:
  - Remove vcsel parameters from sol file
  - Ensure electrical behavior for a basic diode is preserved

```
$stop
$
newton_par damping_step=1. var_tol=1.e-4 res_tol=1.e-4 &&
max_iter=50 opt_iter=25 stop_iter=10

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

$ better to start with low RTG and progress slowly
$ auto_finish=rtgain is mandatory to get RTG ready
$
scan var=current_1 value_to=8.e-3  print_step=0.15e-3 &&
init_step=0.1e-4 min_step=1.e-6 max_step=0.5e-3 &&
auto_finish=rtgain auto_until=0.95 auto_condition=above


$ it is wise to start with a small step here.

scan var=current_1 value_to=8.e-3  solve_rtg=yes  &&
init_step=0.01e-3 max_step=0.1e-3

$
end
$*****************************
```

Step 02 – Layer File Update

- Identify DBR stacks in .layer.
- Convert the single-layer effective/average material of DBR stack to actual individual DBR layers:
  - All layers must be explicitly defined
  - It's recommended to make use of loops to simplify the input.
- (Optional) Remove unneeded vcsel_section definitions and vcsel_type tags. These are ignored in FDFD approach.

Step 02 – Layer File Update

- Update Layer file
  - Bottom DBR
    - Remove vcsel section

```
vcsel_section vcsel_type=n-dbr &&
dbr_period_from_macro=yes &&
active=no mesh_points=10

$ this is the effective medium
layer_mater mater_lib=AlGaAs var1=0.625 column_num=1 var_symbol1=x

$ let's define a DBR period using macro like this (use column 1 only)
$ (also possible to define grading within a DBR period)
vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=0.25 &&
thick=0.0595
vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=1. &&
thick=0.0706

$ thickness here is actually determined by DBR periods above
layer d=1.  n=15  r=0.9 &&
n_doping1=2.e24  vcsel_type=n-dbr use_dbr_period=29
```

Step 02 – Layer File Update

- Update Layer file
  - Bottom DBR
    - Remove vcsel section
    - Add full DBR definition

```
start_loop symbol=%k value_from=1 value_to=29
$vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=0.25 &&
$  thick=0.0595
layer_mater mater_lib=AlGaAs var1=0.25 column_num=1 var_symbol1=x &&
n_doping=2.e24
layer d=0.0595 n=5  r=1.
$vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=1. &&
$  thick=0.0706
layer_mater mater_lib=AlGaAs var1=1. column_num=1 var_symbol1=x &&
n_doping=2.e24
layer d=0.0706 n=6  r=1.
end_loop
```

Step 02 – Layer File Update

- Update Layer file
  - Bottom DBR
  - Top DBR
    - Remove vcsel section

```

vcsel_section vcsel_type=p-dbr &&
dbr_period_from_macro=yes &&
active=no mesh_points=10

$ effective medium layer
layer_mater mater_lib=AlGaAs var1=0.625 column_num=1 var_symbol1=x

$ let's define a DBR period using macro like this (use column 1 only)
$ (also possible to define grading within a DBR period)
vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=1. &&
thick=0.0706
vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=0.25 &&
thick=0.0595

$ thickness here is actually determined by DBR periods above
layer d=1.  n=12  r=1.1 &&
p_doping1=3.e24  vcsel_type=p-dbr use_dbr_period=20
$
```

