Super-Luminescent LEDs — Modeling of Emission Spectra and LI-Characteristics

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EXALOS The bright light source company SYNOPSYS KTI CTI

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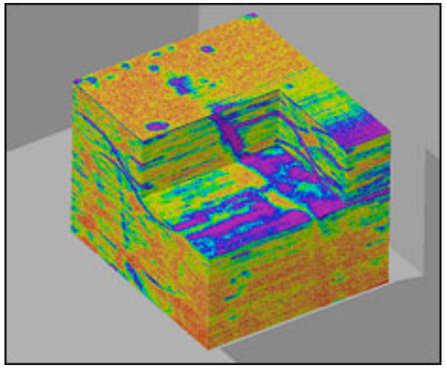
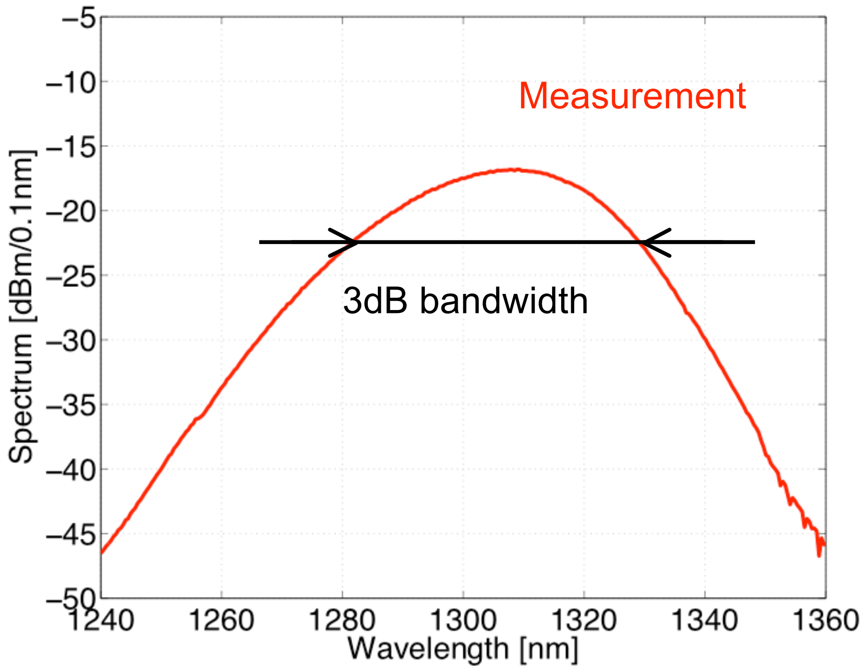
SLEDs as Attractive Light Sources

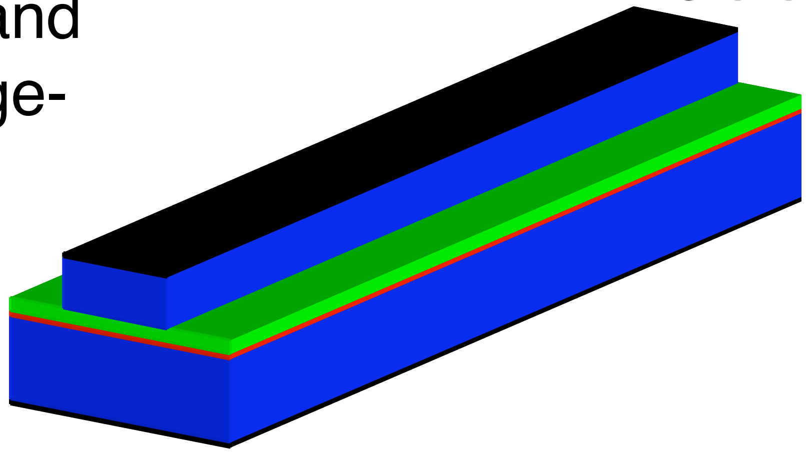
- Optical sensing: optical coherence tomography (biomed, material sciences,...)
- Navigation: fiber-optic gyroscopes
- Fiber-optic sensors (temperature, pressure, strain,...)



Application of TCAD for SLED Design

- Main design goals:
  - High output power
  - Broad 3dB bandwidth
  - Short coherence length.
- How can simulations help to design SLEDs with optimized performance?
- Comparison of simulated and measured data for two edge-emitting SLEDs.





