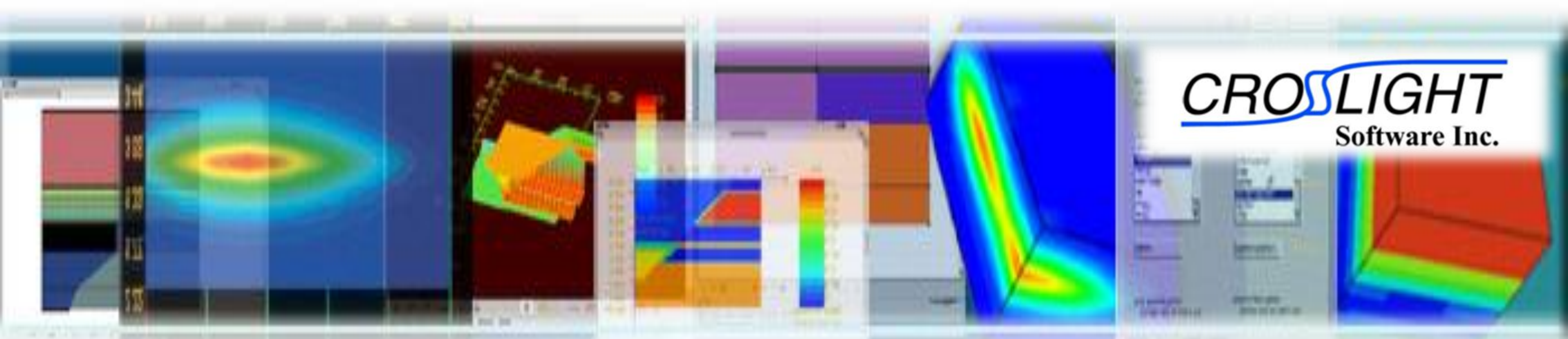


Lighting up the Semiconductor World…

Simulation of Quantum Cascade Lasers

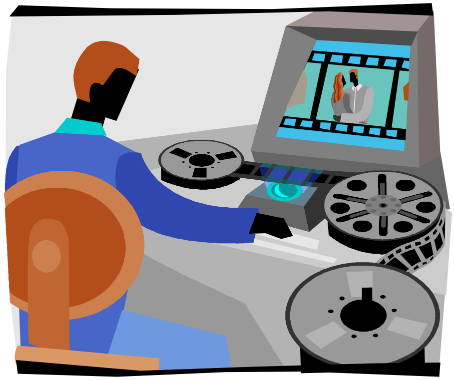
Contents

- **Microscopic rate equation approach**
- **Challenge in carrier transport modeling**
- **Solution in 2/3D simulator**

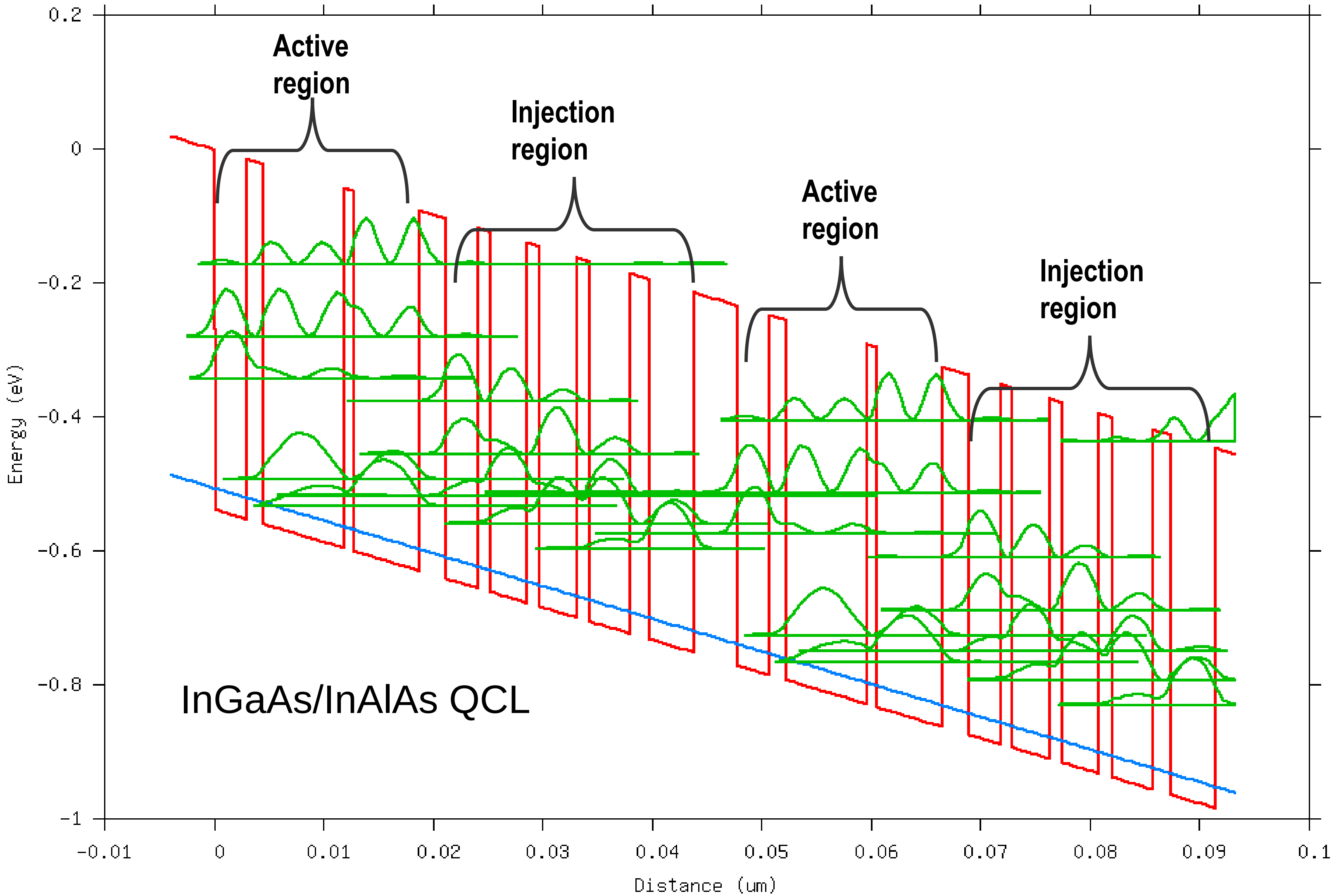
Subband engineering

- Given MQW structure, all quantum states are solved.
- Energy levels and intersubband transition dipole moments computed for all pairs of states.
- Critical states identified according to design ideas such as the so-called 3-level design.

Simulation procedures

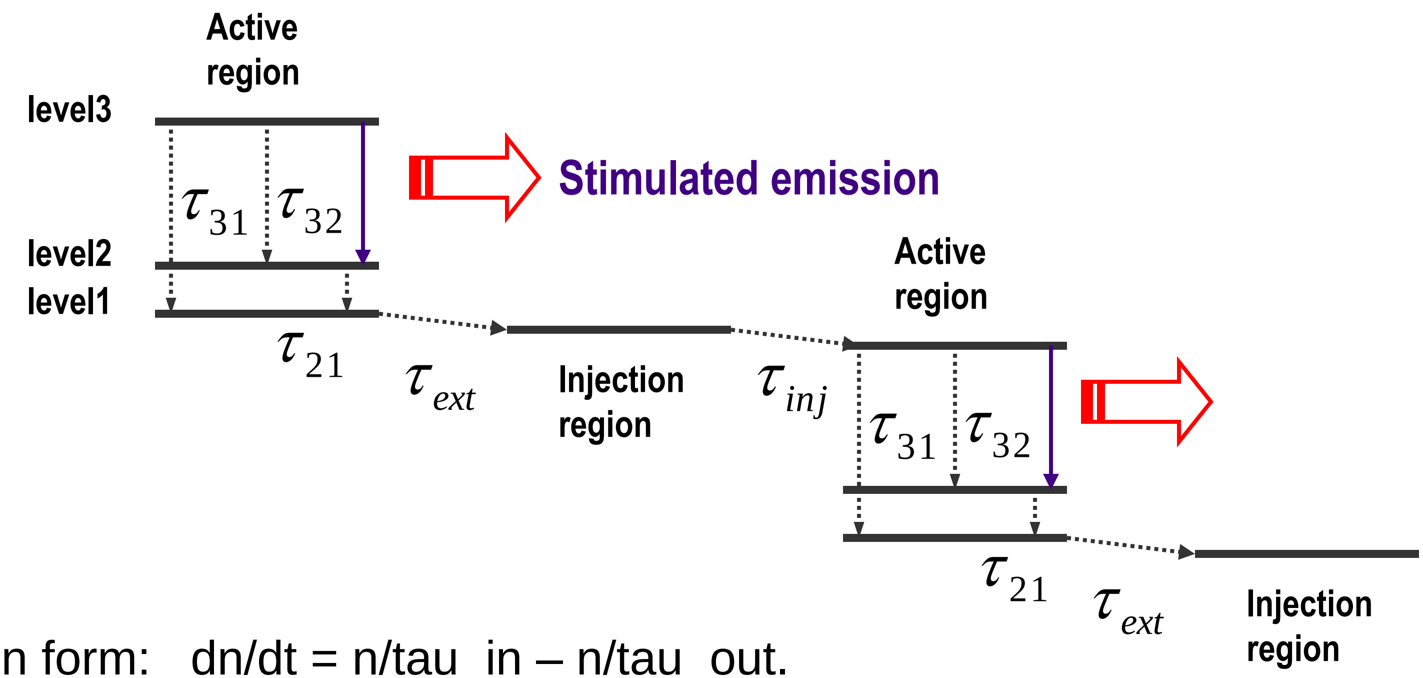


- Set up 1D mesh for two periods of QCL in gain-preview session.
- Assume a uniform applied field and solve the quantum states.
- Discretize Schrodinger equation in 1D and solve with sparse eigen matrix techniques.
- Identify and label states belonging to injection or active regions, based on shape and location of wave functions and their respective energy levels.