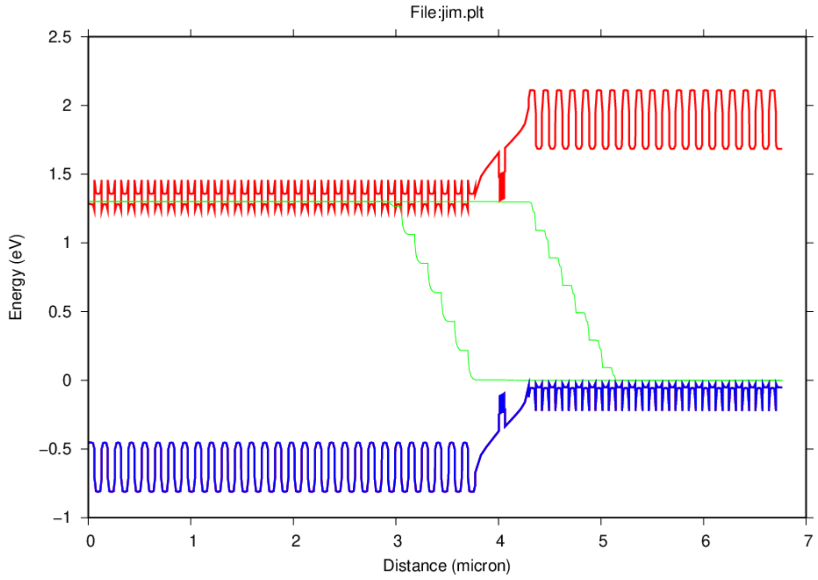
Step 02 – Layer File Update

- Update Layer file
  - Bottom DBR
  - Top DBR
    - Remove vcsel section
    - Add full DBR definition

```
start_loop symbol=%k value_from=1 value_to=19
$vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=1. &&
$  thick=0.0706
layer_mater mater_lib=AlGaAs var1=1. column_num=1 var_symbol1=x &&
p_doping=3.e24
layer d=0.0706 n=6  r=1.
$vertical_dbr_layer_mater mater_lib=AlGaAs var_symbol1=x var1=0.25 &&
$  thick=0.0595
layer_mater mater_lib=AlGaAs var1=0.25 column_num=1 var_symbol1=x &&
p_doping=3.e24
layer d=0.0595 n=5  r=1.
end_loop
```

Step 02 – Layer File Update

- Results
  - Band diagram



Step 03 – Further Sol File Updates

- Add effective_medium to the sol file to prevent anomalous voltage drops over the highly-doped DBR layers.
- Include the microcavity model in the sol file

Step 03 – Further Sol File Updates

- Sol File Update
  - Microcavity parameters
  - Init_wave
    - init_wavel
      - Define the minimum wavelength for the optical mode solver
      - This is a critical parameters it should be selected close to the design value, then tweak it slowly to obtain the required modes

```
cylindrical axis=y
init_wave backg_loss=500. init_wavel=0.835 &&
boundary_type=(2 1 5 5) wavel_range=(0.75, 0.90)
multimode mode_num=10 boundary_type1=(2 1 5 5) &&
boundary_type2=(1 1 5 5)
pml permittivity_real=1.0 permittivity_imag=0. pml_mesh=5 &&
pml_length=0.5 pure_index_loss=no
sparse_eigen_solver
direct_eigen
microcavity_model set_wavelength=0.830 fdfd_vectorial=yes
microcavity_exit above_y=1. power_refl=0.0
$
effective_medium mater1=1 mater2=2
$
```

Step 03 – Further Sol File Updates

- Sol File Update
  - Microcavity parameters
  - Init_wave
    - wavel_range
      - Define the wavelength range to solve in
    - boundary_type
      - Define the termination of the problem

```
cylindrical axis=y
init_wave backg_loss=500. init_wavel=0.835 &&
boundary_type=(2 1 5 5) wavel_range=(0.75, 0.90)
multimode mode_num=10 boundary_type1=(2 1 5 5) &&
boundary_type2=(1 1 5 5)
pml permittivity_real=1.0 permittivity_imag=0. pml_mesh=5 &&
pml_length=0.5 pure_index_loss=no
sparse_eigen_solver
direct_eigen
microcavity_model set_wavelength=0.830 fdfd_vectorial=yes
microcavity_exit above_y=1. power_refl=0.0
$
effective_medium mater1=1 mater2=2
$
```

