



The Impact of Nonequilibrium Gain in a Spectral Laser Diode Model

P.J. Bream¹, J.J. Lim¹, S. Bull¹, A.V. Andrianov², S. Sujecki¹ and E.C. Larkins¹

¹ *School of Electrical and Electronic Engineering
The University of Nottingham; Nottingham NG7 2RD; U.K.*

² *A.F. Ioffe Physical Technical Institute of the Russian Academy of Science,
26 Politechnicheskay, St. Petersburg, 194021 Russia*

Email: Eric.Larkins@nottingham.ac.uk

The Impact of Nonequilibrium Gain in a Spectral Laser Diode Model



The University of
Nottingham

The authors gratefully acknowledge the EC-IST projects **WWW.BRIGHT.EU** (IST-511722) and **FAST ACCESS** (IST-004772).



P. J. Bream gratefully acknowledges the support of the **Engineering and Physical Sciences Research Council**, U.K.

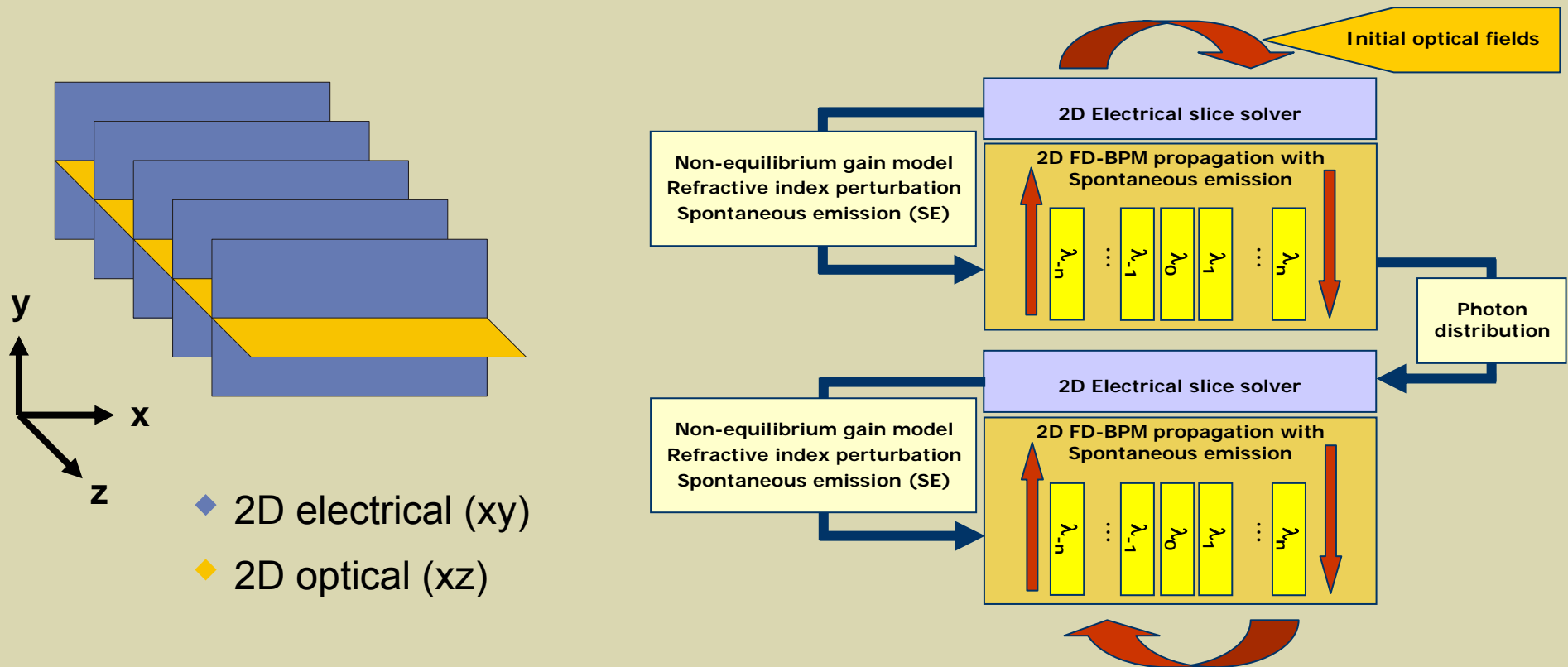


- **Introduction**
- **2.5D spectral laser model**
- **Dynamic gain model**
- **Simulation Results**
- **Experimental Results**
- **Conclusion**



