Modelling optical properties & gain spectra of VCSEL devices

EPIC Meeting on VCSELs at SONY

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Lumerical Inc.
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Outline

1. Introduction
2. Optical properties of a VCSEL layer stack
    - Reflectivity Spectrum
    - Quantum Well gain
3. Optical response using 3D FDTD
    - Modal properties of Photonic Crystal VCSELs
4. What's next ?

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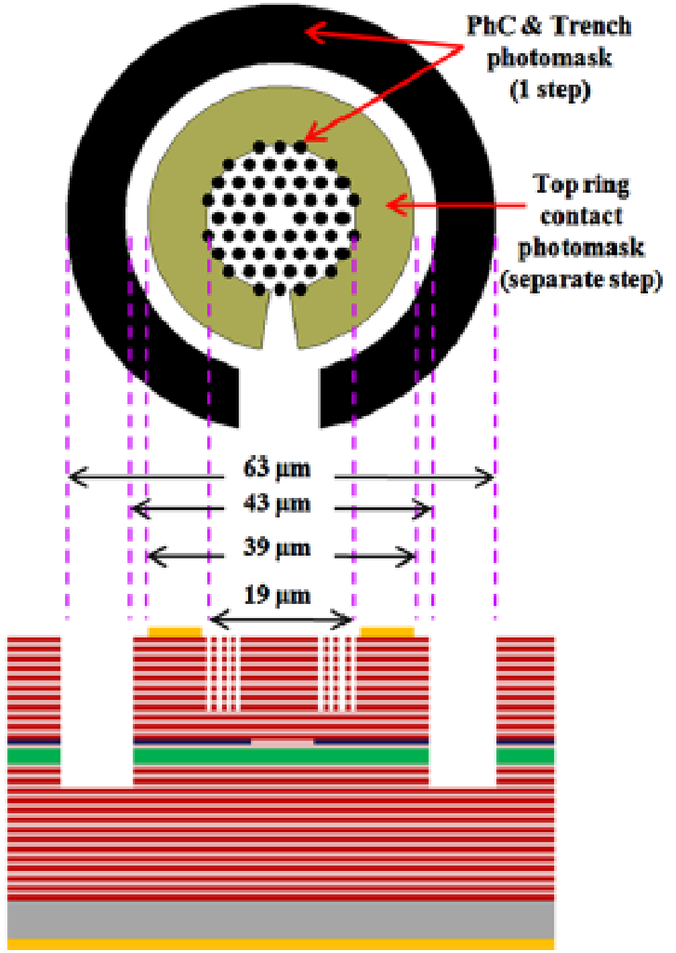
Introduction

VCSEL device manufacture is complex

1. Control of multilayer epitaxy
    - Thickness and composition
    - Doping profiles
    - Graded compositions
    - MQW active regions
2. Multistep device fabrication
    - Oxidation or implantation
    - Multiple etching and lithographic steps
    - Added surface relief or microstructures to achieve desired modal properties
        - *Single mode operation*



Optical Modelling can help with characterization and design

- *Reduces cost and cycle time*

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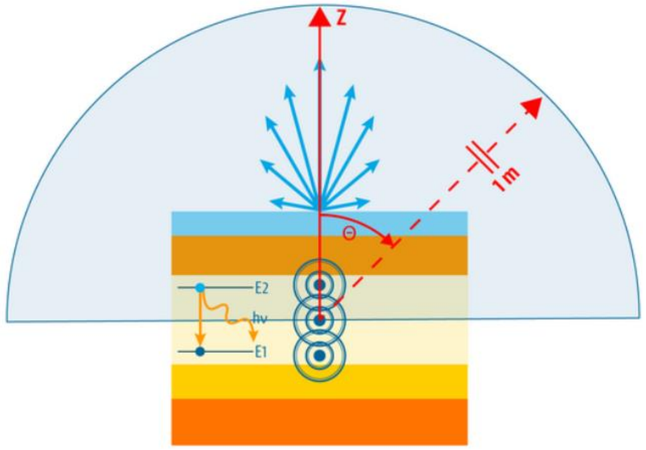
Planar VCSEL Modelling

1-D modelling using a script based approach

- Models can be built using a GUI, or
- Can import data from external sources e.g. excel spreadsheet
- Uses Lumerical's STACK solver
  - An extensive material database of III-V materials, Eg, ref. index etc…
    - User defined if preferred