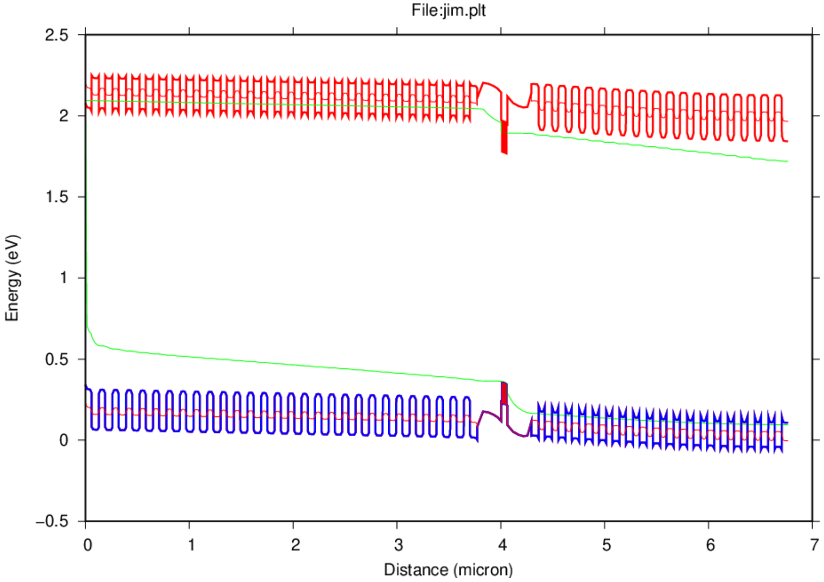
Step 03 – Further Sol File Updates

- Sol File Update
  - Microcavity parameters
  - multimode
    - Mode_num
      - Define the number of modes to solve for
  - pml
    - Define the Perfectly matched layer boundaries
    - This is the state of art of the absorbing boundary conditions. It is used to truncate the computational window.

```
cylindrical axis=y
init_wave backg_loss=500. init_wavel=0.835 &&
boundary_type=(2 1 5 5) wavel_range=(0.75, 0.90)
multimode mode_num=10 boundary_type1=(2 1 5 5) &&
boundary_type2=(1 1 5 5)
pml permittivity_real=1.0 permittivity_imag=0. pml_mesh=5 &&
pml_length=0.5 pure_index_loss=no
sparse_eigen_solver
direct_eigen
microcavity_model set_wavelength=0.830 fdfd_vectorial=yes
microcavity_exit above_y=1. power_refl=0.0
$
effective_medium mater1=1 mater2=2
$
```

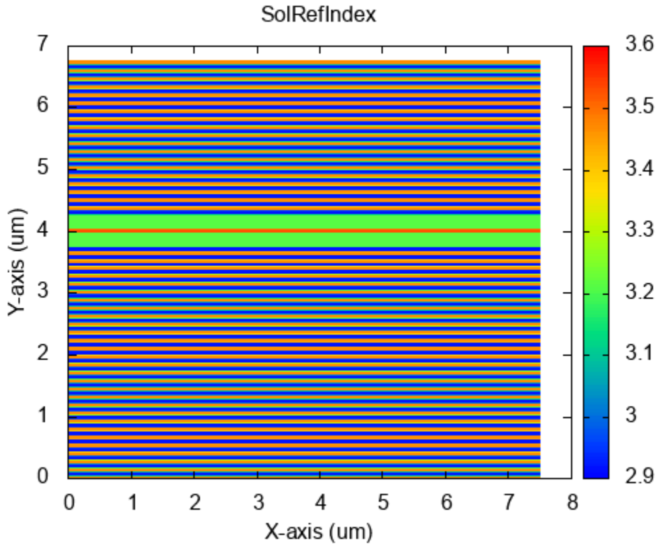
Step 04 – Results

- Results
  - Band diagram



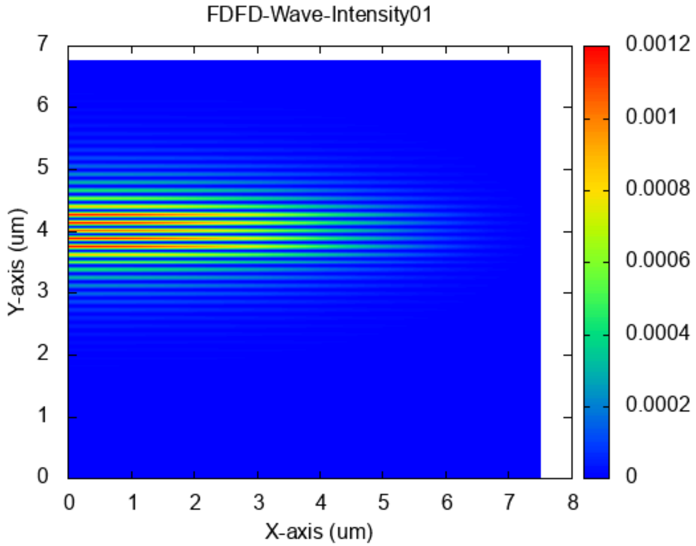
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Refractive Index pattern



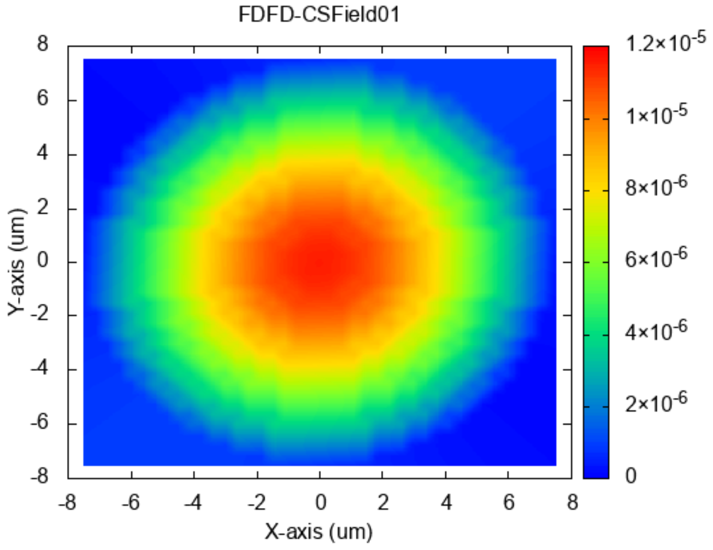
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 01
      - λ=0.838542