- 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

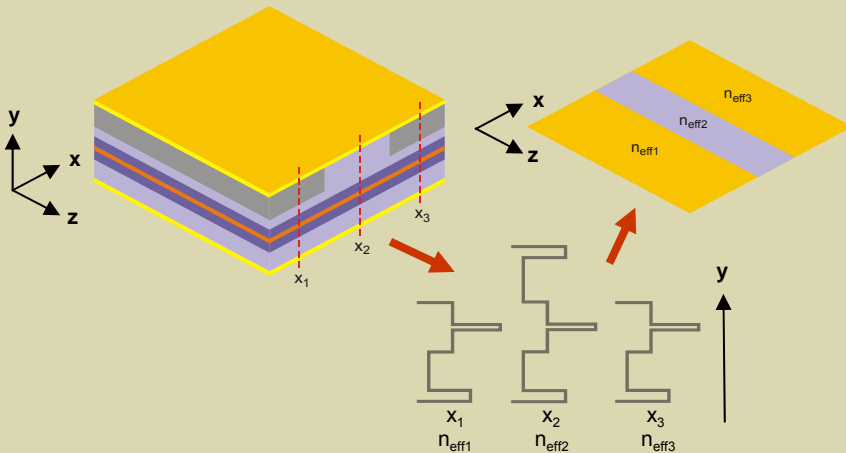
Spectral Laser Model: Flow Diagram and Key Features



