Semiconductor quantum dot lasers: Why are they so quantum?

Frédéric GRILLOT

grillot@telecom-paristech.fr

UC Santa Barbara, Nov. 2, 2017

Acknowledgments

Involved in this work

Dr. H. Huang, Télécom ParisTech

Dr. K. Schires, Télécom ParisTech

J. Duan, Télécom ParisTech (PhD)

Collaborations

Germany, TU Berlin, Prof. D. Bimberg

USA, UC Santa Barbara, Prof. J. Bowers

USA, VirginiaTech, Prof. L. Lester

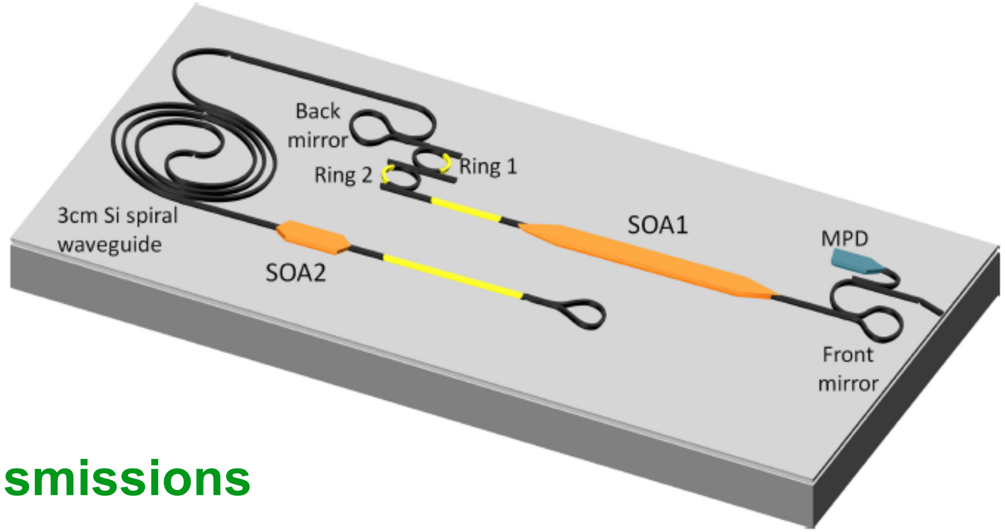
Canada, NRC Ottawa, Dr. P. Poole

Why dynamical studies?

Integration of optical and electronic components

Several sources of optical feedback due to the various possible interfaces

- **Short cavities: a few centimeter**
- **Long cavities: several meters**



Isolator-free transmissions

Encoded communications

….

T Komljenovic et al., IEEE J. of Selected Topics in Quantum Electron. Vol. 21, (2015)

Outline

- **Quantum dot lasers: Usefulness and limitations**
- **Nonlinear dynamics of QD lasers**
  - Silicon based QD lasers (UCSB)
  - InAs/GaAs QD lasers (TU Berlin)
- **Conclusions**

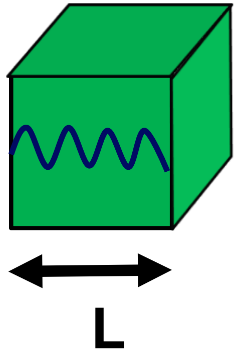
Quantization, what for?

Shape of density of states (gain spectral width)

Number of states (transparency current)

Carrier confinement

Energy tuning

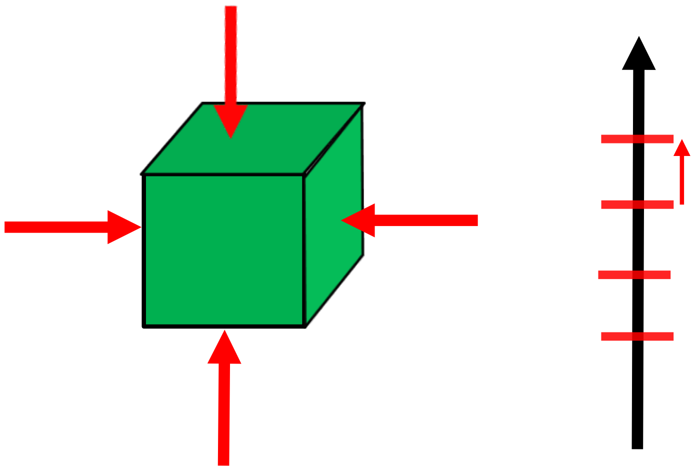


$$k_j L = 2m_j \pi$$

$$j = x, y, z$$

Energy quantization

Wavefunction confinement with heterostructure potential



$$\Delta E \propto \frac{1}{L^2}$$

$$\Delta E >> kT$$

L<< 30 nm at 298K

Quantization, what for?

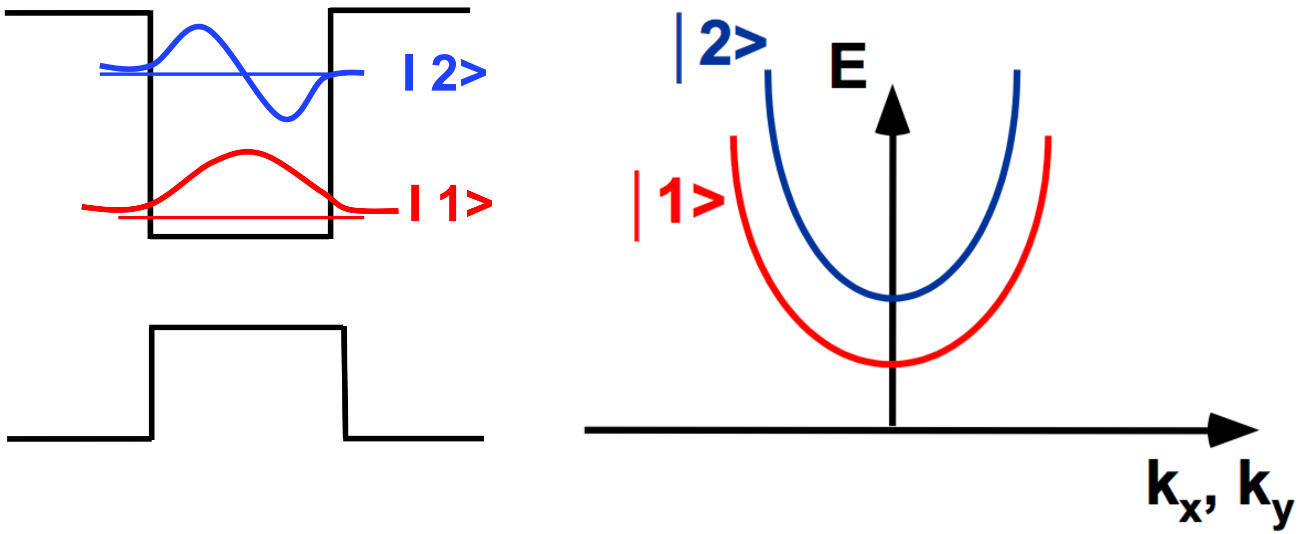
Shape of density of states (gain spectral width)

Number of states (transparency)

Carrier confinement

Energy tuning

2D nanostructures: Quantum well



Continuum of energy states in two directions

Quantization, what for?

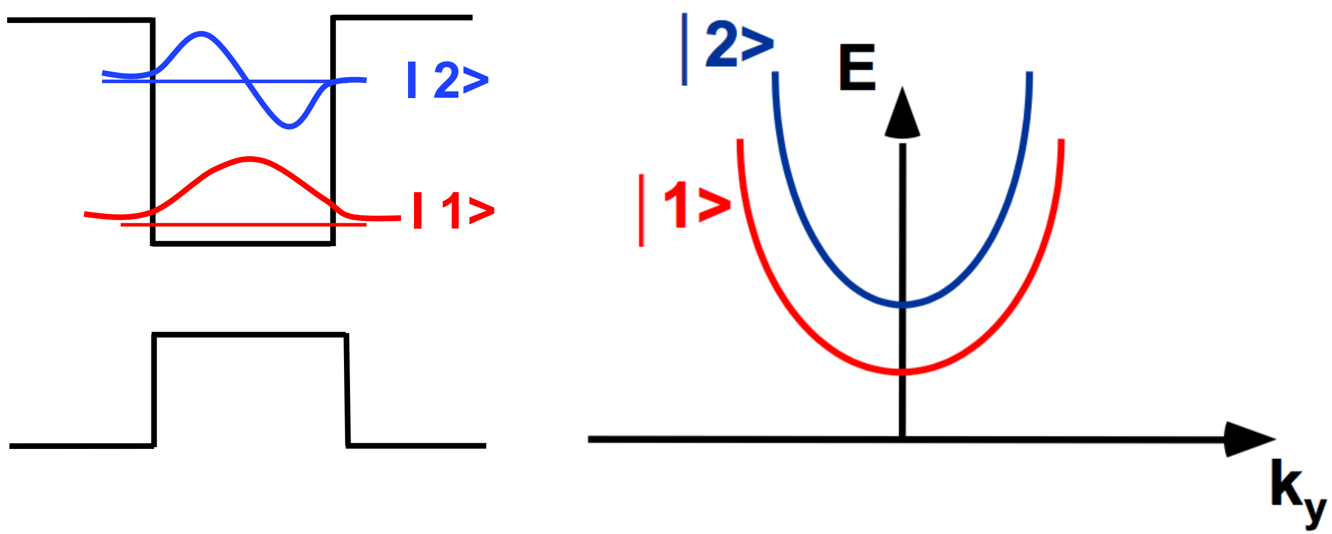
Shape of density of states (gain spectral width)

Number of states (transparency)

Carrier confinement

Energy tuning

1D nanostructures: Quantum wire



Continuum of energy states in one direction

Quantization, what for?

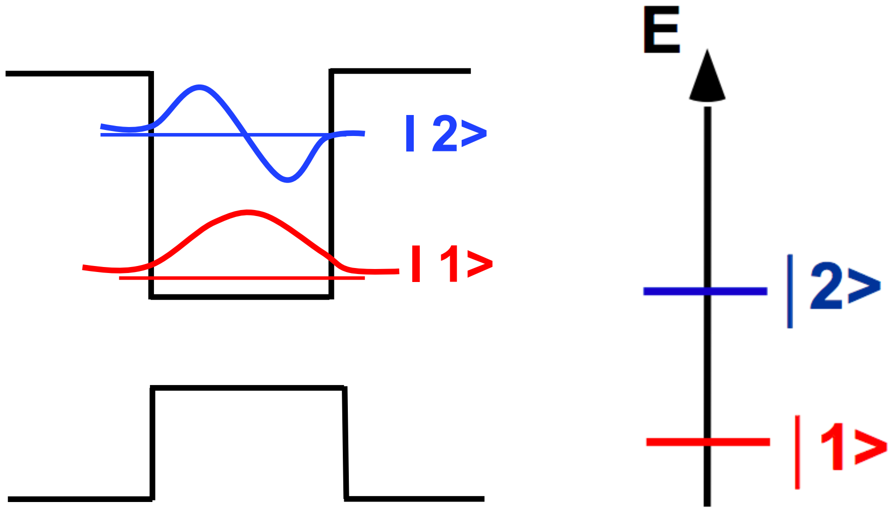
Shape of density of states (gain spectral width)

Number of states (transparency)

Carrier confinement

Energy tuning

0D nanostructures: Quantum dot

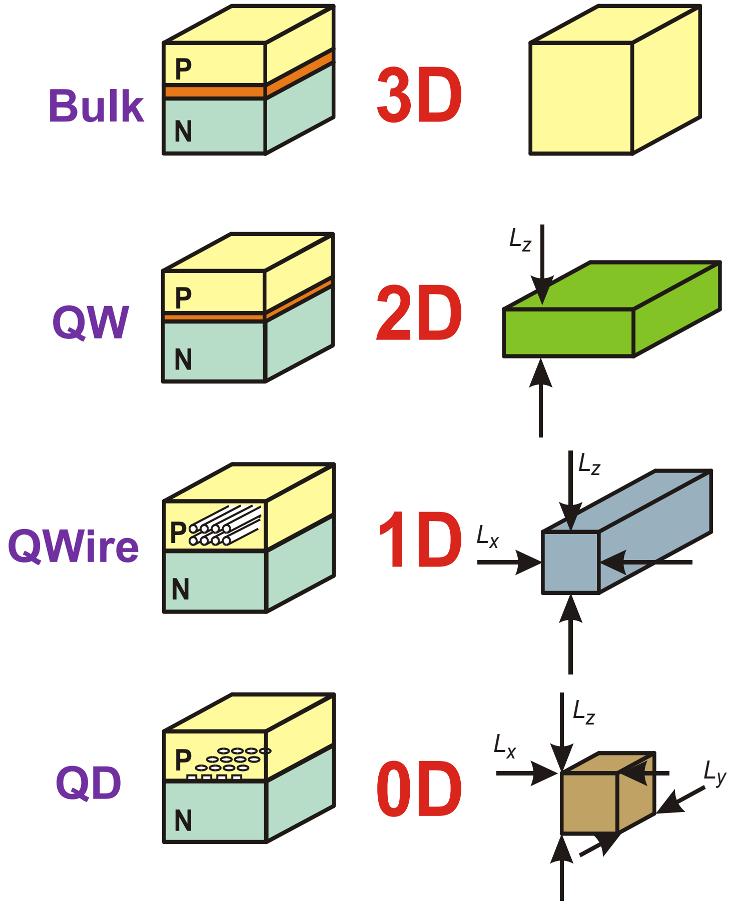


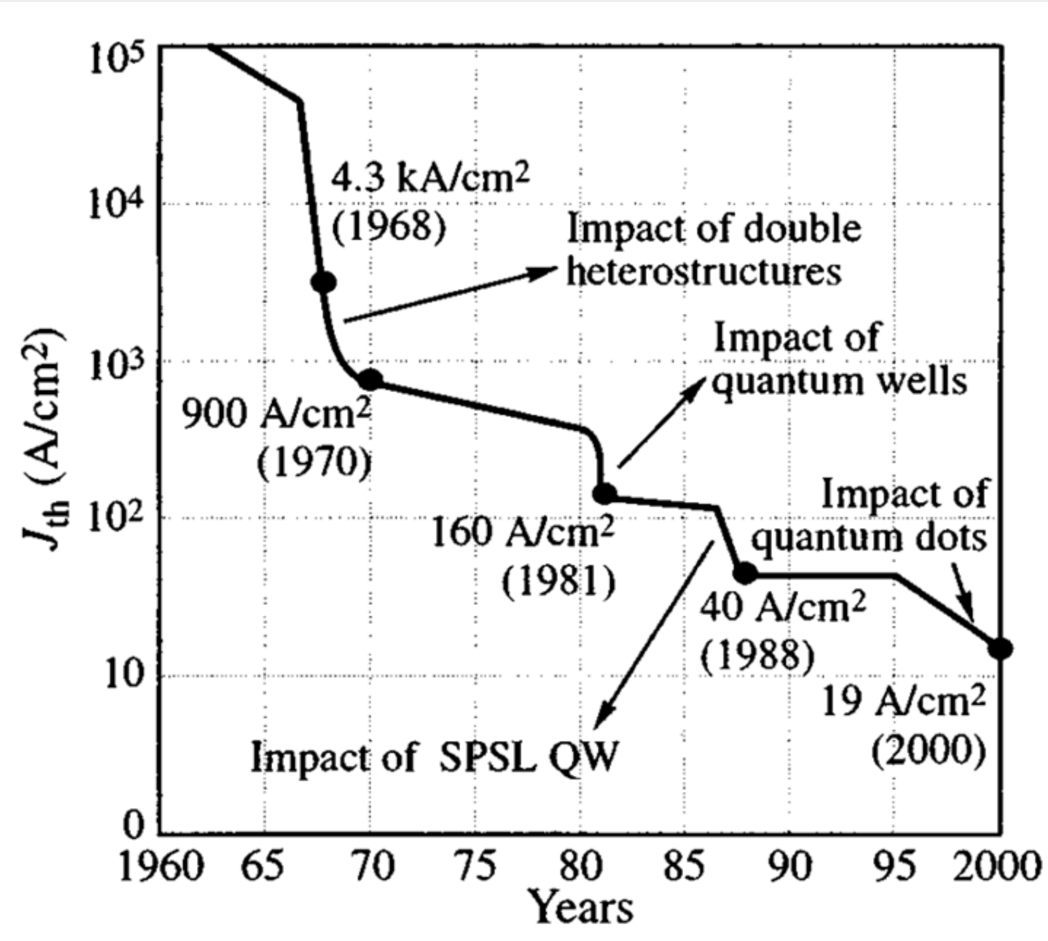
Only in 0D nanostructures, energy levels are completely discrete

→ semiconductor atoms

Quantization, what for?

