The Impact of Nonequilibrium Gain in a Spectral Laser Diode Model

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Presentation outline

- Introduction
- 2.5D spectral laser model
- Dynamic gain model
- Simulation Results
- Experimental Results
- Conclusion

Introduction

- Spectral performance of high power laser diodes just as important as power and beam quality

- Growing interest in exploiting or suppressing optical nonlinearities, which appear at high optical power densities and operating frequencies

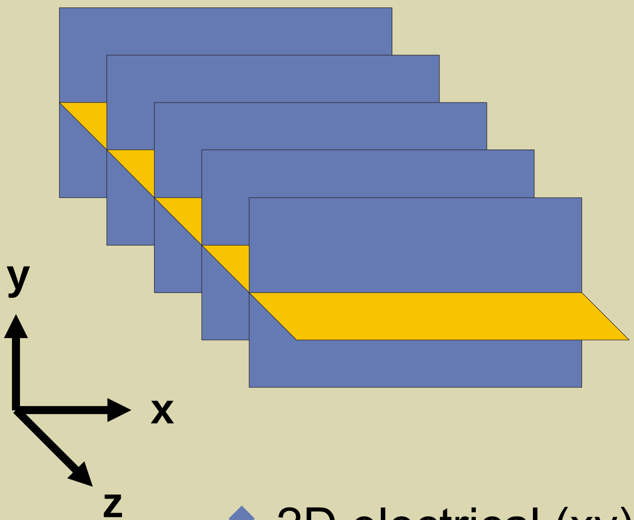
- Design of devices with superior spectral or nonlinear performance requires clear understanding of optical nonlinearities

➔ Laser diode models should include optical, electrical and thermal processes

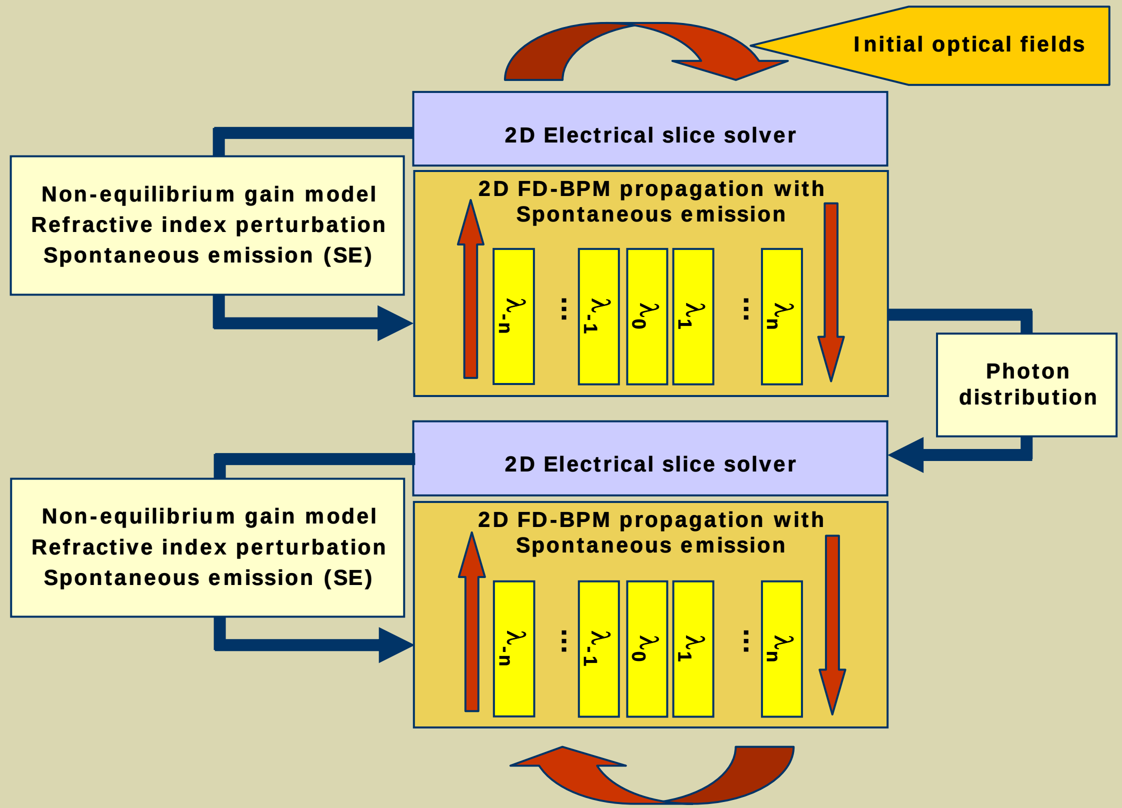
➔ Spontaneous emission coupling into modes should also be considered