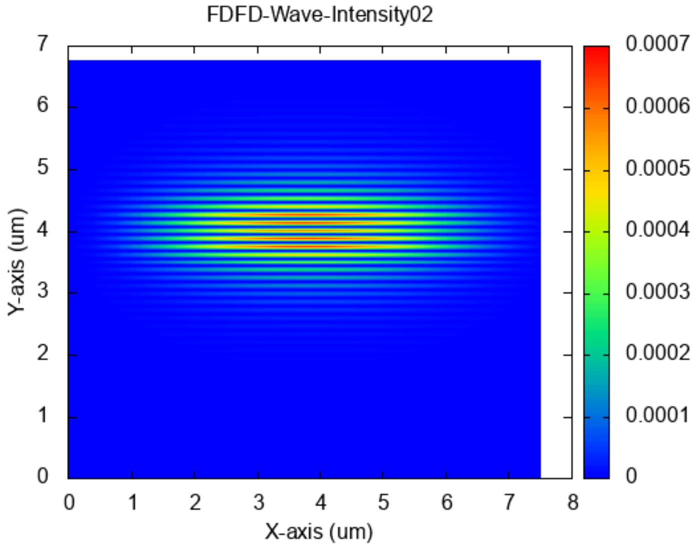
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 01
      - λ=0.838542



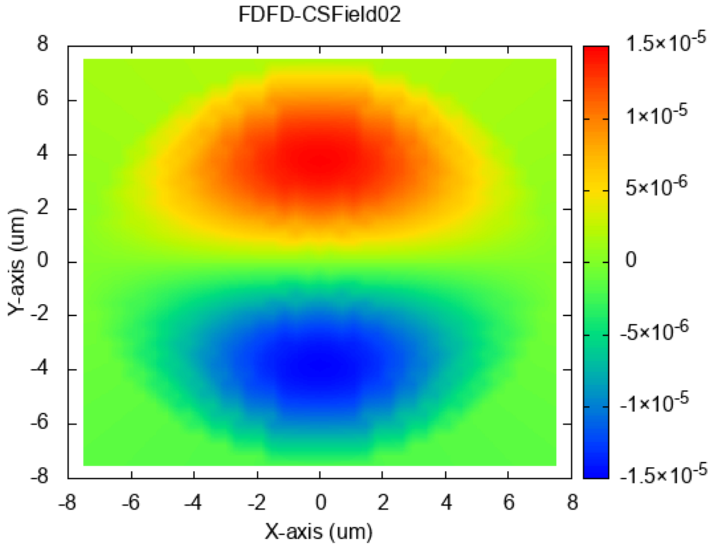
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 02
      - λ=0.838442



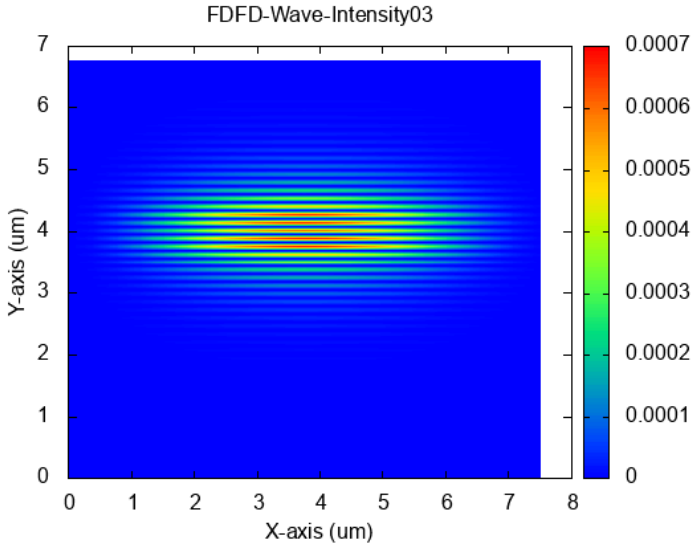
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 02
      - λ=0.838442



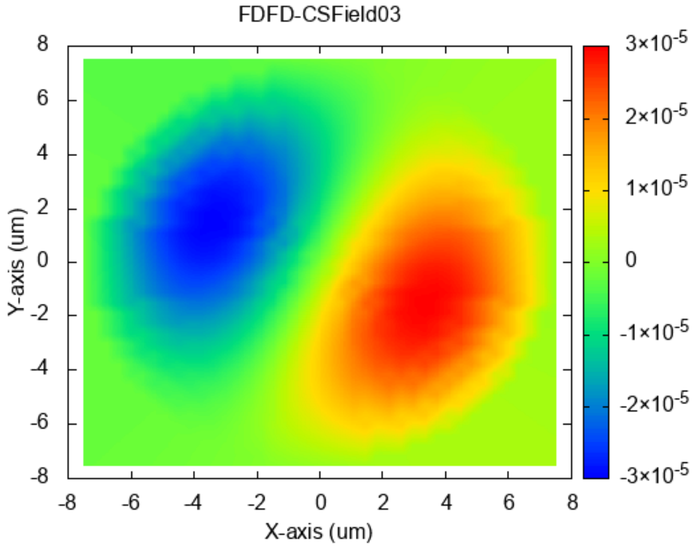
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 03
      - λ=0.838434



