LEHIGH UNIVERSITY IEEE NUSOD 2007, Newark, DE Center for Optical Technologies

Simulation of Derivative Characteristics of Broadband Quantum Dot Lasers

C. L. Tan, Y. Wang, H. S. Djie,* B. S. Ooi†

Center for Optical Technologies and Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, Pennsylvania 18015.

*presently with JDS Uniphase Corporation, San Jose, California 95134

†Corresponding author: bsooi@lehigh.edu
Website: www.ece.lehigh.edu/~bsooi

Acknowledgement: National Science Foundation (Grant No.: ECCS-0725647)

LEHIGH UNIVERSITY

Center for Optical Technologies

Outline

- Introduction
- Theoretical Model
- Simulation Results
- Conclusions

Introduction

Applications of Broad Gain Material & Broadband Laser

Optical Telecommunications

- Ultra-broadband components
  - tunable laser, SOA, EA modulator, detector, etc
- Ultra-short pulse generation
  - Optical clocking , OTDM, etc

Spectroscopy & Sensing

- Molecular spectroscopy (1450-1650nm)
  - Strong overtone spectra of CO, C_2H_2, and NH_3
- Atmospheric and planetary gas sensors
  - CH_4, CO, CO_2, H_2S, HCl, NH_3, C_2H_4, C_2H_2, C_2H_6, C_6H_6, etc
- General Spectroscopy
  - Material absorption, transmission, luminescence, etc

Metrology

- Optical test and measurements, etc
- Optical time domain reflectrometry (OTDR)

Imaging

- Bio-imaging (Optical Coherence Tomography)
- Ultra-short pulse imaging, etc

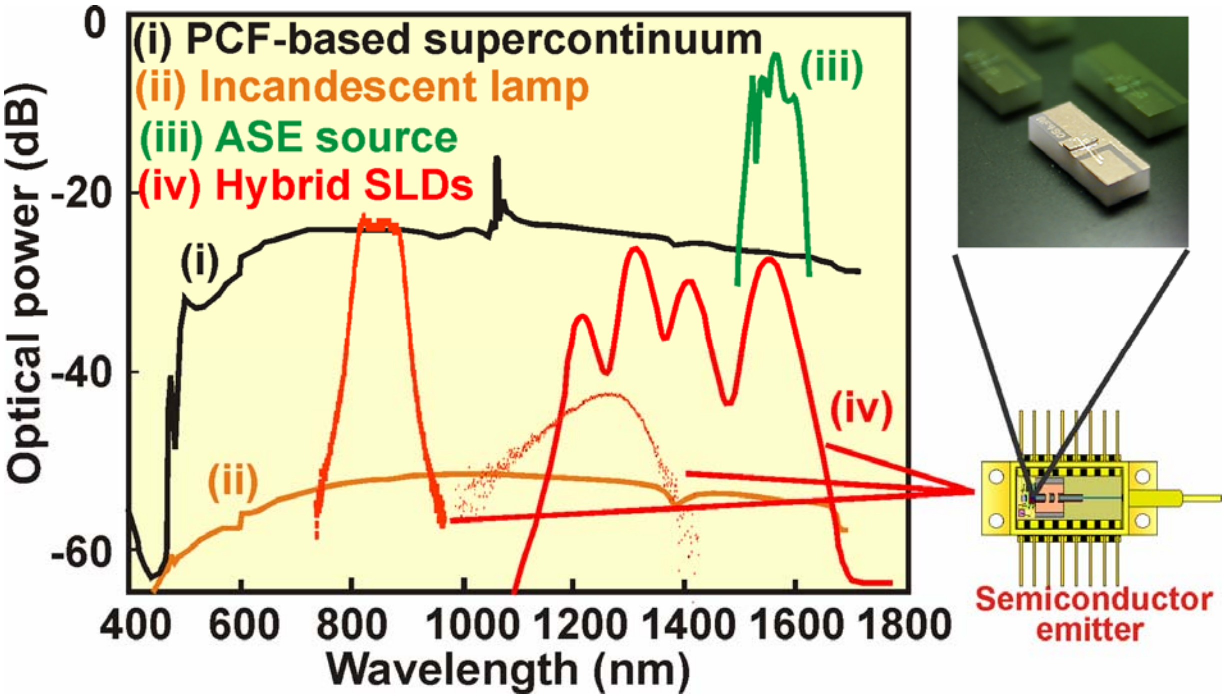
Others

- High sensitive fiber gyroscope
- Instrumentation, etc

Introduction (con't)

Center for Optical Technologies

Broadband Light Source Technology



Existing technologies:

•Photonic crystal fiber (PCF)

•Incandescent lamp

•Amplified spontaneous emission (ASE) source

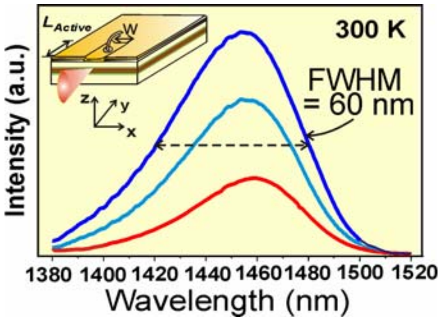
•Semiconductor broadband emitter:

- Light-Emitting Diode (LED) & Superluminescent Diodes (SLD)
- Broadband intersub-band Quantum Cascade Laser (QCL)

Introduction (con't)