2.5D spectral laser model

Spectral Laser Model: Flow Diagram and Key Features



- 2D electrical (xy)
- 2D optical (xz)

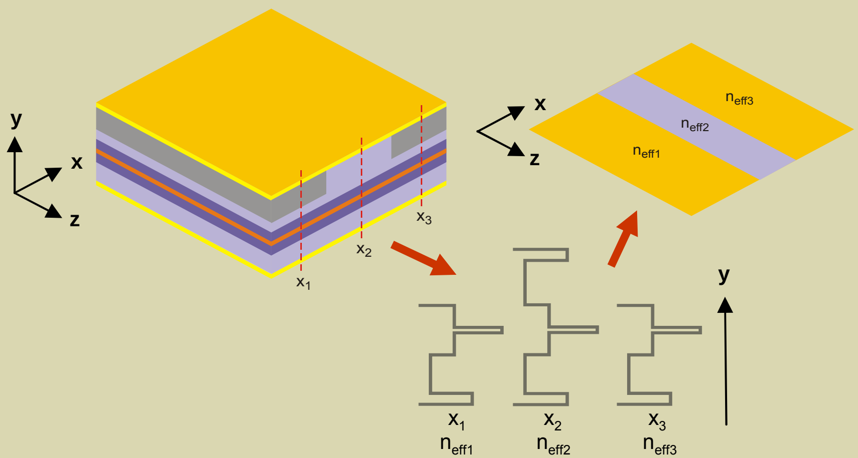


2.5D spectral laser model

Spectral Laser Model: Optical and Electrical Solvers

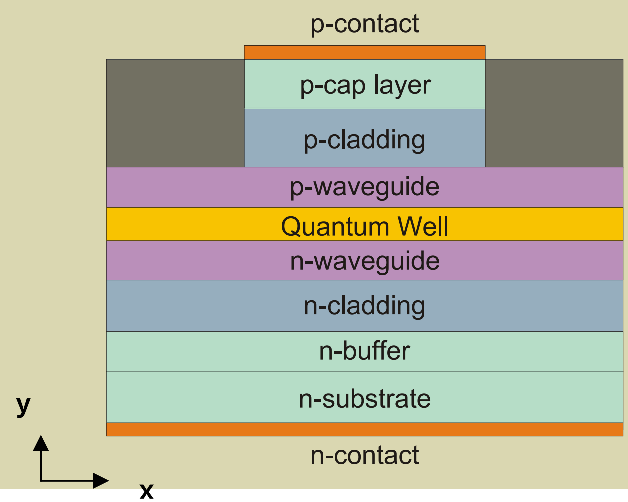
Optical Solver

- Wide-angle, finite-difference beam propagation method (WA-FD-BPM)
- 3D simulation reduced to 2D (x,z) using the effective index method
- Extended to multiple wavelengths
- Spontaneous emission (SE) coupled to each wavelength