An heuristic approach
→ Low dimensionality & laser performance





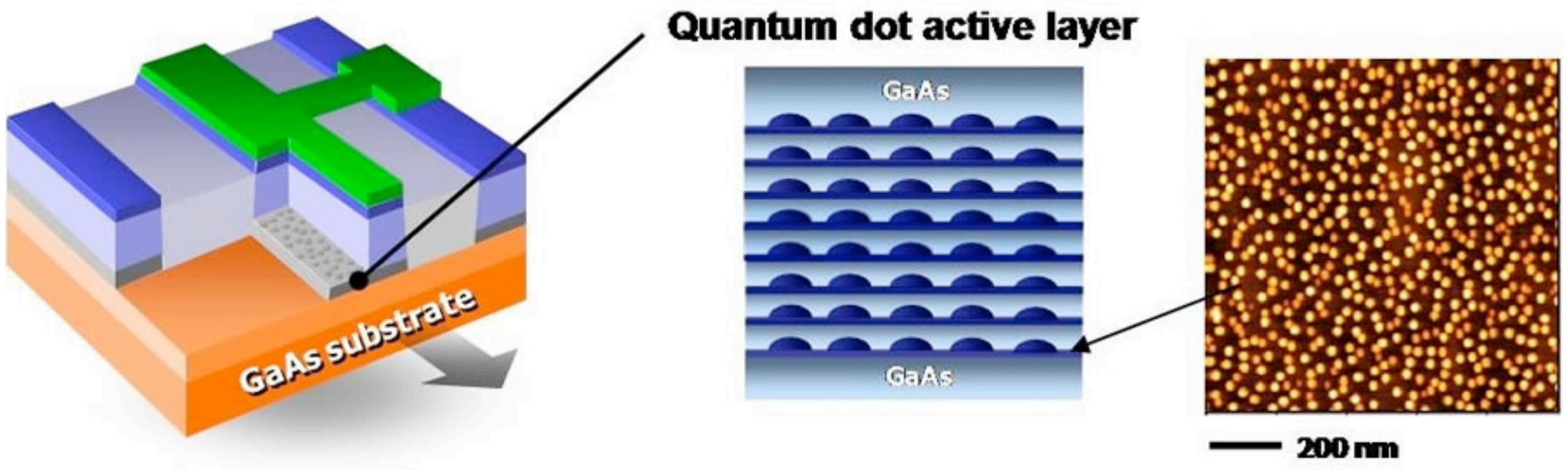
Major breakthroughs

1994	1st lasing (optical pumping)	Ioffe Institute
1994	1st lasing (current injection)	TU Berlin & Ioffe Institute
1999	Near-zero α - factor	Univ. New Mexico & AFRL
2000	Record-breaking $J_{th} = 19\ \mathrm{A/cm^2}$	Univ. Texas, Austin
2002-3	Superior temperature stability	Univ. Texas, Austin Univ. Michigan, Ann Arbor Ioffe Institute
2013	Hybrid QD silicon lasers	University of Tokyo
2014	QD silicon lasers	UC Santa Barbara

Commercialization

2001	Zia Laser Inc.	USA
2003	NL Nanosemiconductor – GmbH	Germany
2006	QD lasers	Japan

Fabrication



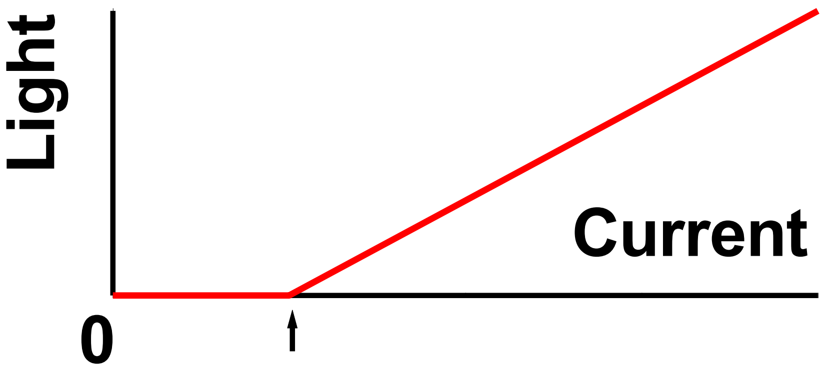
Stranski-Krastanov growth

- **Self-assembling dot formation;**
- **Various material systems;**
- **Emission wavelength depends on material gap and dot size**

Common structure for fiber communications: **InAs dots**	on	**GaAs substrats** ~1.31 µm emission MOCVD, MBE, MOVPE	**InP substrats** ~1.55 µm emission CBE, MBE, MOCVD

M. T. Crowley et al., Semiconductors and Semimetals: Advances in Semiconductor Lasers, Vol. 86, pp. 371-405, (2012)

Advantages of idealized QD lasers



$$j_{th} = j_0 \exp(T/T_0)$$

→ Significantly lower threshold current density j_{th}

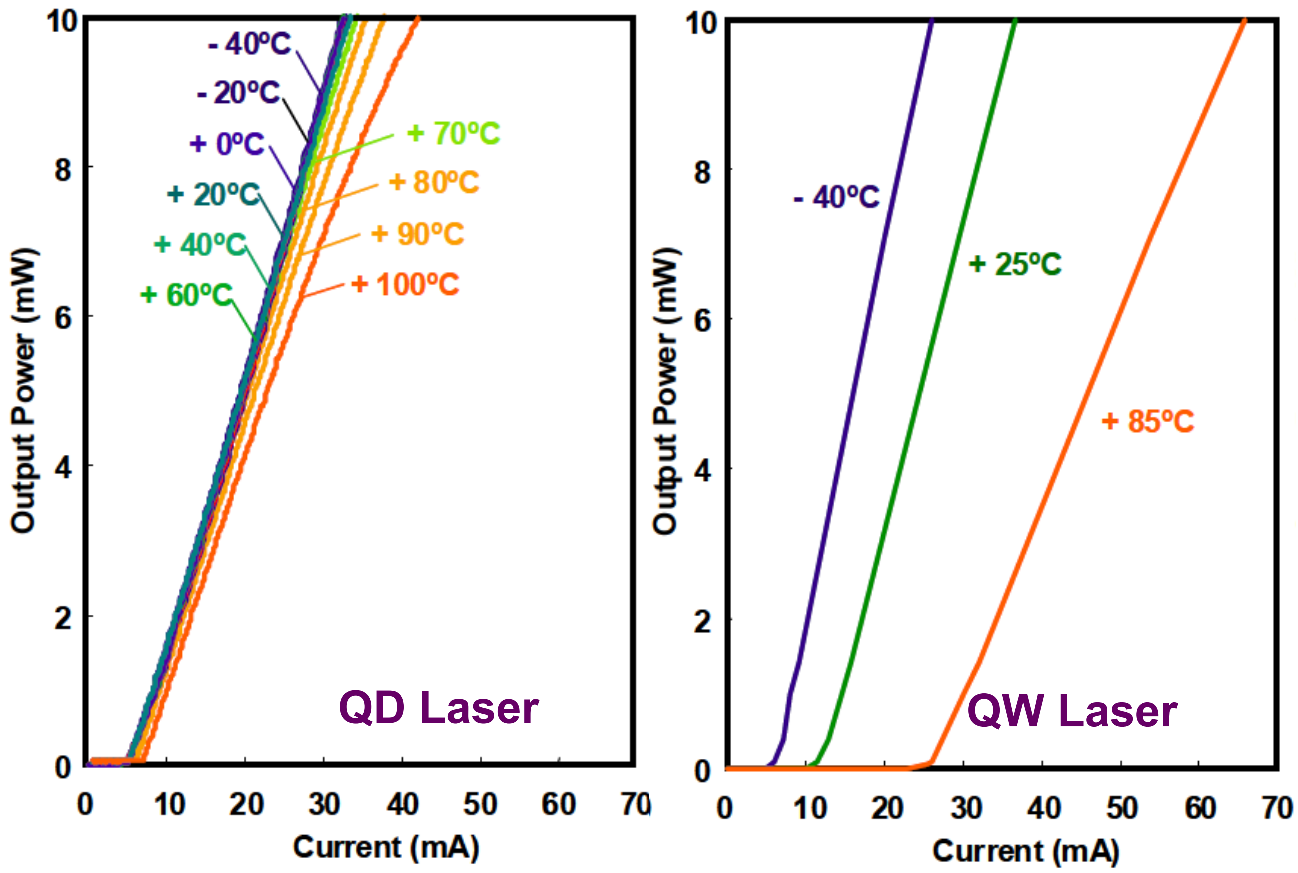
→ Significantly weaker temperature dependence of j_{th}; ideally, temperature-insensitive j_{th} $(T_0 = \infty)$

→ Superior opportunity for tuning gain spectrum width & emission wavelength (color of light)

→ Low chirp (shift of lasing wavelength with injection current); ideally, zero $\alpha-$ factor

Advantages of QD lasers

Low threshold and high thermal stability



Reduced energy consumption in input power and cooling

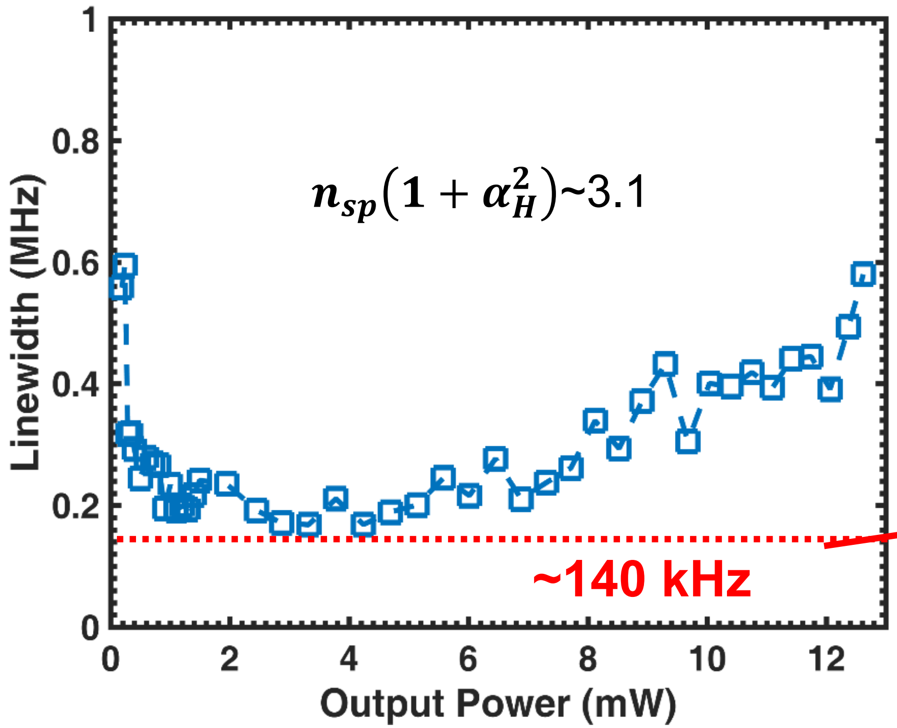
Z. Alferov et al., IEEE J. Sel. Topic. Quantum Electron., vol. 6, pp. 832 (2000)

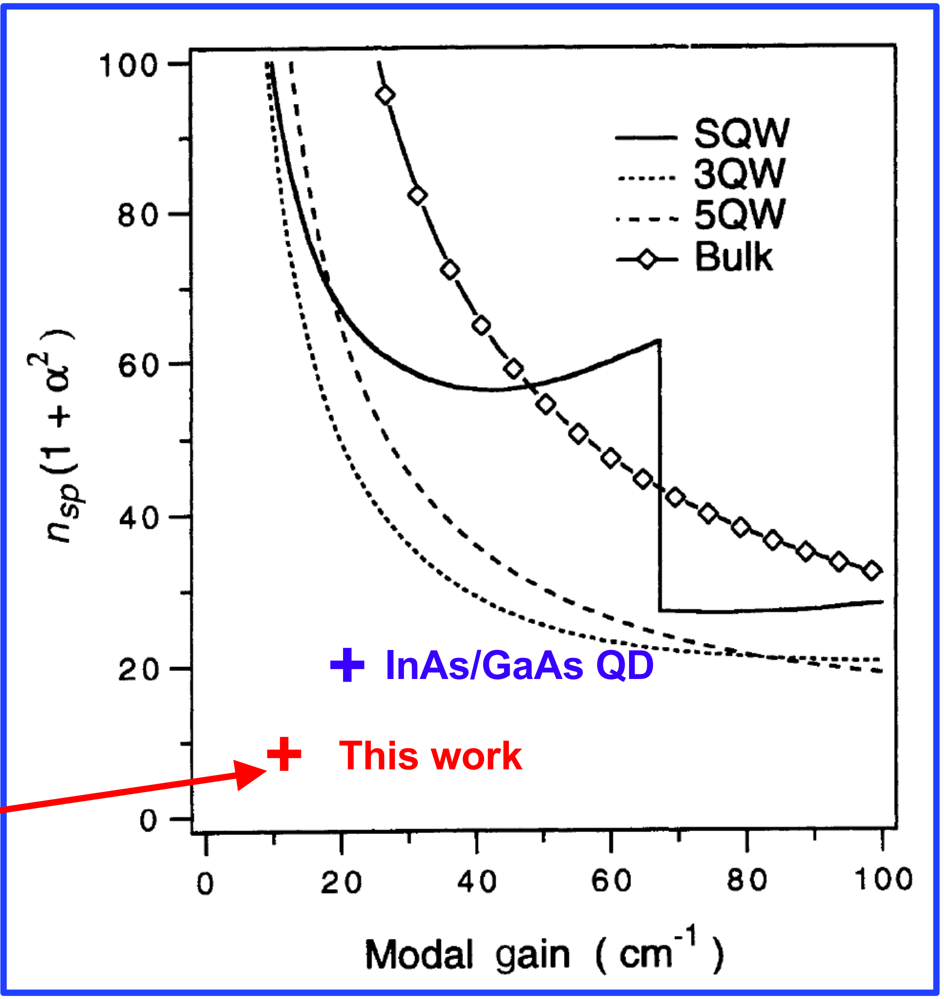
QD Laser Inc., White Paper, qdlaser.com (2008)

Advantages of QD lasers

Narrow linewidth QD lasers

$$\Delta\nu = \frac{h\nu v_g^2 \Gamma G_{th} n_{sp} \alpha_m}{4\pi P}\left(1+\alpha_H^2\right)$$

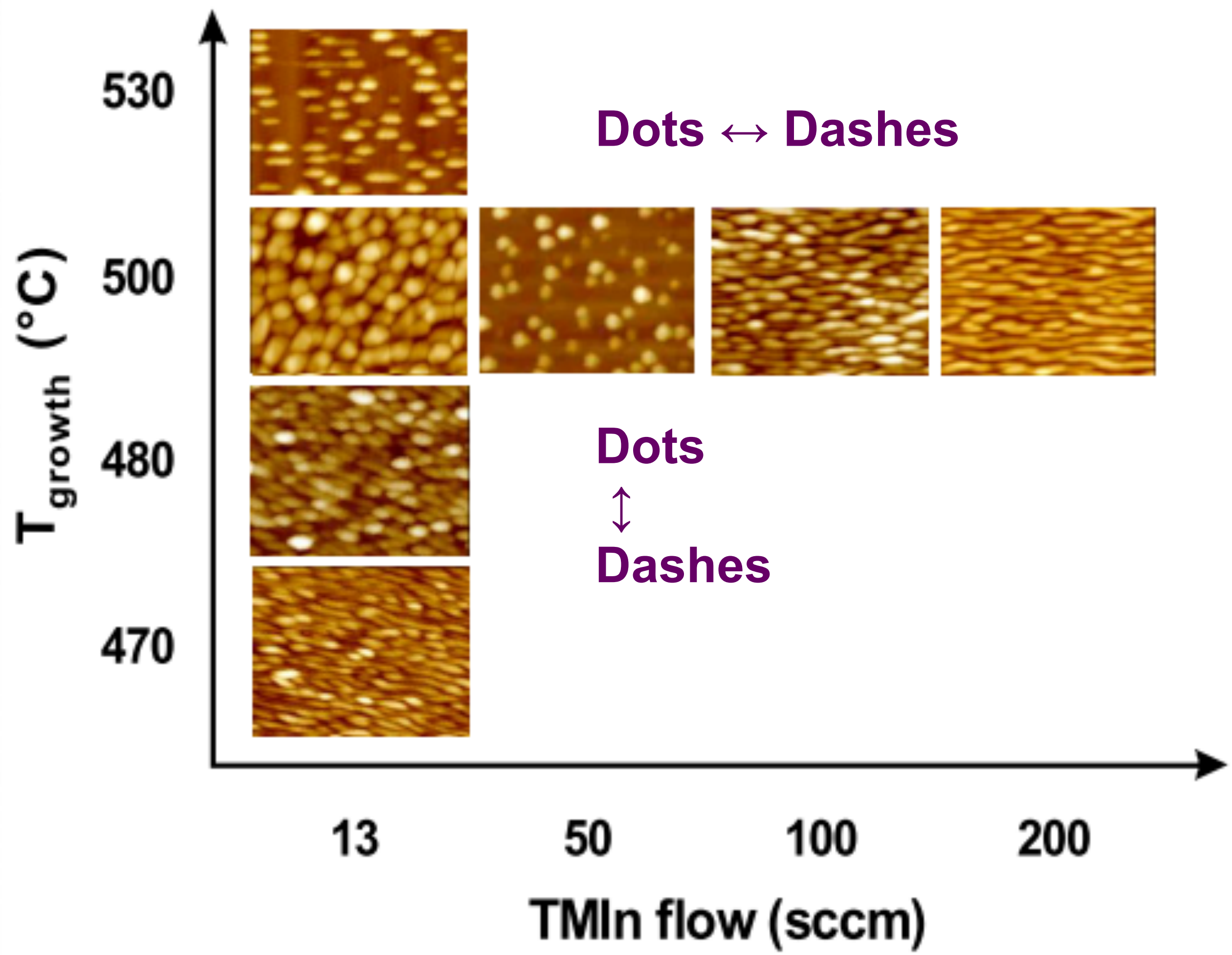




E. Kapon, Semiconductor lasers I Fundamentals, Elsevier Science (1999)
J. Duan et al., Coumpound Semiconductor Week, paper C7.4, Berlin (2017)