LEHIGH UNIVERSITY

Center for Optical Technologies

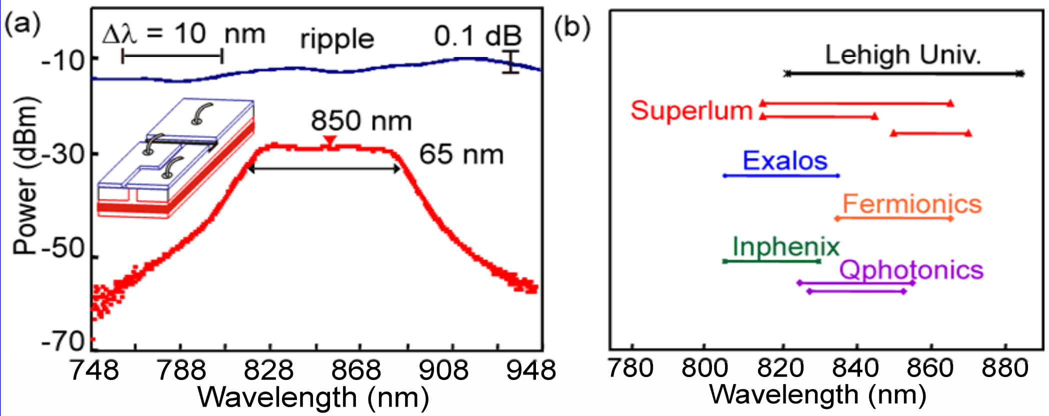


1550nm Quantum-Well Superluminescent Diode (SLD):

- **Performance**: Bandwidth 60nm, output power >20mW
- **Technology transfer**: *Denselight Semiconductor Ltd.*, Singapore

IEEE J. Sel. Topics Quantum Electron., vol.8, p.870, 2002

US Patent 6,617,188, granted : 9 September 2003

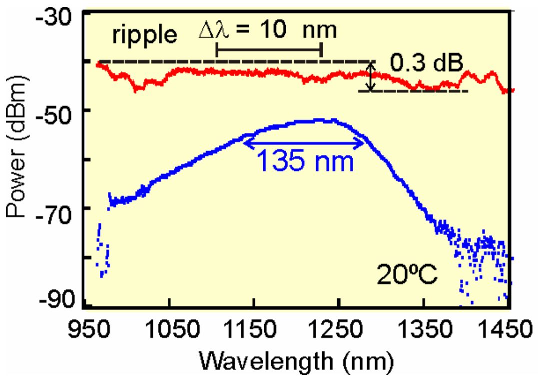


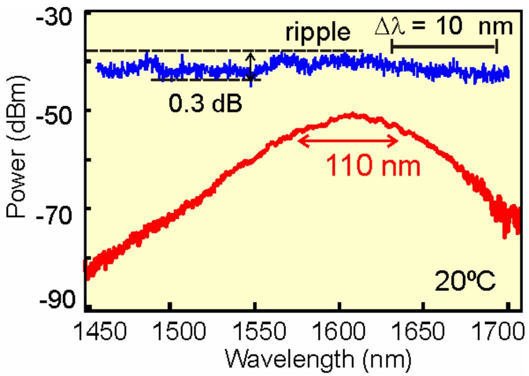
850nm Quantum-Well SLD

- **Performance**: Bandwidth: 65nm, ripple:<0.1dB
- **Technology transfer**: *Carl Zeiss Meditec Inc.*

IEEE J. Quantum Electronics, submitted, 2007

USA Patent Application, submitted October 2005





1200nm & 1600nm Quantum-Dot/Dash SLDs:

- 1200nm SLED: Bandwidth: 135nm, ripple: 0.3dB, 10s μW
- 1600nm SLED: Bandwidth: 110 nm, ripple: 0.3 dB, power: 2 mW

IEEE Photon.Tech. Lett., vol. 18, p1747, 2006

J. of Crystal Growth, vol.288, pp.153-156, 2006

IEEE Sensor Journal,2007

Introduction (con't)

LEHIGH UNIVERSITY

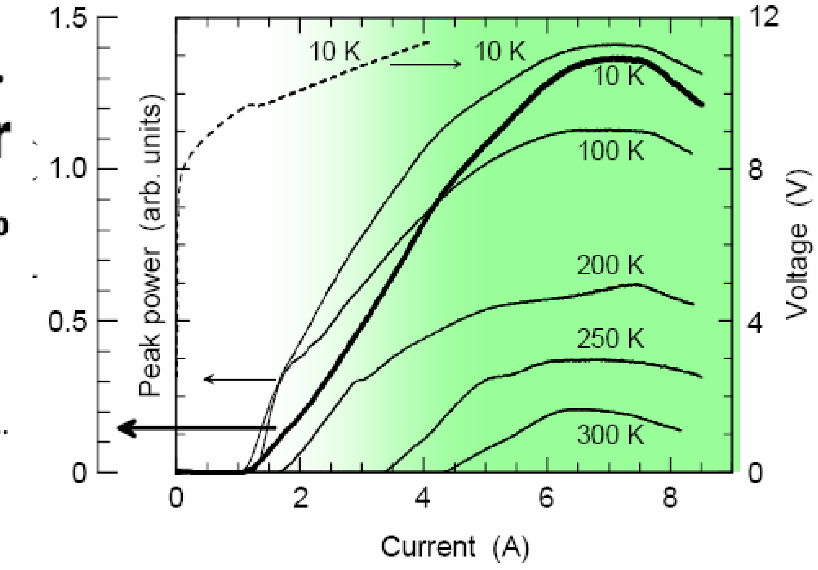
Center for Optical Technologies

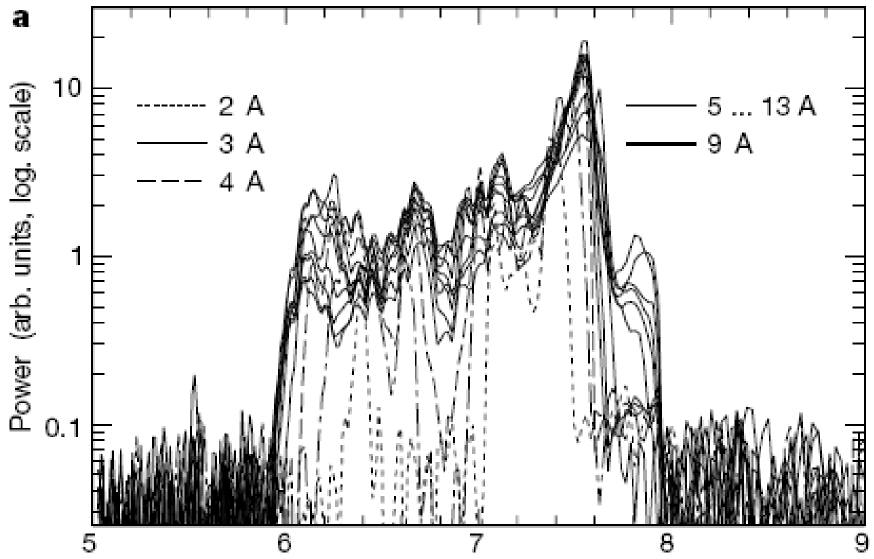
NATURE | VOL 415 | 21 FEBRUARY 2002 | www.nature.com