Spectral Laser Model: Optical and Electrical Solvers

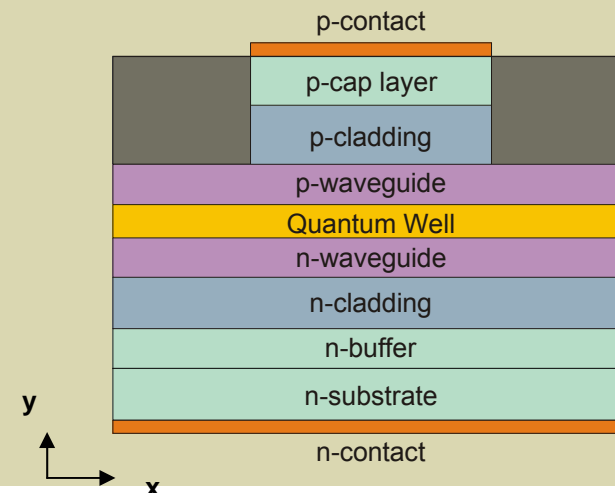
Optical Solver

- 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



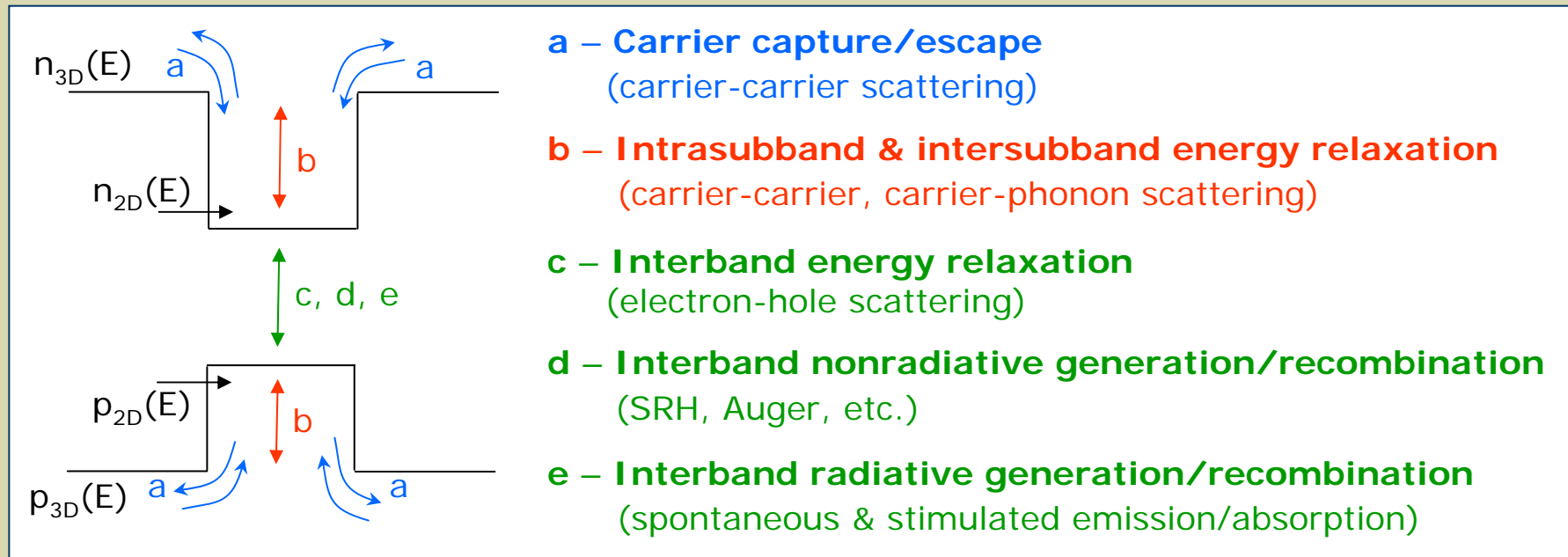
Electrical Solver

- 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



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



Model too numerically intensive to include directly in the spectral model

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



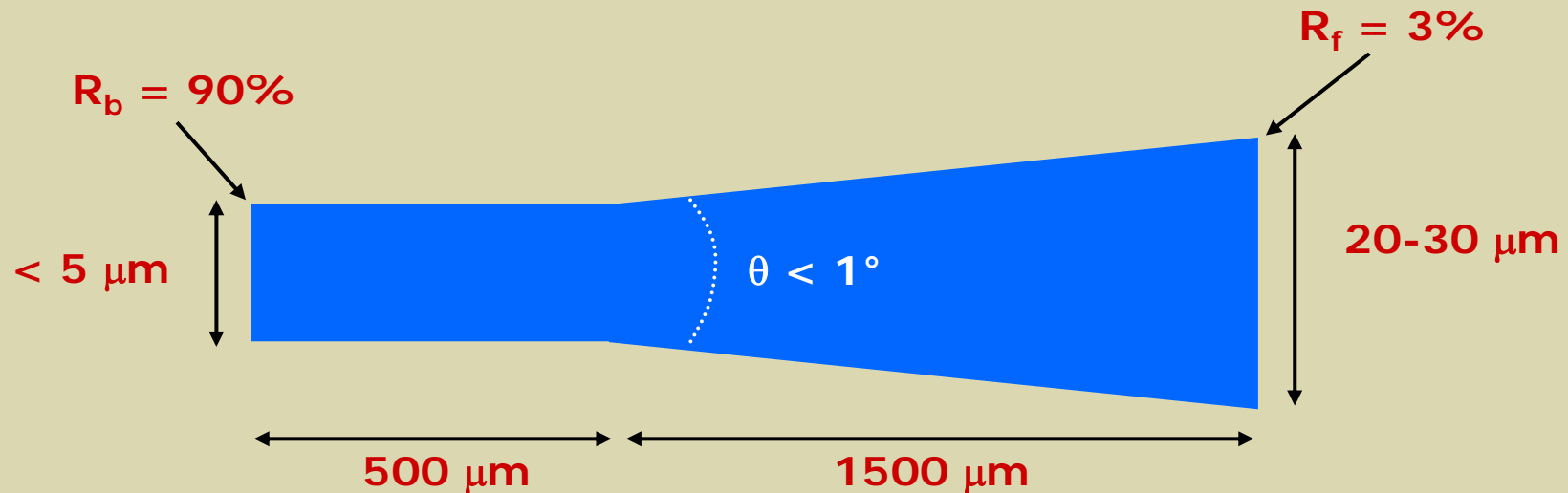
- Carrier distributions calculated for the range of CW electrical and optical excitation conditions required by spectral laser model
- Fermi-Dirac distributions fit to carrier distribution in each subband
 - Subband carrier density and total subband energy conserved
 - Gain and spontaneous emission spectra 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 ($\varepsilon = 7 \times 10^{-23} m^3$)