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Simulated Geometry

&

Fundamental Equations

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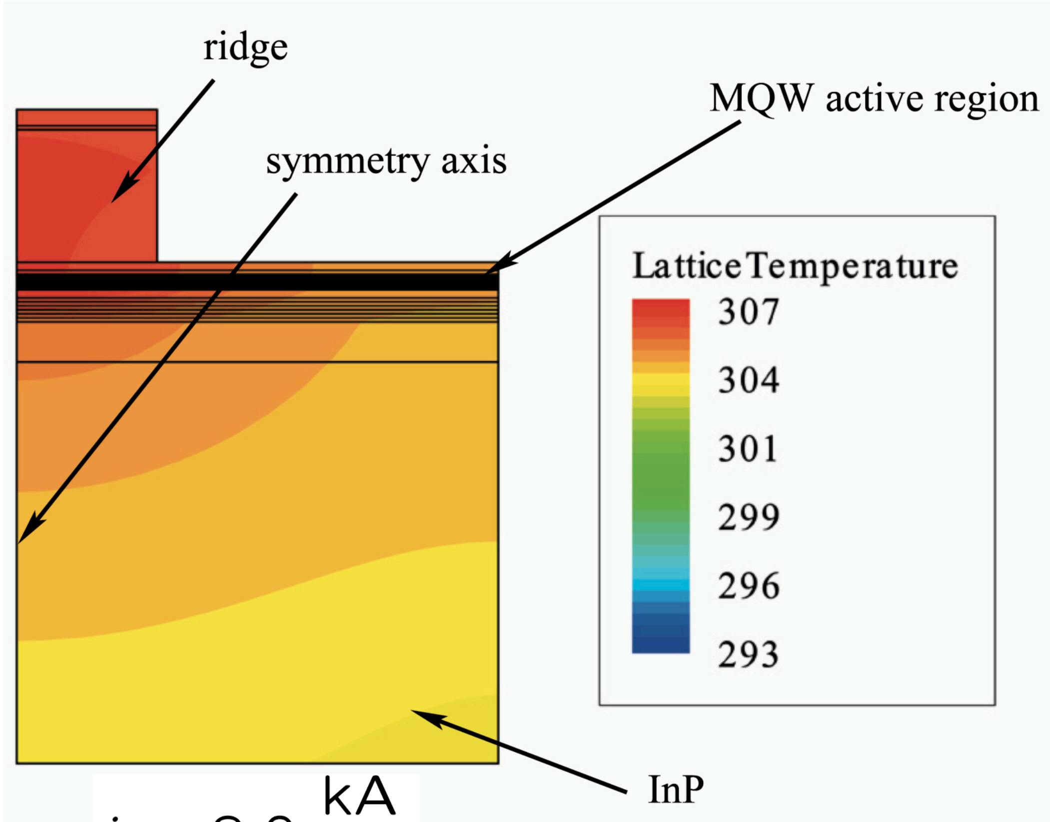
Benchmark: Edge-Emitting SLED

- Benchmark devices:
  two SLEDs, cavity length 500µm and 950µm.
- Electro-Opto-Thermal simulation
- Simulated geometry: 2D (transverse cut)

2D simulation model



$$j = 8.0 \frac{\mathrm{kA}}{\mathrm{cm}^2}$$

Simulation Model — Electro-Thermal Problem

$$\mathbf{j}_n = -e(\mu_n n \nabla \Phi - D_n \nabla n + \mu_n n P_n \nabla T)$$
$$\mathbf{j}_p = -e(\mu_p p \nabla \Phi + D_p \nabla p + \mu_p p P_p \nabla T)$$

Drift-Diffusion-Model

$$\nabla \mathbf{j_p} = -q\left(\tilde{R} + R_{stim}^{ASE} + \frac{\partial p}{\partial t}\right)$$

$$\nabla \mathbf{j_n} = q\left(\tilde{R} + R_{stim}^{ASE} + \frac{\partial n}{\partial t}\right)$$

Continuity Equations

$$\nabla(\epsilon \nabla \Phi) = -q(p + n + N_D^+ + N_A^-)$$

Poisson Equation

$$c_{tot}\frac{\partial T}{\partial t} - \nabla(\kappa_{th} \nabla T) = H$$

Heat Equation

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3D Optical Problem

Langevin force equation (electric field)

$$\left(\nabla^2 + \frac{\omega^2}{c^2}\epsilon_\omega\right) E_\omega(x,y,z) = F_\omega(x,y,z)$$

Assumption: complete set of pairwise orthonormal transverse modes $\Psi_n(x,y)$

Decomposition of the electric field into modes

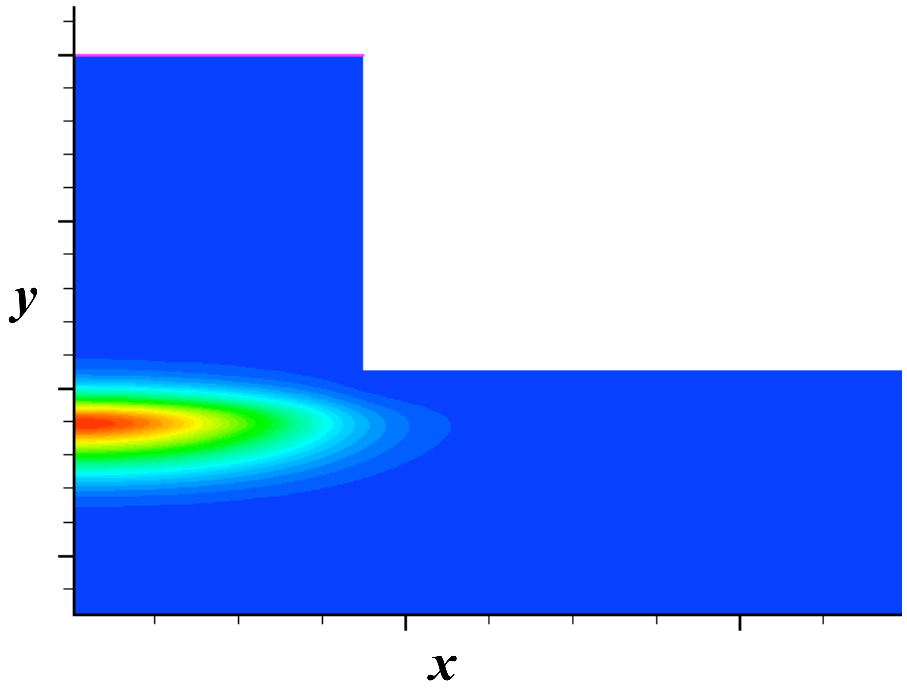
$$E_\omega(x,y,z) = \sum_n (\Psi_n(x,y)\ \psi_n(z,\omega))$$