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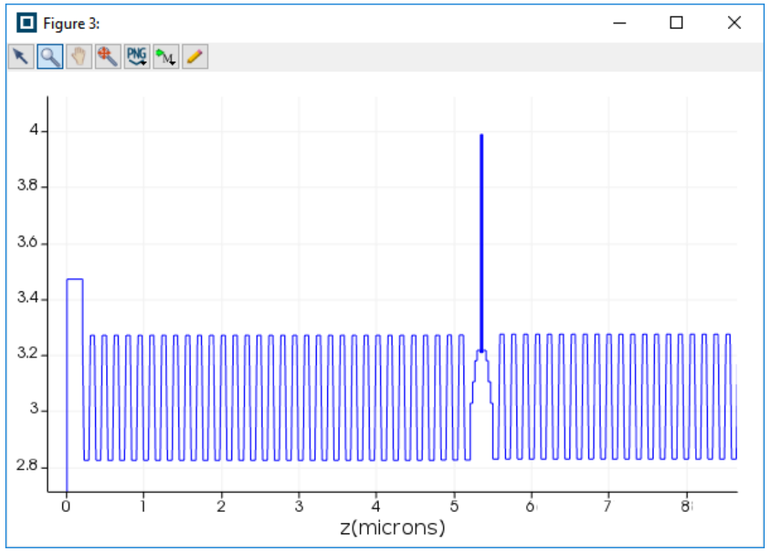
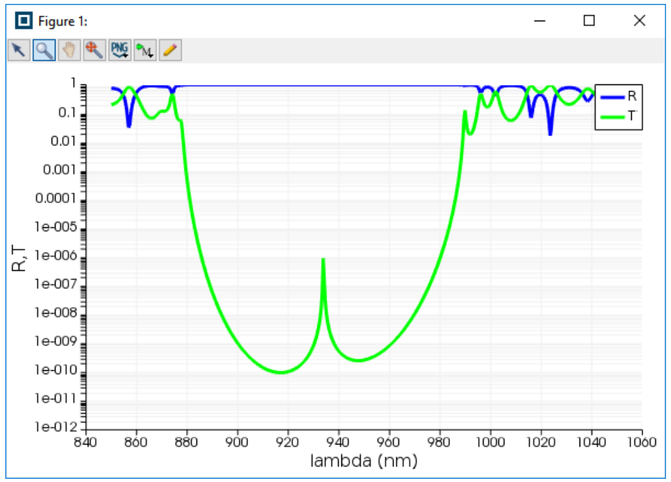
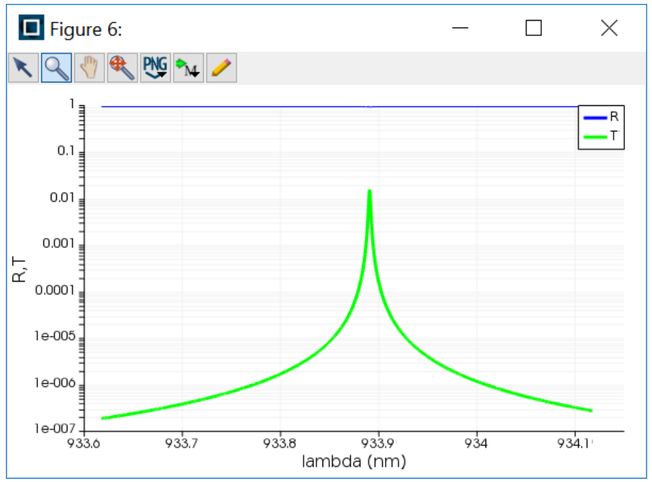
A simple example

Run the script file

- It reads the layer table and plots n vs z
- It calculates R, T
- It identifies the peak in a given range
- It does a higher resolution calculation near to peak
- It extracts the resonant wavelength
- Purcell factors and dipole emission can also be calculated







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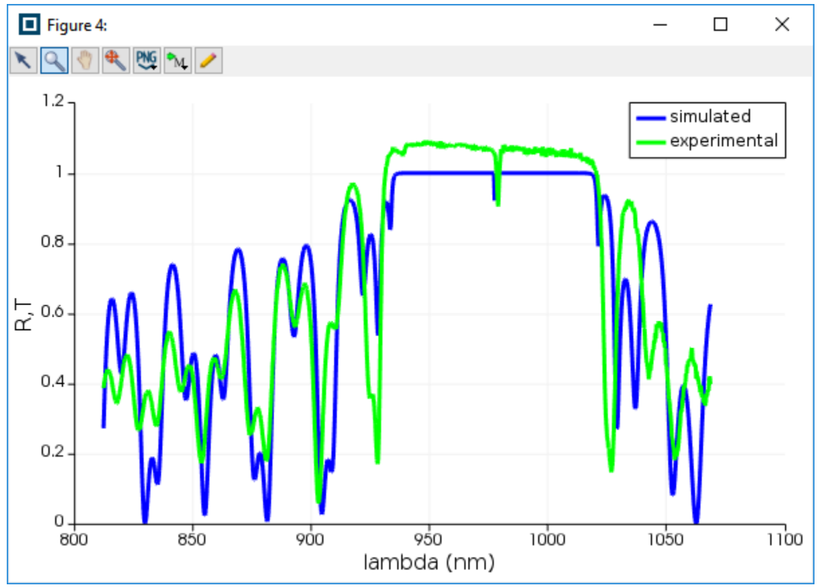
Comparison with experiment

Run a second script

- Uses Python optimization routines to make a constrained fit of the calculated reflectivity to the experimentally observed values
    - Can choose the “best” parameters to vary based on experience
    - Here we varied Al mole fraction and layer thicknesses



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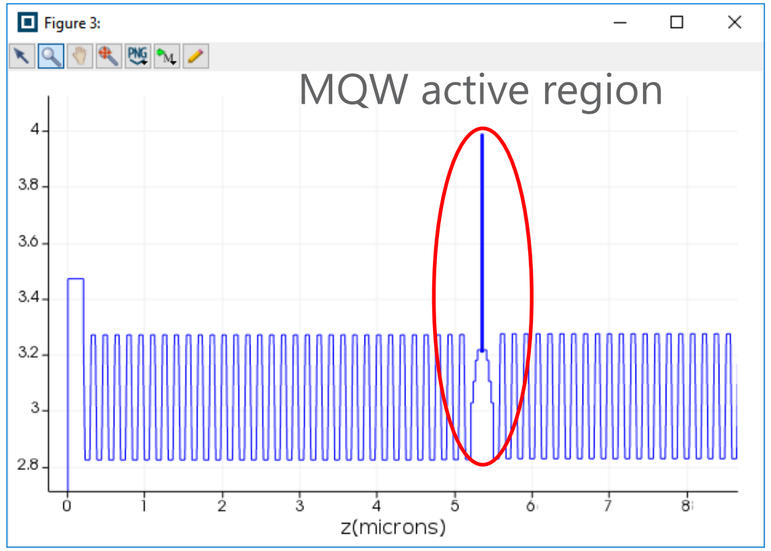
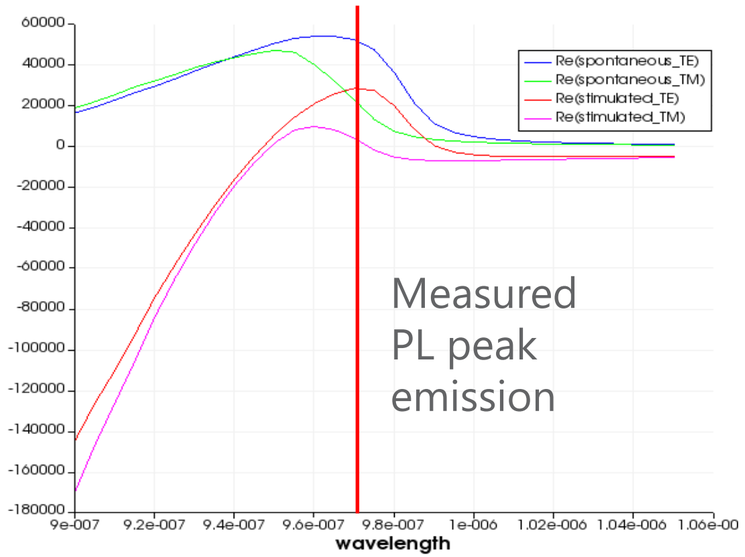
Gain and spontaneous emission from QWs