Ultra-broadband semiconductor laser

Claire Gmachl, Deborah L. Sivco, Raffaele Colombelli, Federico Capasso & Alfred Y. Cho

Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974, USA





- •Intersub-band cascade → mid-IR
- •Quantum band engineering:
  - 36 different active regions
- •Covering 6-8 μm emission
- •Low wall-plug efficiency at RT (<0.1%)
- •Side-mode-supression-ratio : ~20 dB
- •Material challenge for <u>near-IR region</u>!

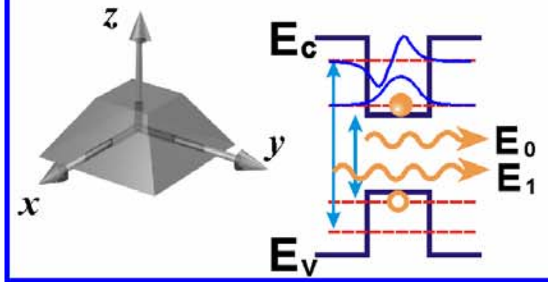
Gmachl *et al.*, Nature 415, 883 (2002).

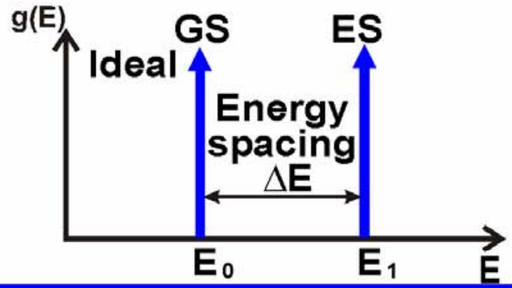
LEHIGH UNIVERSITY

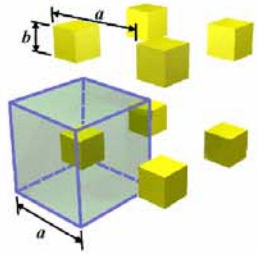
Introduction (con't)

Center for Optical Technologies

Ideal QD gain media







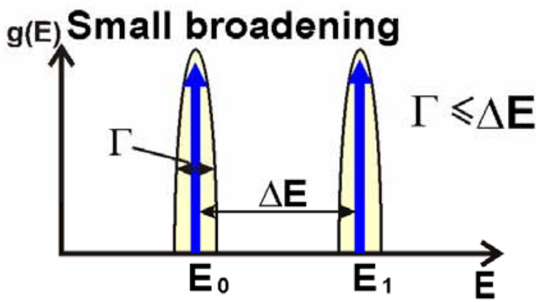
So far...

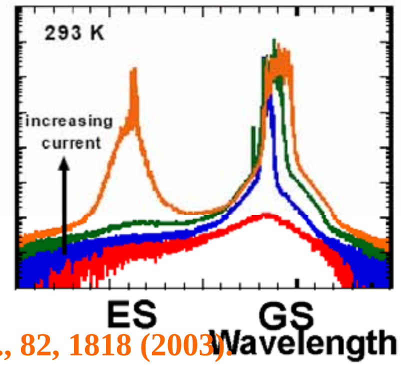
Inhomogeneous QD

Large energy spacing

DISCRETE-transition band

→ Dual-state lasing action





Markus *et al.*, Appl. Phys. Lett., 82, 1818 (2003).

Sugawara *et al.*, J. Appl. Phys., 97, 043523 (2005).

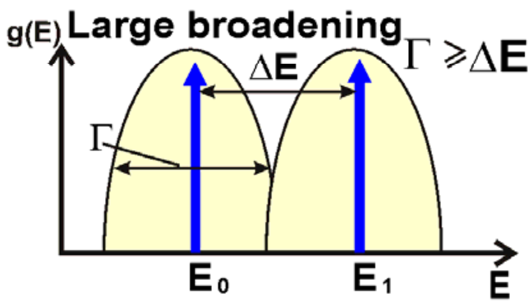
Now...