Self-assembled nanostructures

Variation of growth parameters (AFM 1x1 µm)

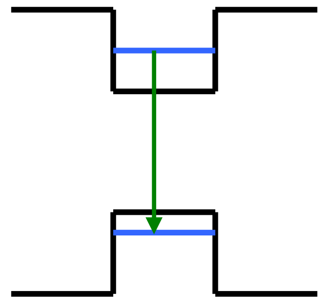


A. Lenz et. Al, Appl. Phys. Lett. Vol. 95, pp. 203105 (2009)

Excited states

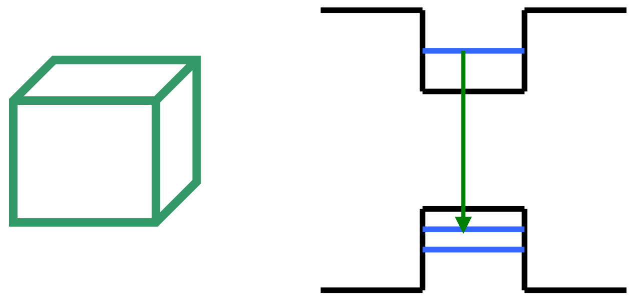
Ideal situation

Single electron level
Single hole level



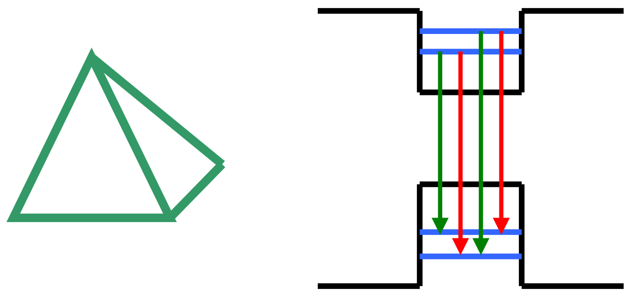
Satisfactory situation (high-symmetry QDs)

Single electron level
Multiple hole levels

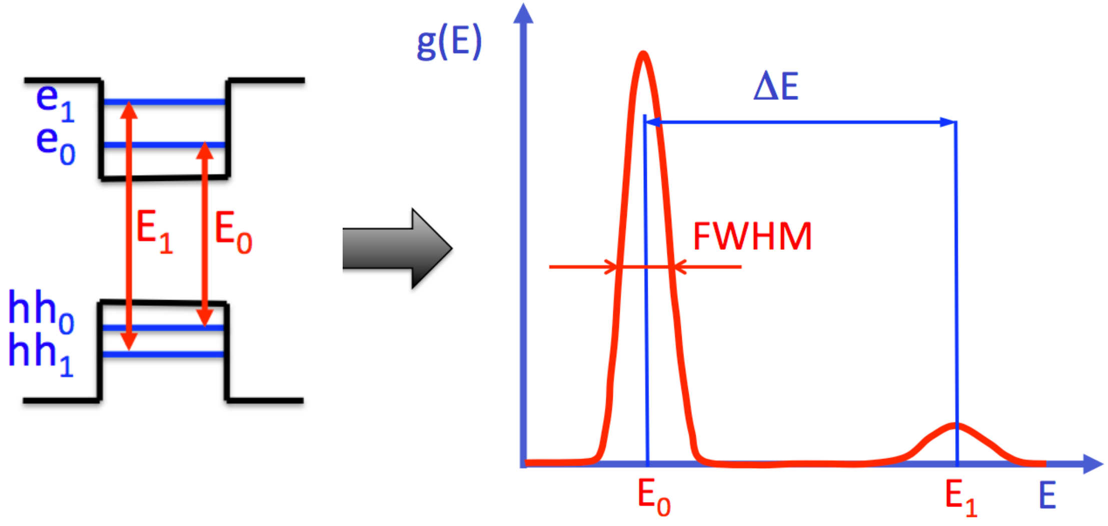


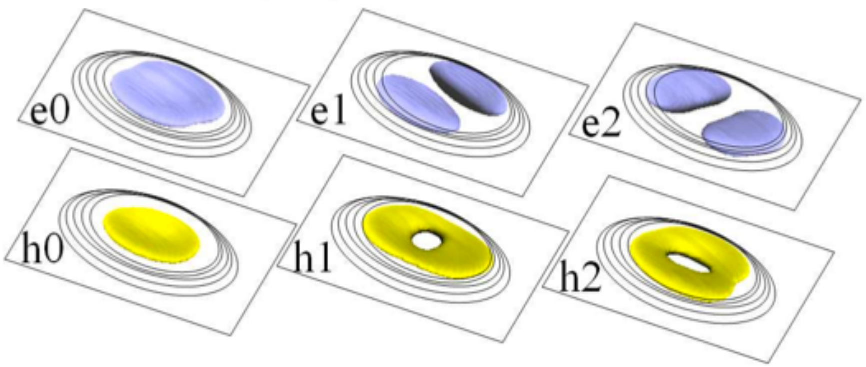
Actual (low-symmetry large-sized QDs)

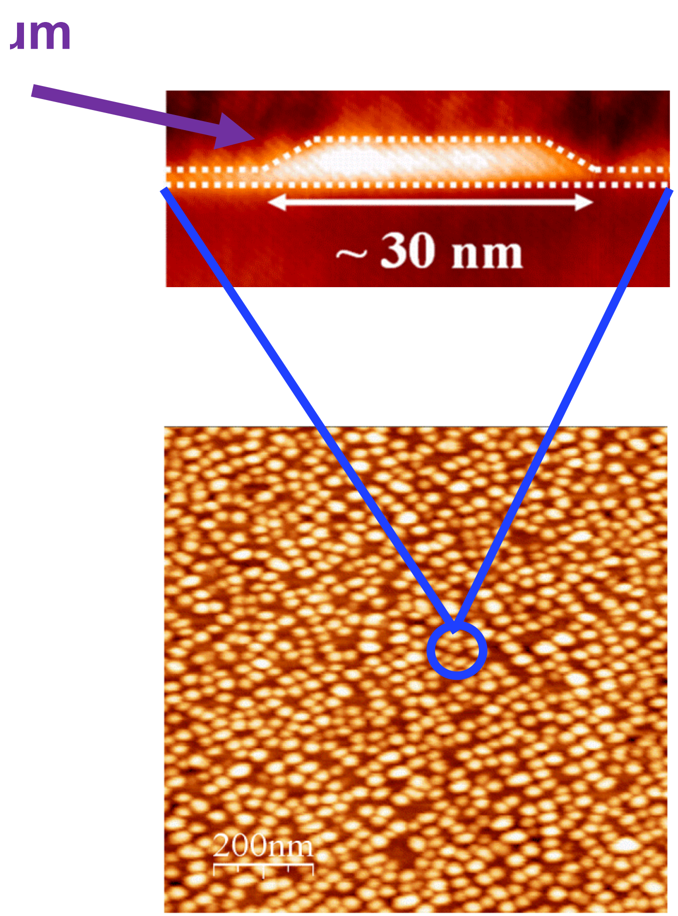
Multiple electron levels
Multiple hole levels



Electronic structure

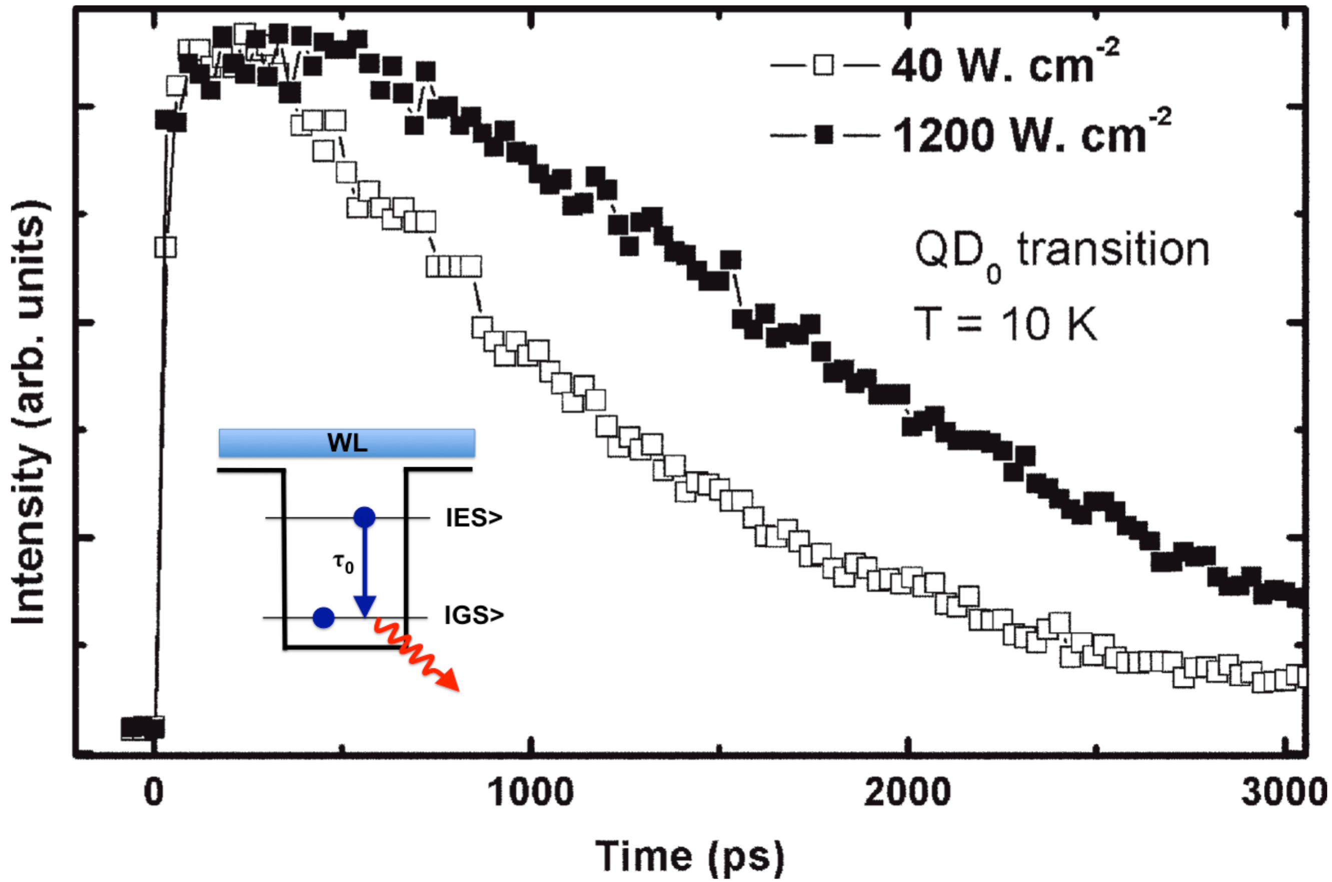






K. Veselinov et al., Optical and Quantum Electronics, Vol. 38, pp. 369-379, (2006)

Intradot relaxation



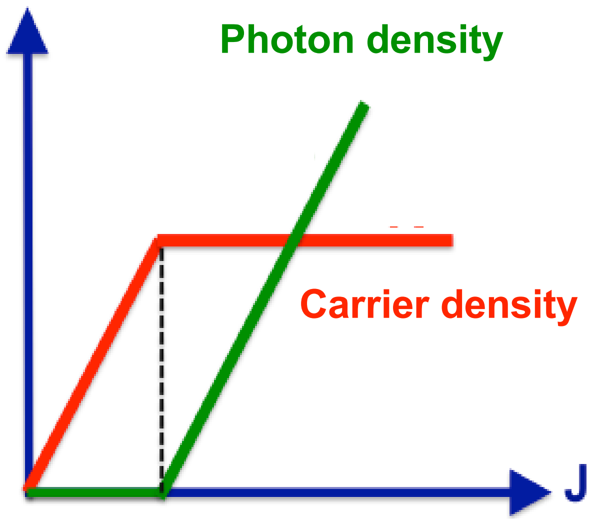
PL rise time: ~ 80 to 10 ps

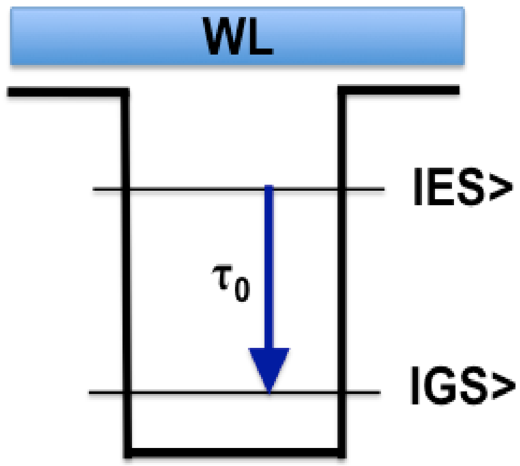
Phonon-assisted relaxation, Auger effect

K. Veselinov et al., Opt. Quant. Electron., vol. 38, pp. 369-379, (2006)

Gain clamping with QD laser

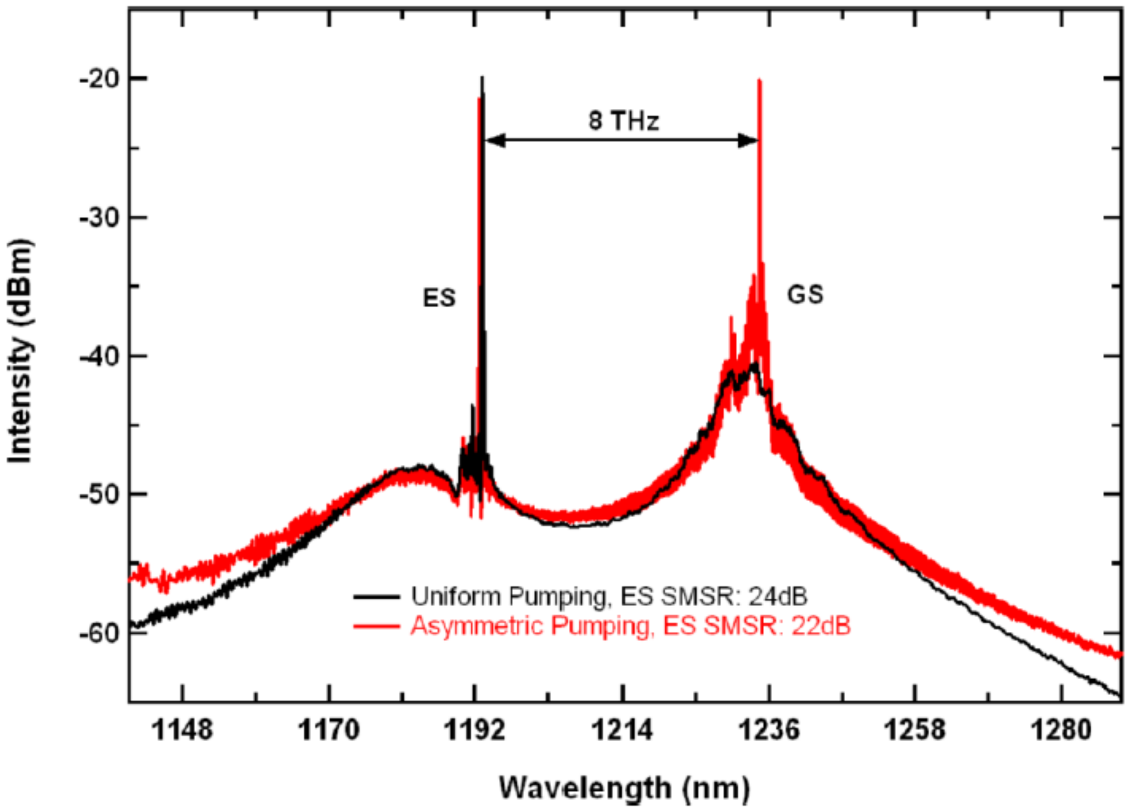
Slow intraband relaxation
Unclamped gain above threshold
Dual state lasing





B. Lingnau et al., New J. Phys., vol. 15, pp. 093031 (2013)
N. A. Naderi et al., Opt. Express, vol. 18, pp. 136197 (2010)

Gain clamping with QD laser



→ **Oscillator strength: Richer & complex dynamics**

B. Lingnau et al., New J. Phys., vol. 15, pp. 093031 (2013)
N. A. Naderi et al., Opt. Express, vol. 18, pp. 136197 (2010)

Non uniformity of QDs

Adversely affected characteristics:

Gain decreases

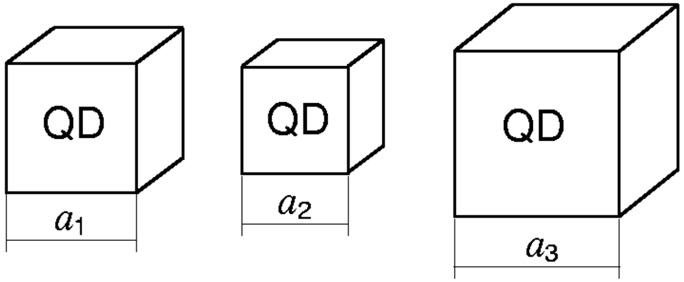
J_{th} increases & is more *T*-sensitive

(T_0 decreases)