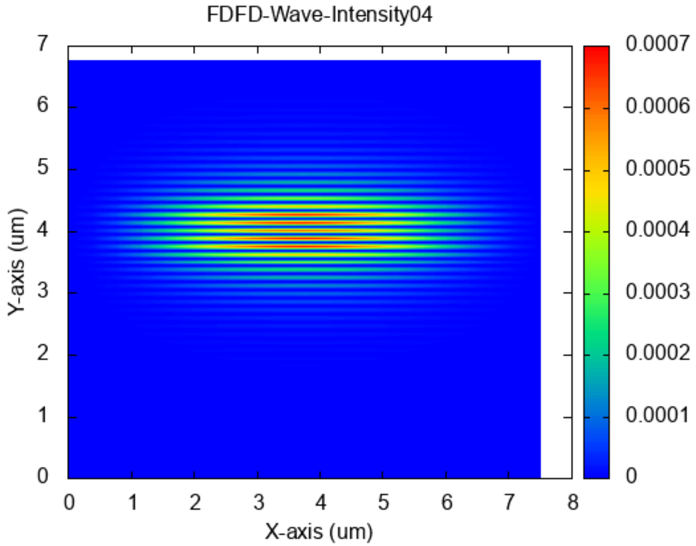
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 03
      - λ=0.838434



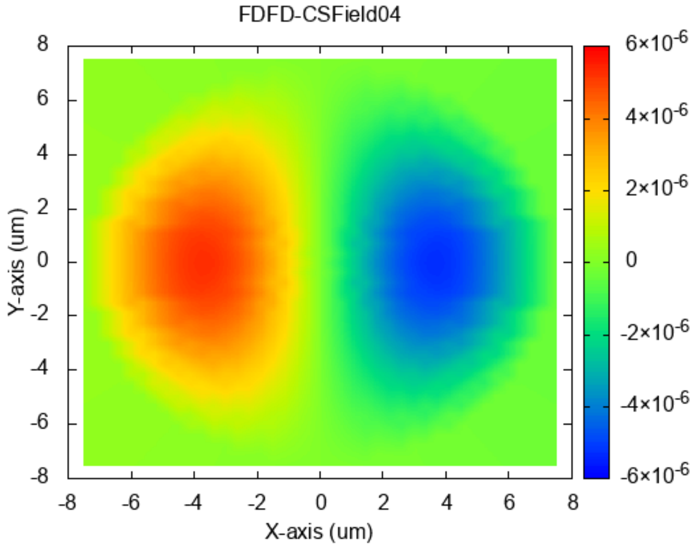
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 04
      - λ=0.838426



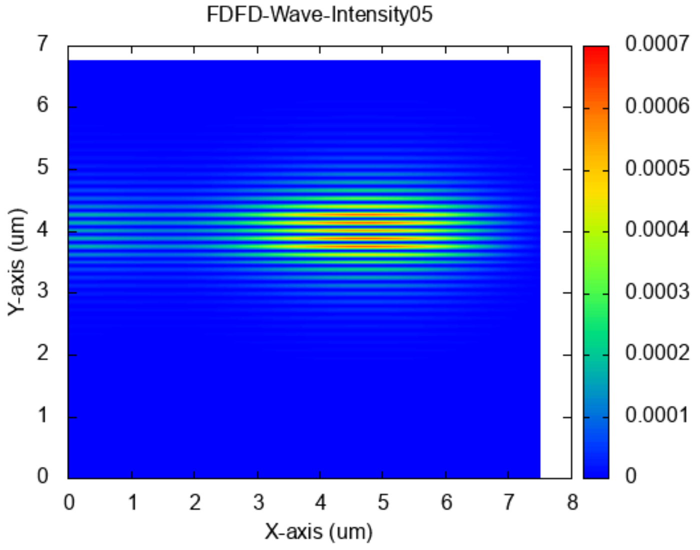
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 04
      - λ=0.838426