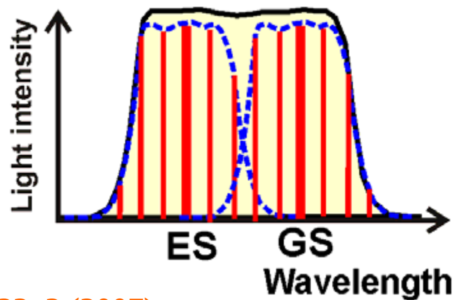
Highly inhomogeneous QD

Narrow energy separation

QUASI-transition band

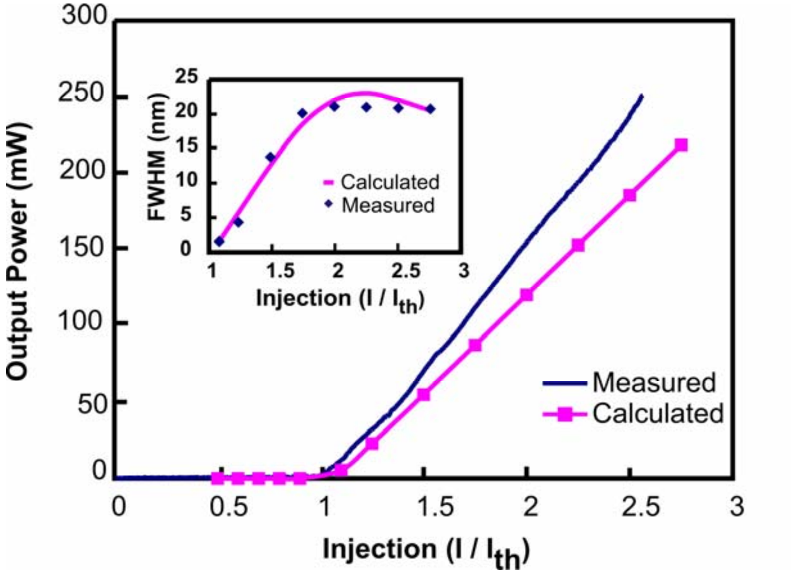
→ Broadband interband laser

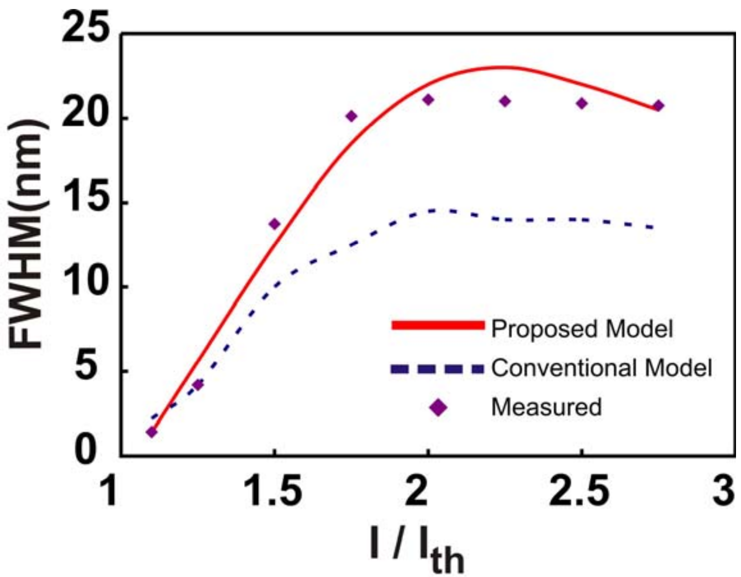


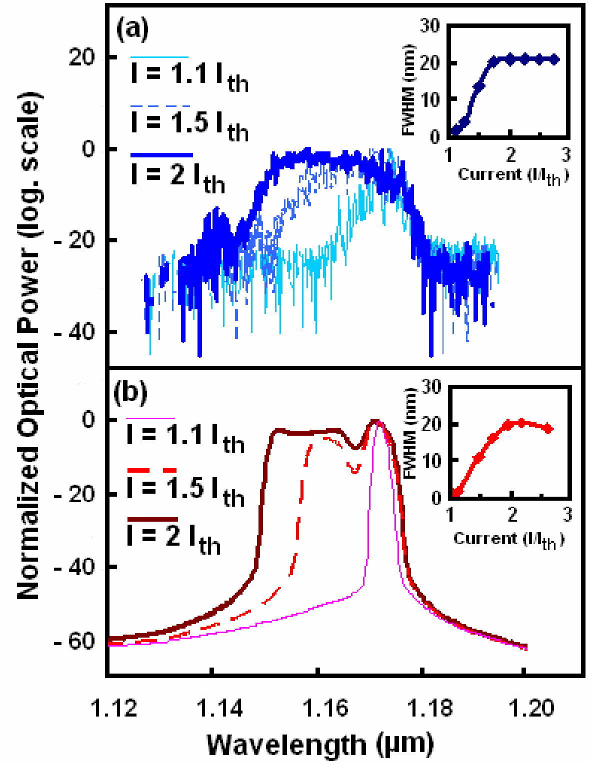


Djie *et al.*, Optics Letters, 32, 2 (2007).

Introduction (con't)