Simulations were performed for a 975nm tapered laser diode

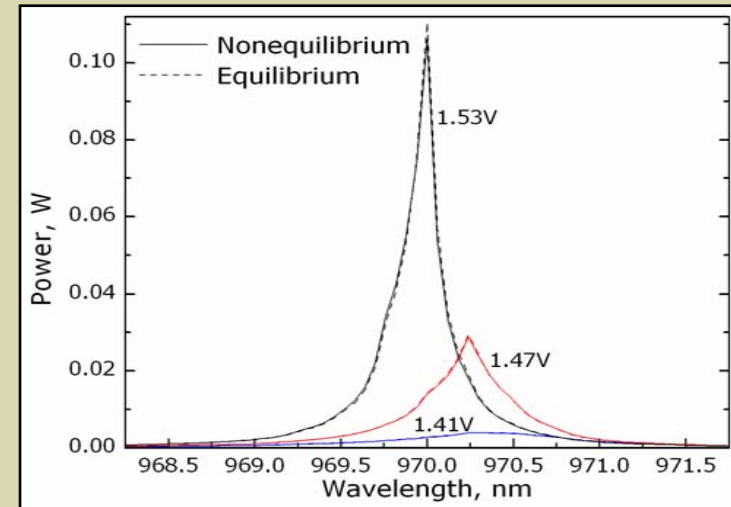
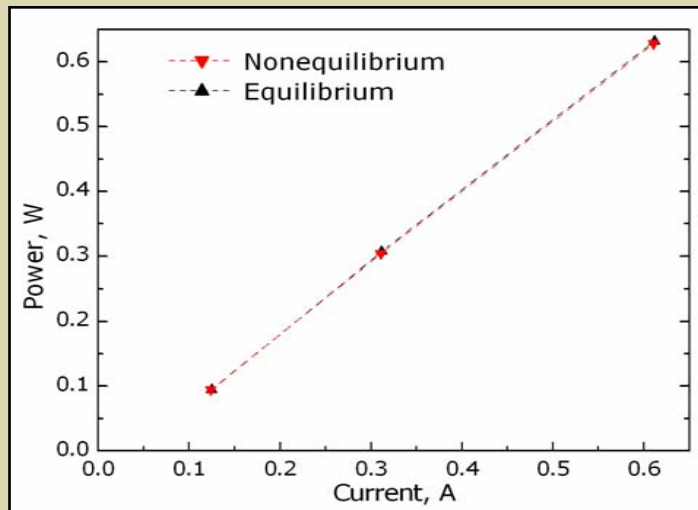
- ~9nm InGaAs/InGaAsP SQW
- Ridge waveguide length 0.5mm
- Tapered section length 1.5mm
- 3 bias voltages considered: 1.41V, 1.47V and 1.53V