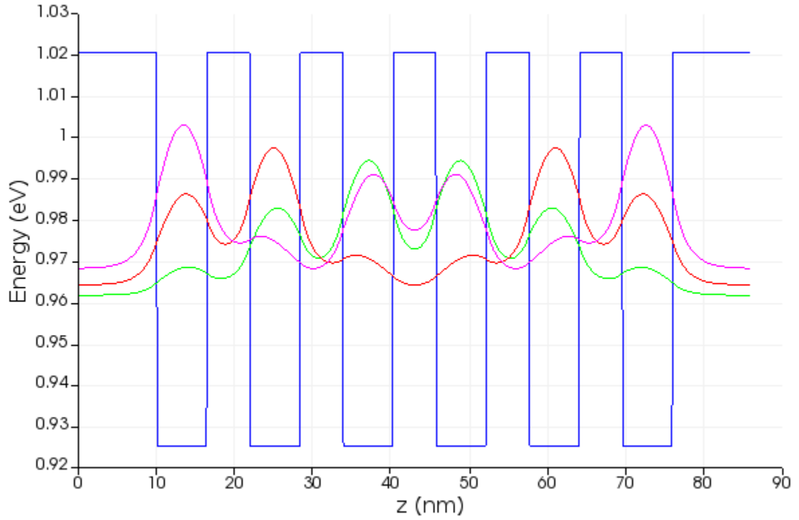
Refractive index in the growth direction



MQW gain simulation



Band diagram and wavefunctions



Calculate gain and spontaneous emission for a multiple quantum well structure

- Accessible through the mqwgain script command

Suitable for III-V material with Zincblende crystal structure (4x4 k.p method)

- Default material database provided for common III-V materials and alloys (e.g. InGaAsP)

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VCSEL Modal properties

Single mode operation of Photonic Crystal VCSELs

Photonic Crystal (PhC) VCSELs

High Speed Photonic Crystal Vertical Cavity Lasers

Kent D. Choquette, Chen Chen[1], Dominic Siriani, Meng Peun Tan, Matthias Kasten, and David V. Plant[1]
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University of Illinois, Urbana, IL, USA
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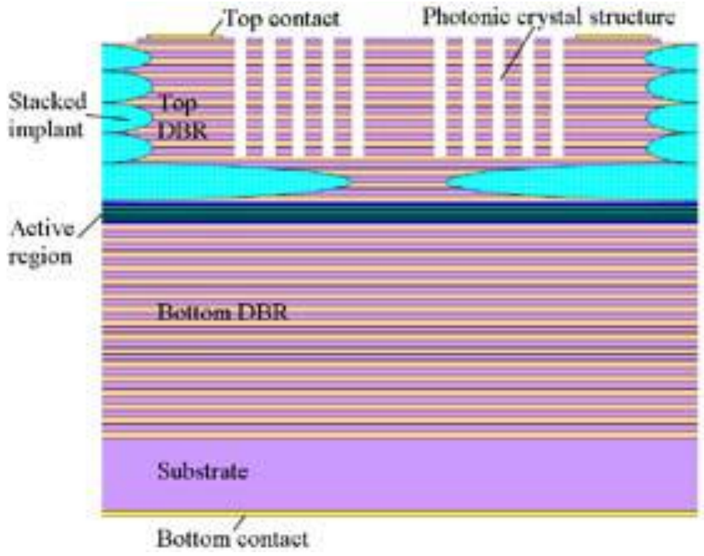
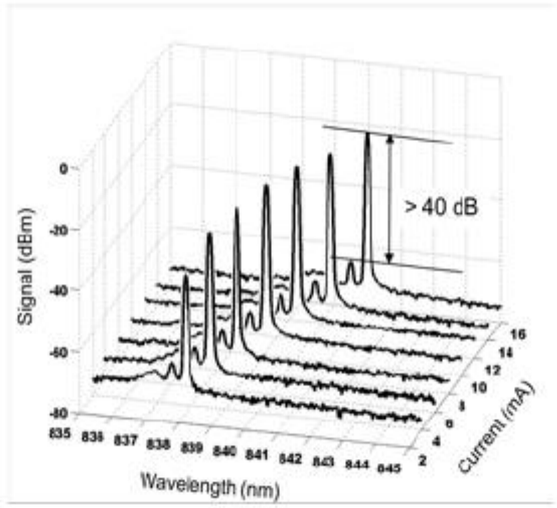
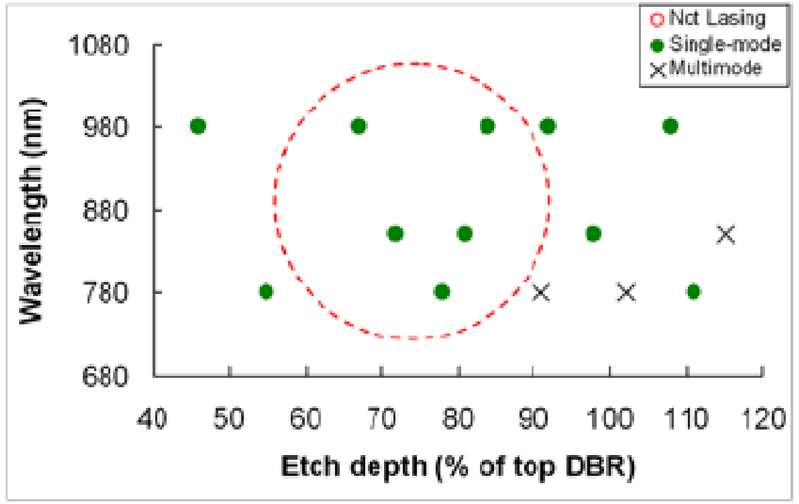
choquett@illinois.edu