2D - FEM

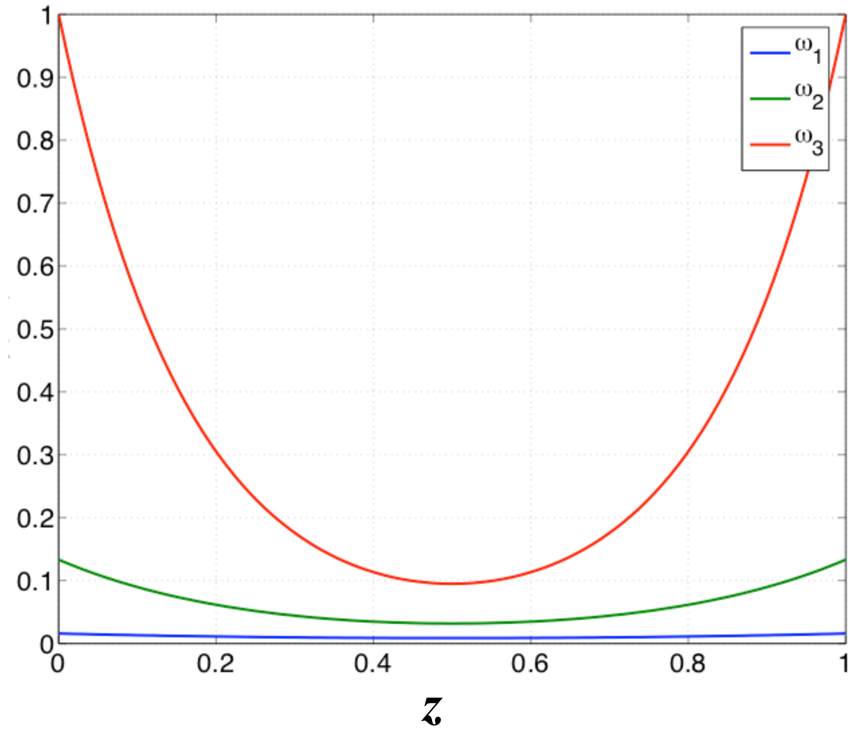
1D - Green's functions

Model Solution of 3D Optical Problem: 2D × 1D

Transverse mode profile



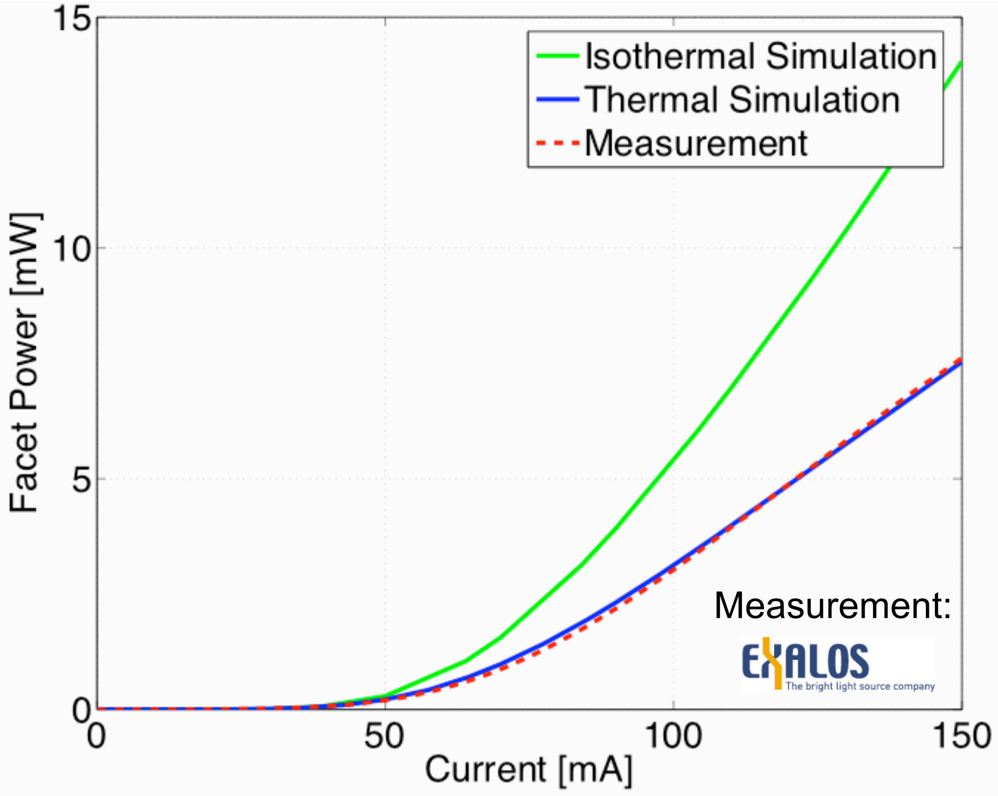
Longitudinal field distribution for various ω