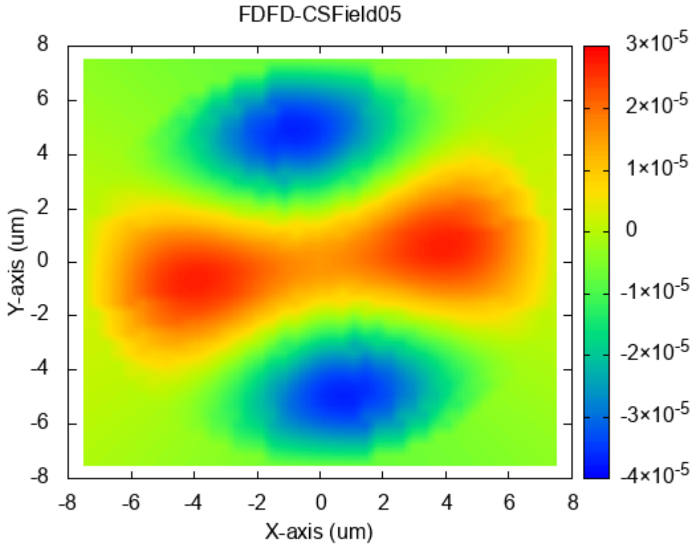
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 05
      - λ=0.838297



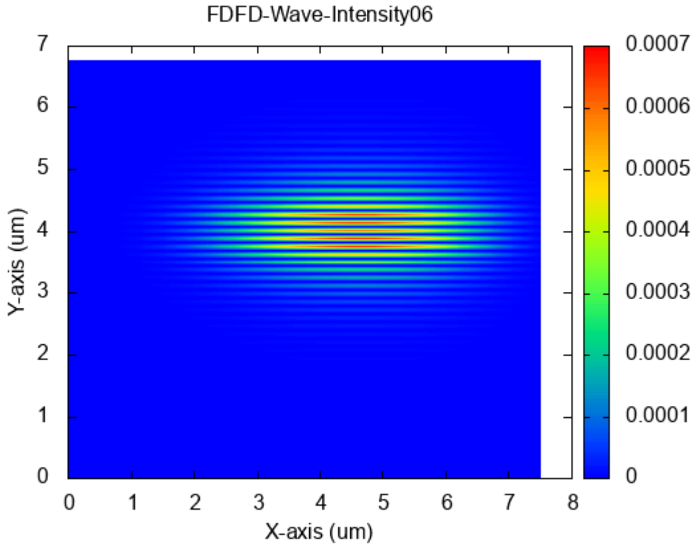
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 05
      - λ=0.838297



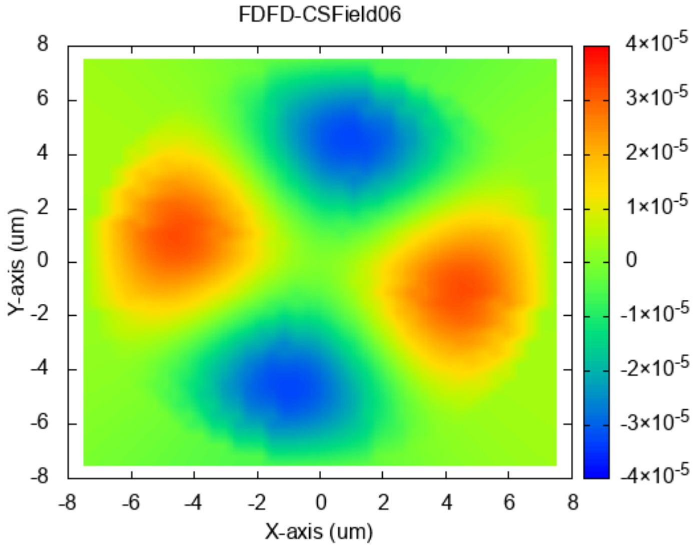
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 06
      - λ=0.838292



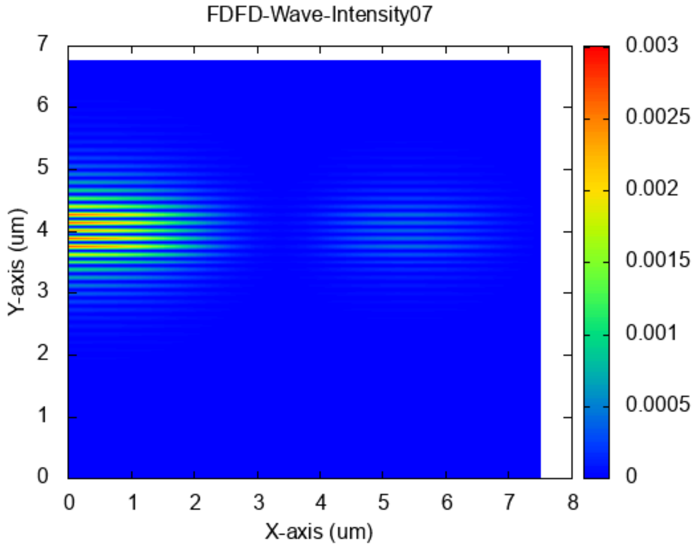
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 06
      - λ=0.838292