Electrical Solver

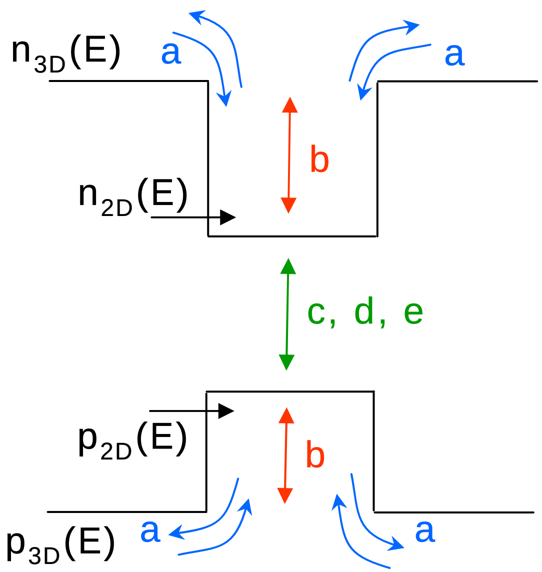
- 2D (x,y) bipolar model using Newton's method to simultaneously solve:
  - Poisson's equation
  - Current continuity equations
  - QW capture / escape equations
- Non-equilibrium gain model



Dynamic gain model

Non-Equilibrium Gain Model: Overview and Key Features

- Calculates dynamic changes to the carrier energy distributions in the QW subbands under electrical and/or optical excitation conditions



a – Carrier capture / escape
(carrier-carrier scattering)

b – Intrasubband & intersubband energy relaxation
(carrier-carrier, carrier-phonon scattering)

c – Interband energy relaxation
(electron-hole scattering)

d – Interband nonradiative generation / recombination
(SRH, Auger, etc.)

e – Interband radiative generation / recombination
(spontaneous & stimulated emission/absorption)

Model too numerically intensive to include directly in the spectral model

$\Rightarrow$ **Steady-state non-equilibrium gain and spontaneous emission spectra are parameterised (n_{2D},p_{2D},λ,S) and stored in a software database**

Dynamic gain model

- Carrier distributions calculated for the range of CW electrical and optical excitation conditions required by spectral laser model

- Fermi-Dirac distributions fit to carrier distribution in each subband
  - Subband carrier density and total subband energy conserved
  - Gain and spontaneous emission spectra include only carrier heating (CH)

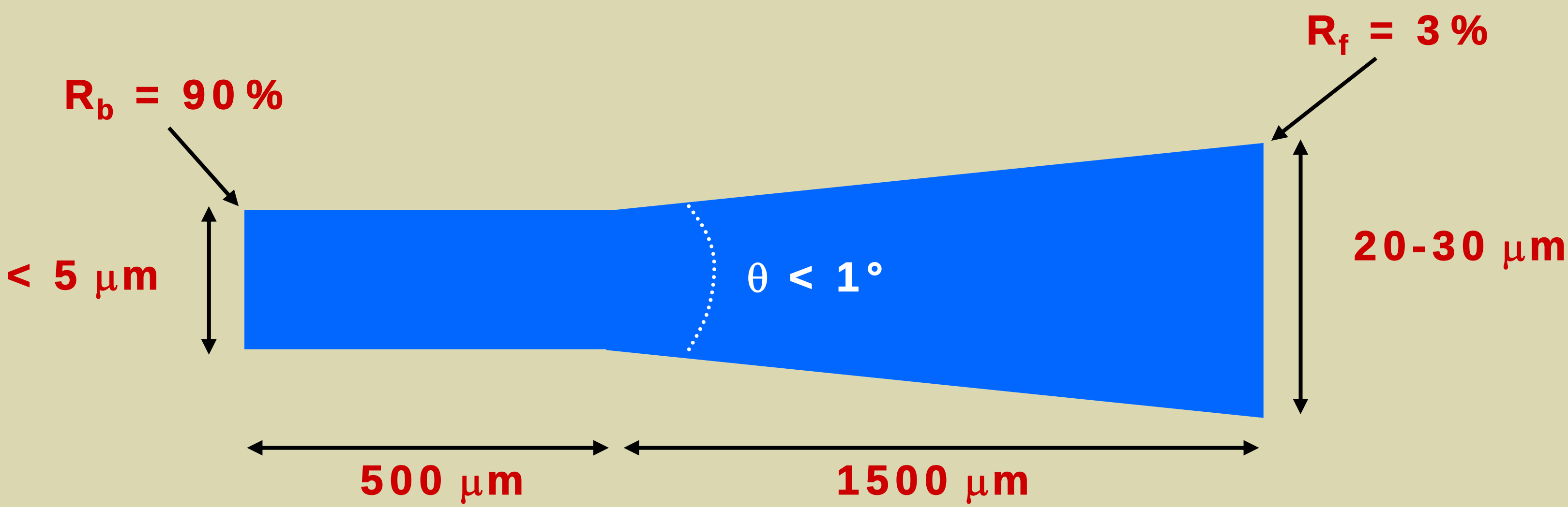
- Spectral hole burning (SHB) introduced phenomenologically as function of total photon density, S_{tot}