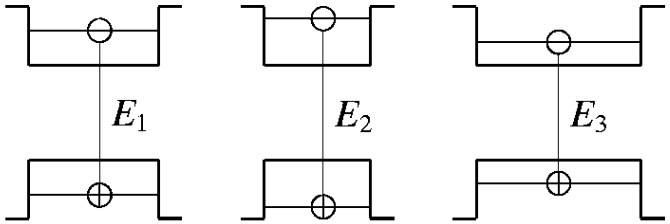
Output power decreases

Advantages can only be realized if QDs are sufficiently uniform

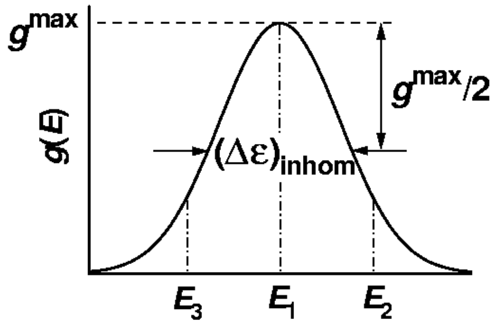
Fluctuations in QD sizes



Fluctuations in energy levels in QDs



Inhomogeneous line broadening



Non uniformity of QDs

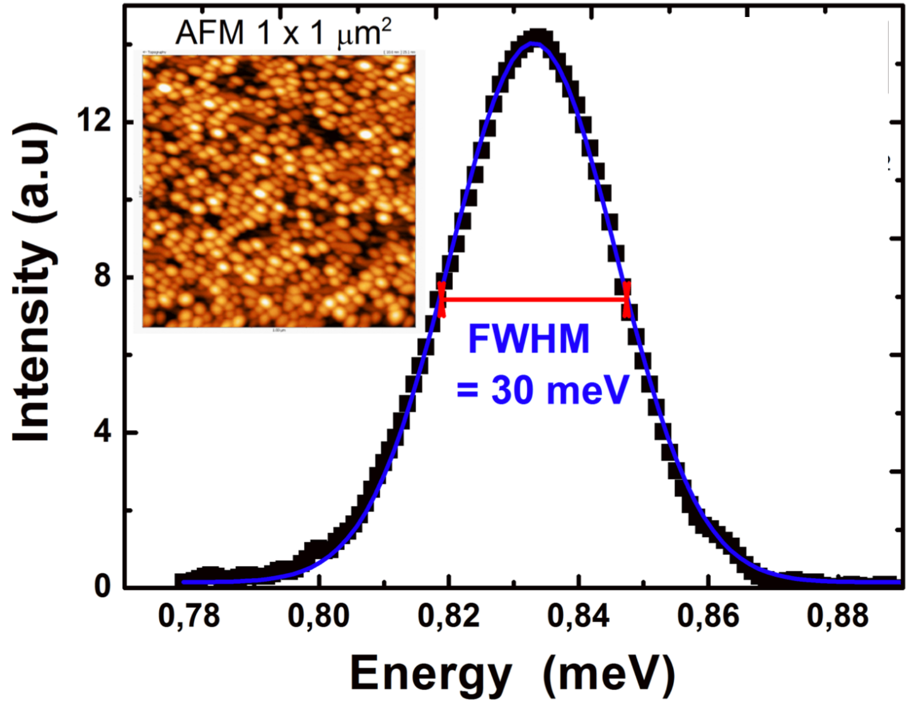
Adversely affected characteristics:

Gain decreases

J_{th} increases & is more T-sensitive

(T_0 decreases)

Output power decreases

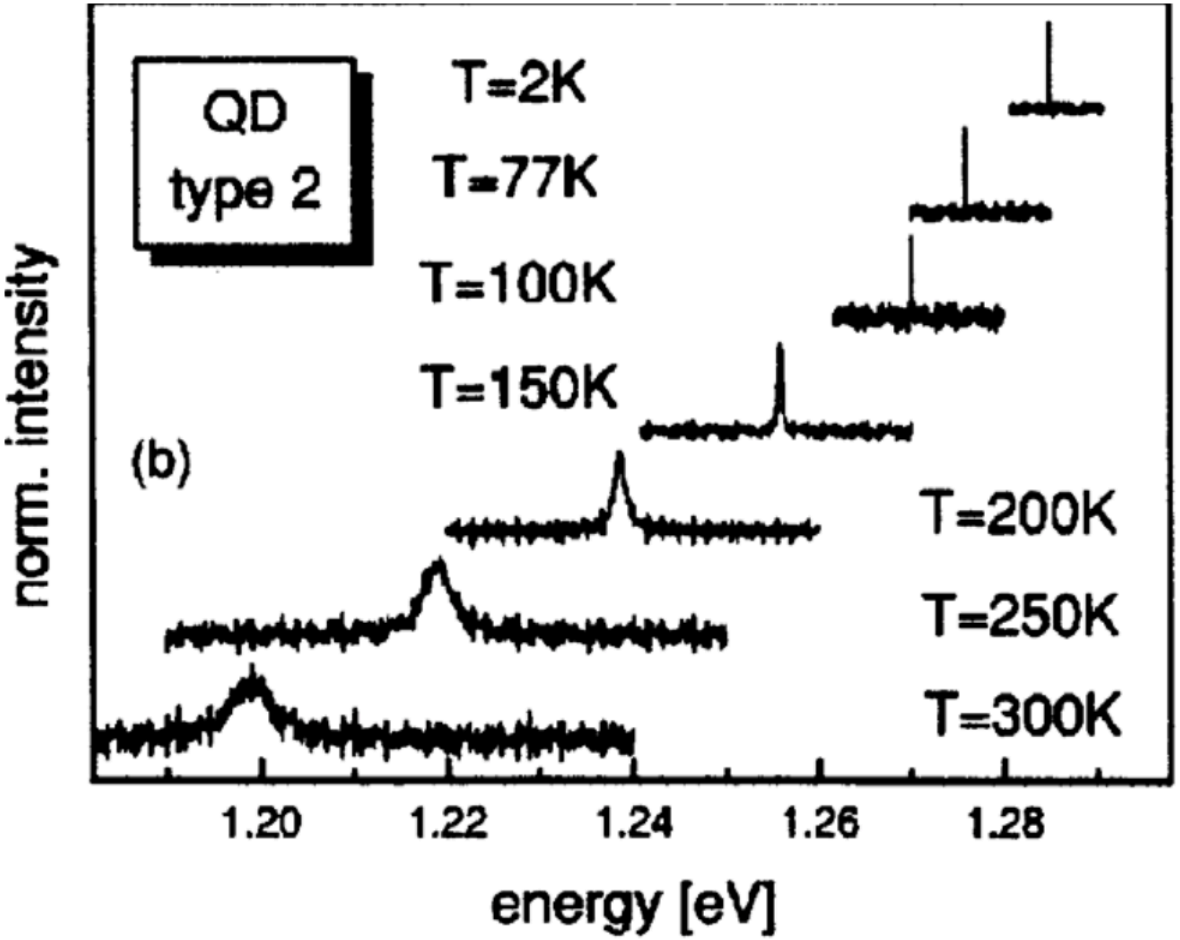


Courtesy of Prof. Reithmaier
(U. Kassel, Germany)

Advantages can only be realized if QDs are sufficiently uniform

Non uniformity of QDs

Single dot spectroscopy reveals the temperature dependence of the homogeneous broadening



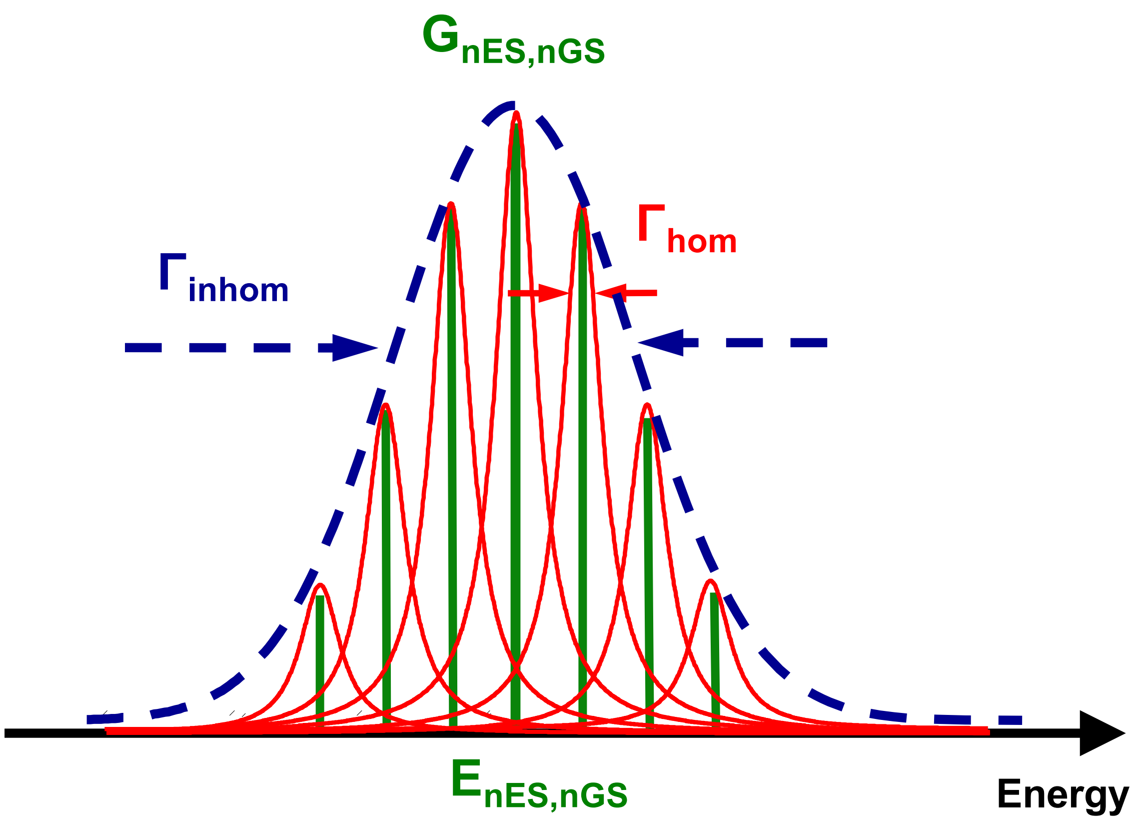
M. Bayer and A. Forchel, Phys. Rev. B, Vol. 65, (2002)

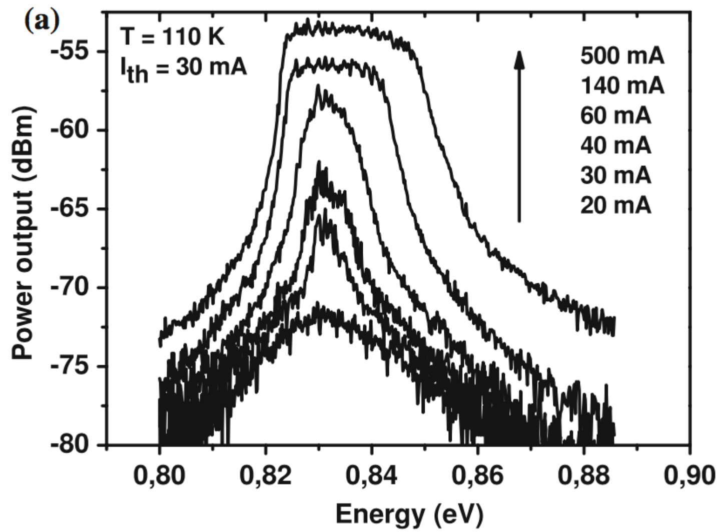
Non uniformity of QDs

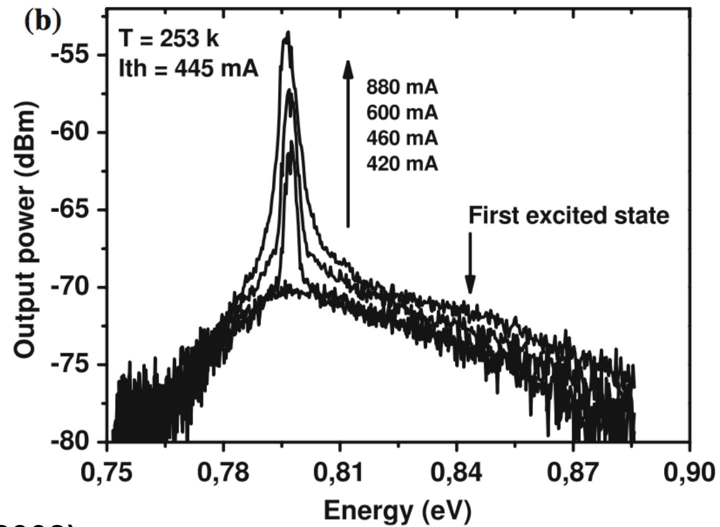
A direct competition between line broadening mechanisms

Low temperature, many independent emitters

High temperature, carrier thermalization







K. Veselinov et al., Optical and Quantum Electronics, Vol. 40, pp. 227-237, (2008)

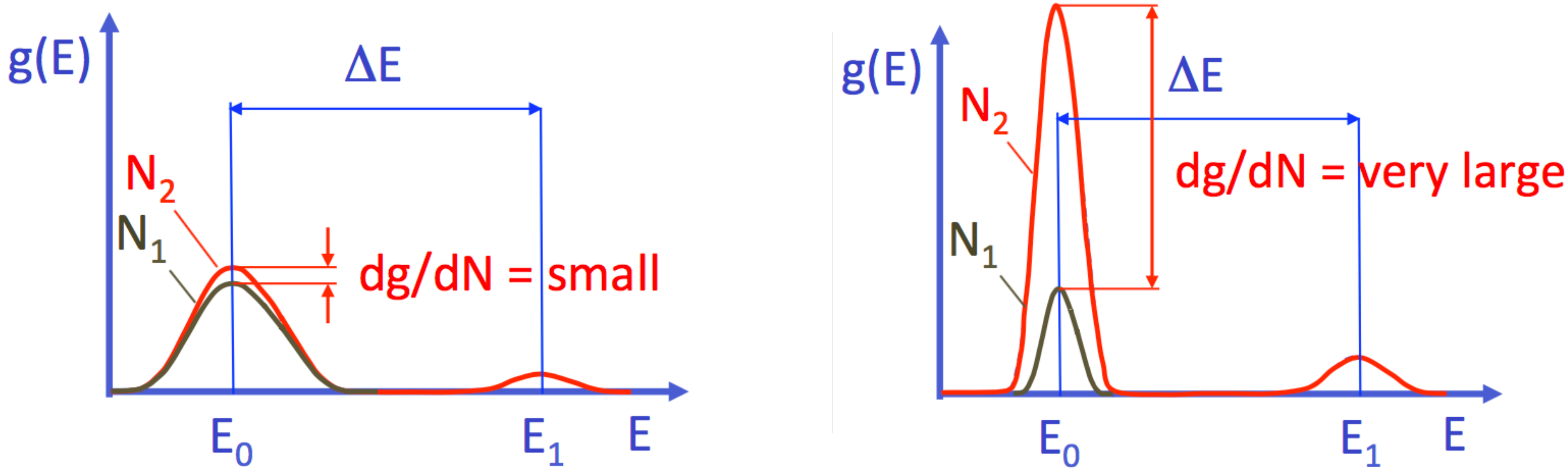
Linewidth broadening factor

$$\alpha_H = -\frac{4\pi}{\lambda}\frac{dn/dN}{dG_m/dN}$$

Contributing features to α_H-factor in QD lasers

Discrete higher energy levels

Dot size dispersion (inhomogeneous broadening)

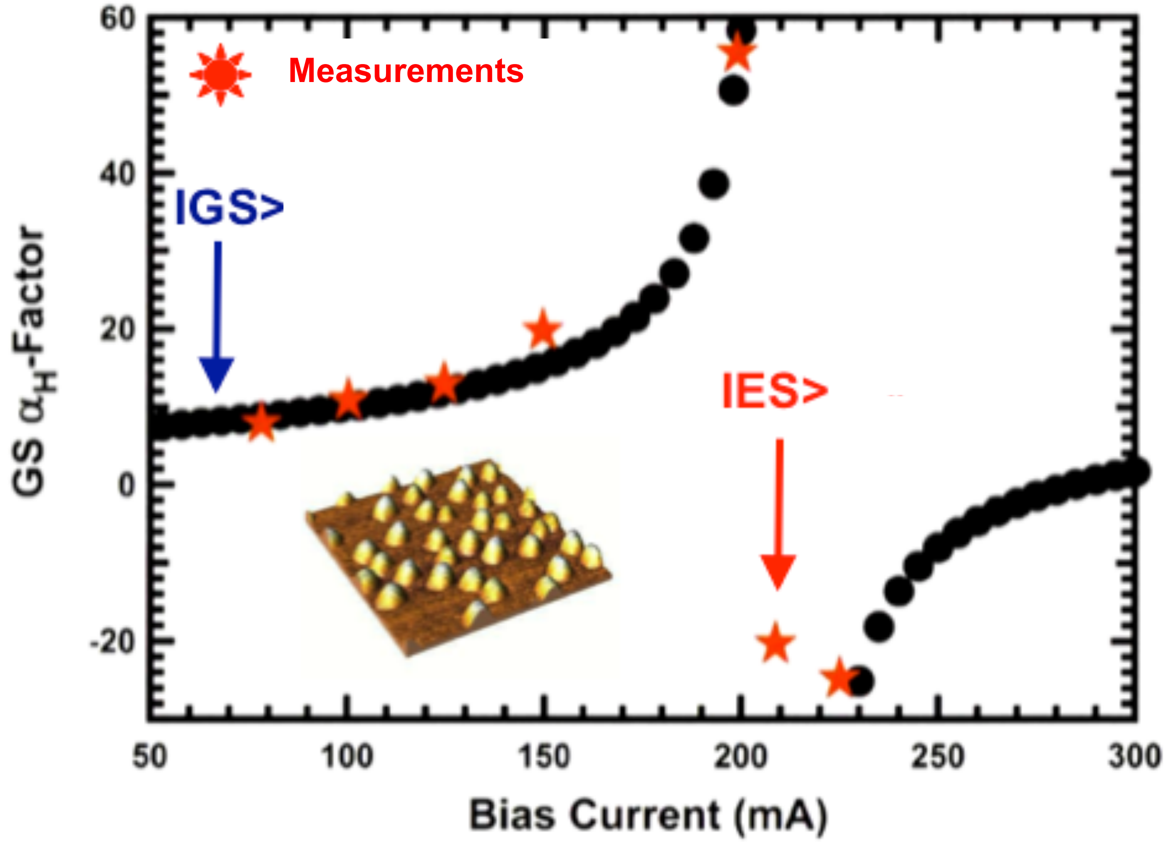


Crucial for understanding the dynamical complexity of semiconductor lasers

D. Bimberg et al., Quantum Dot Heterostructures, John Wiley & Sons (1999)

Linewidth broadening factor

Two-state lasing operation balloons the α_H-factor of the GS transition



F. Grillot et al., IEEE Journal of Quantum Electronics, Vol. 44, pp. 946-963, (2008)

Dynamical features of lasing states

Ground-state lasing

Highly damped;