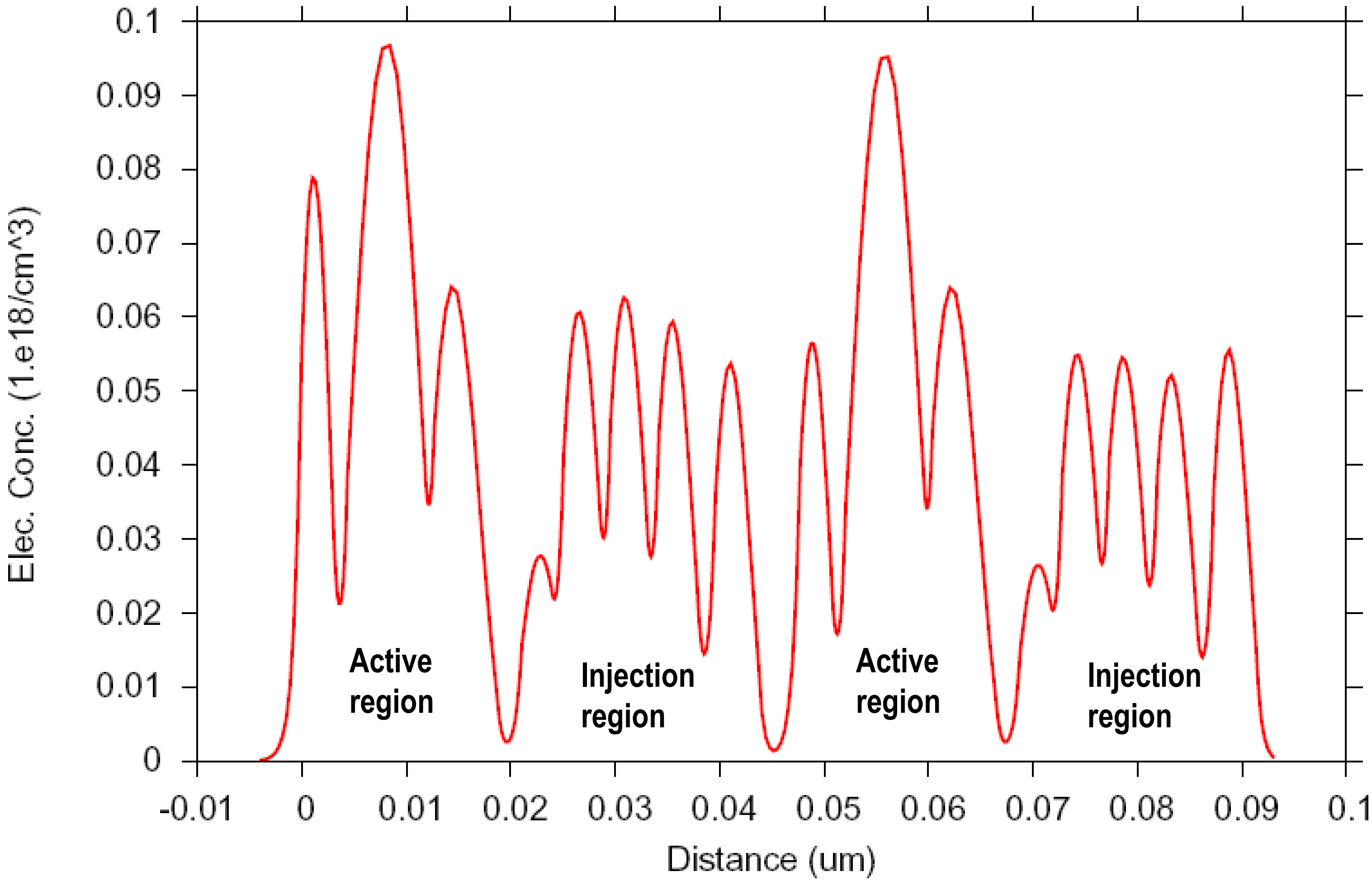
Following J. Kim et. al., IEEE JQE Vol. 40, p. 1663, 2004. Red lines: Conduction bands; Green lines: subband levels and envelop wave Functions. Blue line: macroscopic single Fermi level.

Microscopic rate equations



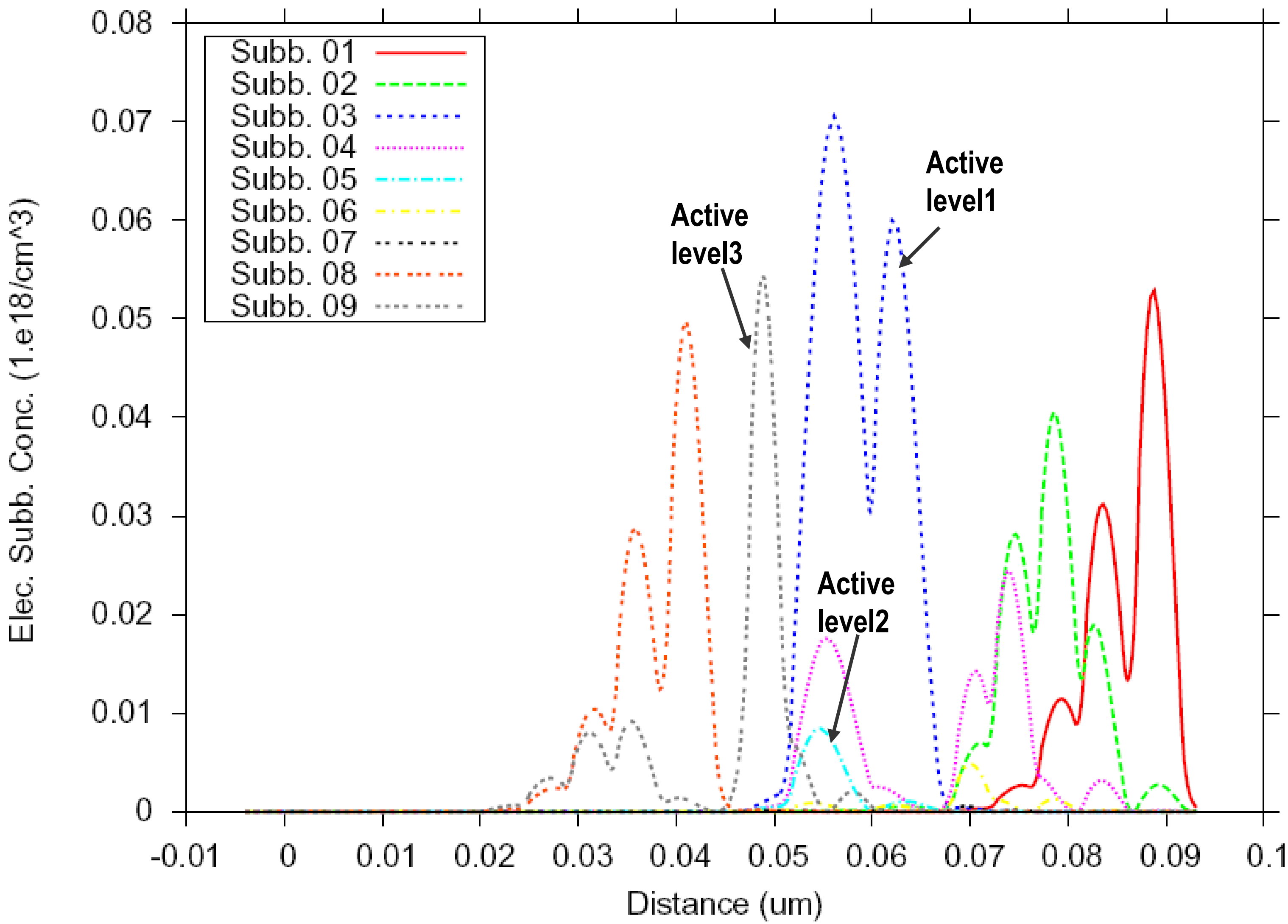
- Equations in form: dn/dt = n/tau_in – n/tau_out.
- Coupled with cavity photon rate equation.
- Relate device current to injection region current.
- Closed set of equations to get lasing characteristics.

Distribution of Electrons



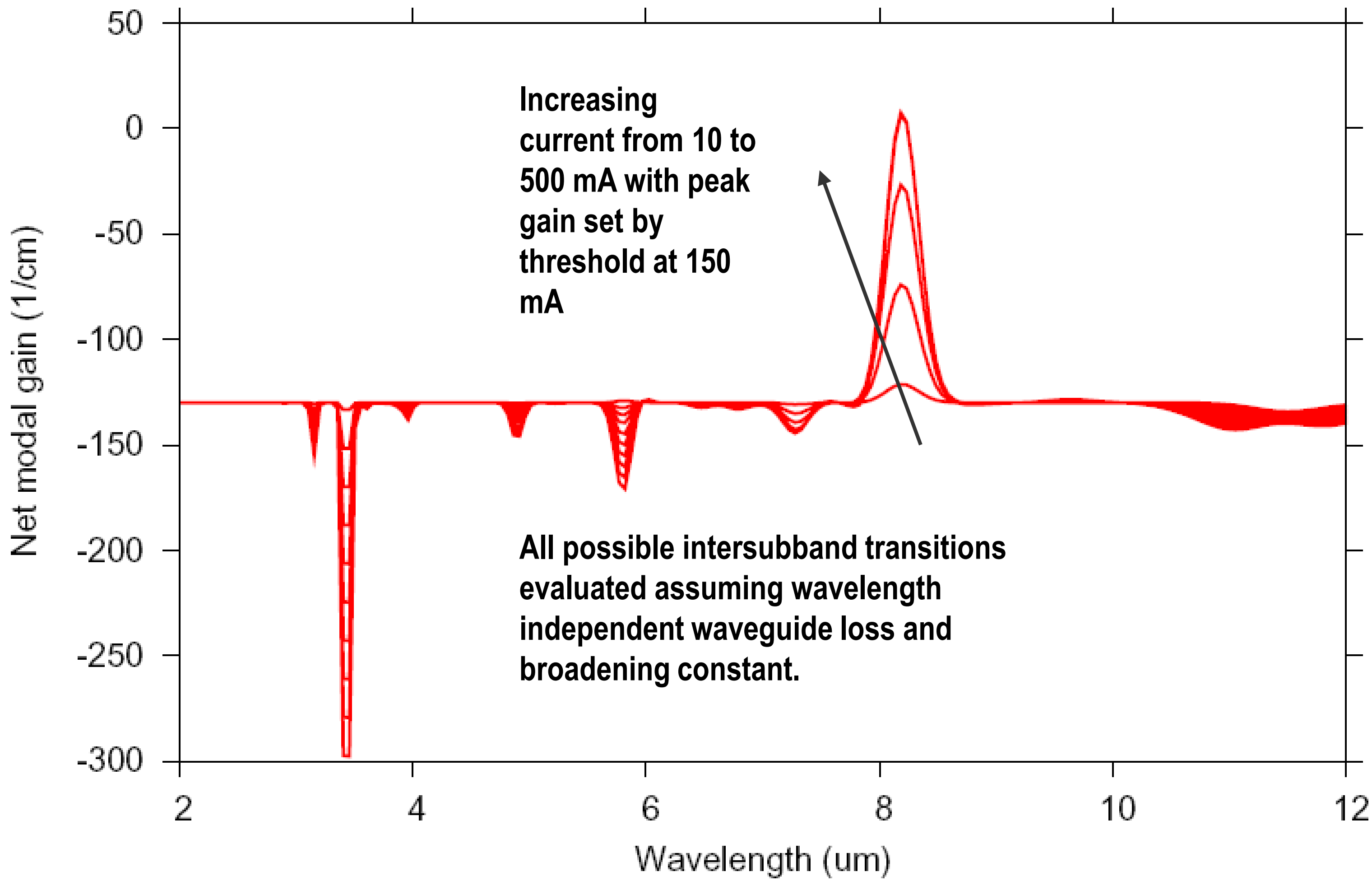
Electron distribution based on subband population calculated by microscopic rate equations