VCSELs require lateral mode control for high performance optical communications and some sensing applications

PhC offer one method of control by varying etch depth and pitch







Choquette et al., “High Speed Photonic Crystal Vertical Cavity Lasers” (2011), Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011.

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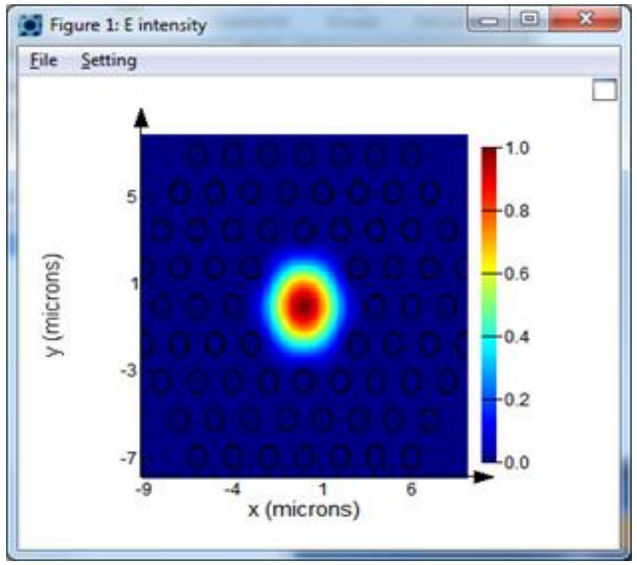
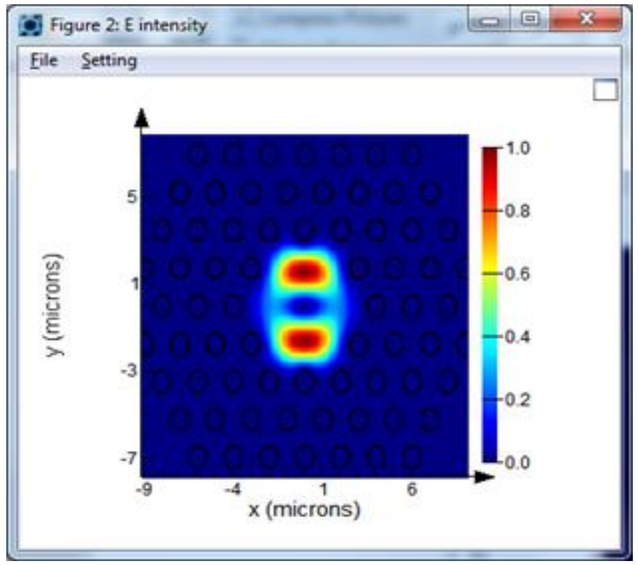
Optical Simulation to predict VCSEL Modal Properties

Use a combination of tools to simulate the VCSEL modal behaviour

1. Create a model of the planar VCSEL using STACK
2. Examine transverse modes using Finite Difference Eigenmode (FDE) or Finite Element Eigenmode (FEEM) methods





- *Cavity can clearly support several modes*

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3D FDTD Modelling

Set up a 3D simulation

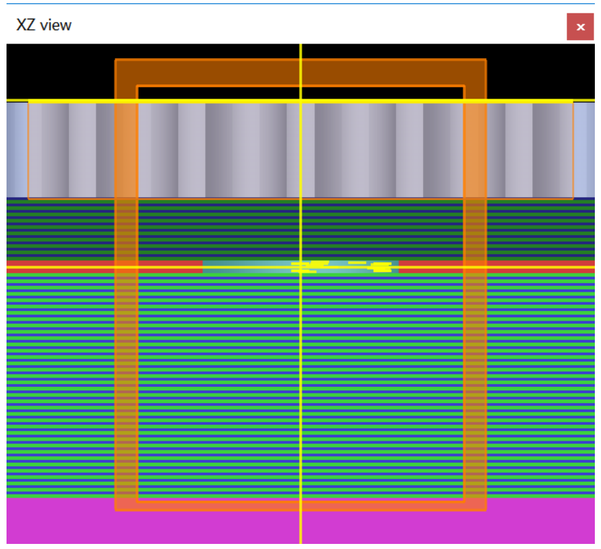
- Modal analysis of the cold cavity

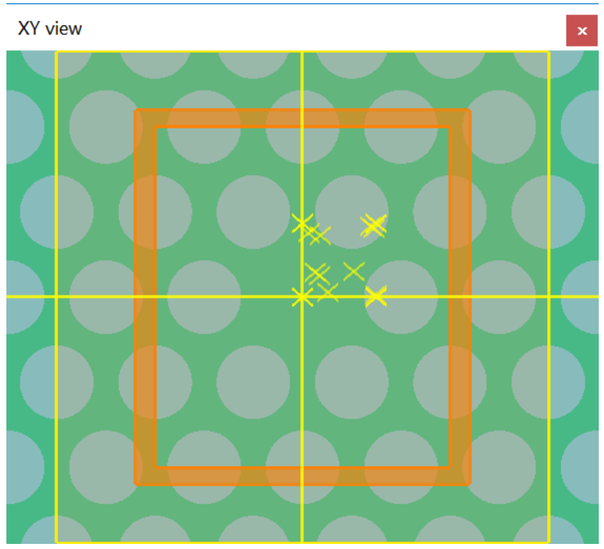
Create an electrically pumped gain medium in FDTD and let the mode competition play out