L-I characteristics and emission spectra

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

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

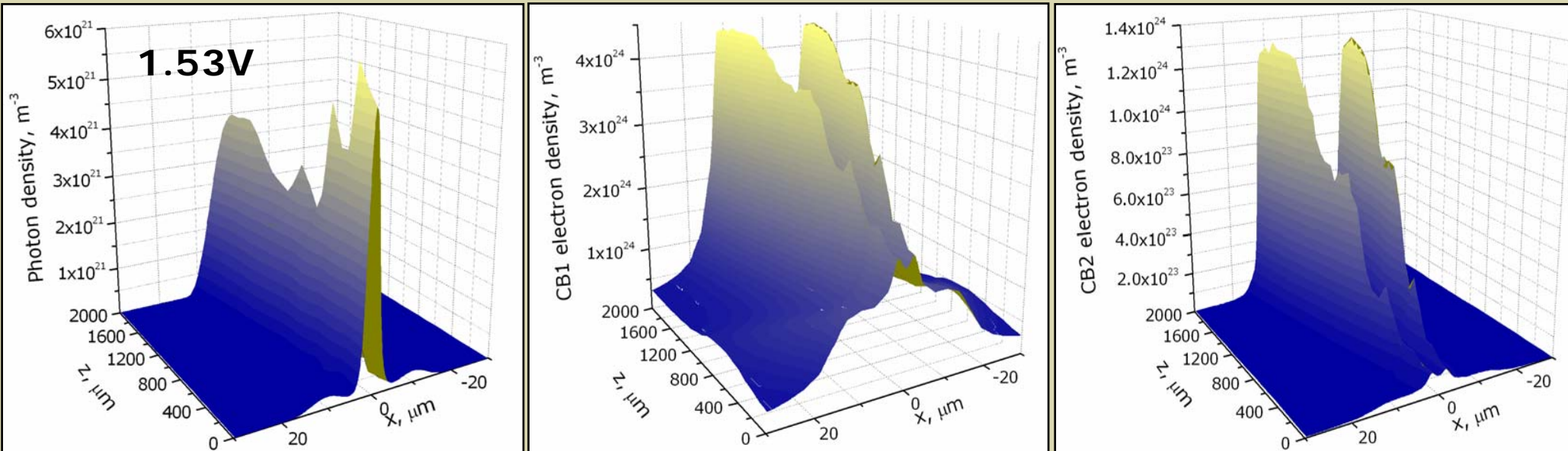


Equilibrium and nonequilibrium beam spectra (right) also very similar

- 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!**

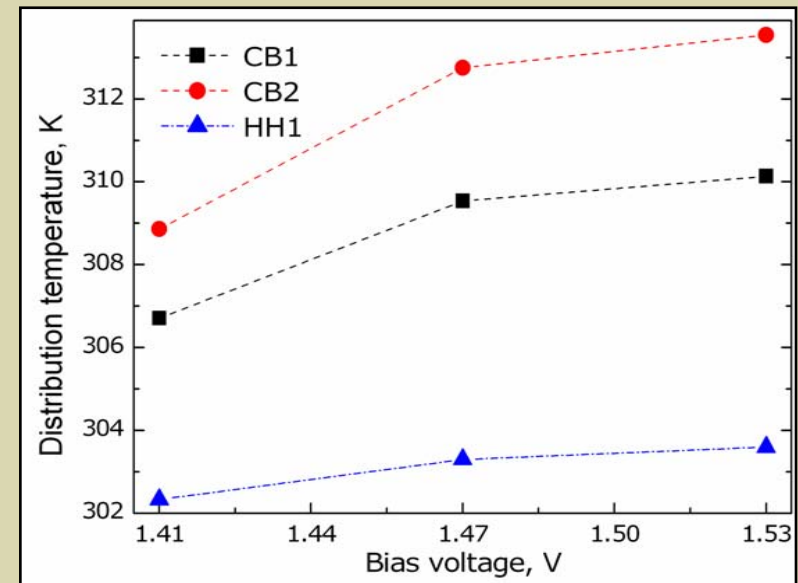
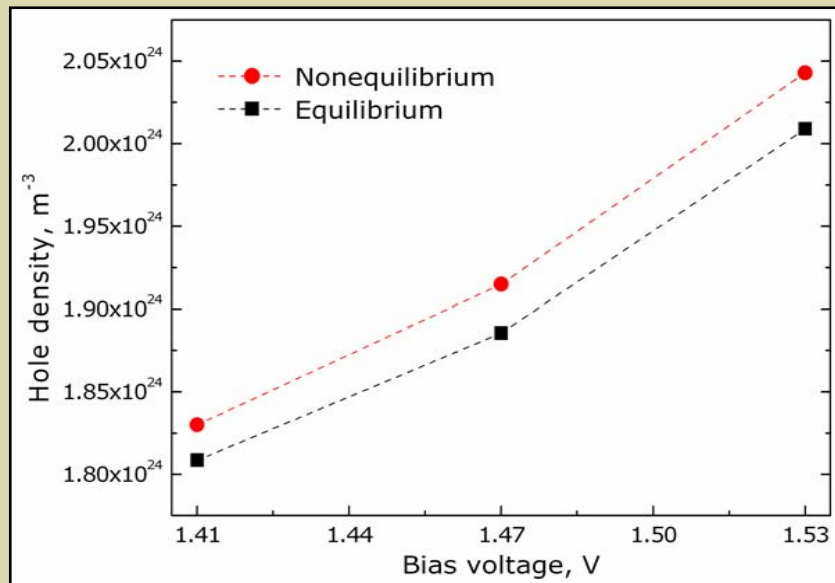
Photon density and subband carrier distributions