Distribution of subband electrons

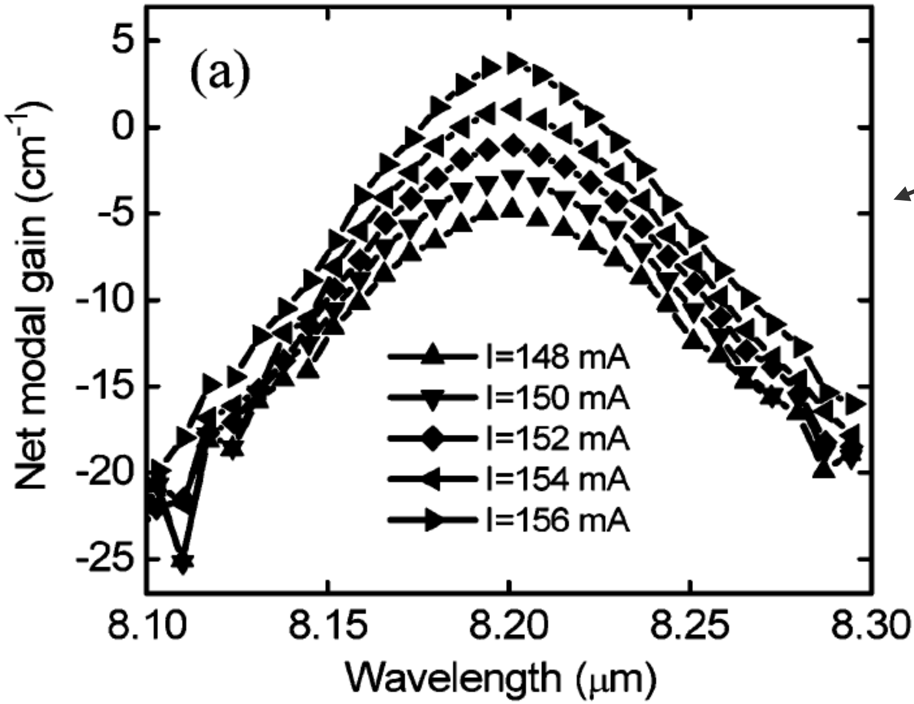


First 9 levels are plotted with the first three levels in active region labeled

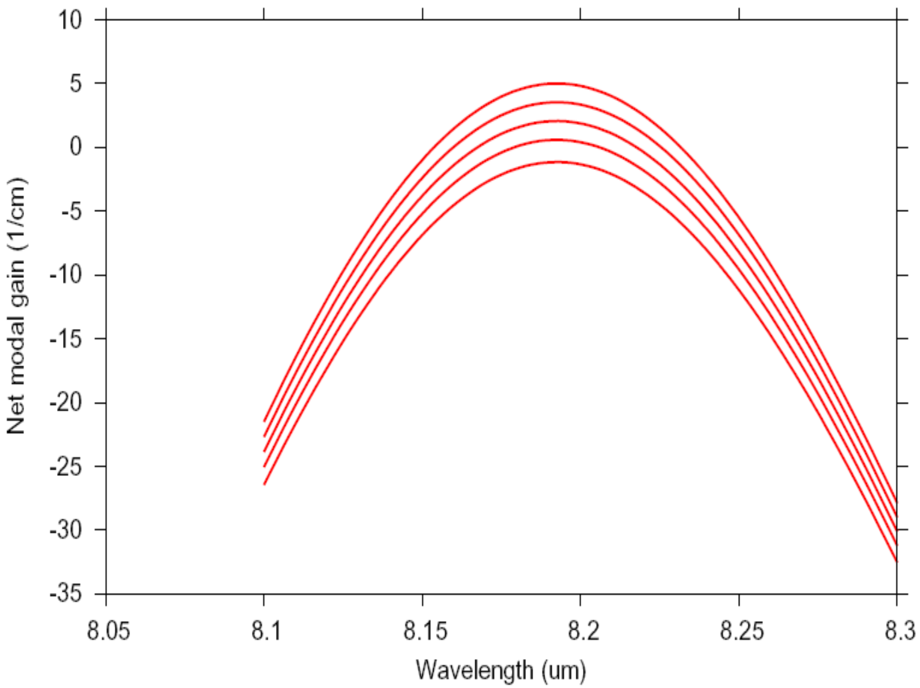
Gain spectrum-I



Gain spectrum-II

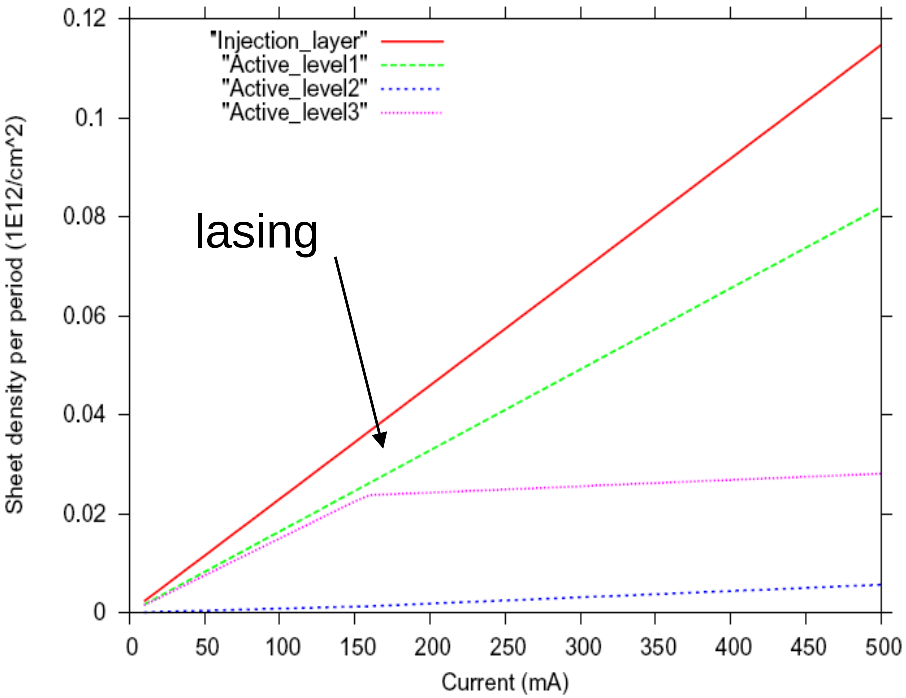


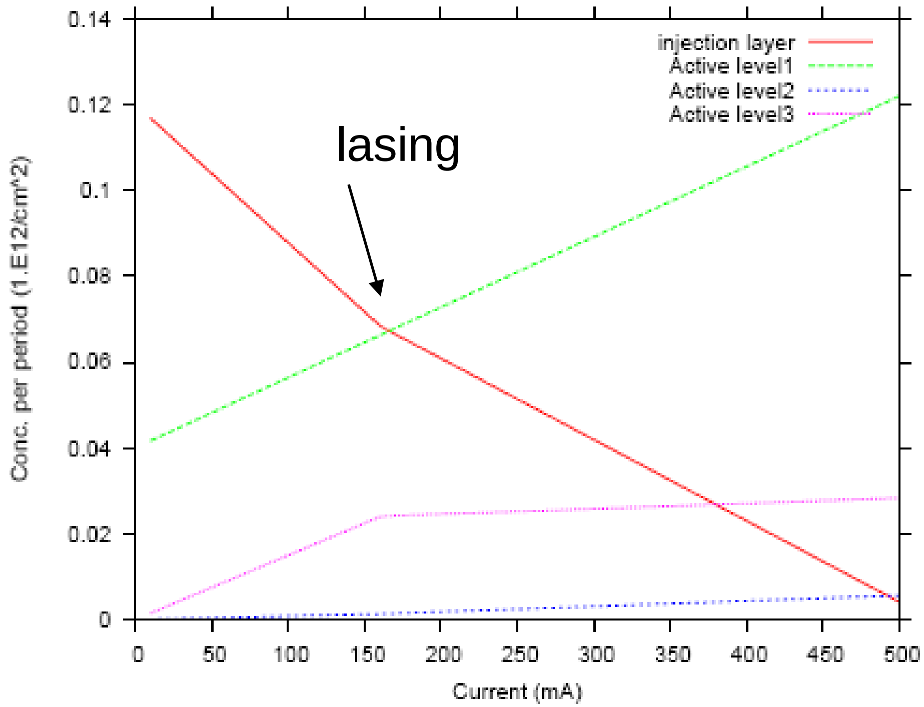
J. Kim et. al., IEEE JQE Vol. 40, p. 1663, 2004



Reasonable agreement with experiment achieved.

Two injection schemes

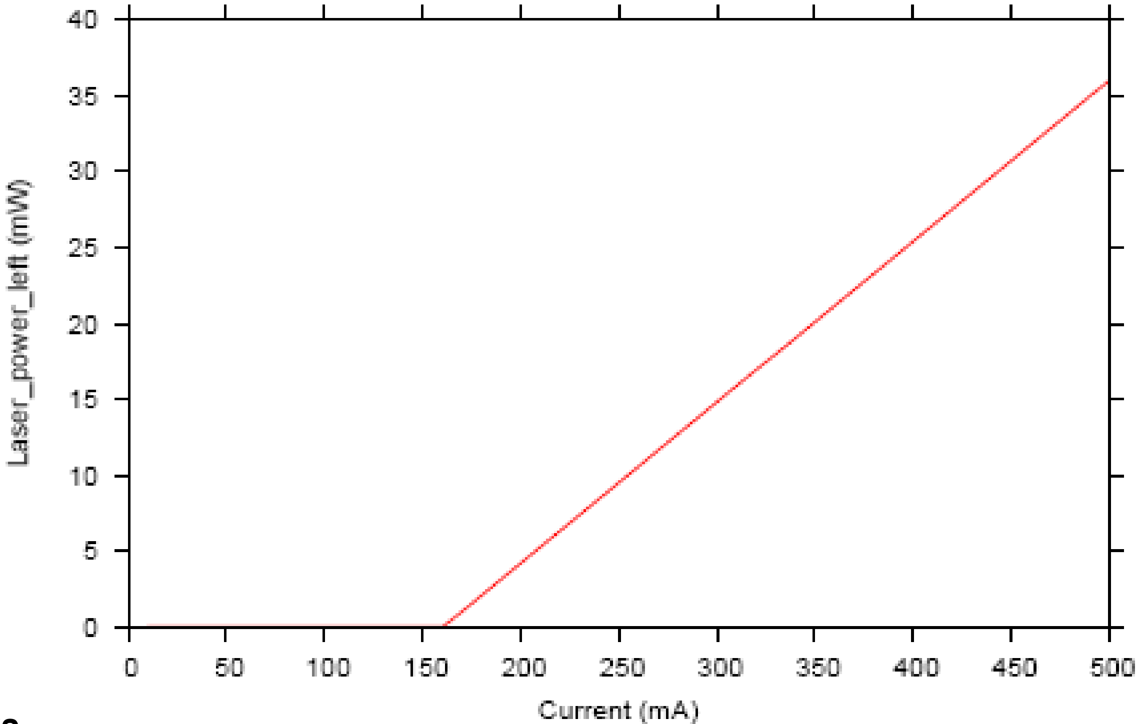




(a) Assume all tau's are constants and all levels are initially unoccupied. Current injection increases occupancy until lasing.

(b) Assume injection region and active level1 are initially occupied. 1/tau_injection set to increase linearly with current to preserve total sheet charge.

Both schemes result in same lasing characteristics



Remarks

•Stimulated recombination in QC laser does not pin the carrier density but only levels it off. Overall densities in active region still increase substantially as current is injected.