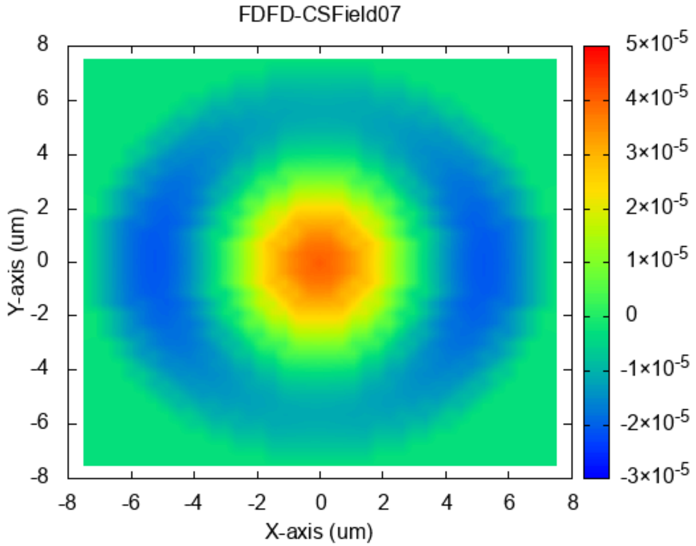
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 07
      - λ=0.838239



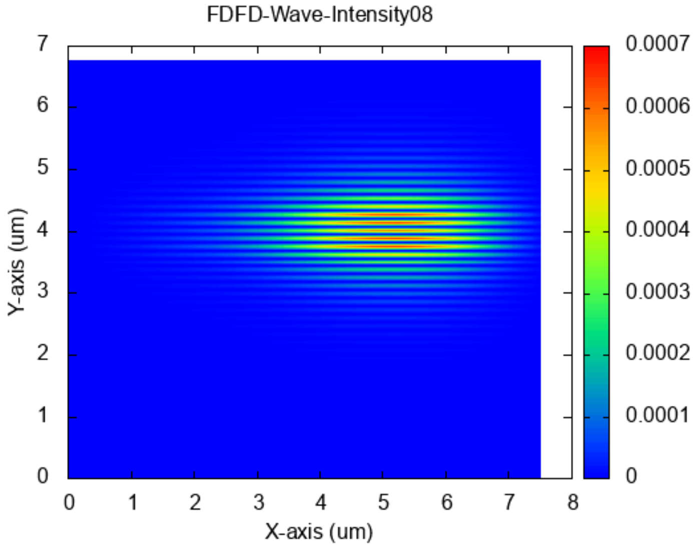
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 07
      - λ=0.838239



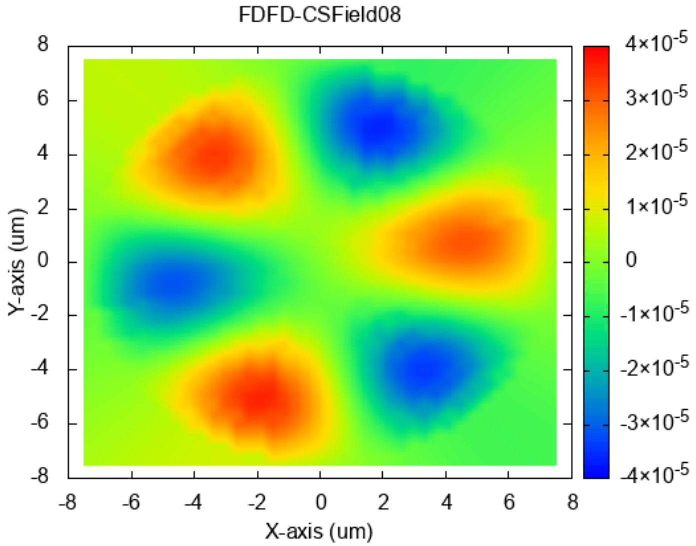
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 08
      - λ=0.838124



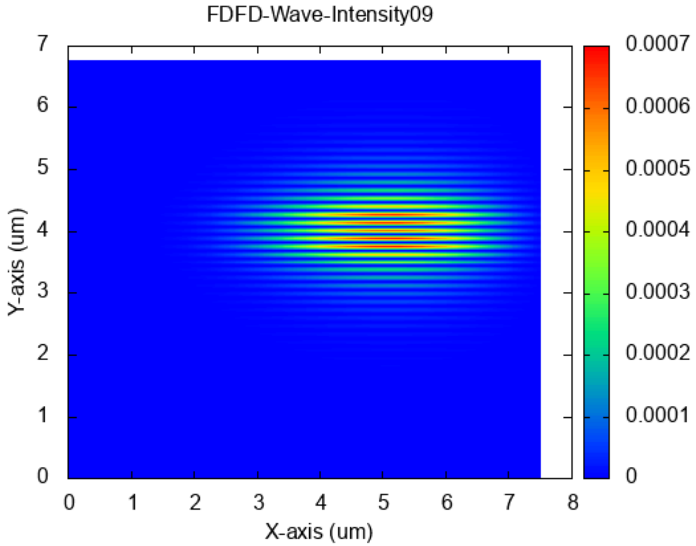
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 08
      - λ=0.838124