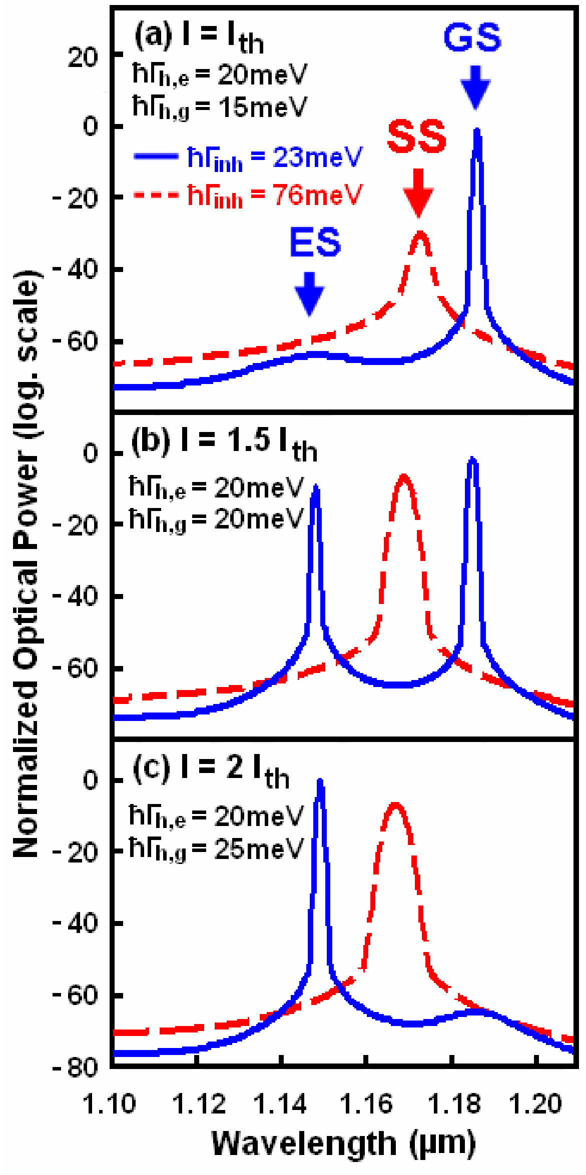


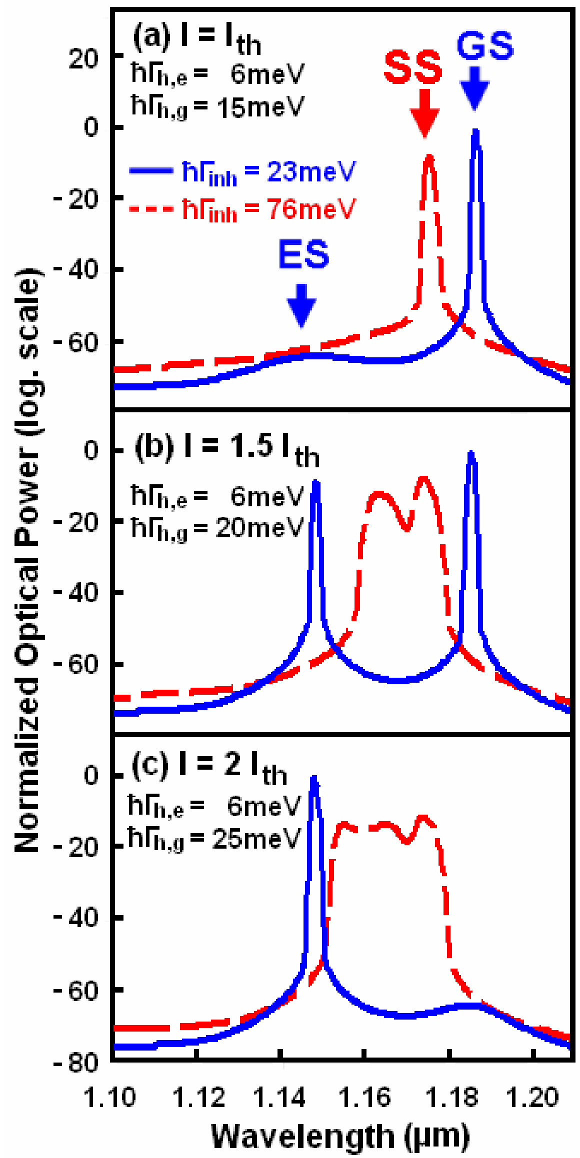


- The calculated output power shows slight variation with experimental measurement that may due to the cleaving precision of the device.
- The calculated linewidth match well with measured data due to the optical gain broadening.

H. S. Djie *et al.*, Opt. Lett. 32, 44 (2007).
C. L. Tan *et al.*, Appl. Phys. Lett., 91, 061117 (2007).
C. L. Tan *et al.*, (submitted to Computational Materials Sci.)

Introduction (con't)





C. L. Tan *et al.*, Appl. Phys. Lett., 91, 061117 (2007).

LEHIGH UNIVERSITY

Center for Optical Technologies

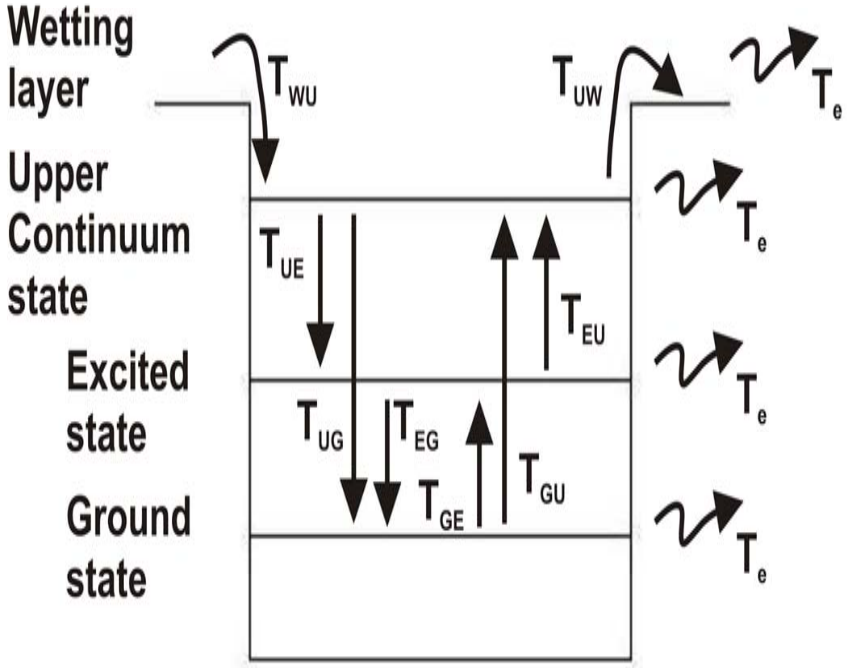
Theoretical Model

$$\frac{dN_w}{dt} = \frac{\eta_i I}{q} - \frac{N_w}{T_{wr}} - \frac{N_w}{T_{wu}} - \frac{N_e}{T_e} + \frac{\sum N_{u,j}}{T_{uw}}$$

$$\frac{dN_{u,j}}{dt} = \frac{N_w G_n}{T_{wu,j}} + \frac{N_{g,j}}{T_{gu,j}} + \frac{N_{e,j}}{T_{eu,j}} - \frac{N_{u,j}}{T_{ug,j}} - \frac{N_{u,j}}{T_{ue.j}} - \frac{N_{u,j}}{T_{uw}} - \frac{N_{u,j}}{T_r} - \frac{N_{u,j}}{T_e} - \frac{c\Gamma}{n_r}\sum_m g_{mn} Sm$$

$$\frac{dN_{e,j}}{dt} = \frac{N_{u,j}}{T_{ue,j}} + \frac{N_{g,j}}{T_{ge,j}} - \frac{N_{e,j}}{T_{eu,j}} - \frac{N_{e,j}}{T_{eg.j}} - \frac{N_{e,j}}{T_r} - \frac{N_{e,j}}{T_e} - \frac{c\Gamma}{n_r}\sum_m g_{mn} S_m$$

$$\frac{dN_{g,j}}{dt} = \frac{N_{u,j}}{T_{ug,j}} + \frac{N_{e,j}}{T_{eg,j}} - \frac{N_{g,j}}{T_{gu,j}} - \frac{N_{g,j}}{T_{ge.j}} - \frac{N_{g,j}}{T_r} - \frac{N_{g,j}}{T_e} - \frac{c\Gamma}{n_r}\sum_m g_{mn} S_m$$