$$g_{SHB}(\lambda) = \frac{g(\lambda)}{1+\varepsilon S_{tot}}$$

where ε is the gain compression coefficient ($\varepsilon = 7x10^{-23} m^3$)

Simulations were performed for a 975nm tapered laser diode

- ~9nm InGaAs/InGaAsP SQW
- Ridge waveguide length 0.5mm
- Tapered section length 1.5mm
- 3 bias voltages considered: 1.41V, 1.47V and 1.53V

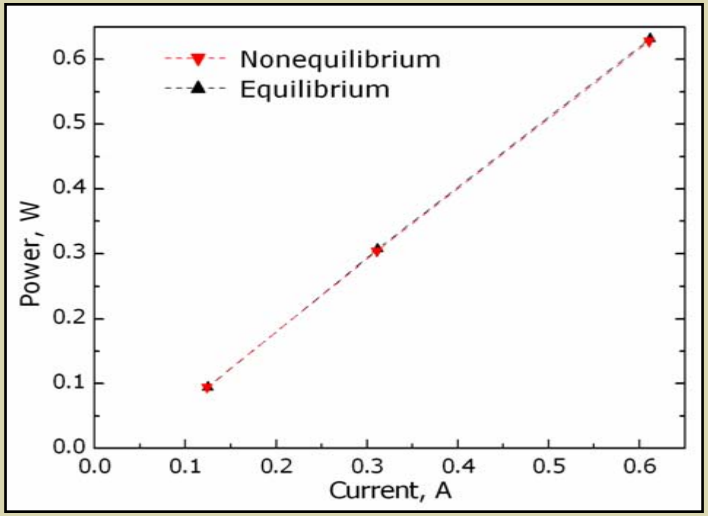


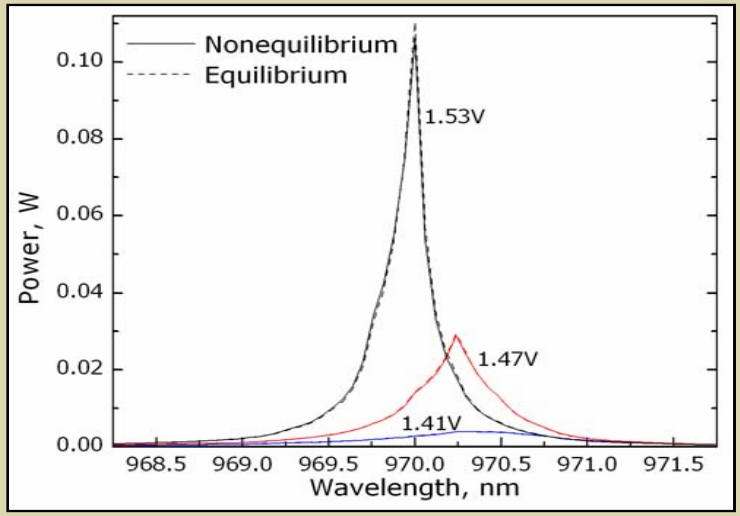
Simulation results

L-I characteristics and emission spectra