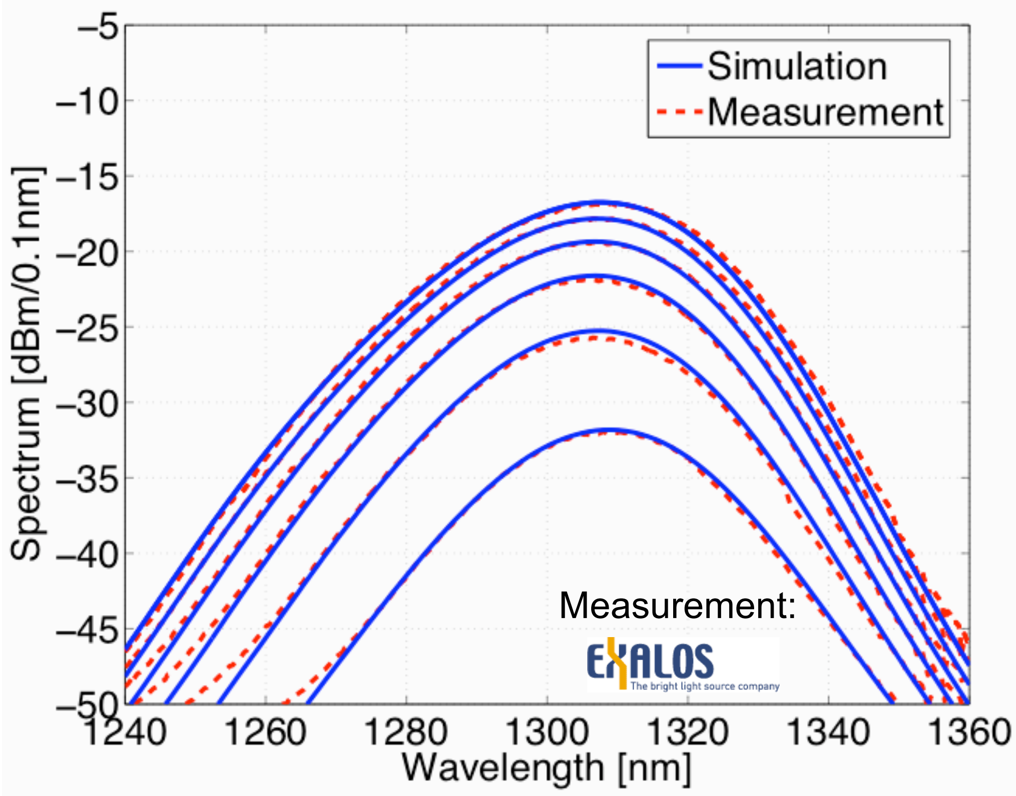


- Simulation in 2D
- Longitudinal problem solved analytically
- Gain & spontaneous emission constant in z-direction