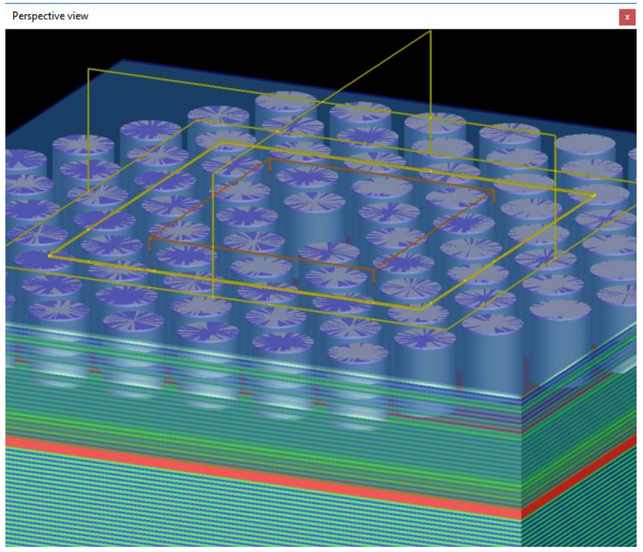
- Follow evolution of modes in the cavity

Large, long, computationally intensive 3D FDTD simulations

- Modern workstations make it quite tractable in hours to ~ 1 day on a single workstation
- HPC and clusters can go even faster







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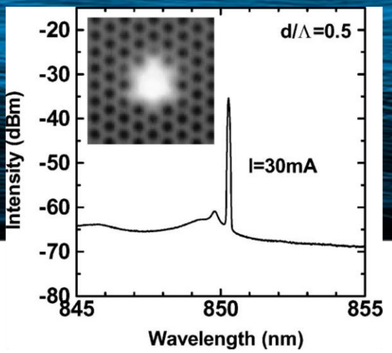
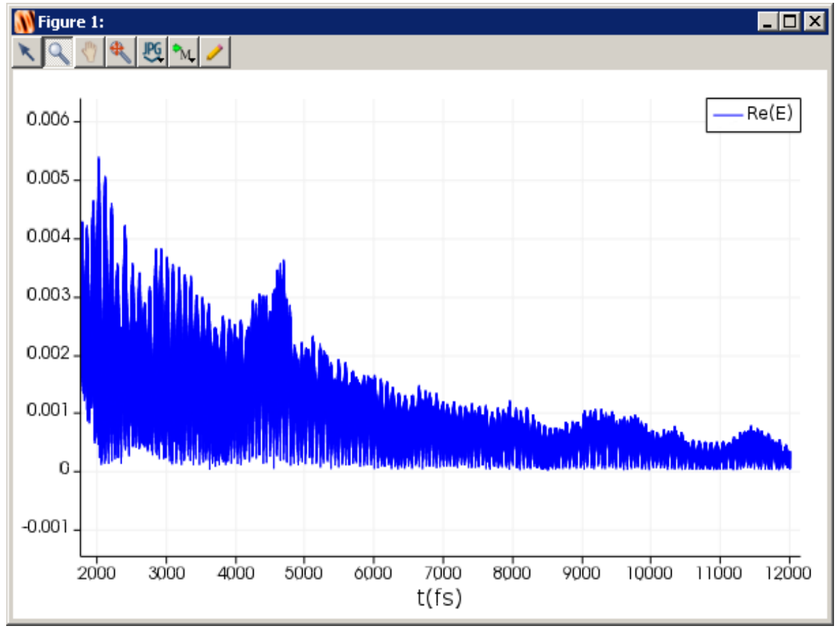
PhC VCSEL example: cold cavity with dipole sources



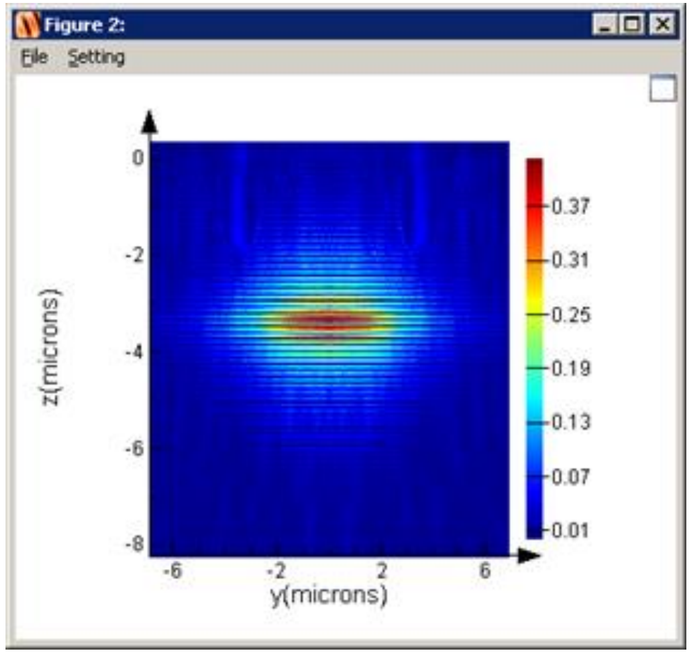
Yokouchi et al., Appl. Phys. Lett., Vol. 82, No. 21, 26 May 2003