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

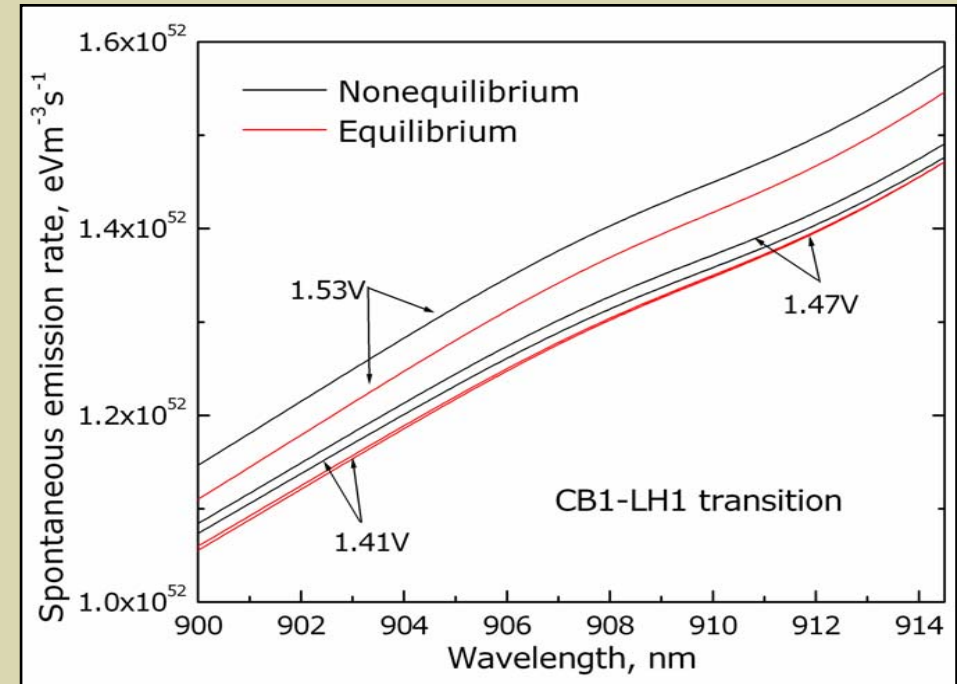
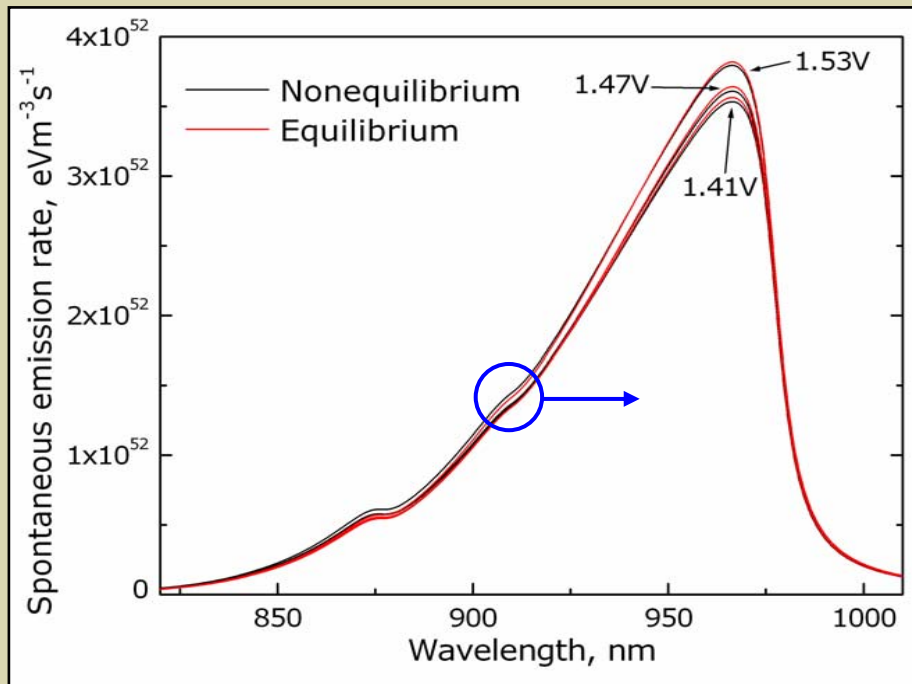
Simulated carrier distribution at centre of front facet ($x=0$, $z=2\text{mm}$)