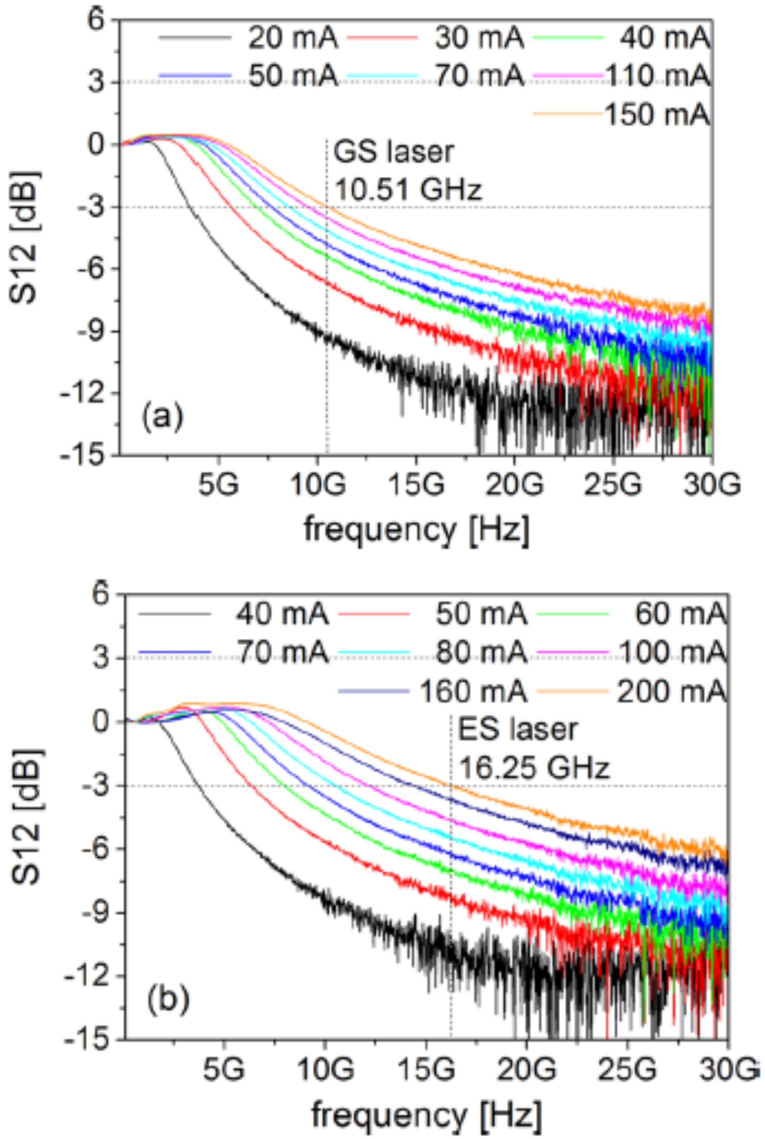
Lower modulation bandwidth

Excited-state lasing

Higher material gain;

Better modulation performances

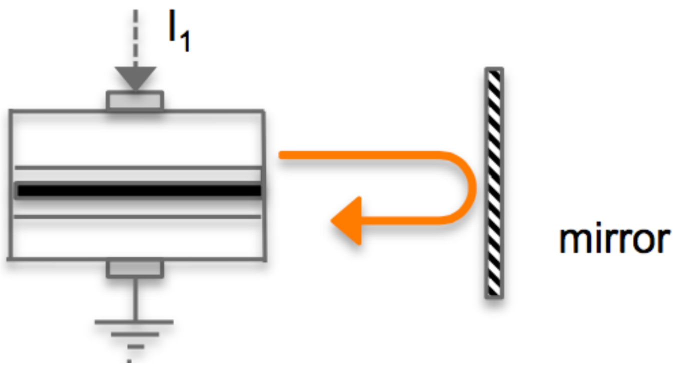
Nonlinear dynamical characteristics of QD lasers? Impact of the lasing states?



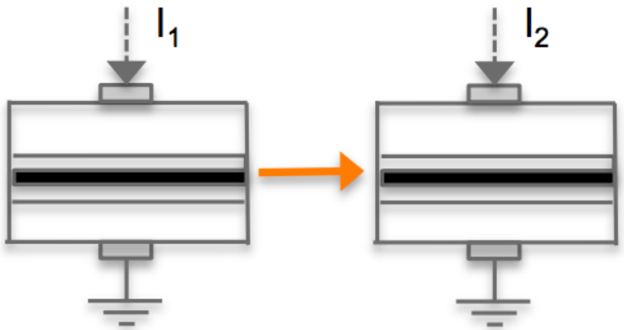
D. Arsenijević et al., Appl. Phys. Lett., Vol. 104, pp. 181101 (2014)

QD lasers with optical perturbations

Optical feedback



Optical injection



Nonlinear physical mechanism must exist

Linewidth broadening factor > 0

Coupling between gain and refractive index

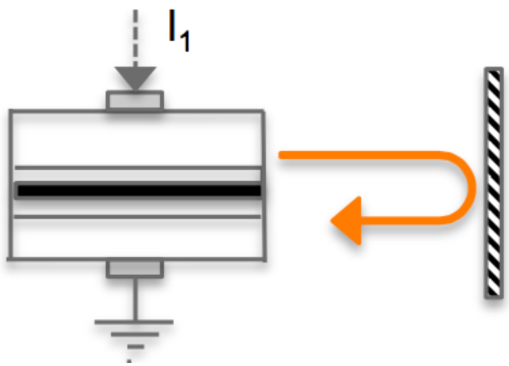
Coupling between field magnitude and phase

→ Okay for bulk and quantum well lasers

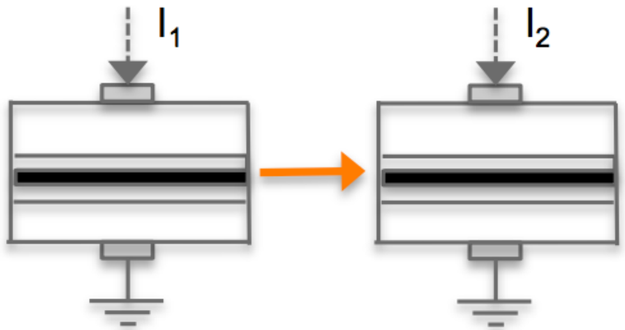
M. Sciamanna and K. A. Shore, Nature Photonics, Vol. 9, pp. 151-162, (2015)

QD lasers with optical perturbations

Optical feedback



Optical injection



Peculiar features from QD lasers

Vertical coupling (E_{GS}-E_{ES})

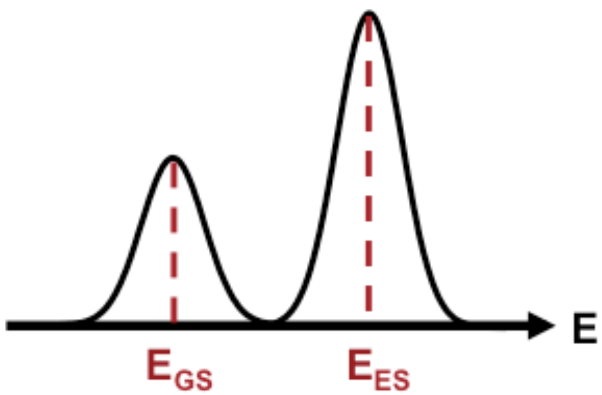
Inhomogeneous broadening

α_H-factor

Oscillator strength

→ Richer nonlinear dynamics

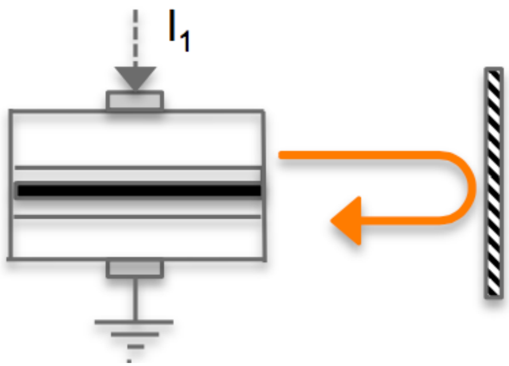
InAs/GaAs

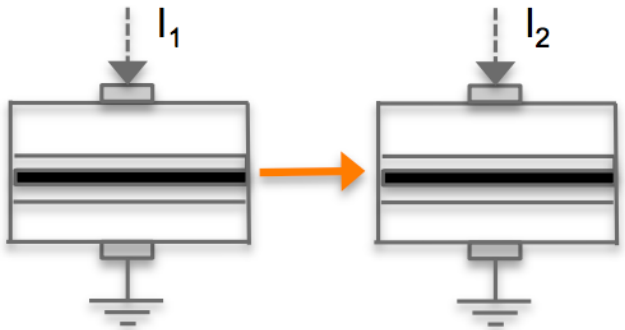


$\Gamma_{inhom} < E_{ES}$-E_{GS}

QD lasers with optical perturbations

Optical feedback | **Optical injection**





Peculiar features from QD lasers

Vertical coupling (E_{GS}-E_{ES})

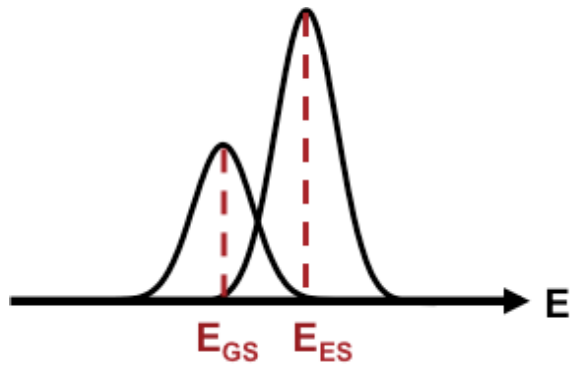
Inhomogeneous broadening

α_H-factor

Oscillator strength

→ Richer nonlinear dynamics

InAs/InP



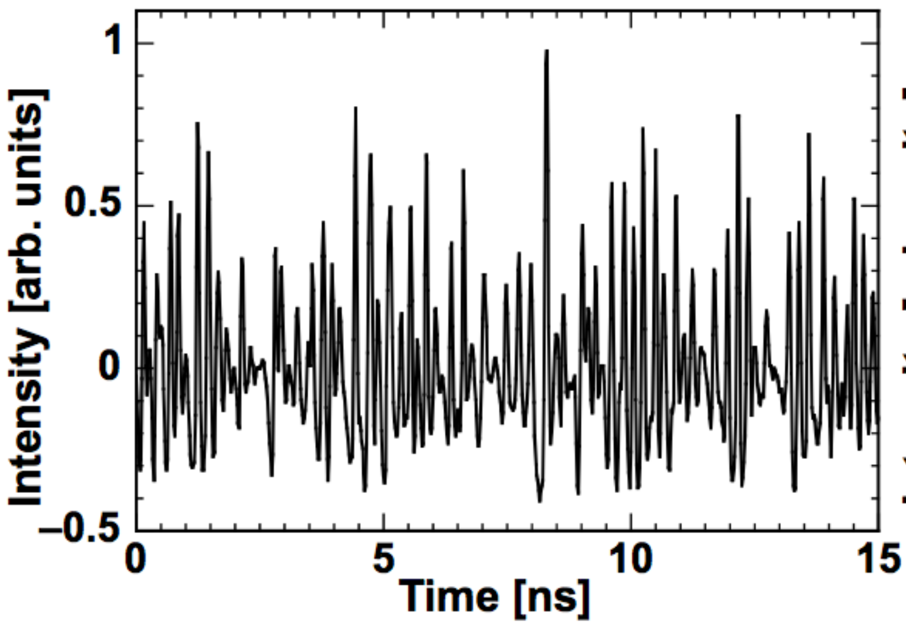
$\Gamma_{inhom} \approx E_{ES}\text{-}E_{GS}$

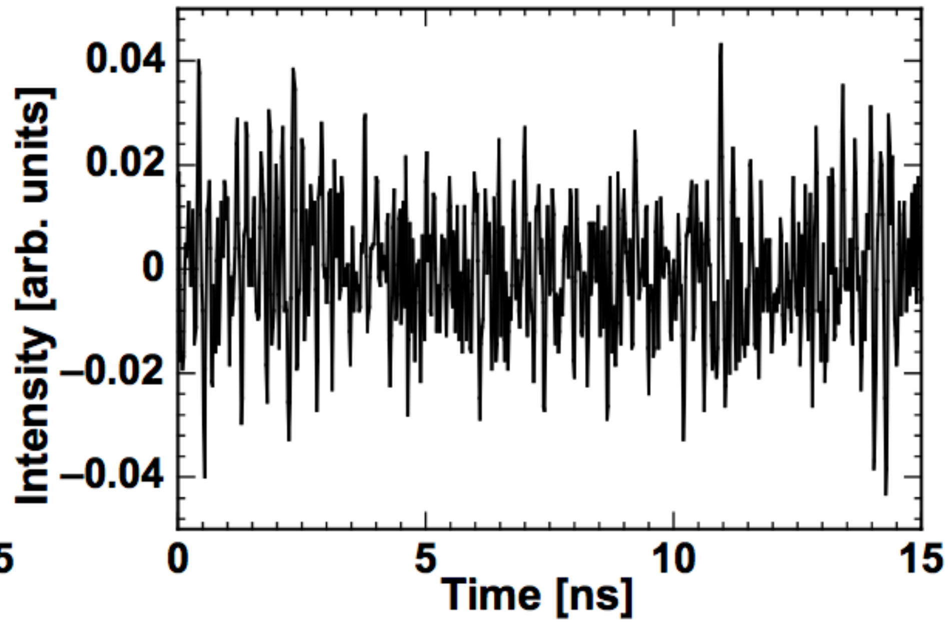
Route to chaos

Undamping of the relaxation oscillations leads to deterministic chaos

	Population lifetime (carrier lifetime) [s]	Photon lifetime [s]	Relaxation oscillation frequency [Hz]
Semiconductor lasers	10^{-9}	10^{-12}	$\sim 10^{9}$
Solid-state lasers	10^{-3}	10^{-9}	$\sim 10^{5}$
Gas lasers	10^{-8}	10^{-7}	$\sim 10^{6}$