3. Examine the modal properties of the cold cavity

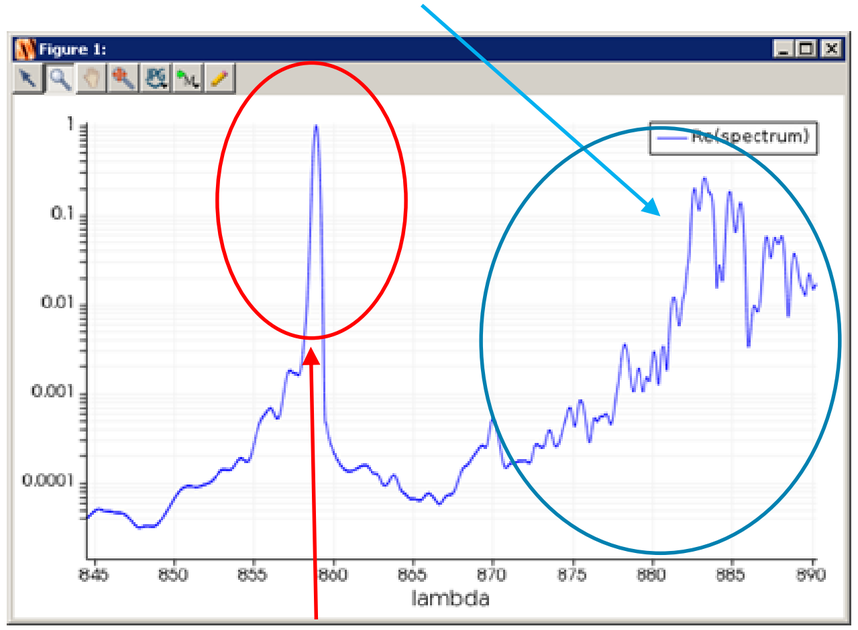


E field decay in time, with the dominant mode remaining

Mode profile



Numerical artifact due to large lateral grid to reduce simulation time (region not of interest)



Fundamental (Laser) Mode

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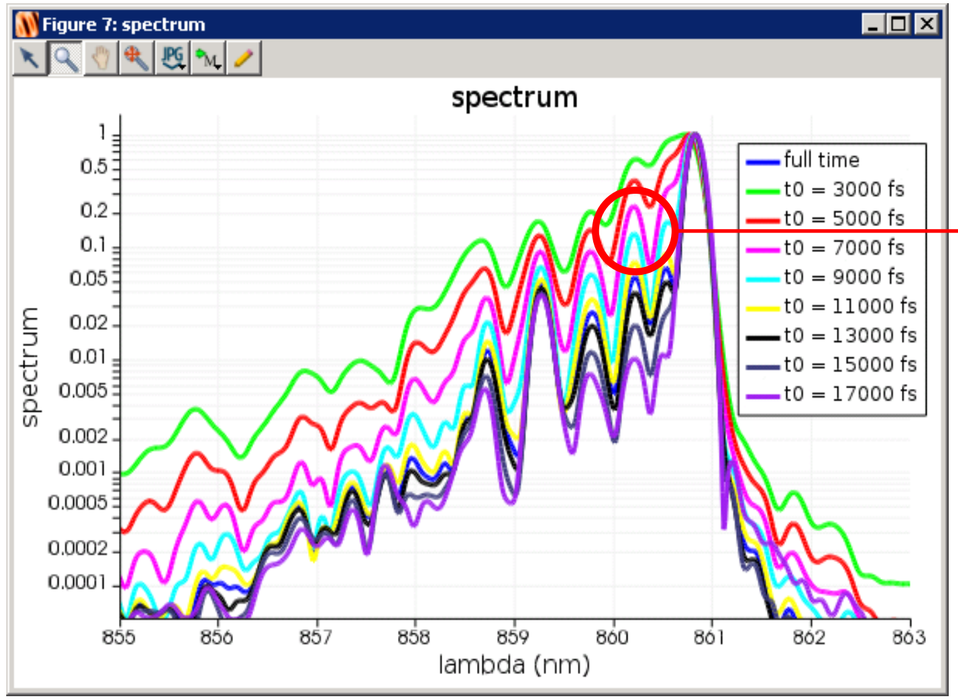
PhC VCSEL example: cavity with saturable gain active region model

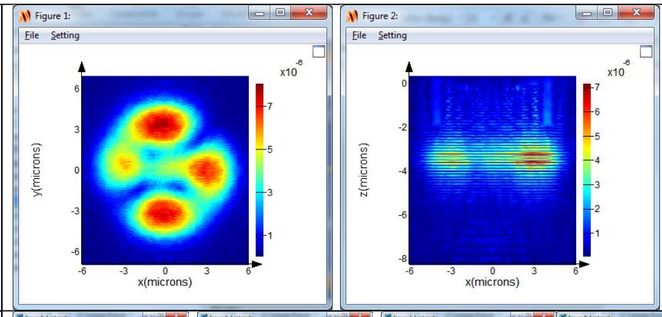
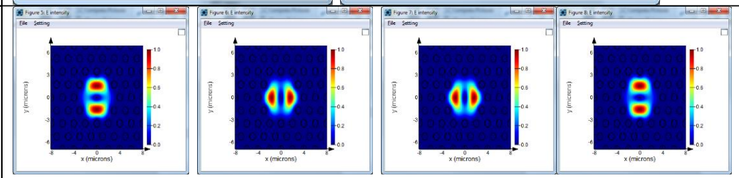
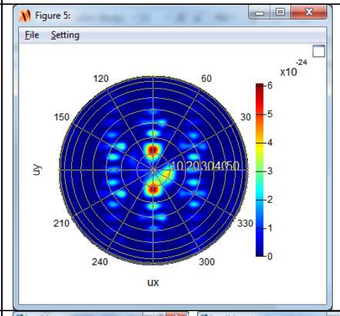
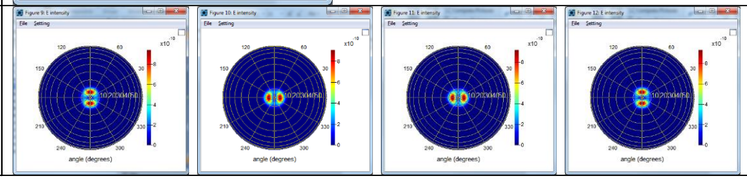
4. Add gain to the model