Electro-Opto-Thermal Simulation Results

Simulation Results: 500μm Cavity



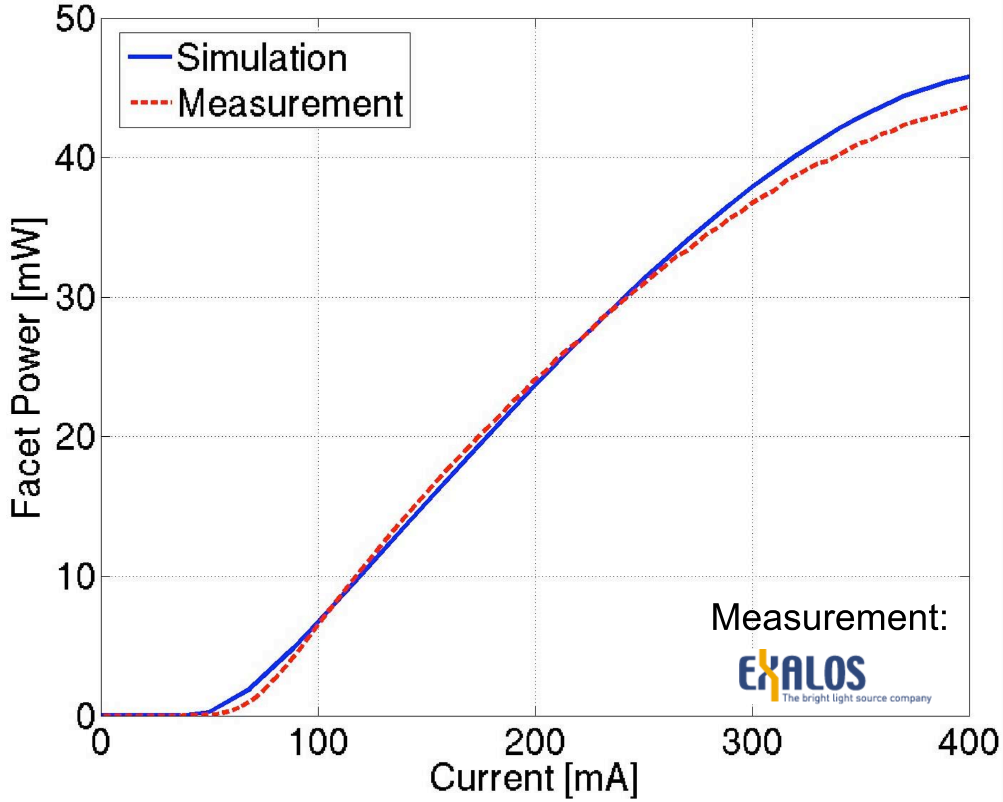


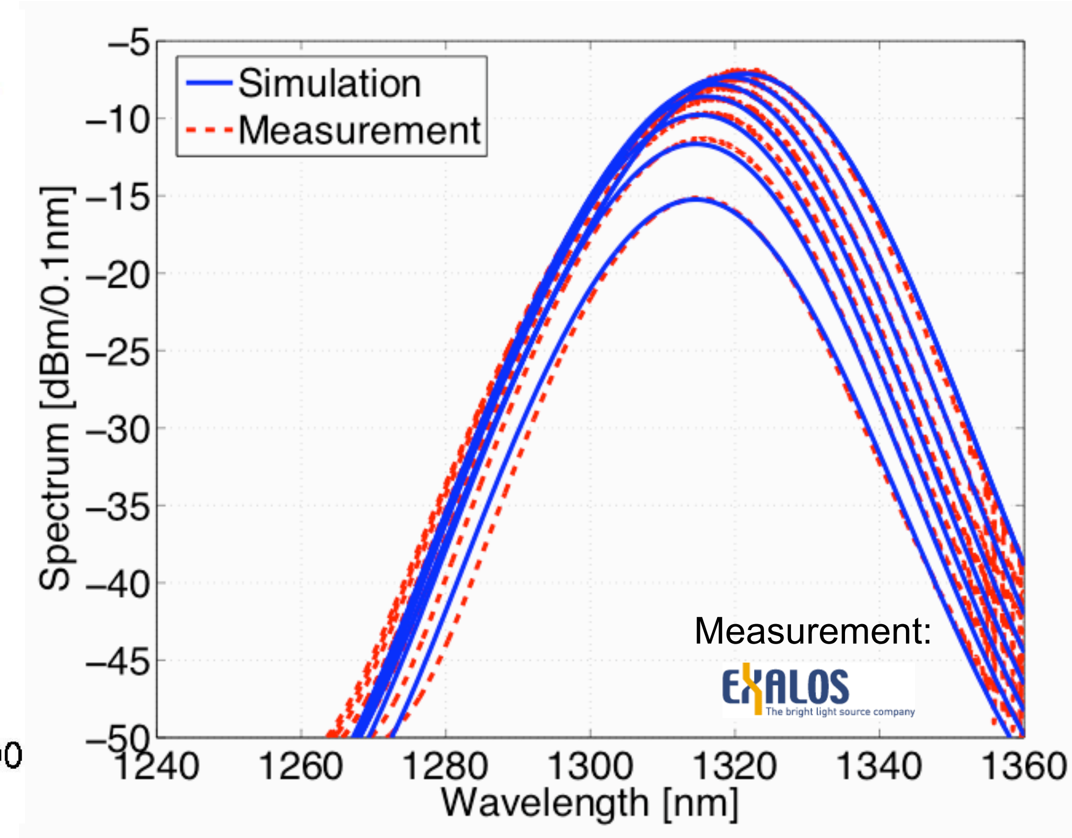
LI-curve: measurement and simulation.

$$P = \int_{\lambda} P_{ASE}(\lambda)\ d\lambda$$

Measured and simulated ASE spectra, drive current from 50mA to 150mA in steps of 20mA.