Equilibrium and nonequilibrium L-I curves (left) very similar

- η_{ext} decreases slightly with bias for nonequilibrium case





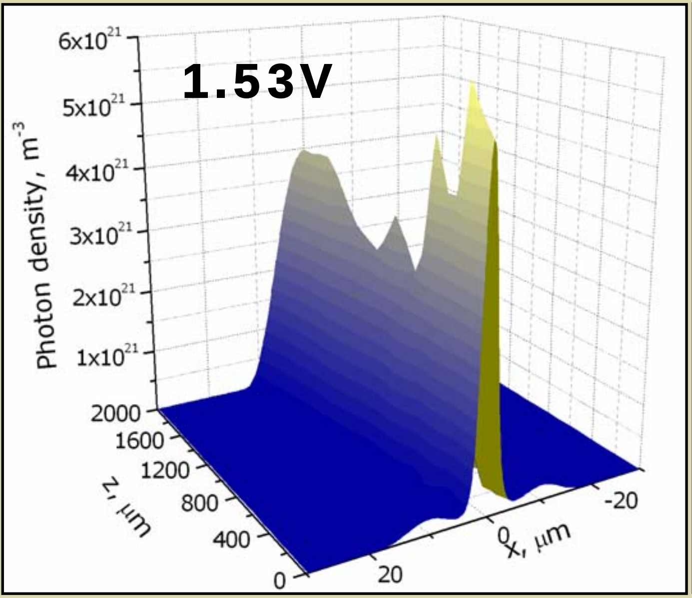
Equilibrium and nonequilibrium beam spectra (right) also very similar

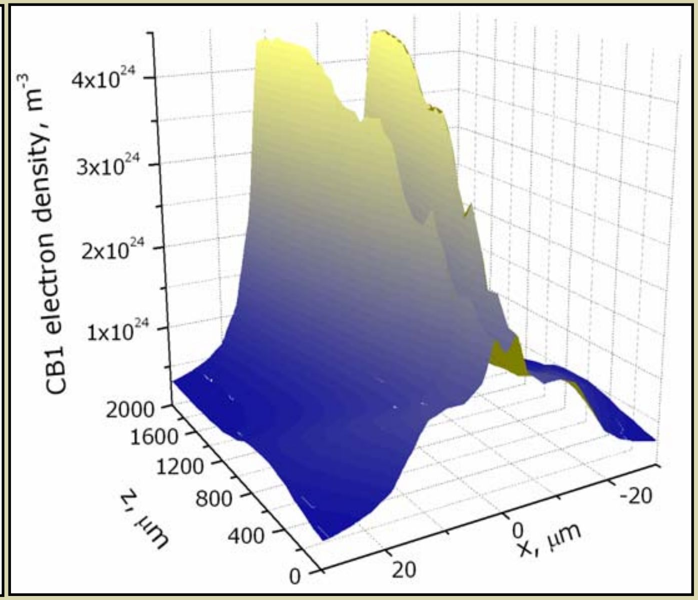
- The intensities are similar (optical gain/losses are the same)
- Increasing carrier density (spectral hole burning) causes blue shift

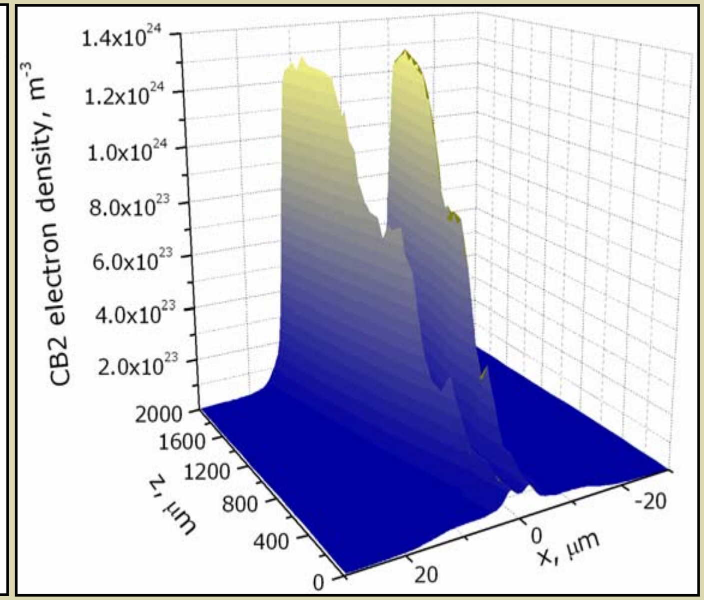
⇒ **This blue shift may have implications for measuring the active region temperature!**