Theoretical Model (con't)

Optical gain modal:

$$g_{mn} = \frac{2\pi q^2 \hbar D_l N_D}{cn_r \varepsilon_0 m_0^2} \frac{|P_{cv}^{\sigma}|^2}{E_{cv,k_l}} (2P_n - 1) G_n B_{cv}(E_m - E_{cv,k_l}^{j})$$

$$P_{l,j} = \frac{N_{l,j}}{2D_l N_D G_n}$$

Homogeneous Broadening function:

$$B_{cv}(E_m - E_{cv,k_l}^{j}) = \frac{\hbar \Gamma_l^j / \pi}{(E_m - E_{cv,k_l}^{j})^2 + (\hbar \Gamma_l^j)^2}$$

Kramers-Kronig relation to Δn in QD ensemble:

$$\Delta n_{QD}(E) = k \frac{\hbar c}{2E} \Gamma N_D \sum_l \sum_j D_l \frac{|P_l^{\sigma}|^2}{E_l} [(2P_{l,j} - 1) G_n \frac{(E - E_{cv,l})/\pi}{(E - E_{cv,l})^2 + (\hbar \Gamma_{cv,l})^2}]$$

M. Sugawara *et al.*, Phys. Rev. B, 61, 11 (2000).
M. Sugawara *et al.*, J. Appl. Phys., 97, 043523 (2005).
M. Gioannini *et al.*, Opt. and Quantum Electron., 38, 381-394 (2006).

LEHIGH UNIVERSITY

Theoretical Model (con't)

Center for Optical Technologies

Contribution of free carriers in the wetting layer to Δn:

$$\Delta n_{WL} = \Gamma_{WL} K_n \frac{\Delta N_{WL}}{E^2}$$

Linewidth Enhancement Factor below threshold:

$$\alpha = -\frac{4\pi}{\lambda} \frac{(\Delta n_E + \Delta n_G + \Delta n_{UC} + \Delta n_{WL}) / \Delta N}{\Delta g / \Delta N}$$

Linewidth Enhancement Factor above threshold:

$$\alpha = \alpha_{QD,E} + \alpha_{QD,G} + (\alpha_{UC} + \alpha_{WL}) \frac{\rho_{th} - 1 + \rho_{th} \frac{J}{J_{th}}}{2\rho_{th} - 1}$$

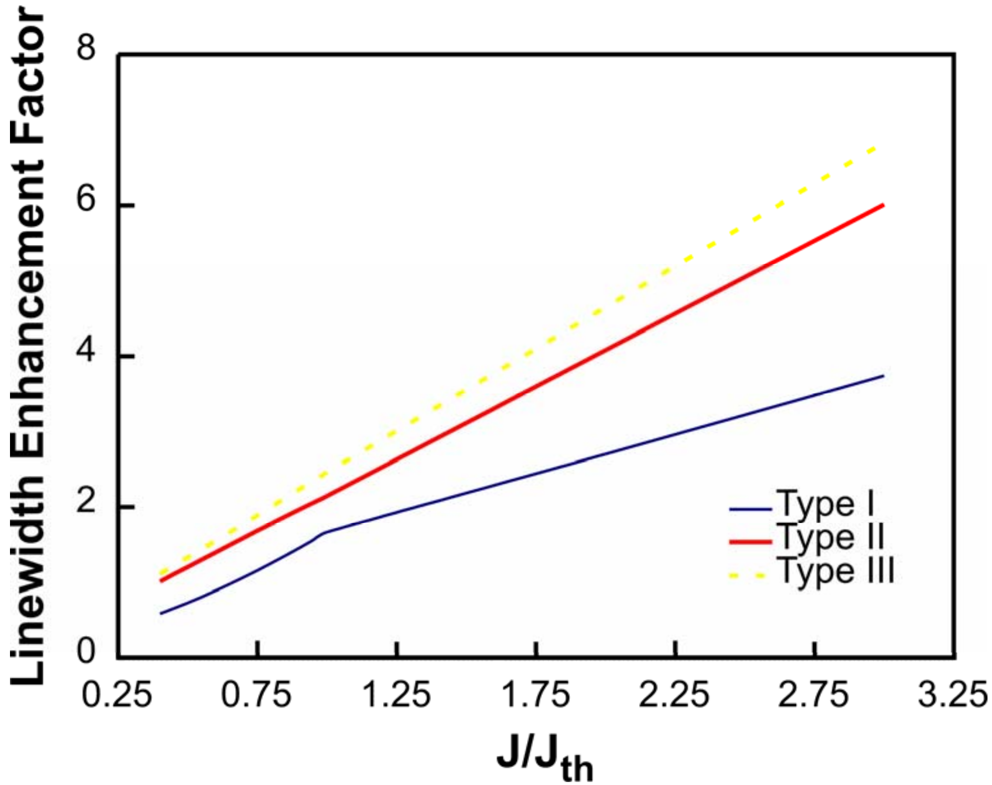
Y. Toda *et al.*, Phys. Rev. Lett., 82, 20 (1999).