$$T = \frac{\tau_c}{\tau_p}$$



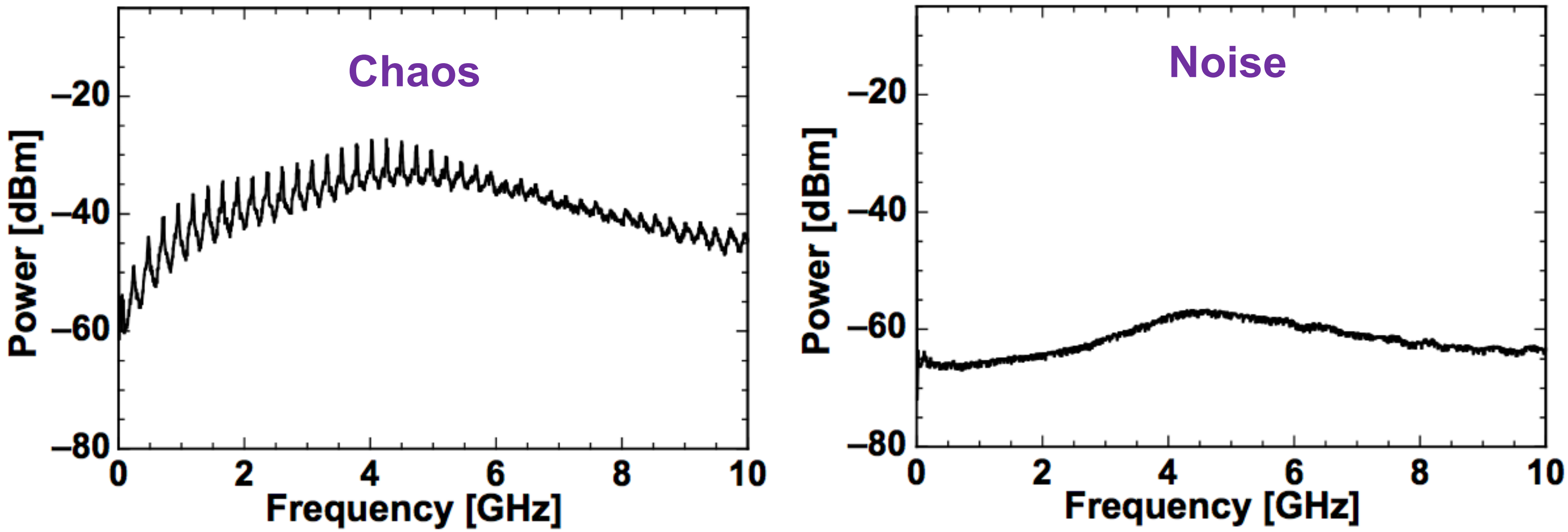


Route to chaos

Undamping of the relaxation oscillations leads to deterministic chaos

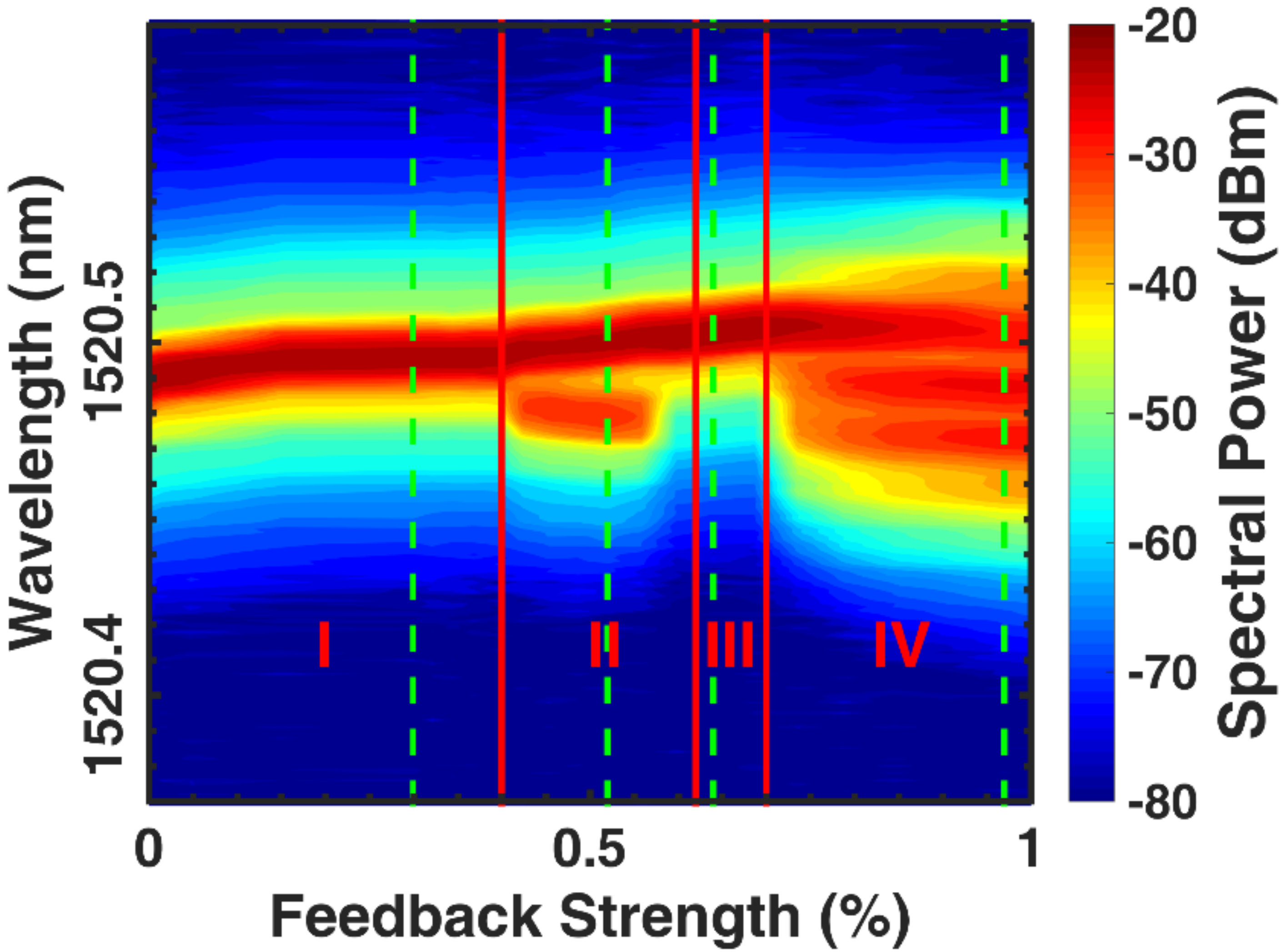
	Population lifetime (carrier lifetime) [s]	Photon lifetime [s]	Relaxation oscillation frequency [Hz]
Semiconductor lasers	10^{-9}	10^{-12}	$\sim 10^9$
Solid-state lasers	10^{-3}	10^{-9}	$\sim 10^5$
Gas lasers	10^{-8}	10^{-7}	$\sim 10^6$

$$T = \frac{\tau_c}{\tau_p}$$



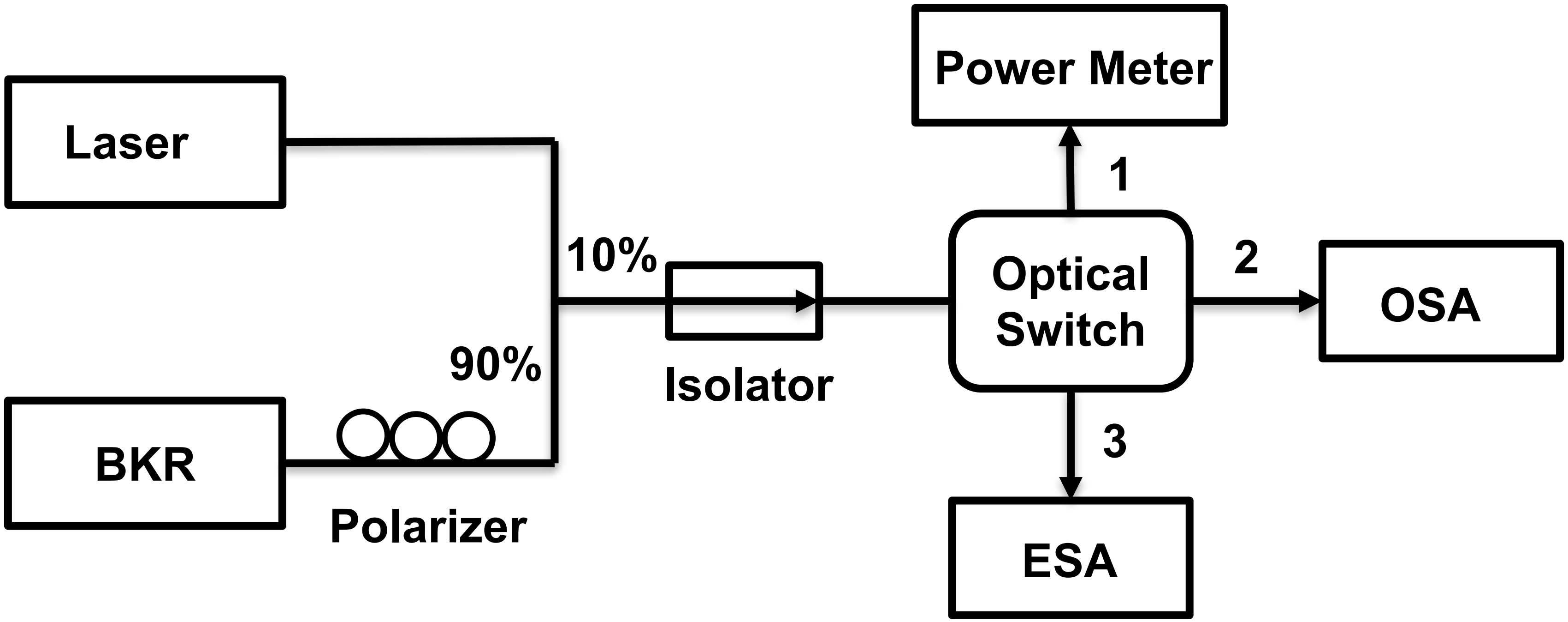
Route to chaos

Undamping of the relaxation oscillations leads to deterministic chaos



Silicon QD lasers

Response to optical feedback of silicon QD lasers grown by hetero-epitaxy?

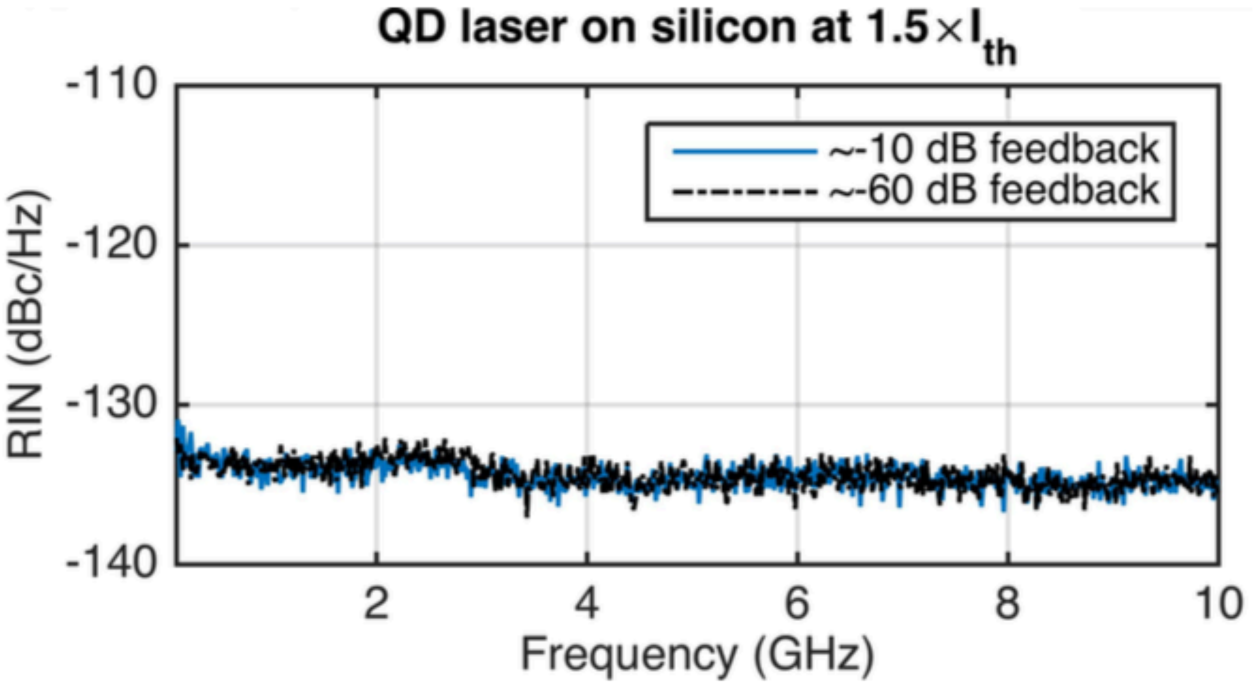


Long delay optical feedback first investigated

Shorter delays should be studied in the near future

Initial results

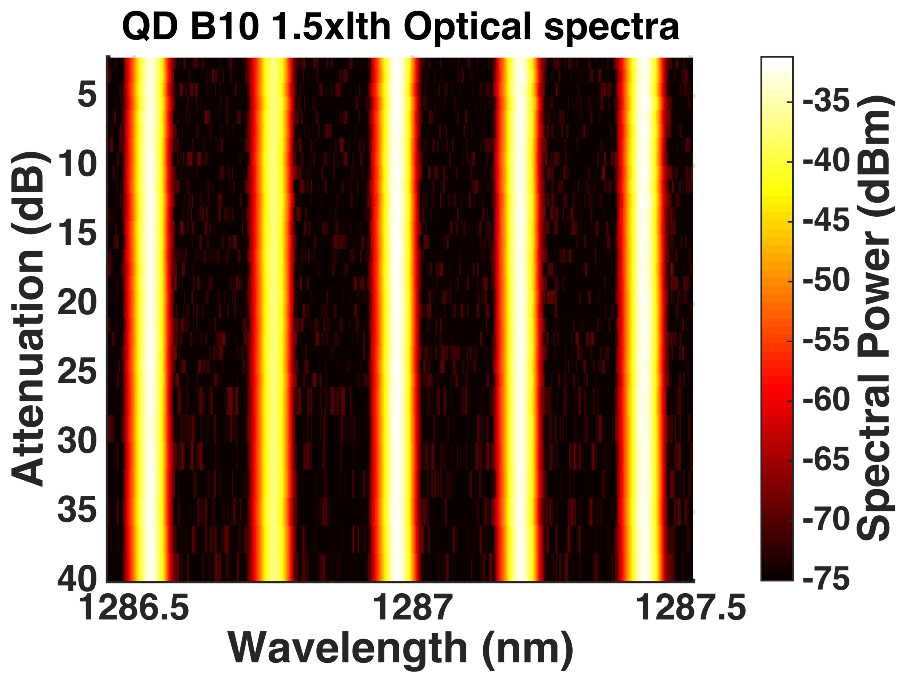
Response to optical feedback of silicon QD lasers grown by hetero-epitaxy

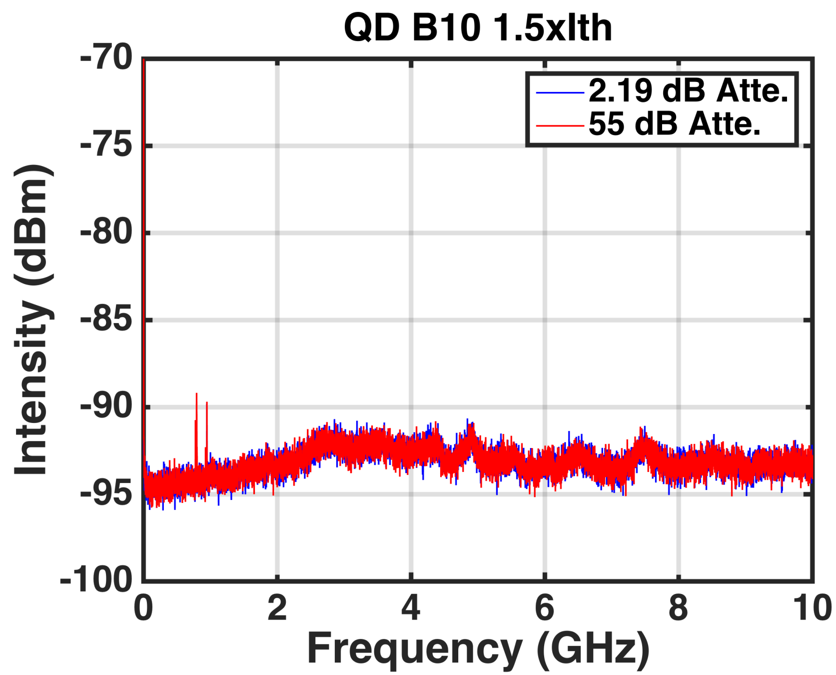


Highly resistance against to optical feedback

A. Y. Liu , Optics Express, Vol. 25, pp. 9535 (2017)

Silicon QD lasers





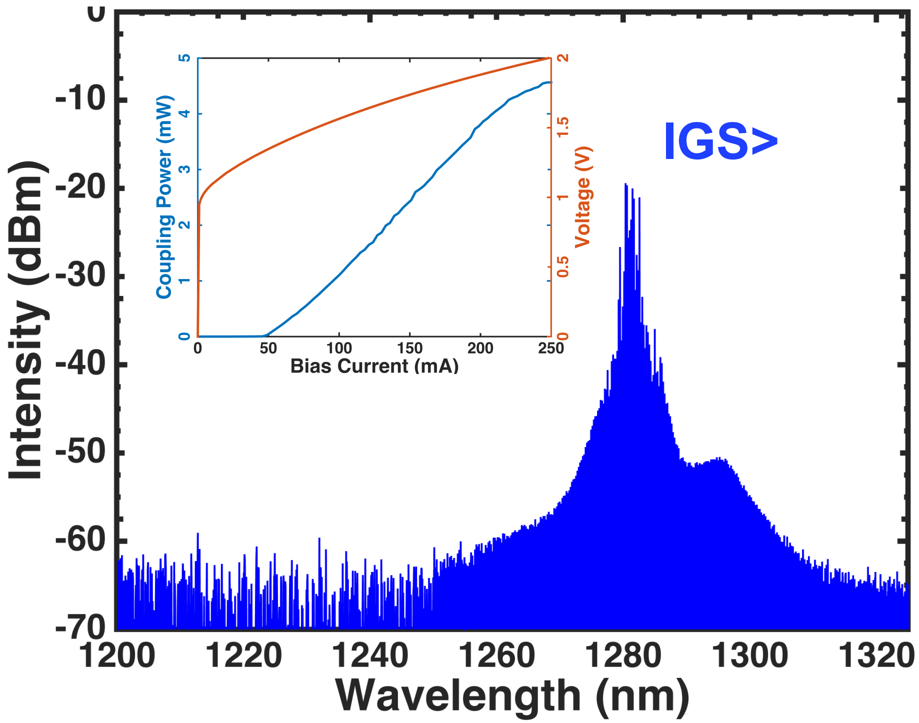
Chaos-free operation

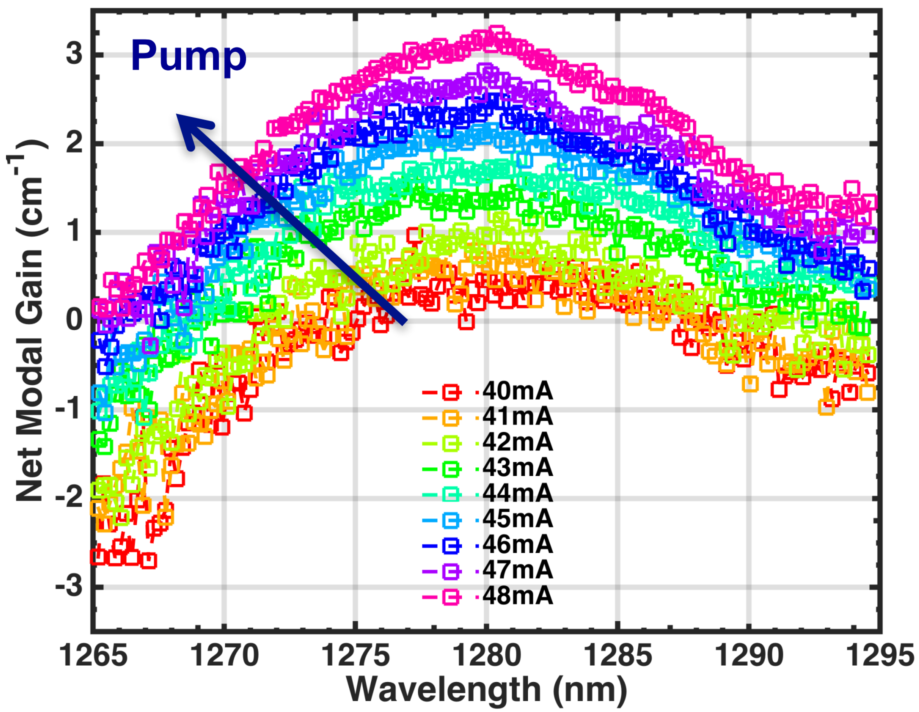
Strong damping of the GS transition?