Simulation results

Photon density and subband carrier distributions





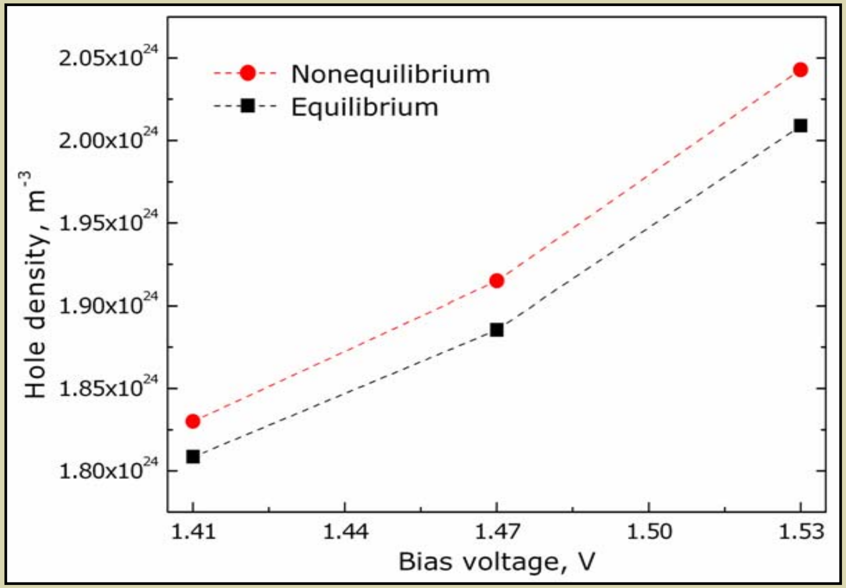


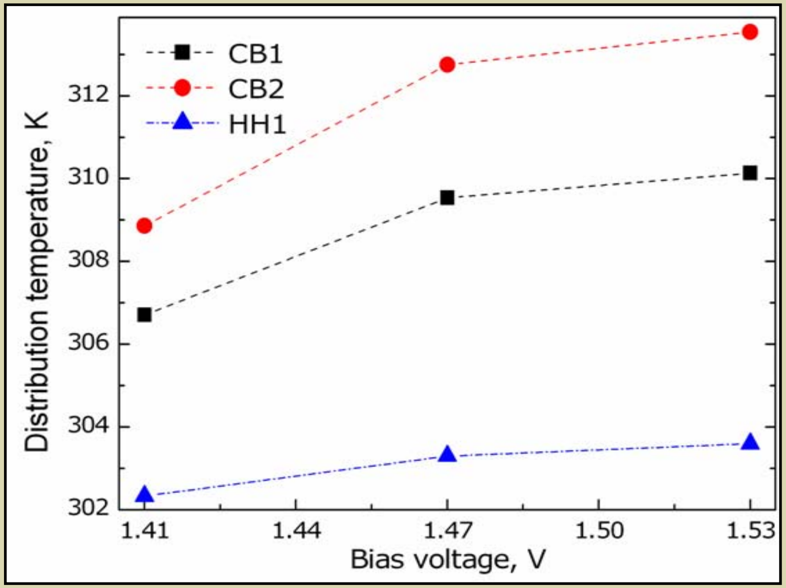
- Higher photon density leads to spatial hole burning
- Details of subband distributions extracted from dynamic gain model results