Simulation Results: 950μm Cavity, Thermal Simulation



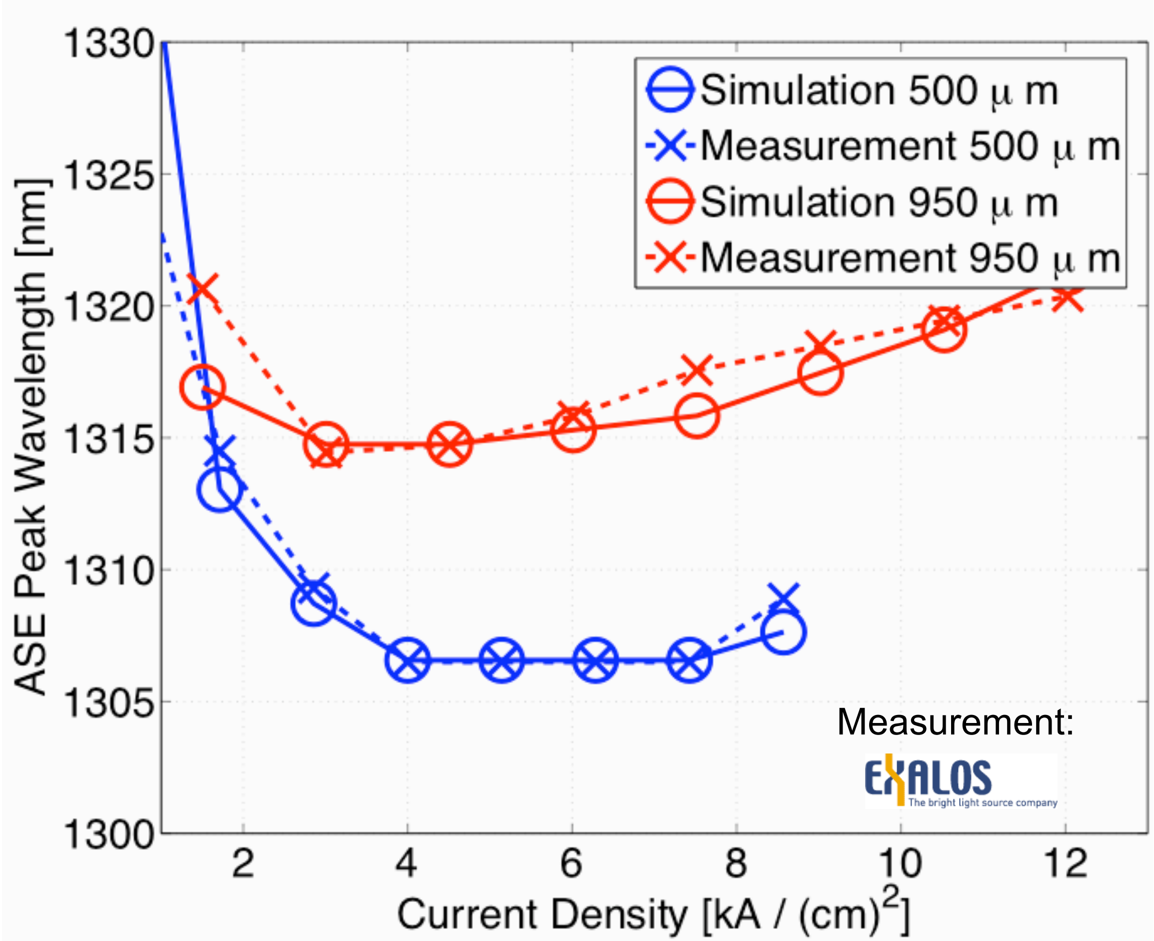


LI-curve: measurement and simulation.

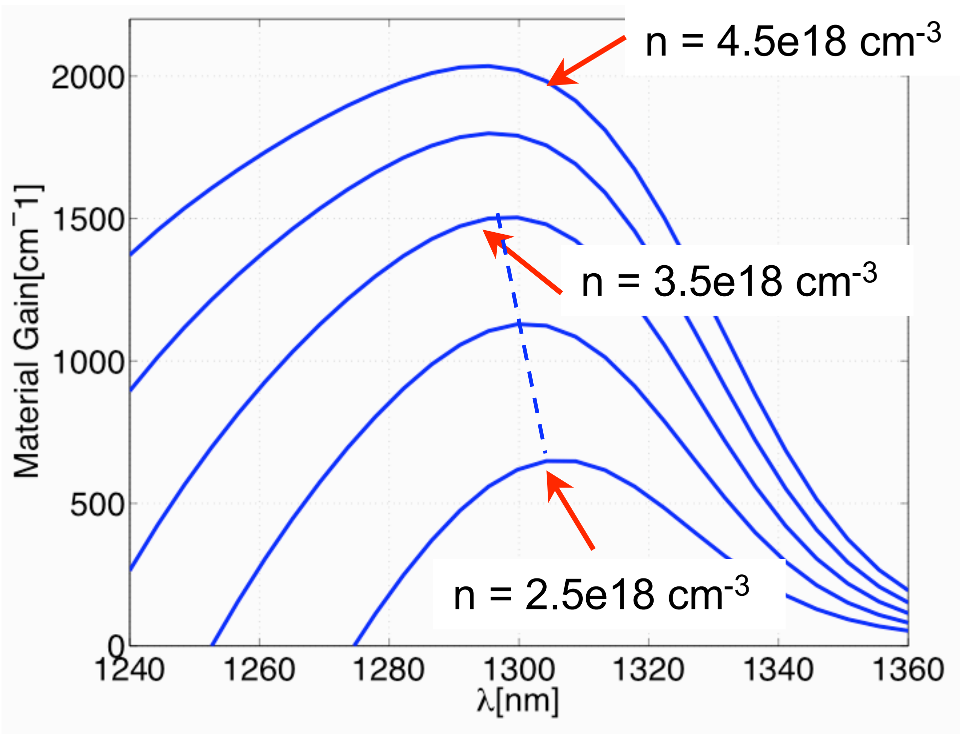
Measured and simulated ASE spectra, drive current from 100mA to 400mA in steps of 50mA.