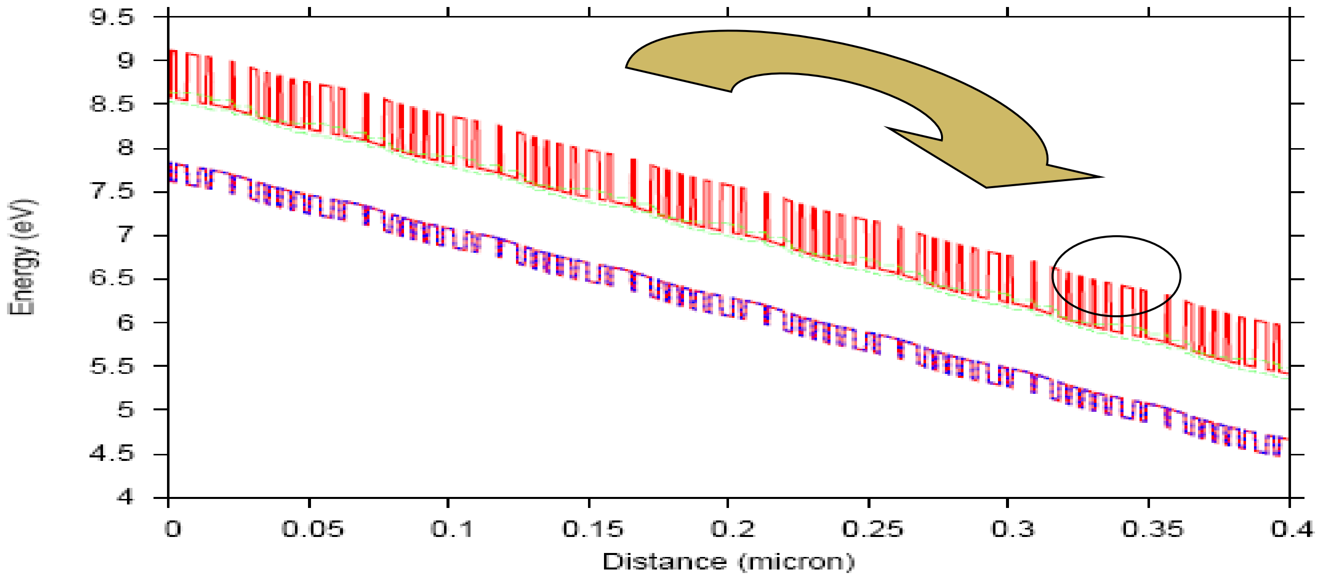
•Lack of density pinning explains absence of lasing relaxation oscillation in laser turn-on/off.

•Lasing action does not require or imply charge neutrality.

Contents

- Microscopic rate equation approach
- **Challenge in carrier transport modeling**
- Solution in 2/3D simulator

Challenges in transport modeling

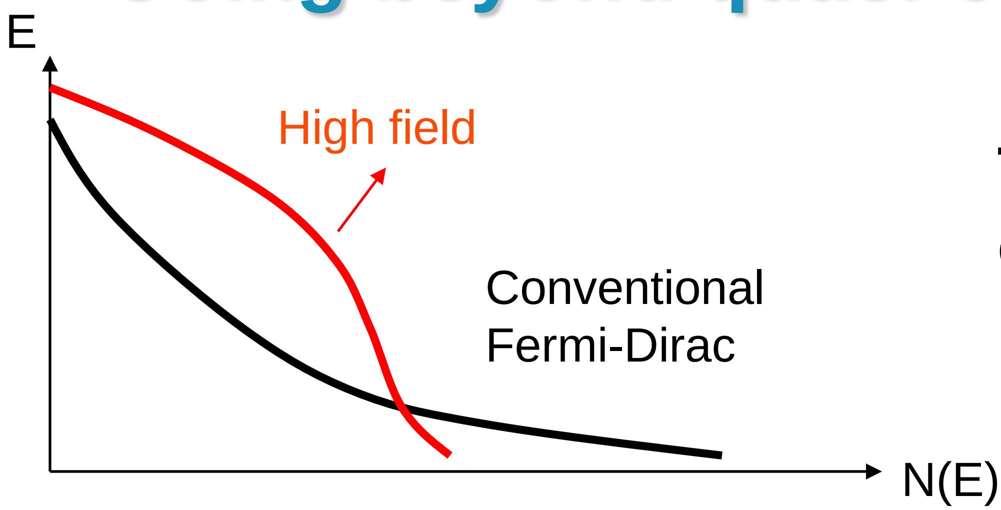


- **Microscopic rate equations:**
  - Time constants contain no information on how electrons get there from the contacts.
  - One still has to work on transport on larger size scale.

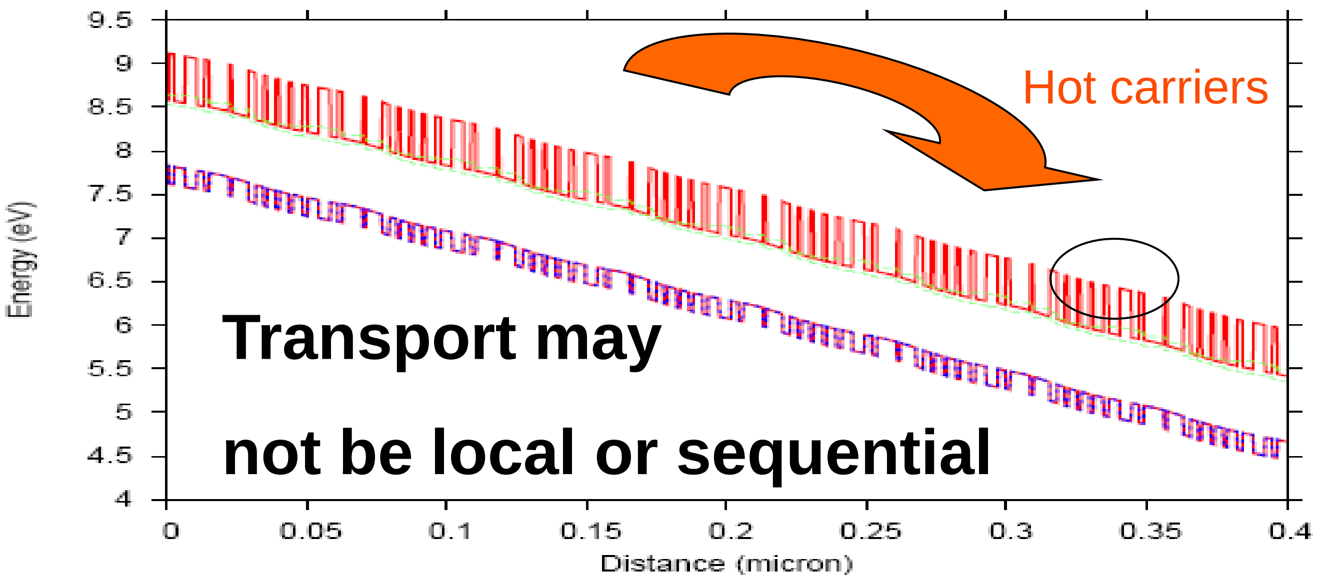
Challenges in transport modeling

- **Commonly used device simulators:**
  - Mobility-based drift-diffusion and thermionic emission.
  - Quantum tunneling done for few barriers as correction to drift-diffusion model.
- **Requirement for QCL:**
  - Drift-diffusion and thermionic emission still needed.
  - Quantum tunneling for hundreds of barriers.

Going beyond quasi-equilibrium?



Tunneling emitter src



Transport may

not be local or sequential

Contents

- Microscopic rate equation approach
- Challenge in carrier transport modeling
- **Solution in 2/3D simulator**

Equations and models

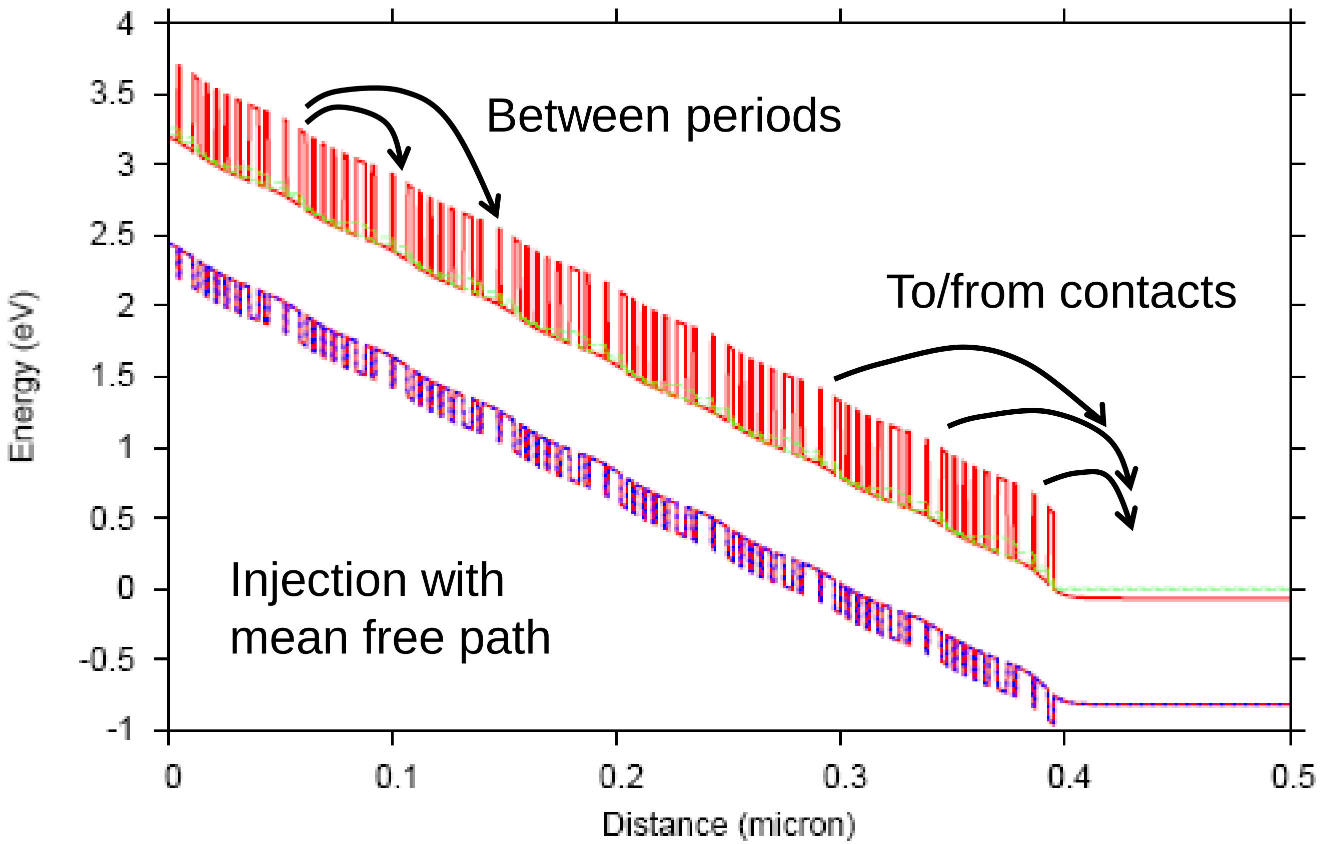
- **The conventional:**
  - Drift-diffusion equations with thermionic boundary.
  - Scalar optical mode solver.
  - Laser cavity photon rate equation.