Simulation results

Simulated carrier distribution at centre of front facet (x=0, z=2mm)

- Total hole density (left) increases with bias because of SHB
- Nonequilibrium hole density larger due to CH
- All subband distribution temperatures (right) increase with bias (CH)
- All valence subband temperatures very close to HH1 temperature





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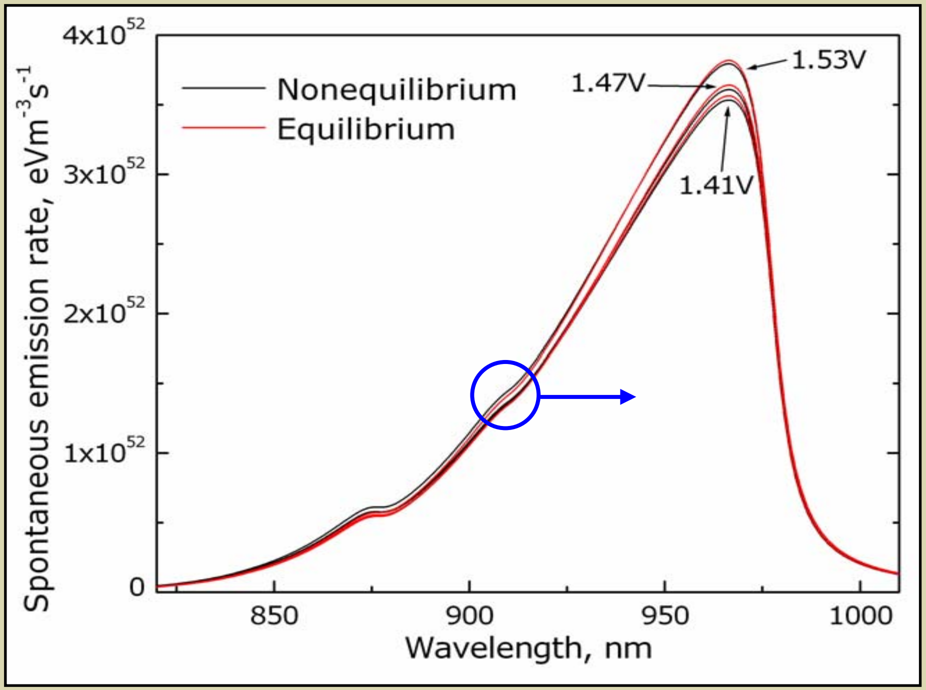
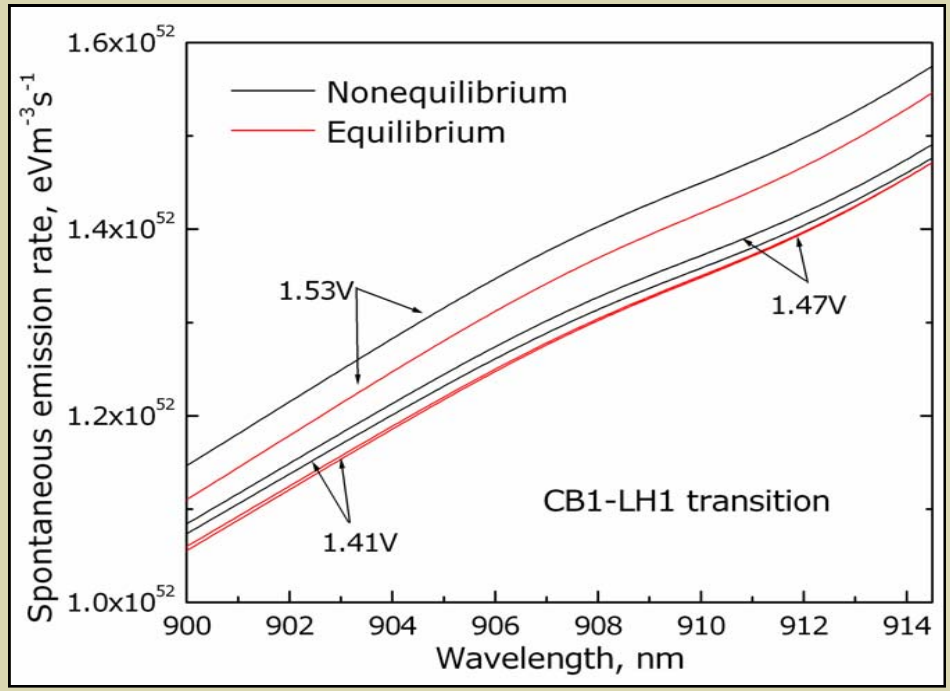
Simulated spontaneous emission spectra at centre of front facet