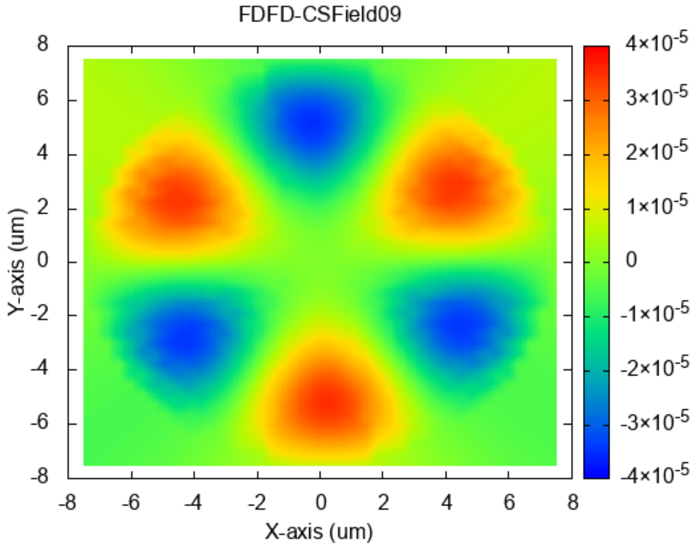
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 09
      - λ=0.838117



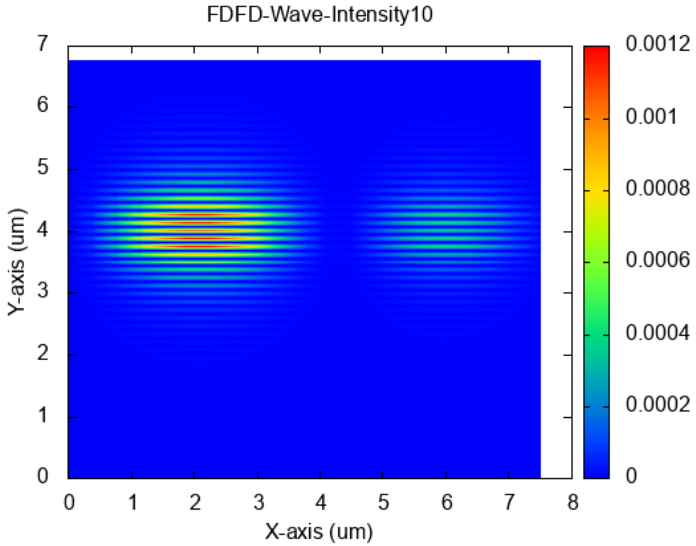
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 09
      - λ=0.838117



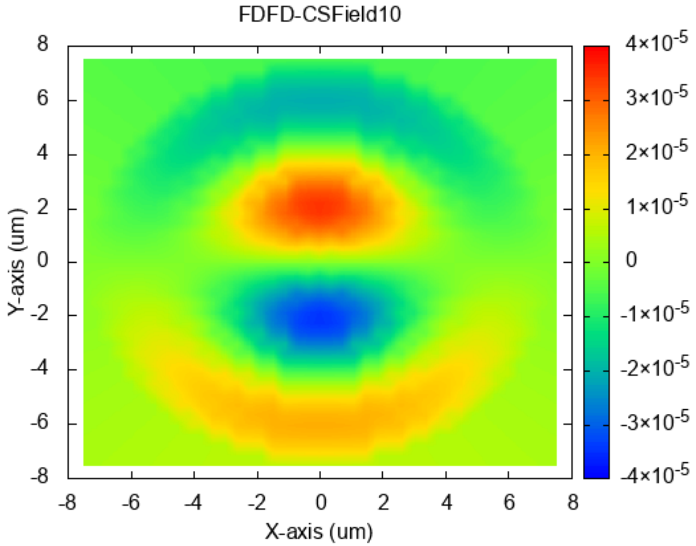
Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 10
      - λ=0.838046



Step 04 – Results

- Results
  - Band diagram
  - Optical modes
    - Mode 10
      - λ=0.838046



Step 04 – Results

- Results
  - Band diagram
  - Optical modes
  - Lasing power