M. Gioannini *et al.*, Opt. and Quantum Elec., 38, 381-394 (2006).

S. Melnik *et al.*, Opt. Exp., 14, 2950-2955 (2006).

Z. Mi *et al.*, IEEE J. Quan. Elec., 43, 5 (2007).

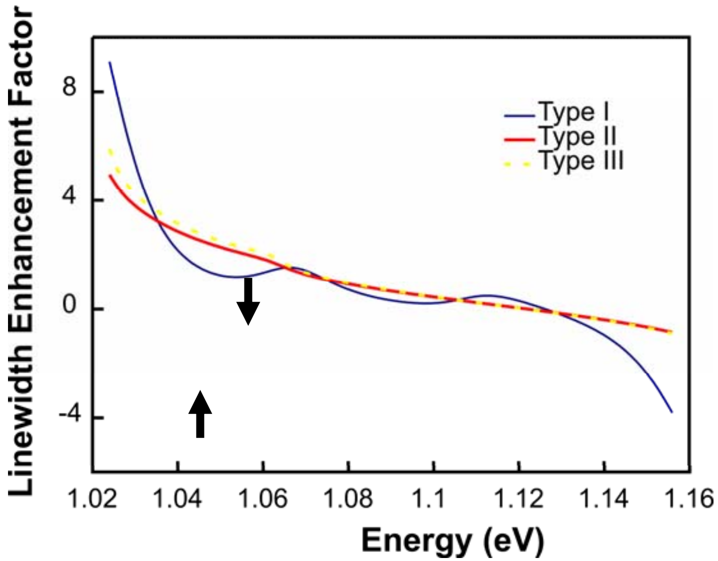
Simulation Results

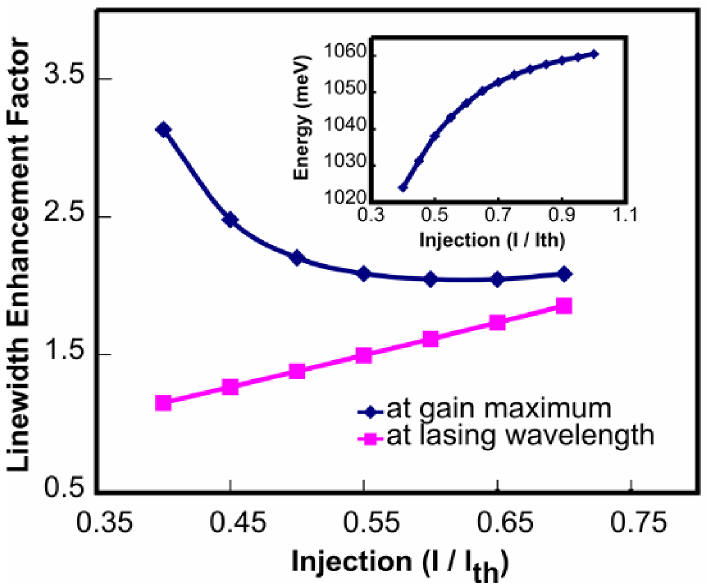


- The calculated alpha of typical QD lasers (Type I) at below and above threshold shows similar trend as reported from literature reviews.
- QD lasers with broadband nature (Type III) shows larger change of alpha above threshold in accordance to injection as compared to typical QD lasers. This is due to the larger alpha contribution from continuum states in large inhomogeneous system, as can be found from following figures.

S. Melnik *et al.*, Opt. Exp., 14, 2950-2955 (2006).
Z. Mi *et al.*, IEEE J. Quantum. Electron., 43, 5 (2007).

Simulation Results (con't)





Type I

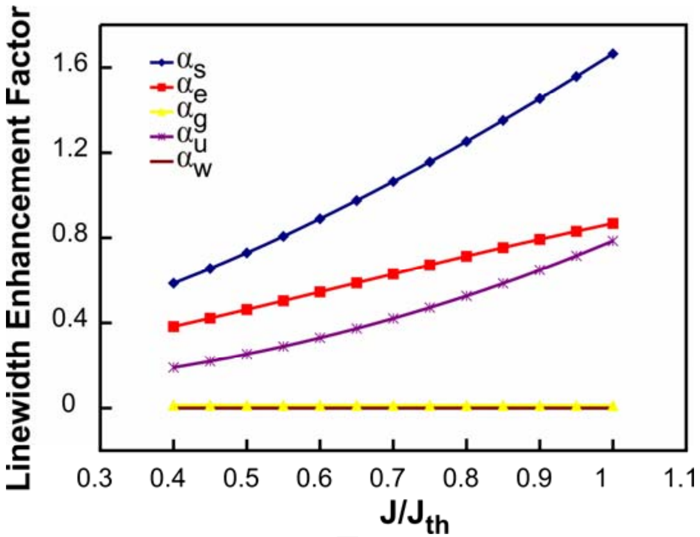
- Broadband QD lasers (Type III) shows a smaller degree of change over energy span as compared to typical QD lasers (Type I) from figure.
- The arrows show the lasing energy of each system. The up-arrow refers to Type I while down-arrow refers to Type II and III.
- The LEF of typical QD lasers shows value below 2 near threshold.

J. Oksanen *et al.*, J. Appl. Phys., 94, 3 (2003).
M. Gioannini *et al.*, Opt. and Quantum Elec., 38, 381 (2006)
S. Melnik *et al.*, Opt. Exp., 14, 2950-2955 (2006).

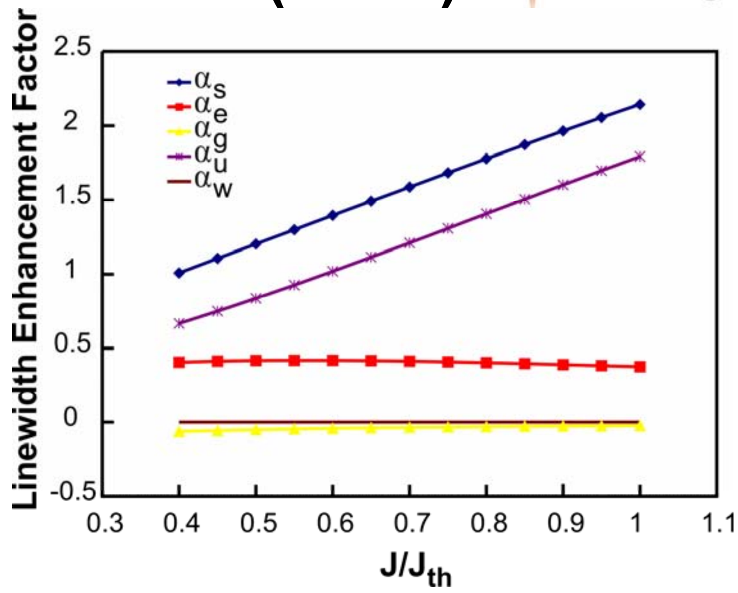
LEHIGH UNIVERSITY

Simulation Results (con't)