- **QCL specifics:**
  - Local optical gain as a function of local current according to microscopic rate: g(J,S).
  - Within period: transport between injection/active regions according to microscropic rate eq.
  - Non-local transport between periods

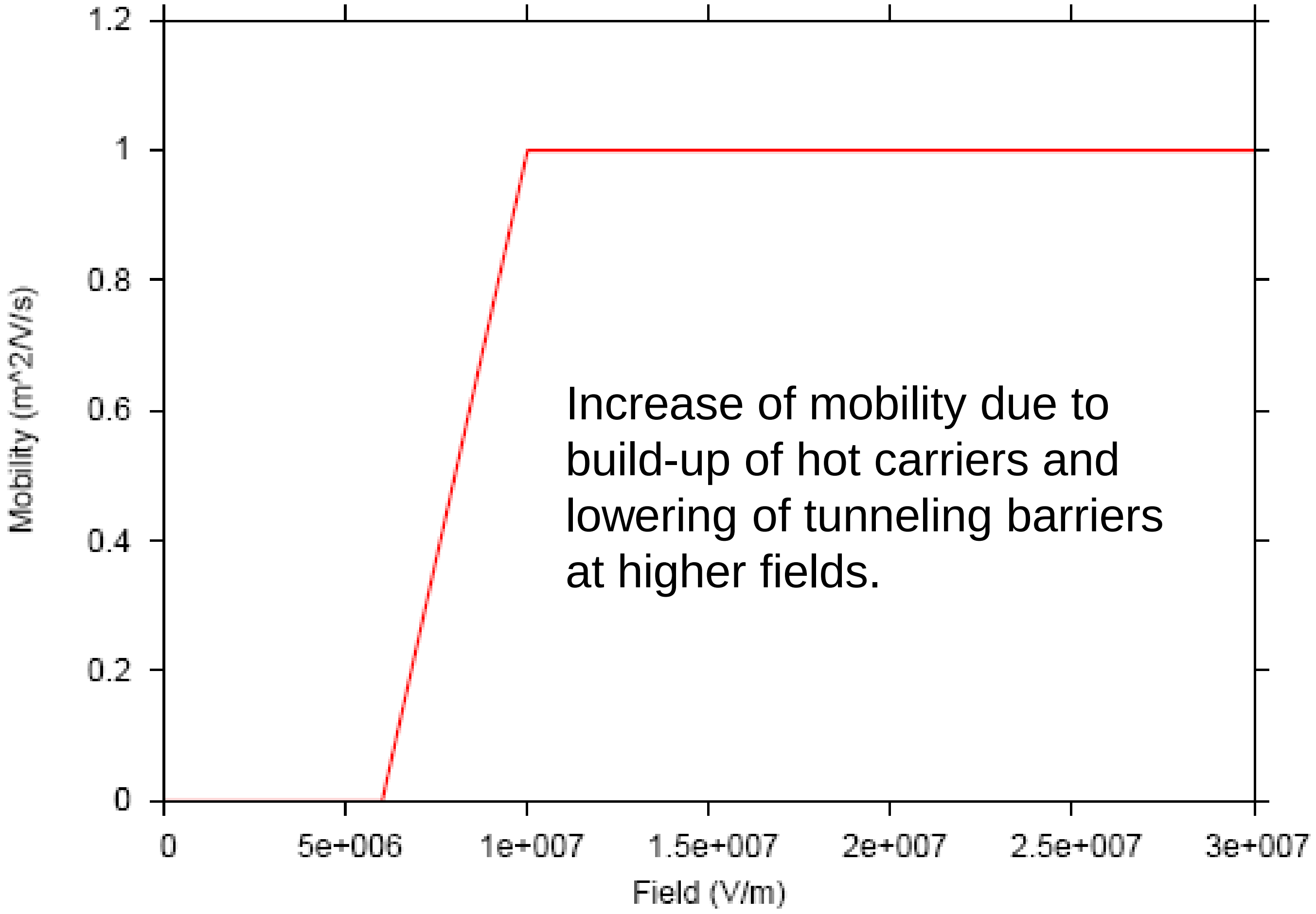
and to/from contacts.