Low α_H-factor?

Ultralow α_H-factor

Silicon QD lasers with GS lasing line at 1280 nm

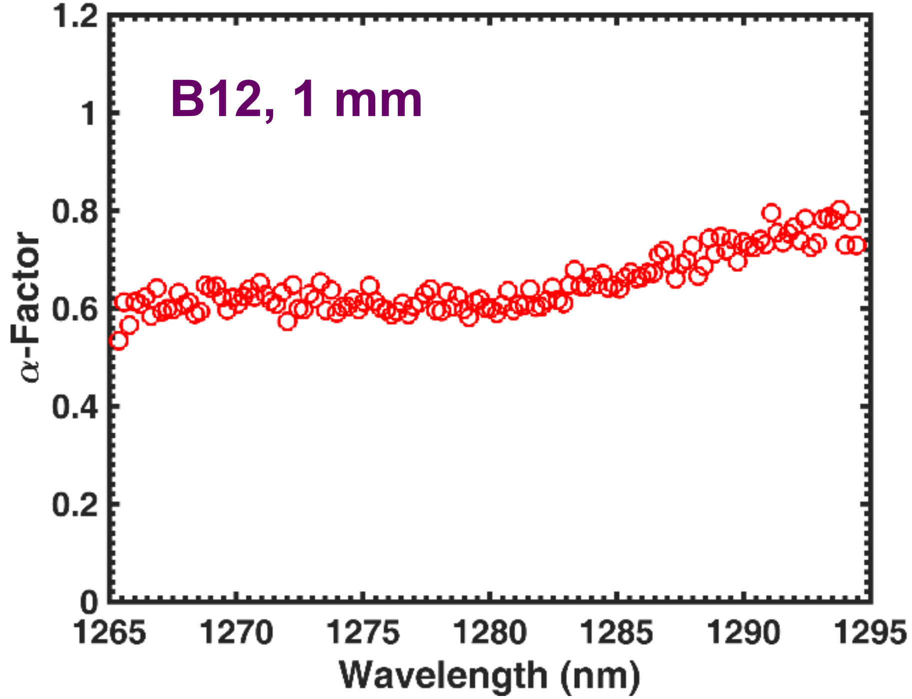


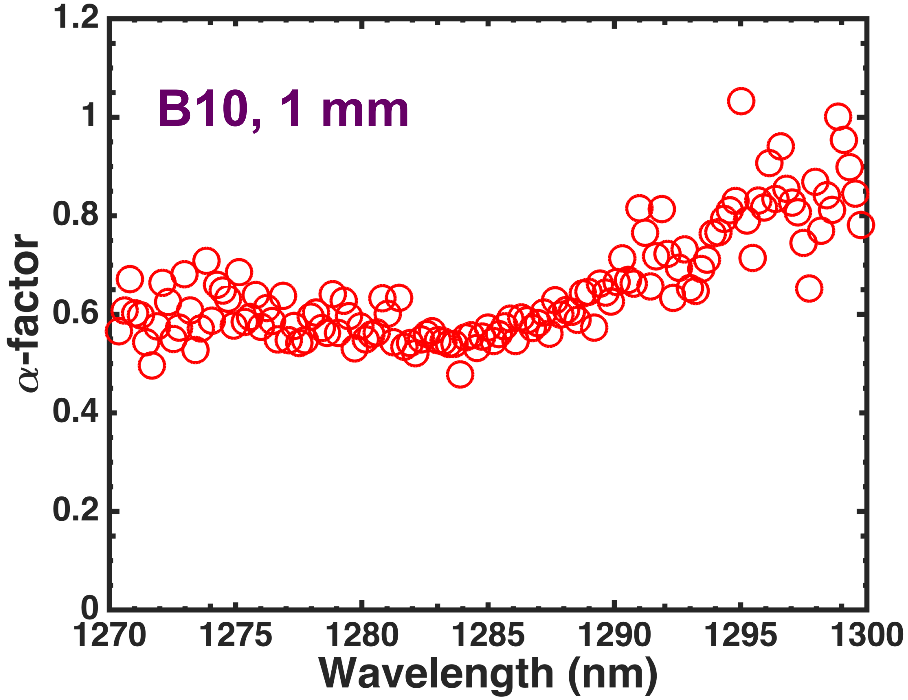


Material gain extracted from amplified spontaneous emission

Ultralow α_H-factor

Silicon QD lasers with GS lasing line at 1280 nm

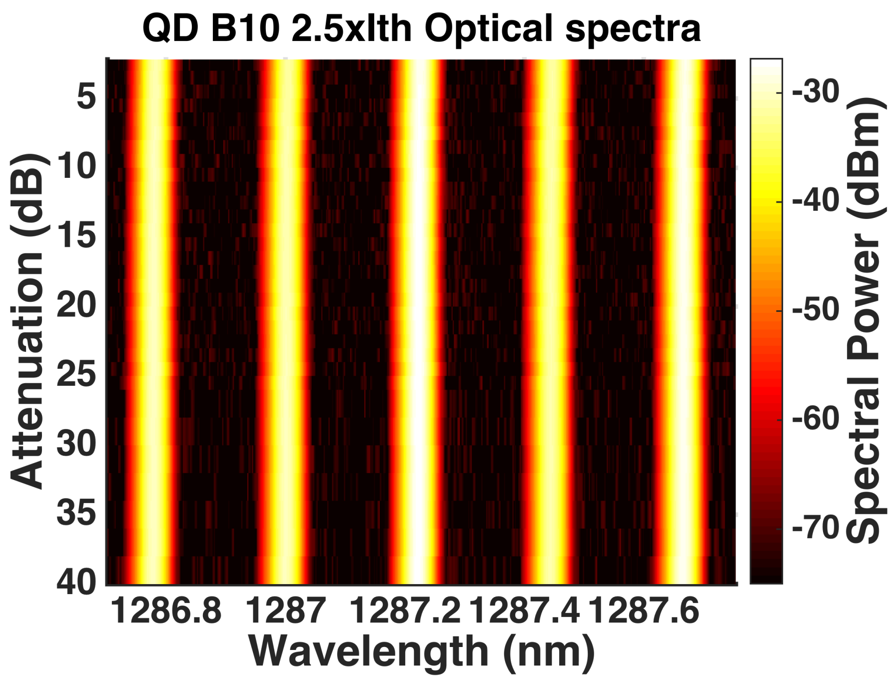


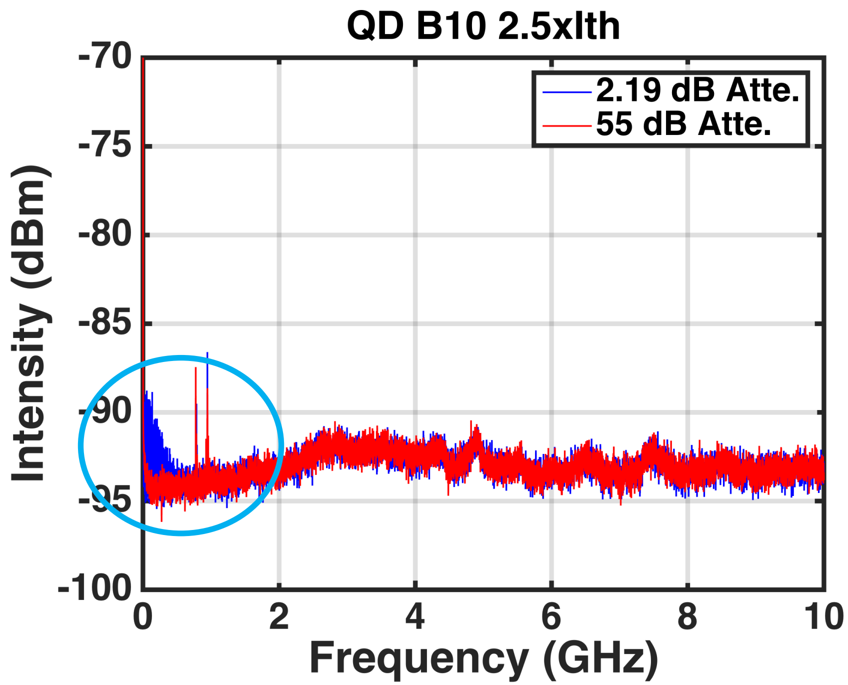


Value at gain peak ~ 0.5

First ever observation of a near zero α_H-factor on a silicon QD laser!

Higher pumping rate



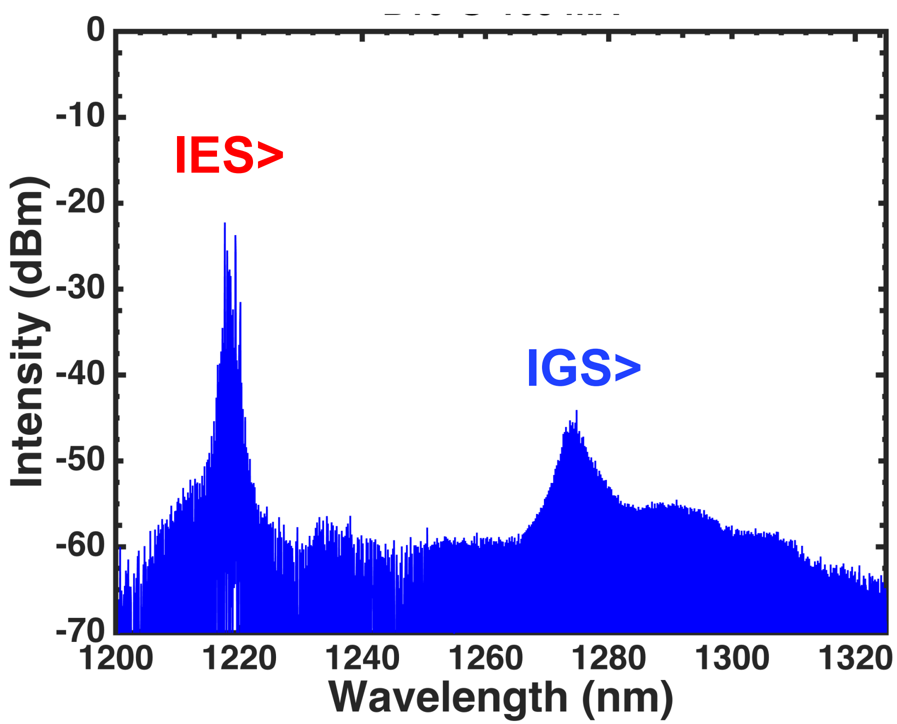


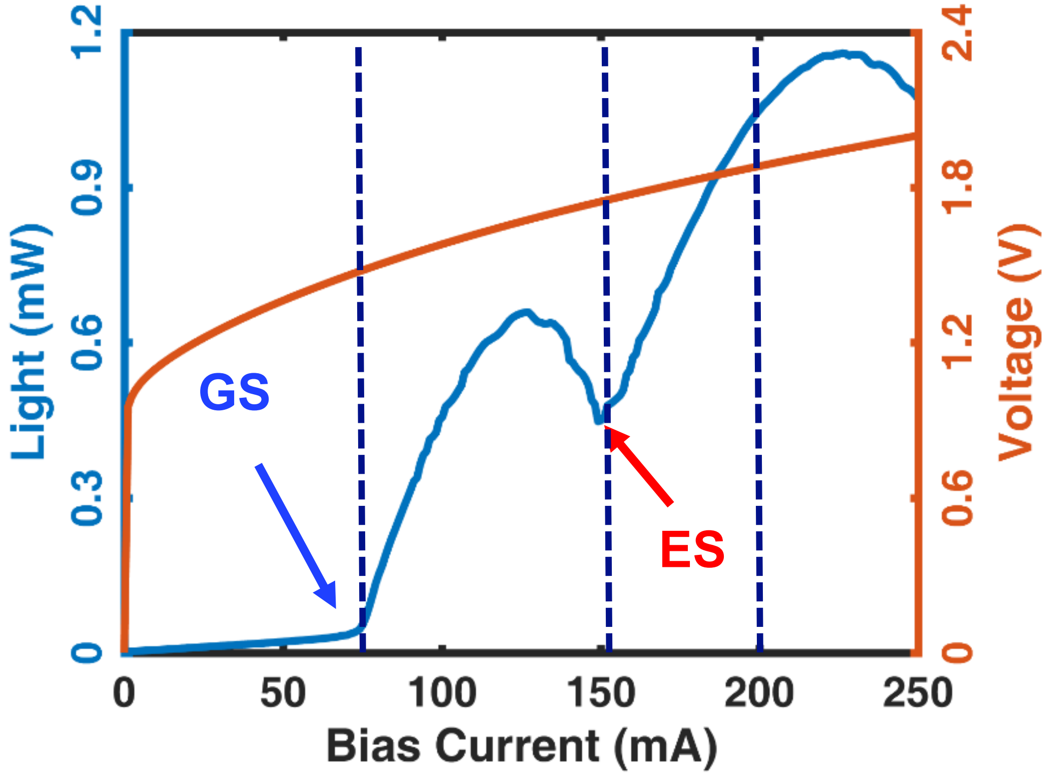
Slight degradation of the electrical spectrum observed at higher pumping

This observation differs from DFB lasers which are usually more robust against optical perturbations at higher bias → FP dynamics is however different because longitudinal modes are in interaction with multiple external cavity modes (long delay)