Laser spectrum at different times



Relatively weak mode suppression ratio

Analysis of the second most dominant mode at 7 ps

Peak B	
Active layer (x-y) plane and (x-z) plane	
Eigenmodes of PC	 neff = 3.48656, 3. 48655, 3. 48655,3. 48654
Far field	
Far field of PC eigenmodes	

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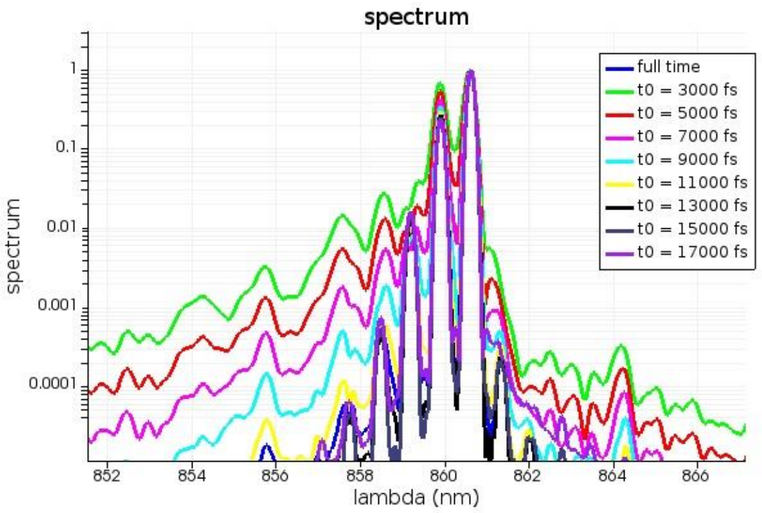
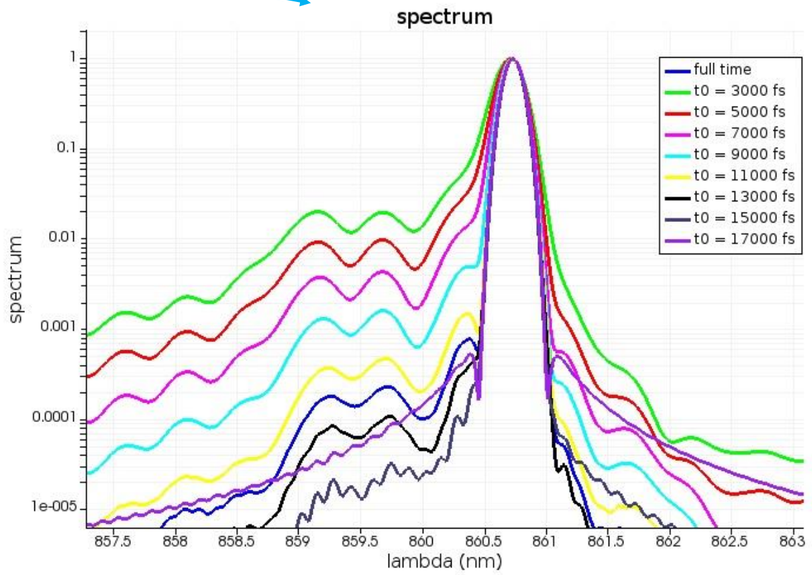
PhC – FDTD of etched DBR structures *(Choquette et al)*

FDTD simulations using 3 different etch depths

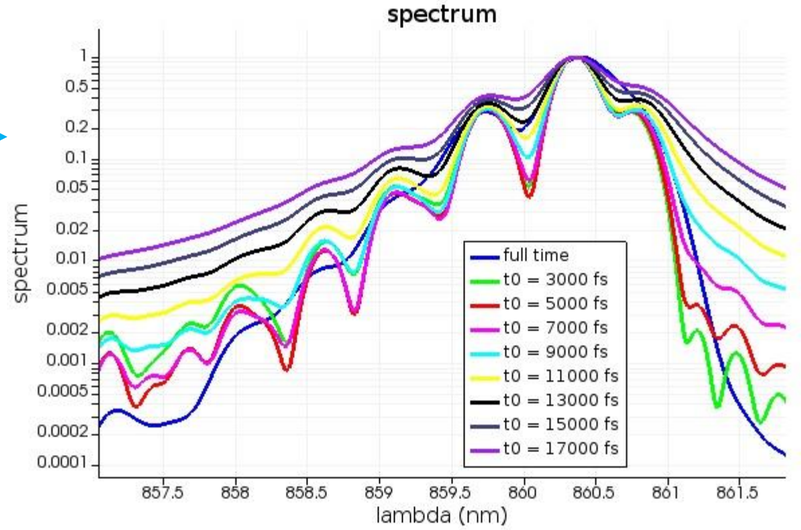
1. Shallow (10 layers, 40% of top DBR)
2. Medium (15,60%)
3. Deep (20,80%)



MM Device
Guided modes of the PhC ?



SM Device
>40dB SMSR



MM Device
No effect of the PhC ?