- 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



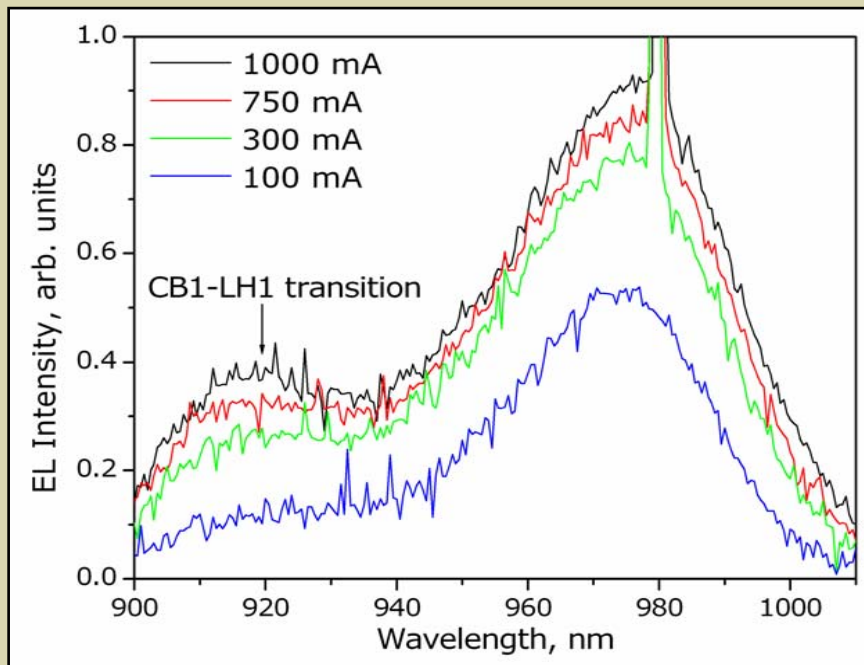
Simulated spontaneous emission spectra at centre of front facet

- 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



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***

⇒ ***Good qualitative agreement with simulation results***

- 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