- Spontaneous emission at ~970 nm increases with bias due to SHB
- Increasing carrier density with bias leads to stronger CB1-LH1 transition
- The CB1-LH1 transition increases faster with the nonequilibrium gain model
- Carrier heating increases the hole density in LH1





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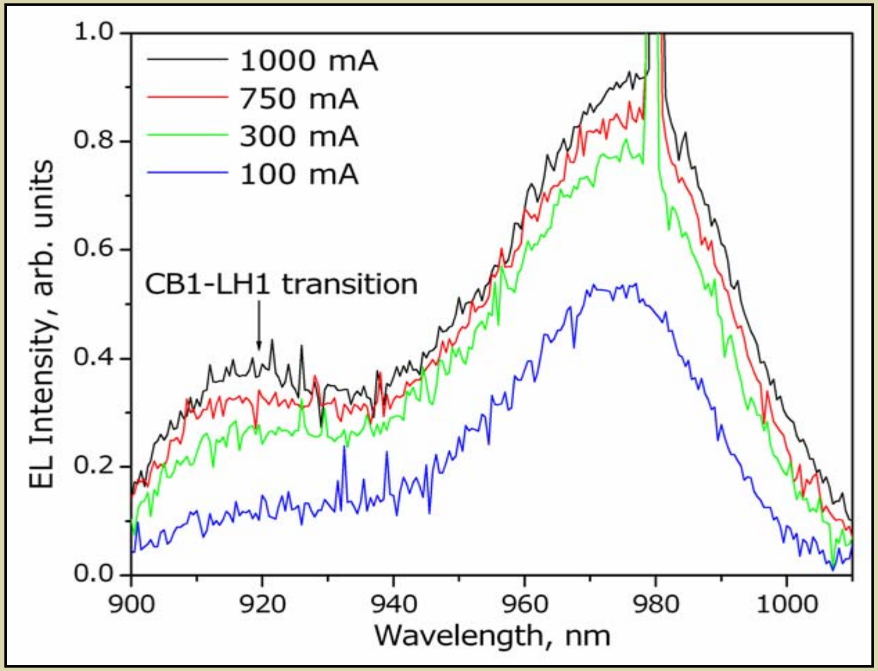
Experimental results

Intracavity μ-EL spectroscopy measurements

- Made through windowed backside contacts
- Same epitaxy as simulated device, but 4° tapered laser
- Uncalibrated spectra corrected for spectral response of Ge detector



Key Observations

- Emission spikes above threshold ***attributed to stimulated emission***
- Carrier density increase with bias ***attributed to spectral hole burning***
- Increasing CB1-LH1 transition strength ***attributed primarily to carrier heating***

$\Rightarrow$ ***Good qualitative agreement with simulation results***

Conclusions

- Carrier heating alone does not significantly affect the lasing spectrum, but increases the spontaneous emission from excited state transitions
- Spectral hole burning leads to increasing carrier density with bias ***- even though gain of lasing modes is pinned!***
- The increasing carrier density (due to SHB) causes a blue shift in the emission ***and may affect active region temperature measurements***
- Experimentally measured intracavity spontaneous emission spectra are in good qualitative agreement with the simulated results
- Intracavity EL spectroscopy is useful for validating dynamic gain calculations