Good qualitative agreement with experimental results

FDTD becomes a predictive tool for evaluating MODE behaviour of VCSEL Structures

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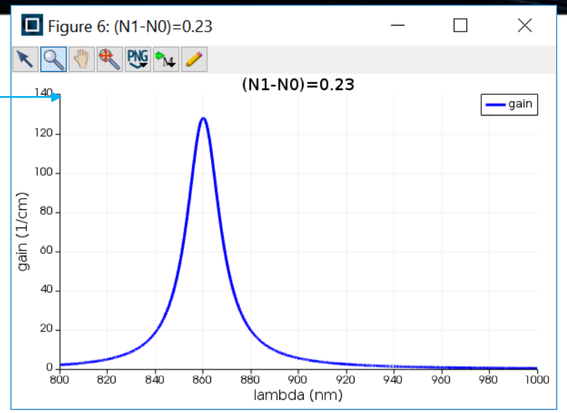
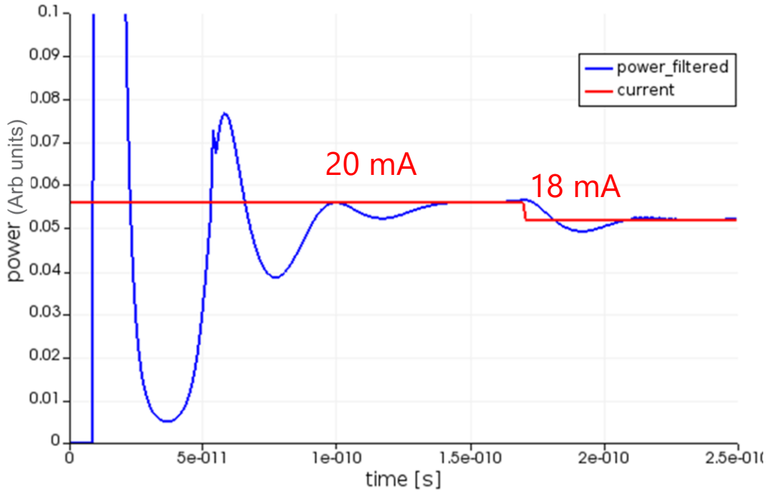
3D FDTD with current driven gain model calibrated by MQW solver

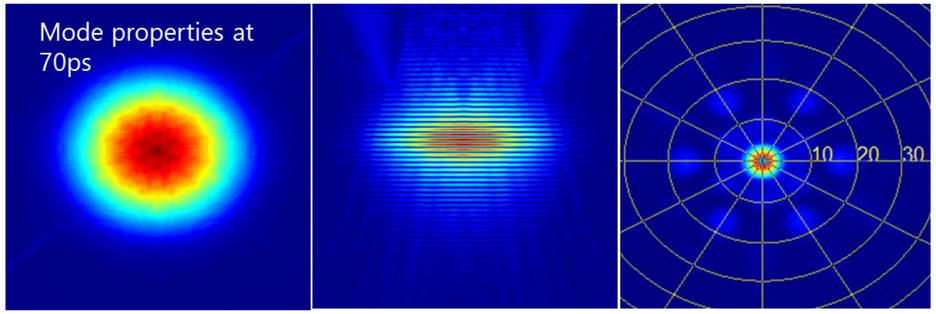
1. Calculate the active properties with MQW gain
2. Current driven gain model for FDTD that uses values calculated by MQW gain
3. To speed onset of steady state, set initial excitation density high
4. Allow current to change by small amount after steady state



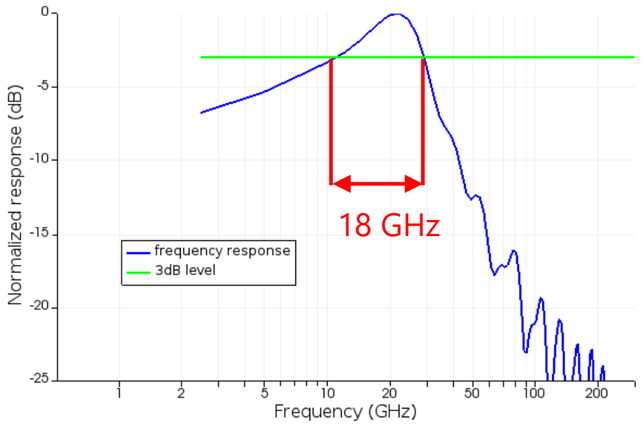
Power emitted by VCSEL vs time

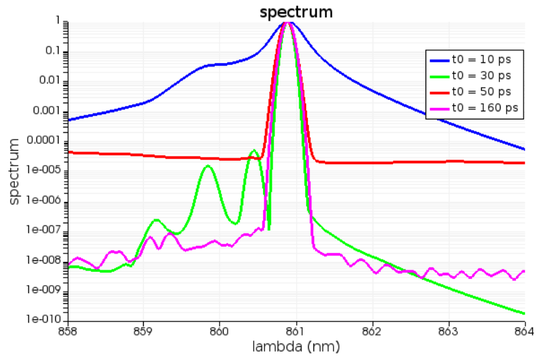


250ps 3D FDTD simulations, takes ~40 hours on one workstation



Bandwidth





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Summary and Future Work

VCSEL Modelling

- R & T Modelling
  - Characterisation tool to determine growth parameters
- Material gain, spontaneous and stimulated emission
- 3D-FDTD
  - Cold cavity
    - Transverse mode properties
  - Far field
  - Laser emission
  - Time dependent mode competition
  - Current driven gain calibrated by MQW (ongoing)

System Modelling *(Future Work)*

- Incorporate VCSEL as a component into Lumerical's INTERCONNECT
  - Variant of the TWLM
- Transceiver performance
  - Monitor response to being electrically driven
  - Eye diagrams etc…

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