Resonant tunneling effects

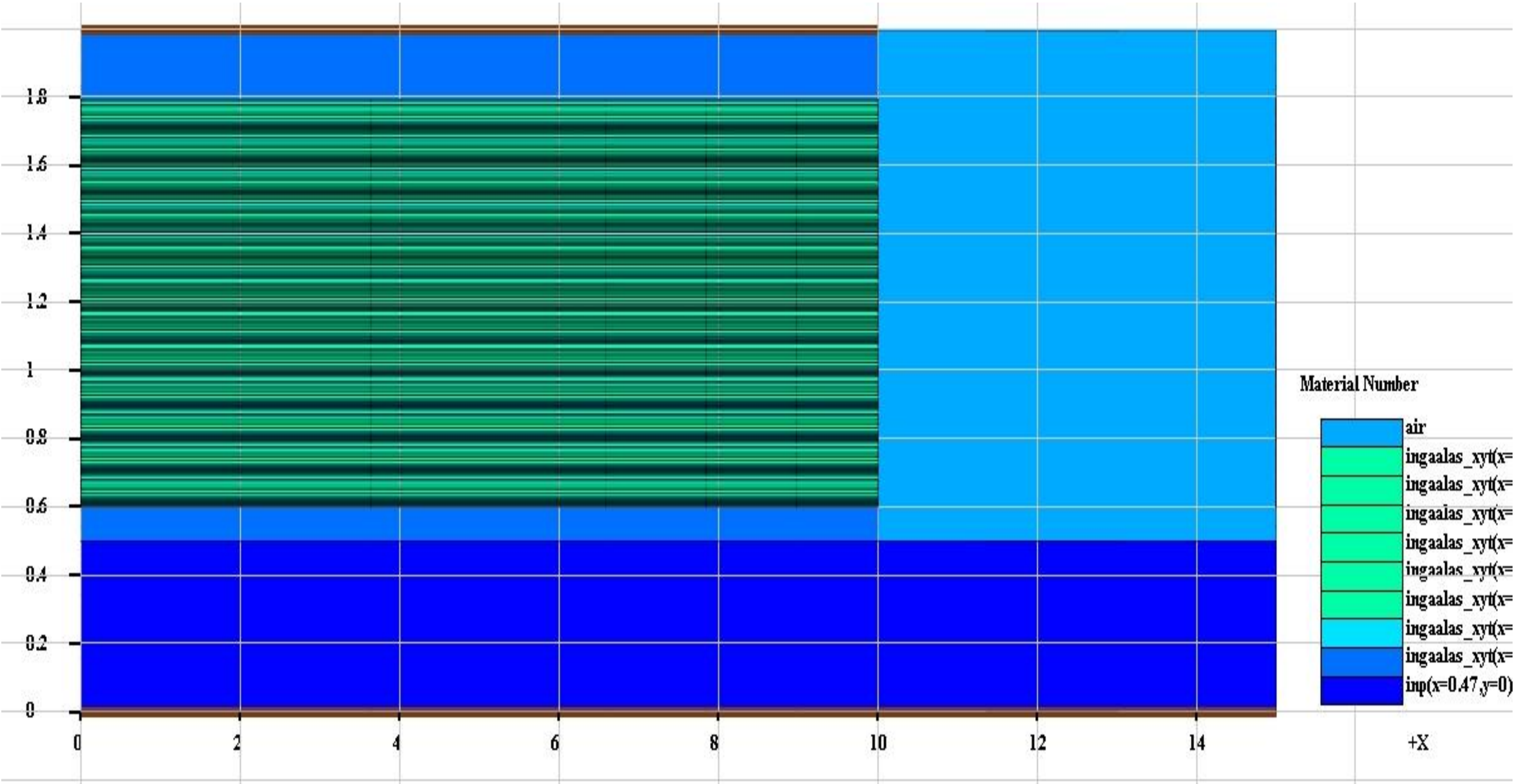
Non-local injection model



Non-local injection mobility

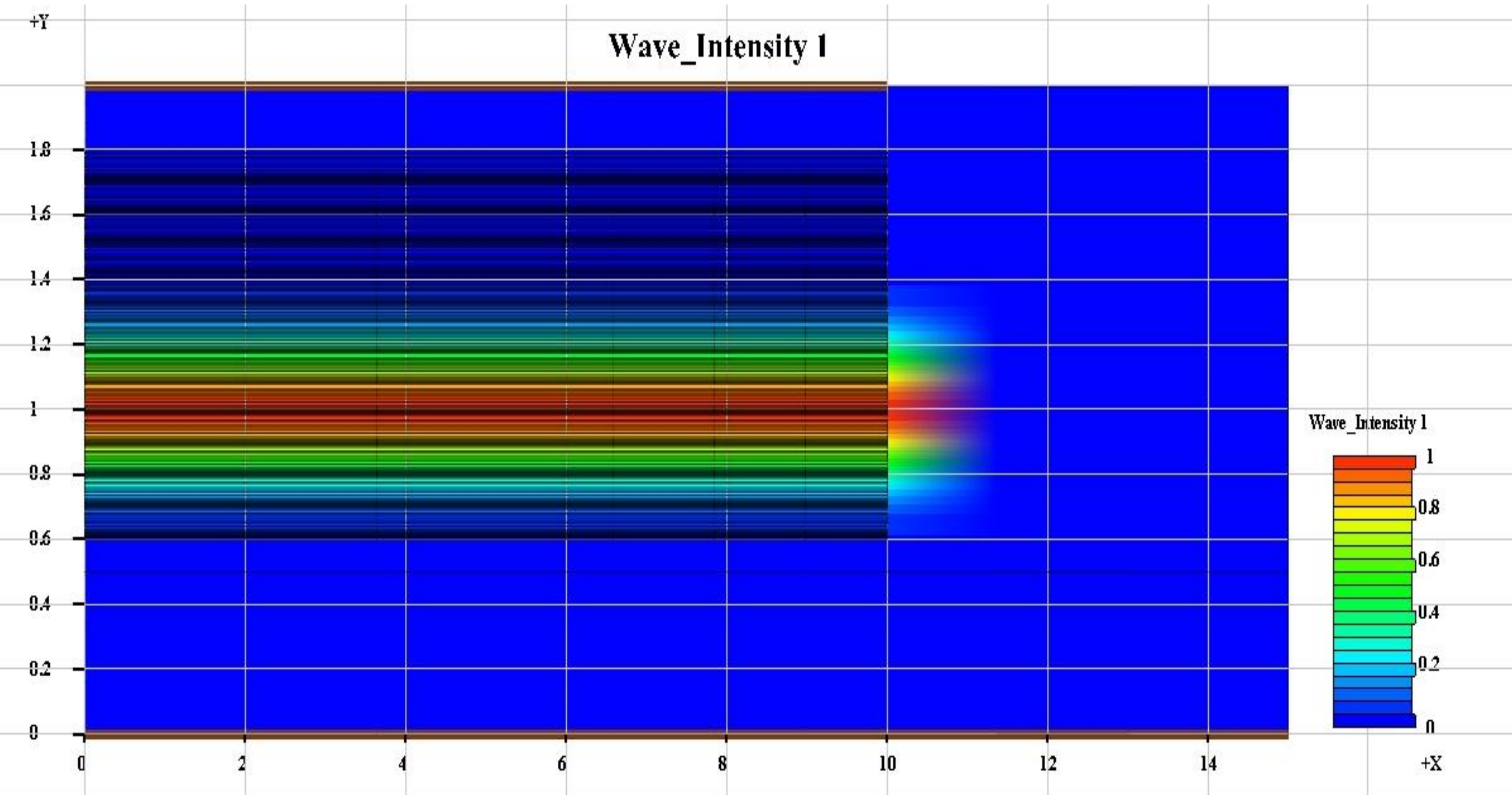


QCL 2D example

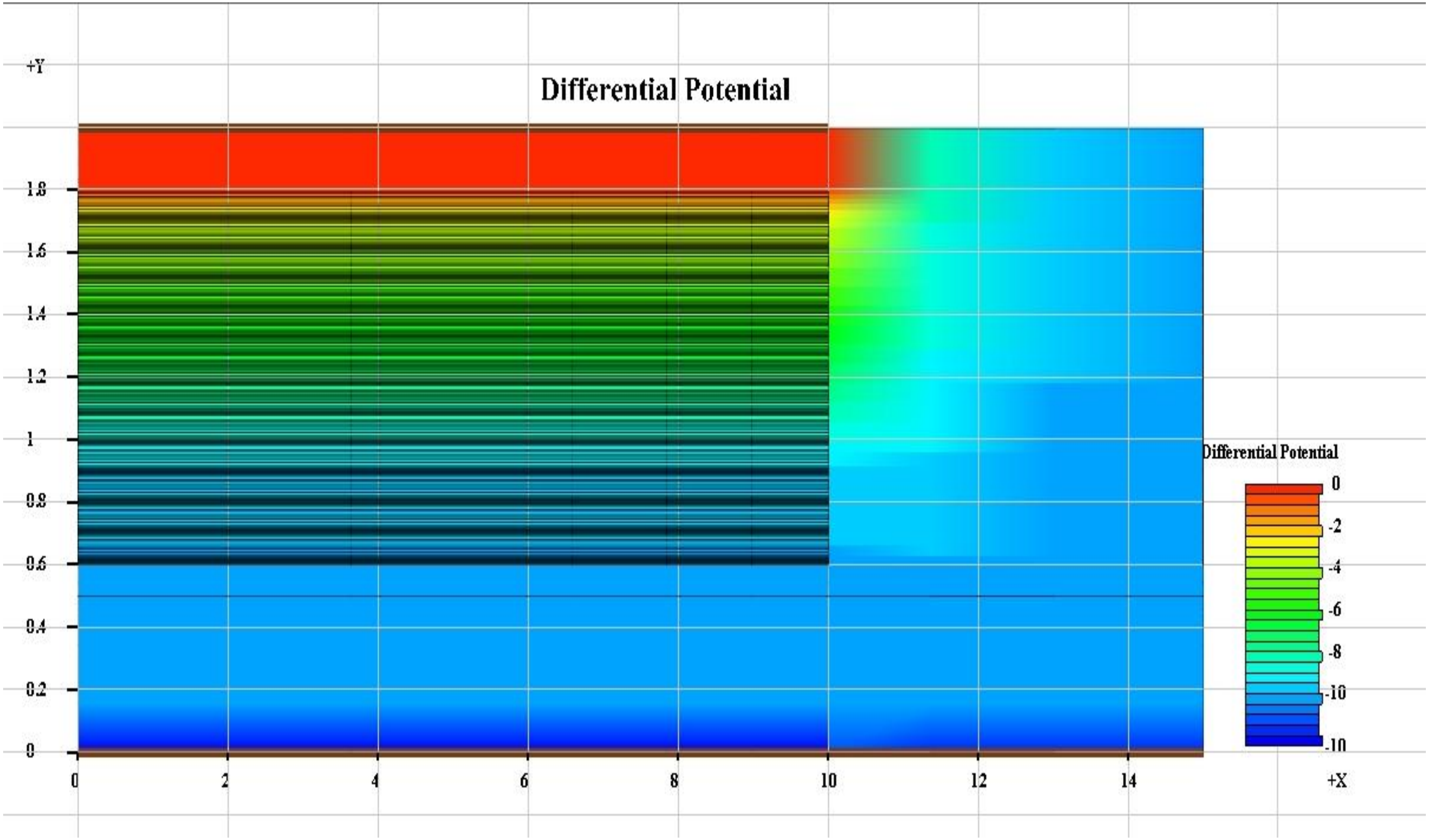


25 periods, assuming same MQW and microscopic rates as in previous sections.