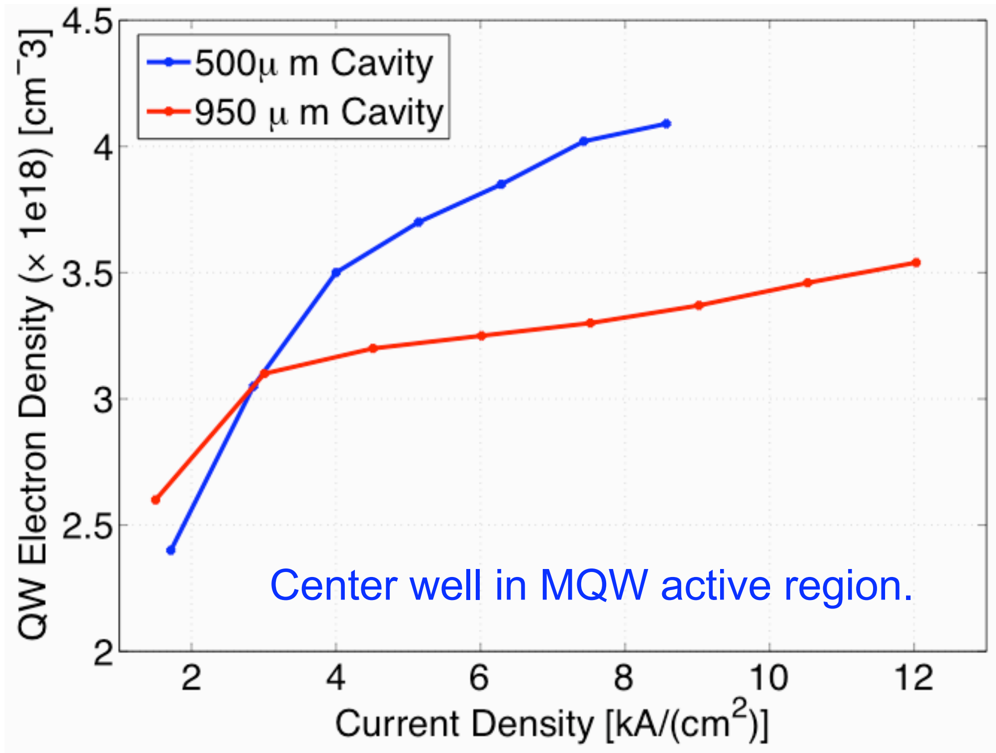
Shift of ASE Peak Wavelength

- Blue shift:
  - Bandfilling effects for high carrier concentrations
  - Many-body effects (Coulomb matrix)
- Red shift:
  - Self-heating
  - Many-body bandgap renormalization
- Long device: U-shape
- Short device: L-shape



Why Do the Benchmark Devices Show Different Shifts?



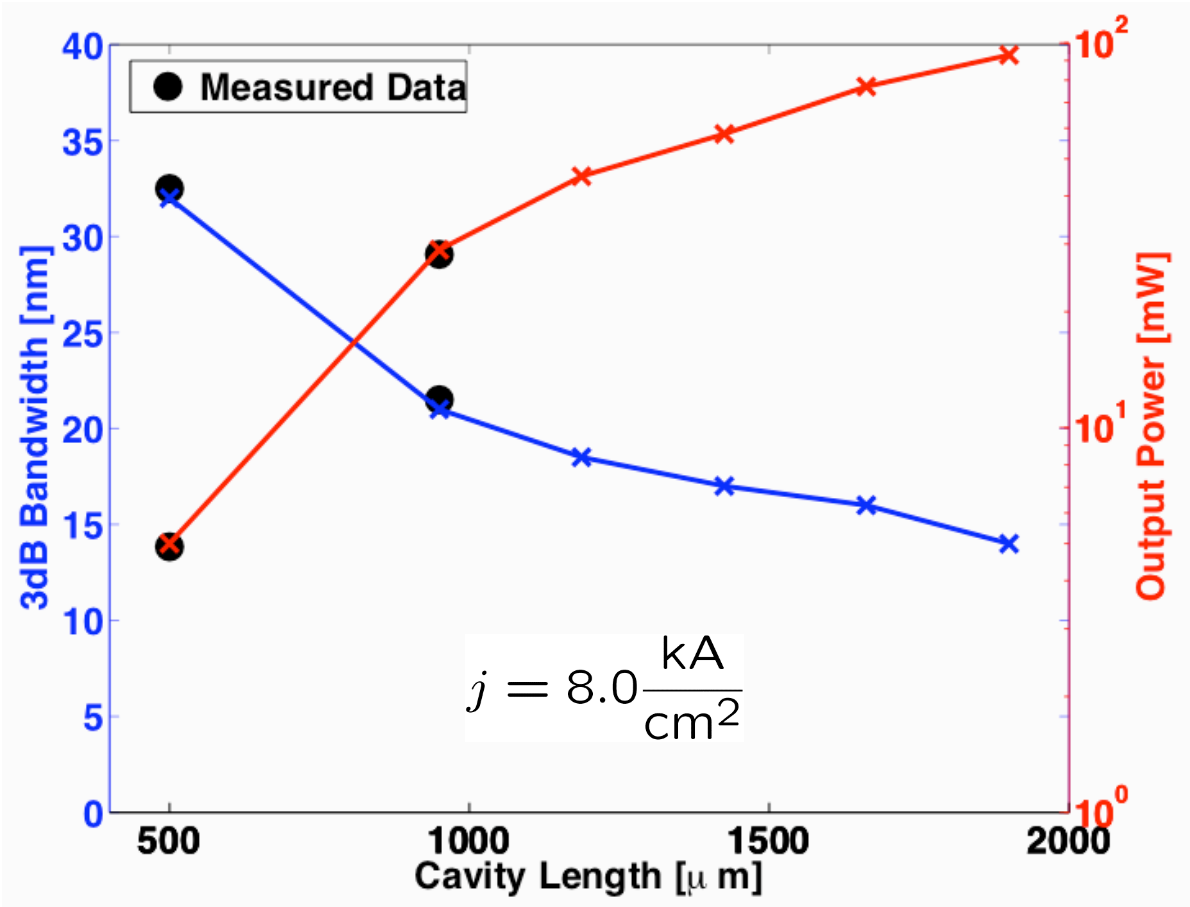


In the regime of operation of our SLEDs the gain shows a blue shift with increasing carrier density.