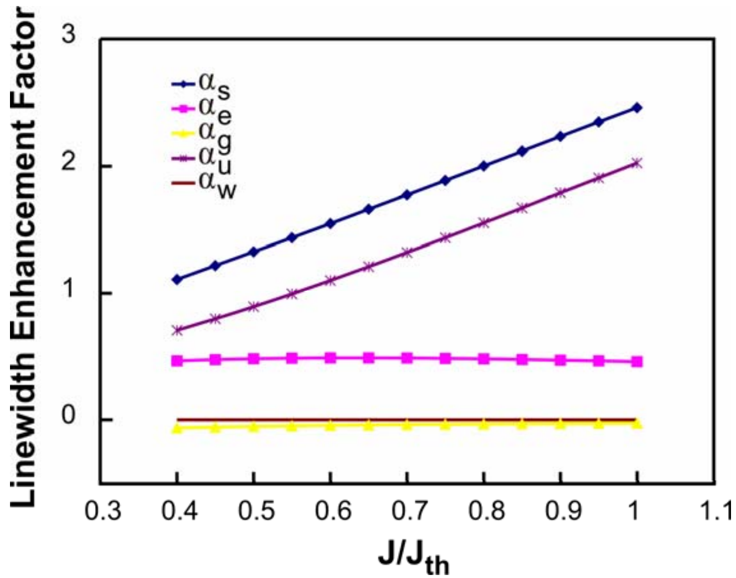
Center for Optical Technologies



Type I



Type II



Type III

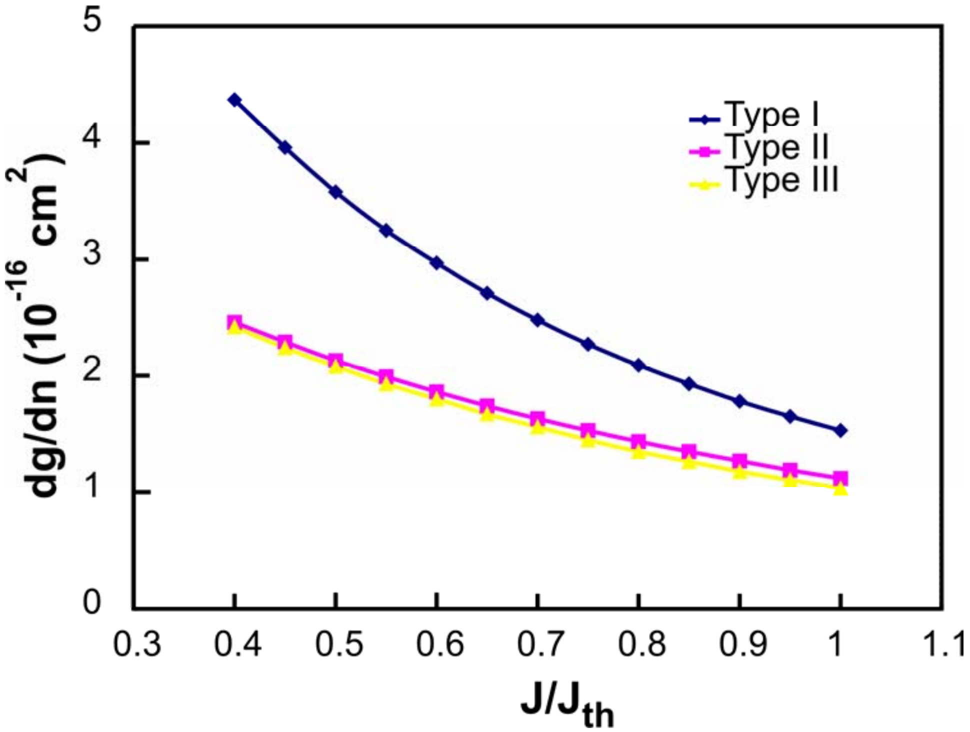
- Typical QD lasers show that alpha contribution from continuum states increase rapidly with injection as compared to alpha contribution from excited and ground states. Hence, continuum states show similar behavior of wetting layer in the calculation model without continuum states.
- However, broadband QD lasers show that alpha contribution from continuum states is the largest and affect the alpha value of the system.

Z. Mi *et al.*, IEEE J. Quantum. Electron., 43, 5 (2007).

Simulation Results (con't)

LEHIGH UNIVERSITY

Center for Optical Technologies



- The value of differential gain of typical QD lasers (Type I) shows similar magnitude of order as reported so far.
- As inhomogeneity of the system increase, differential gain at threshold decrease as compared to typical QD lasers.
- However, the decrease of differential gain is less than 1×10^{-16} cm^2.
- Hence, the degree of modulation bandwidth of broadband lasers will not be degraded too much from typical QD lasers.

A. A. UKhanov *et al.*, Appl. Phys. Lett., 84, 7 (2004).

LEHIGH UNIVERSITY

Center for Optical Technologies

Conclusions

- Derivative characteristics of broadband QD lasers are compared with typical QD lasers.
- A slight increase of linewidth enhancement factor at ground state of 0.8 is observed in broadband QD lasers.
- A slight decrease of differential gain of les than $1x10^{-16}$ cm^2 at threshold is observed in broadband QD lasers.
- The comparable values of GS's LEF in broadband QD lasers shows its competency in providing low frequency chirping as well as a platform of monolithic integration for the GS operation.

LEHIGH UNIVERSITY

Center for Optical Technologies

Thank You

Simulation parameters

E_{GS} = 1050meV	$T_{0,wu}$ = 1ps
E_{ES} = 1090meV	$T_{0,ue} = T_{0,eg} = T_{0,ug}$ = 3.4ps
D_G = 1	n_r = 3.5
D_E = 3	T_r = 1ns
D_U = 10	$N_D = 1.67*10^{23}$
L_{ca} = 800 μm	$V_A = 9.6*10^{-16}$
$R_1 = R_2$ = 0.3	$ß = 10^{-4}$
α_i = 4.5cm^{-1}	Γ_{QD} = 0.03
T_{wr} = 0.4ns	Γ_{WL} = 0.01
T_e = 0.38ns	Γ_{inhomo} = 23meV, 76meV
$T_{0,uw}$ = 10ps	ΔE = 0.22meV