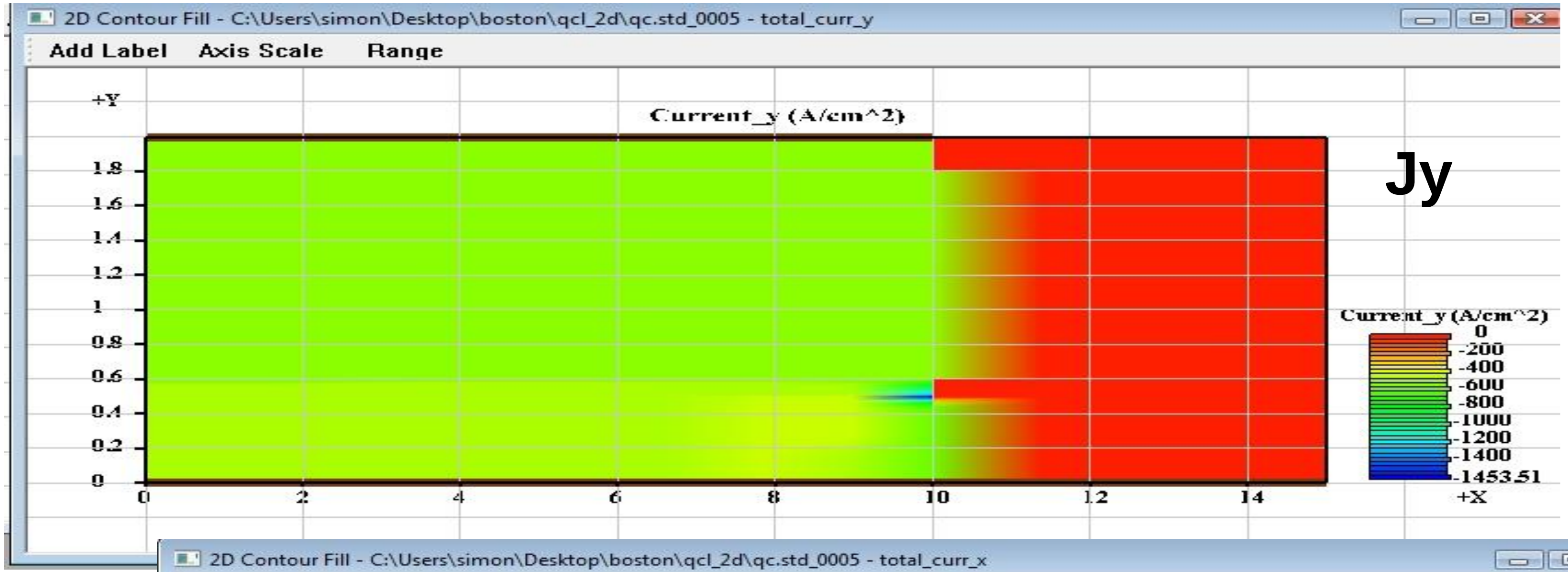
Optical mode



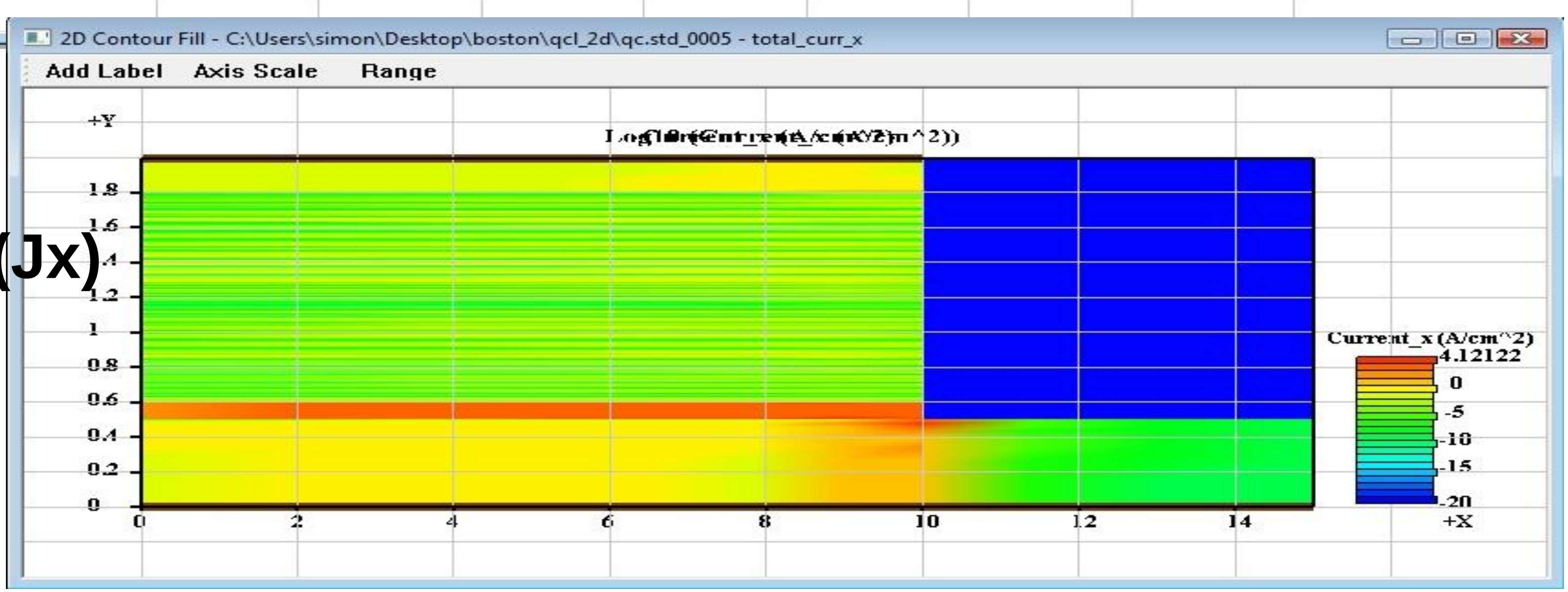
Applied potential



Current distribution

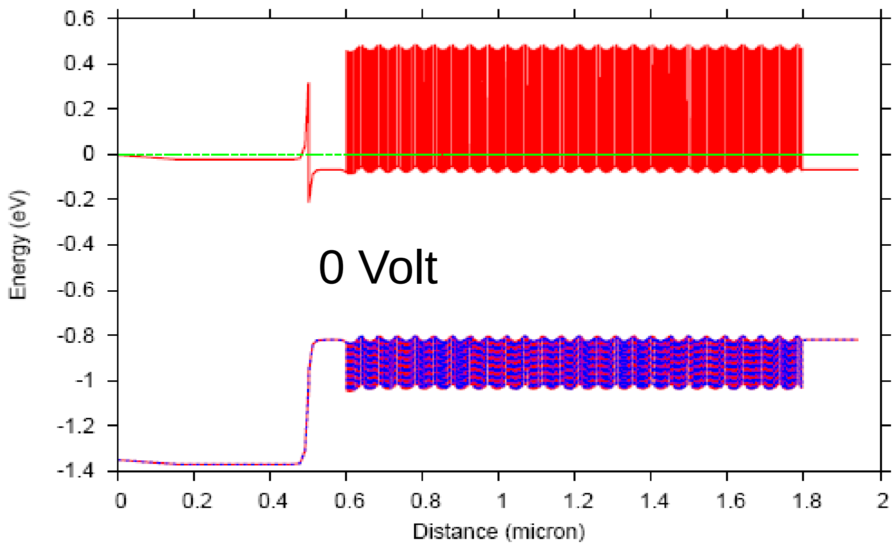


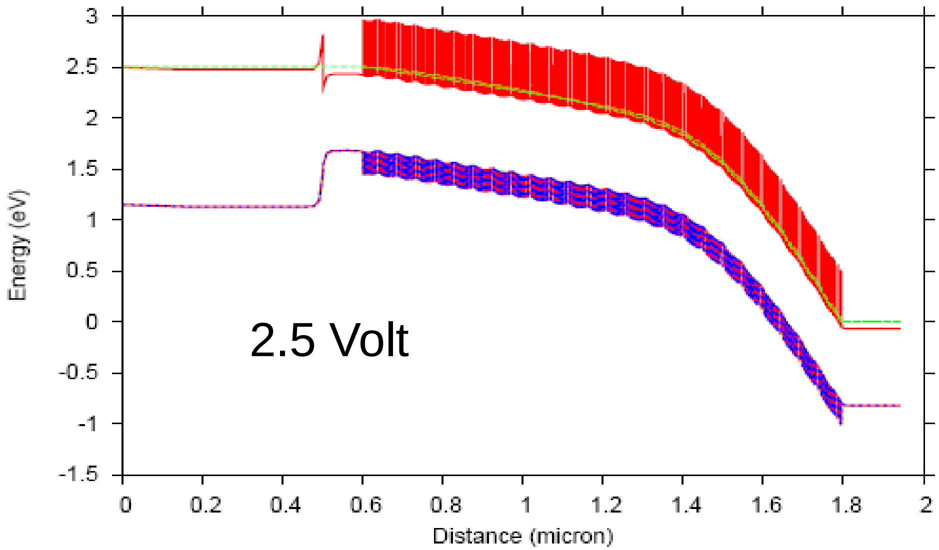
Jy

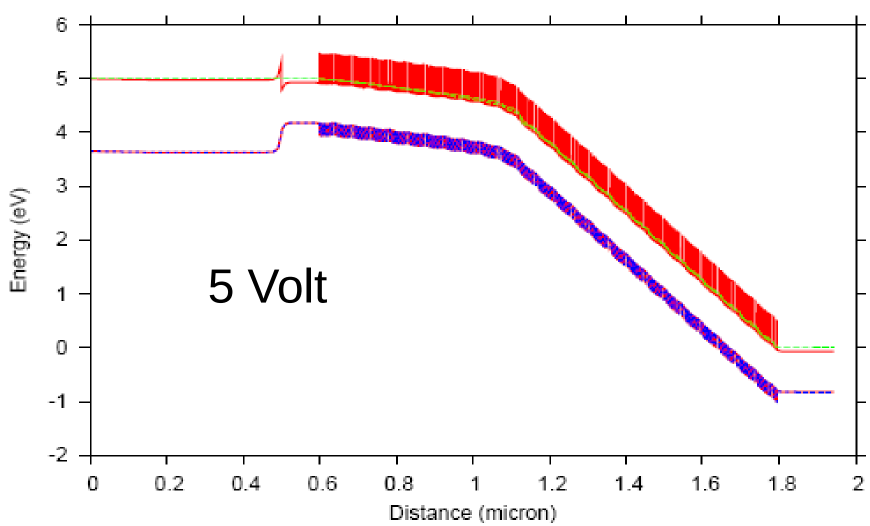


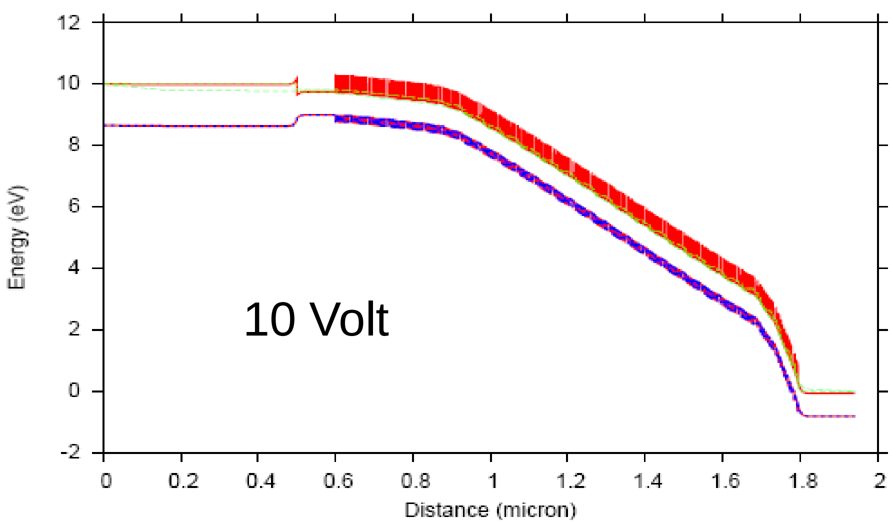
Log10(Jx)

Band diagrams (QCL 25 periods)

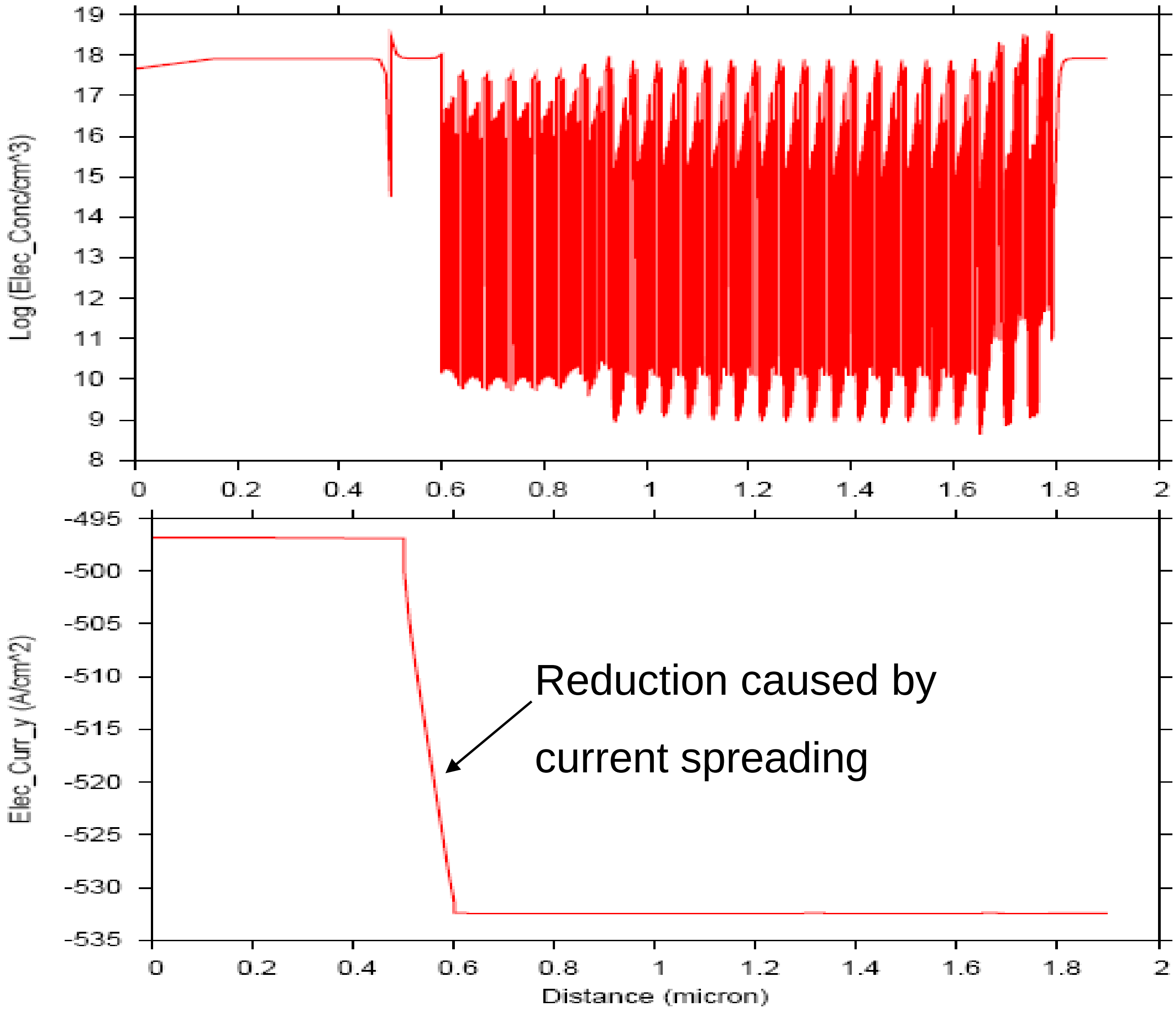




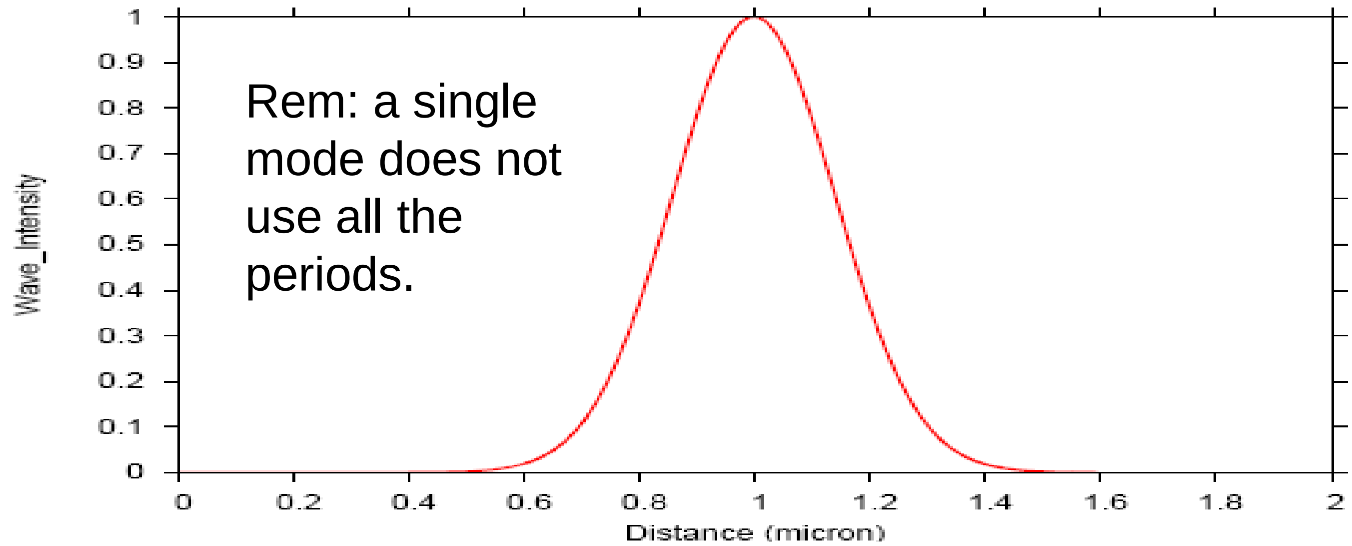


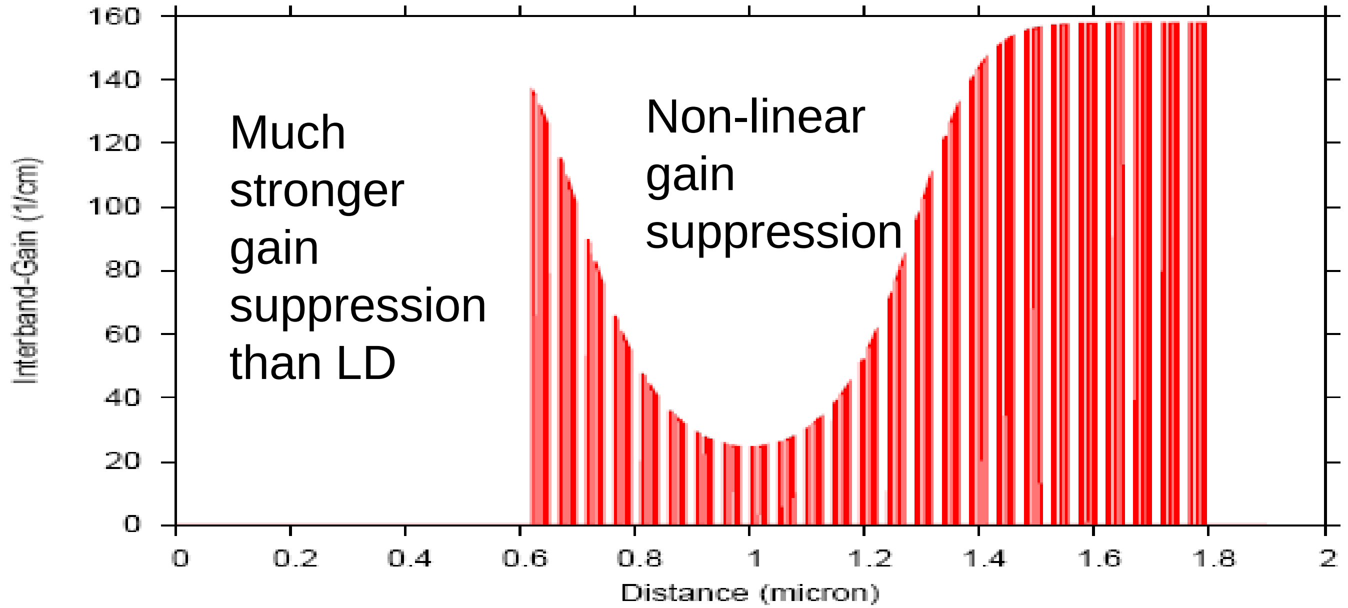


1D cuts of electron concentration and Jy (@10 V)