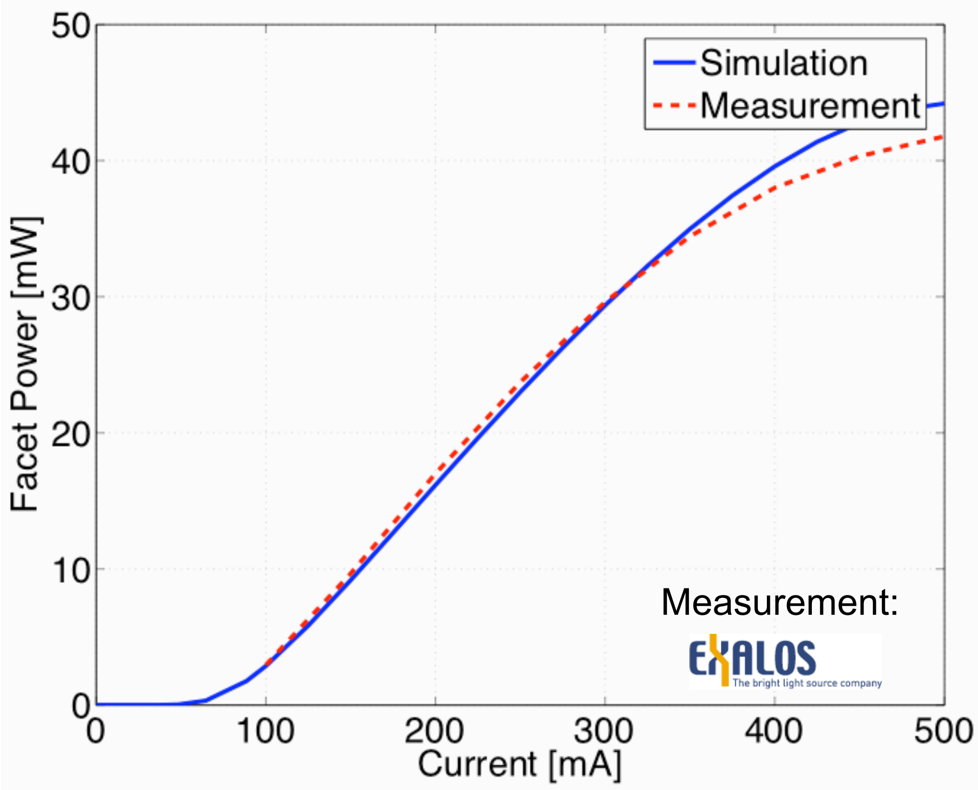
Smaller carrier concentration in long device due to higher stimulated recombination.

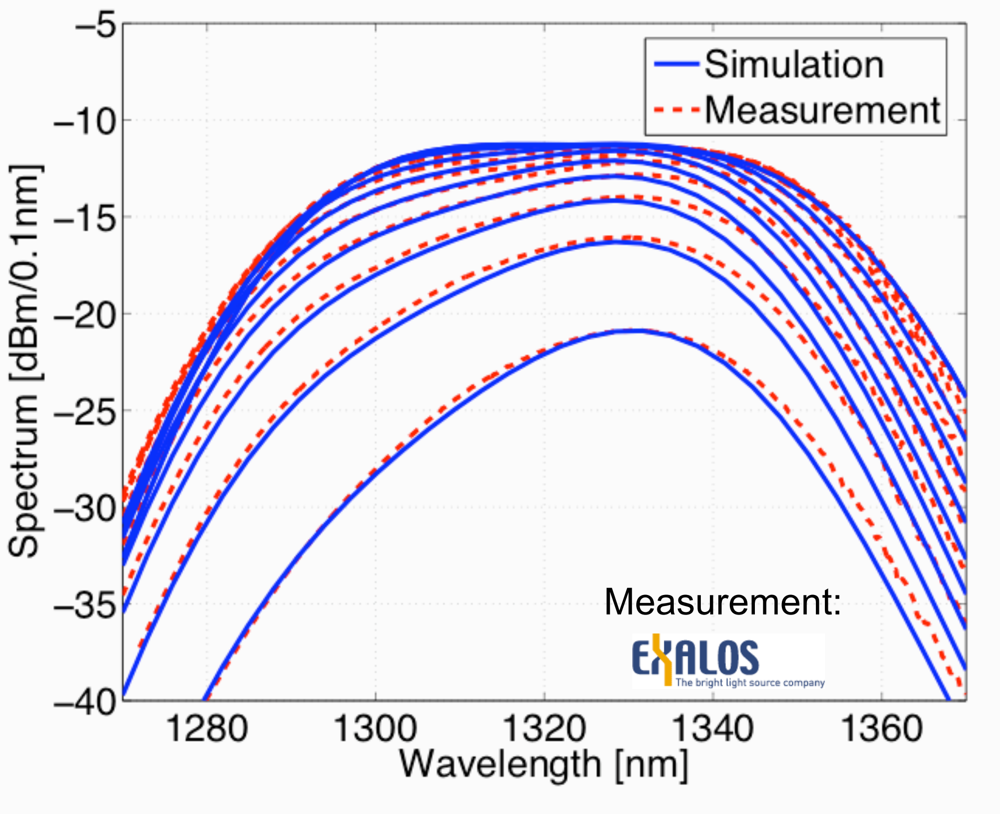
Cavity Length: Output Power vs Bandwidth

- Output power saturates due to carrier saturation (stimulated recombination).
- 3dB bandwidth decreases as the MQW carrier concentration decreases.



New Design: Non-Identical QWs (950μm Cavity)





Output power: 42mW old design, 44mW new design

3dB ASE bandwidth: 21nm old design, 57nm new design.

Conclusion & Outlook

- A two-dimensional simulation tool is benchmarked with spectrally resolved measured data from existing devices and excellent agreement is achieved.
- The simulator is applicable for a multitude of designs (different active regions, modified cavity length, etc.).
- Simulations indicate that QW carrier population and temperature play an all-important role for both shape and position of the ASE spectrum.
- Variations in the cavity length reveal the trade-off between output power and bandwidth.
- Outlook: Transition to full 3D.

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