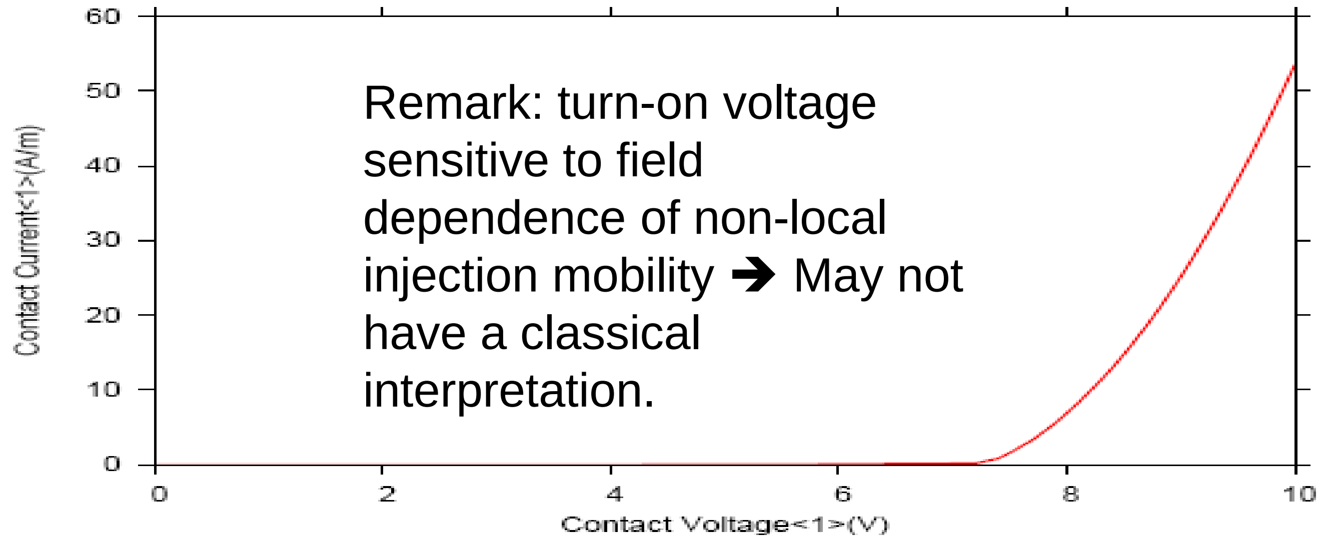


1D cuts of optical intensity and optical gain (@10 V)

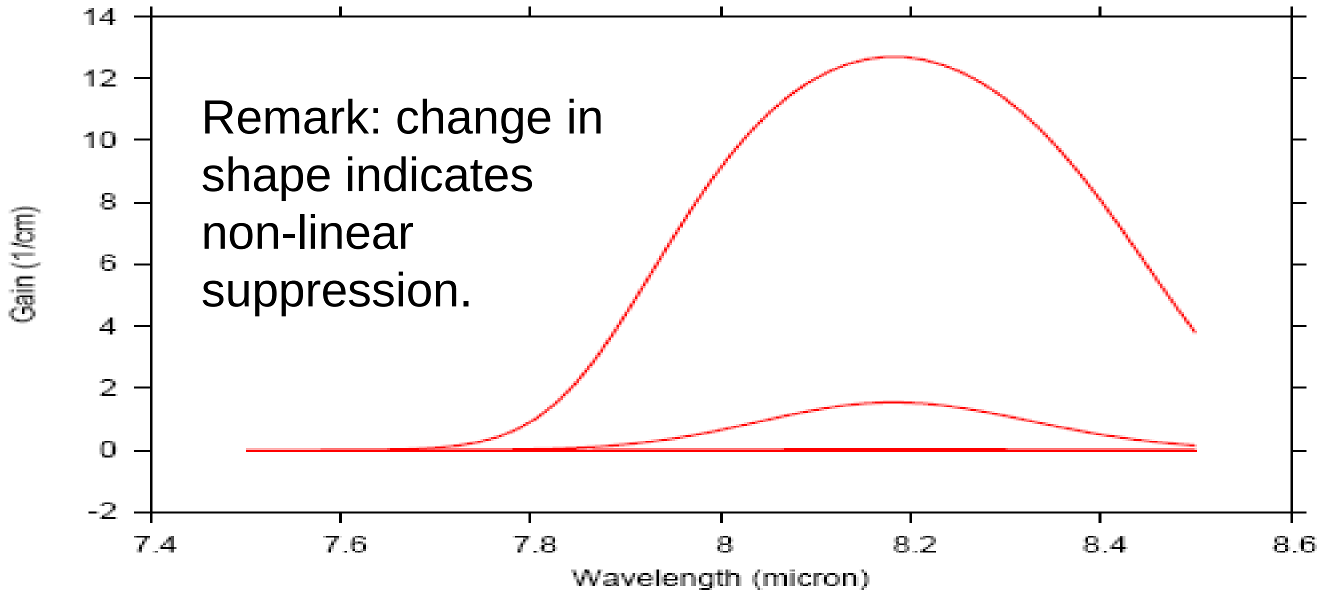




I-V and modal gain spectrum



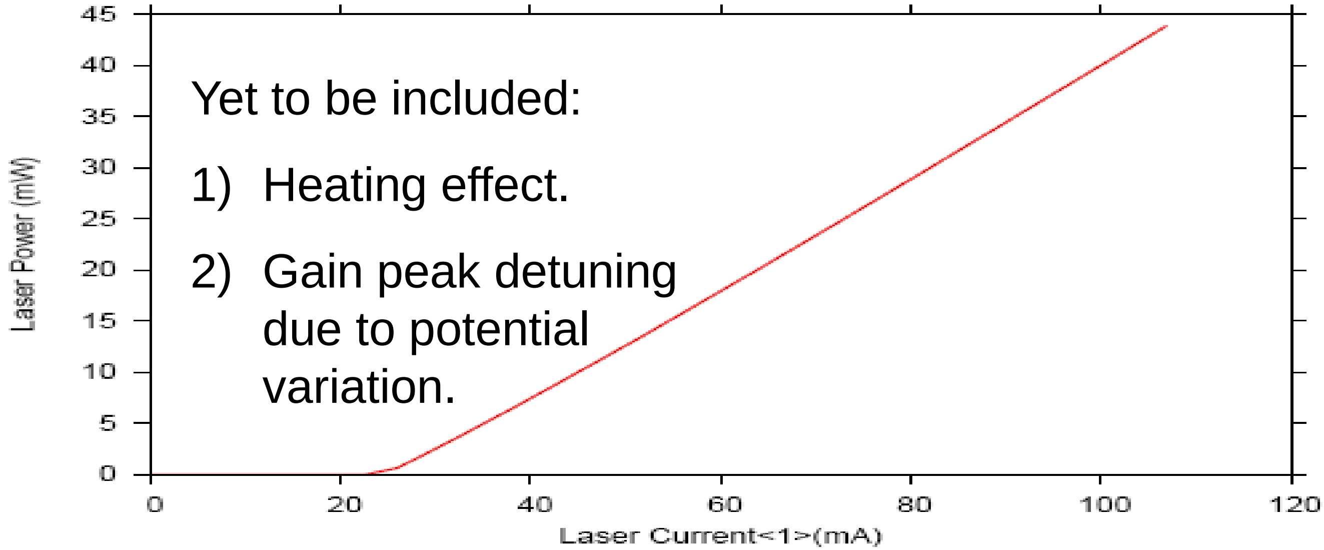
Remark: turn-on voltage sensitive to field dependence of non-local injection mobility → May not have a classical interpretation.

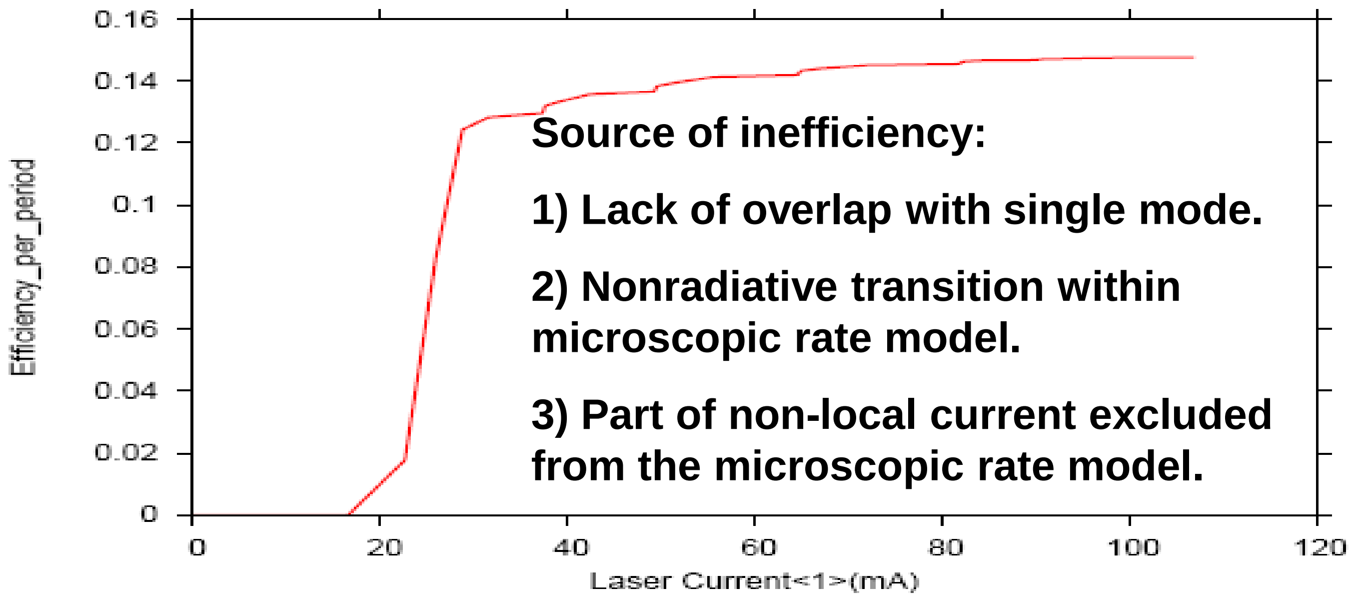


Remark: change in shape indicates non-linear suppression.

Modal gain at 0, 2.5, 5, 7.5 and 10 volts.

Lasing characteristics and efficiency per period





Summary

- Subband structure calculation enables the basic design of QCL such as emission wavelength and miniband alignments.

- Microscopic rate equation model generates a convenient optical gain as a function of local current and photon densities g(J,S).

- Main challenge in macroscopic QCL simulation is to inject electrons from contact to MQW and to collect them from MQW to contact.

- We propose a non-local current injection model with a mean-free-path of 100 -1000 A.

- Field dependent mobility of non-local injection needed to obtain reasonable results.

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