Two-state lasing dynamics

Silicon QD lasers with GS-ES lasing lines



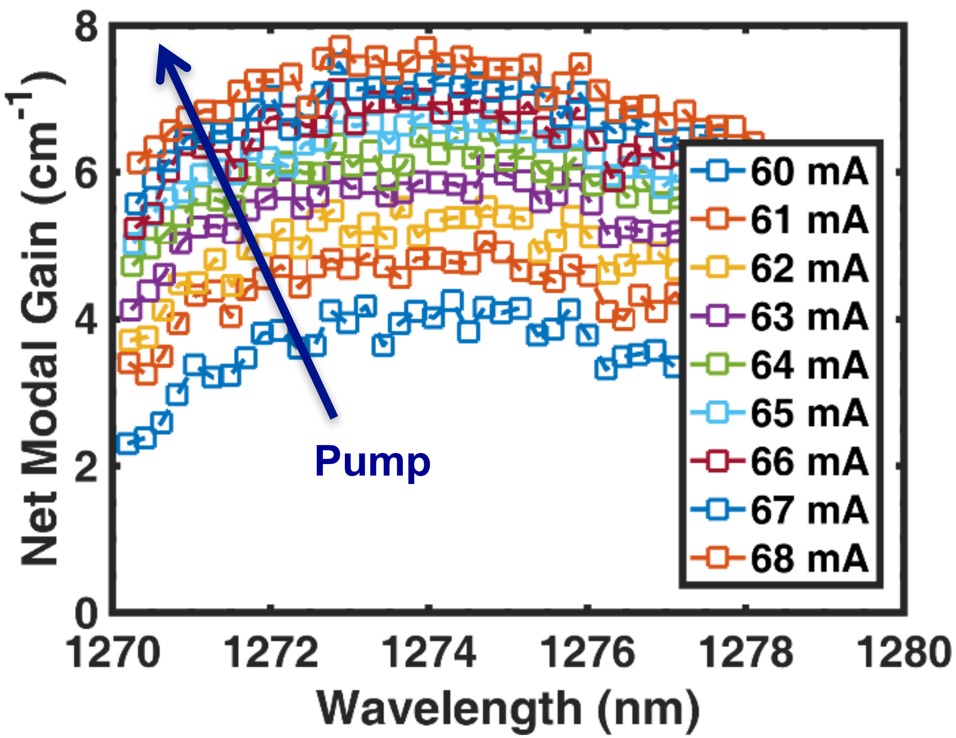


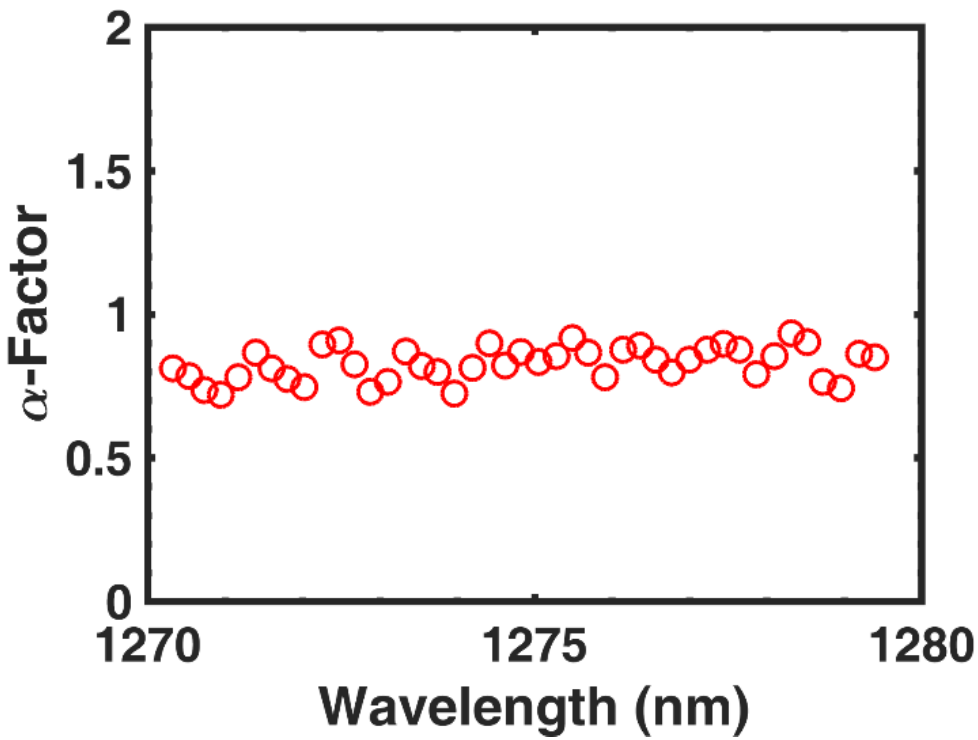
Label B16 (1 mm)

$$I_{th}^{GS} = 69\ \mathrm{mA}$$
$$I_{th}^{ES} = 150\ \mathrm{mA}$$

Two-state lasing dynamics

Silicon QD lasers with GS-ES lasing lines

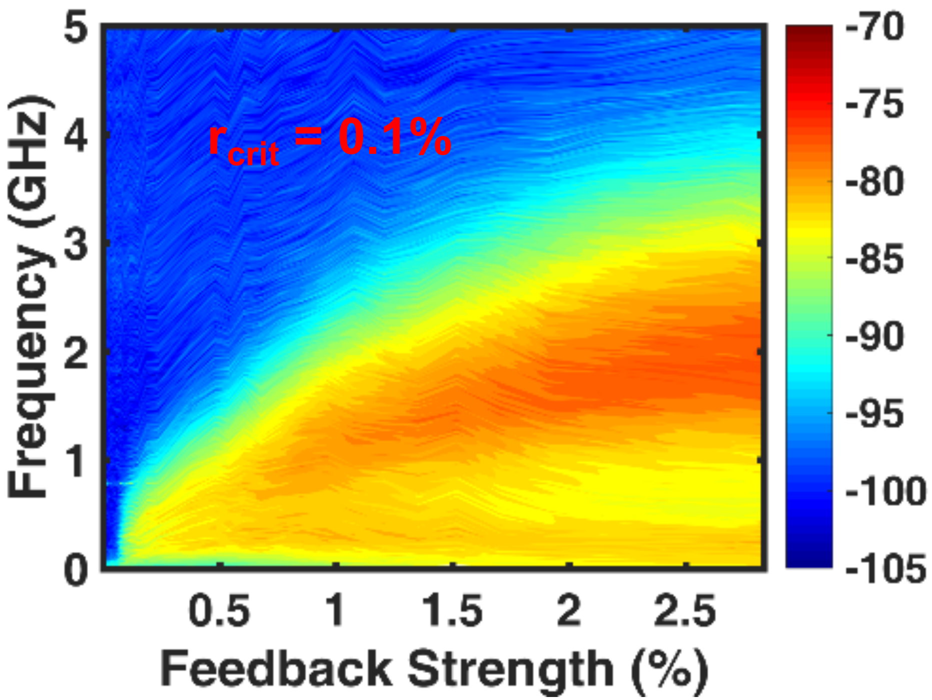


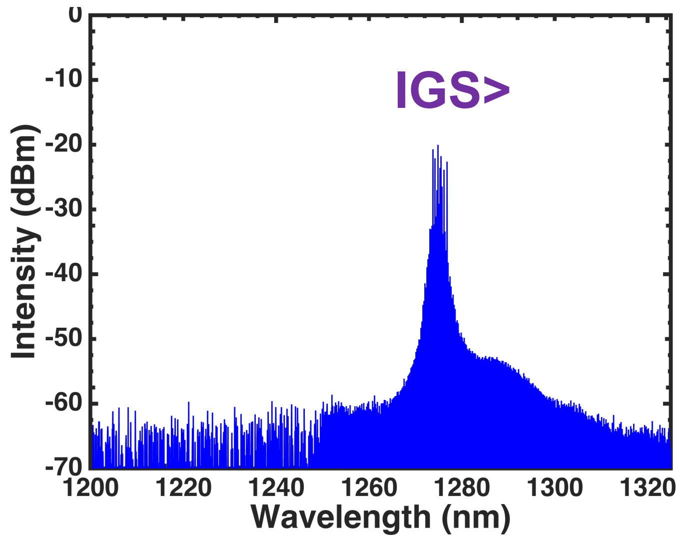


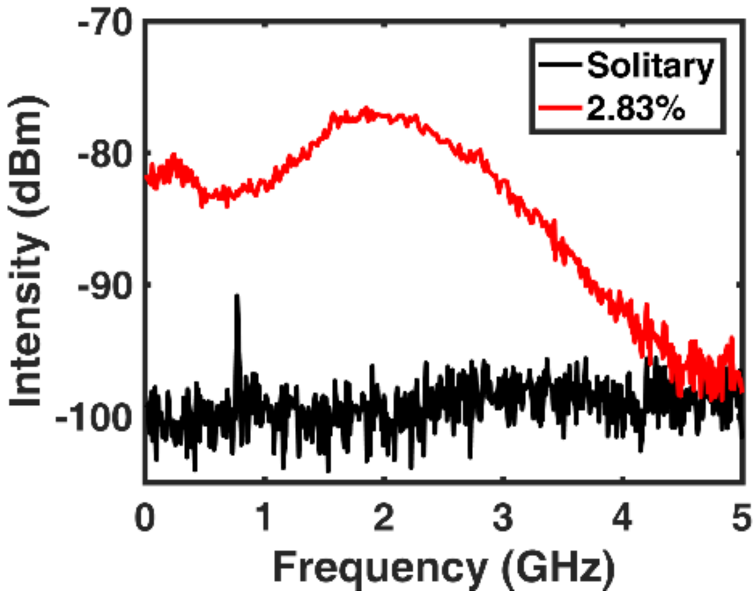
The α_H-factor of the GS transition remains extremely low

GS lasing

Bias current at $1.5\times I_{th}^{GS}$ ($\sim$110 mA)



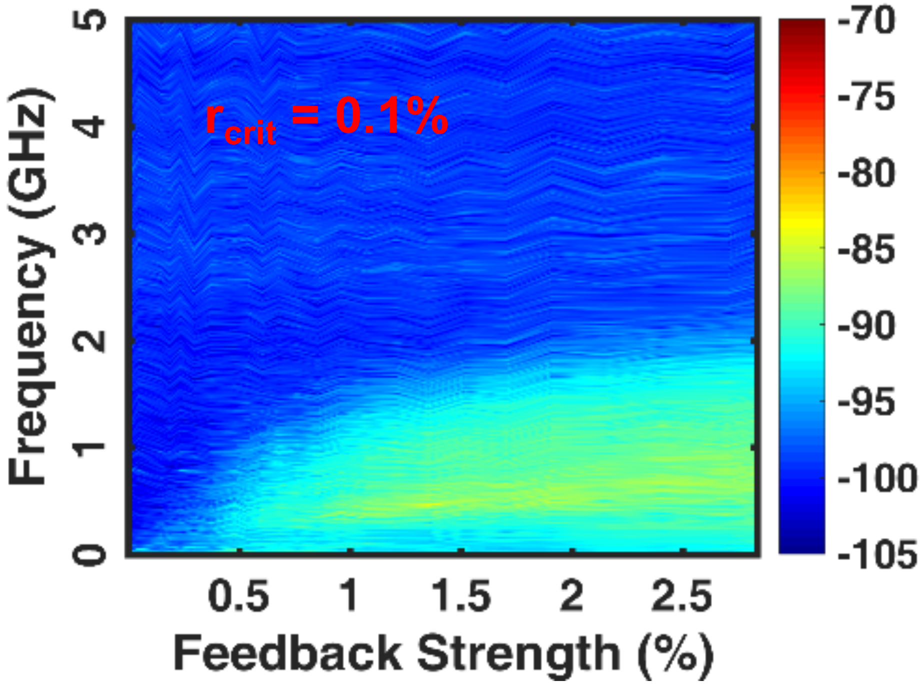


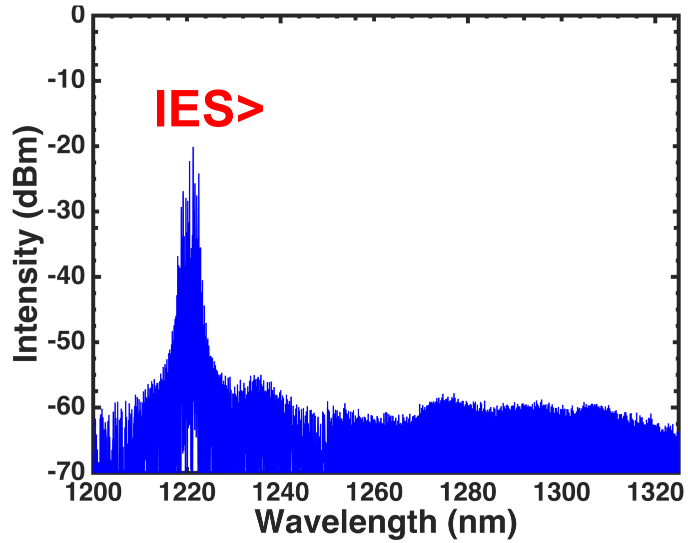


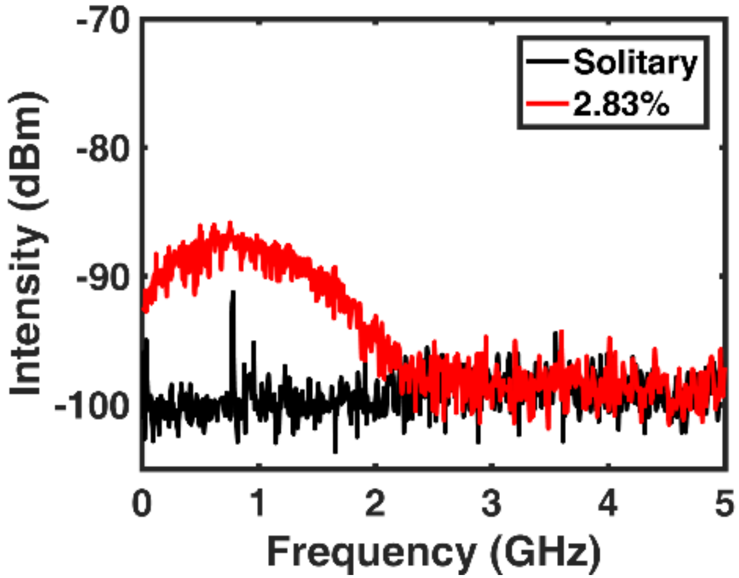
Strong dynamics with chaotic operation
Bifurcation point at 0.1% feedback strength

ES lasing

Bias current at $1.5\times I_{th}^{ES}$ (~225 mA)







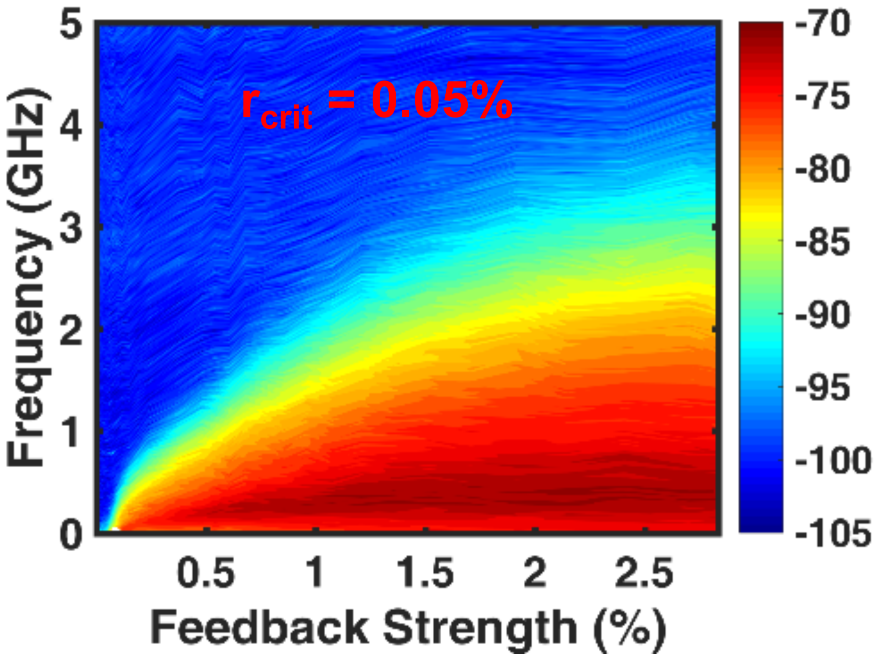
Same bifurcation point as for the GS lasing

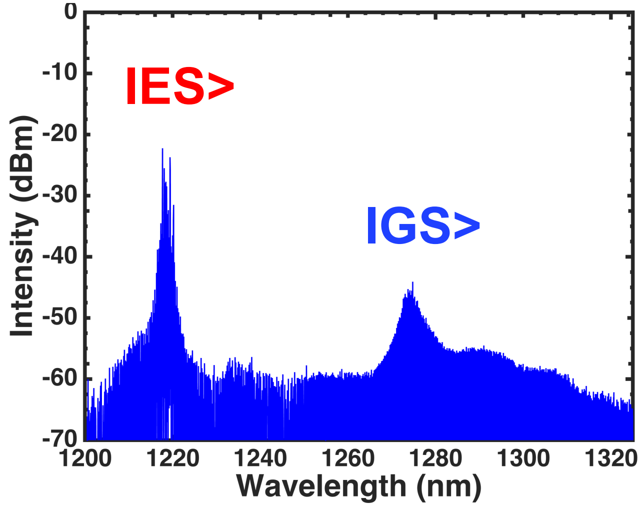
Chaotic operation with lower bandwidth

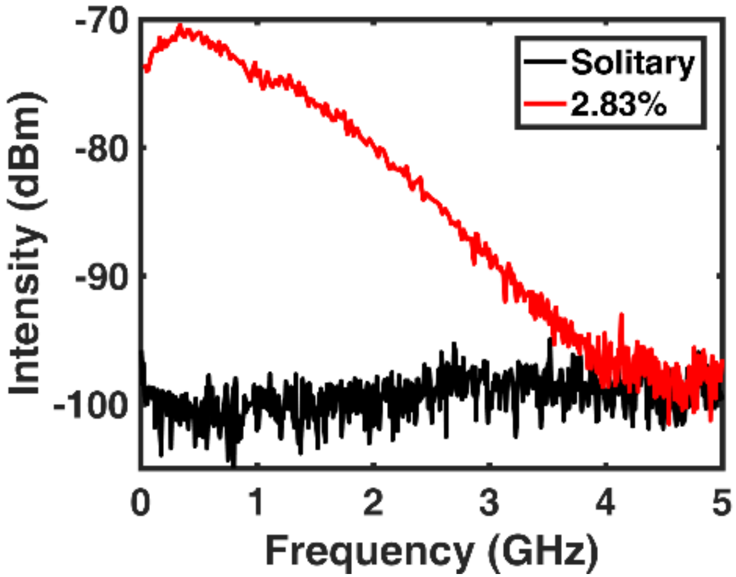
Smaller ES α_H-factor?

GS-ES lasing

Bias current around I_{th}^{ES} (~150 mA)







When bound states are both activated, the chaotic dynamics is accelerated

Bifurcation level reduced down to 0.05%

Increase of the GS α_H-factor?

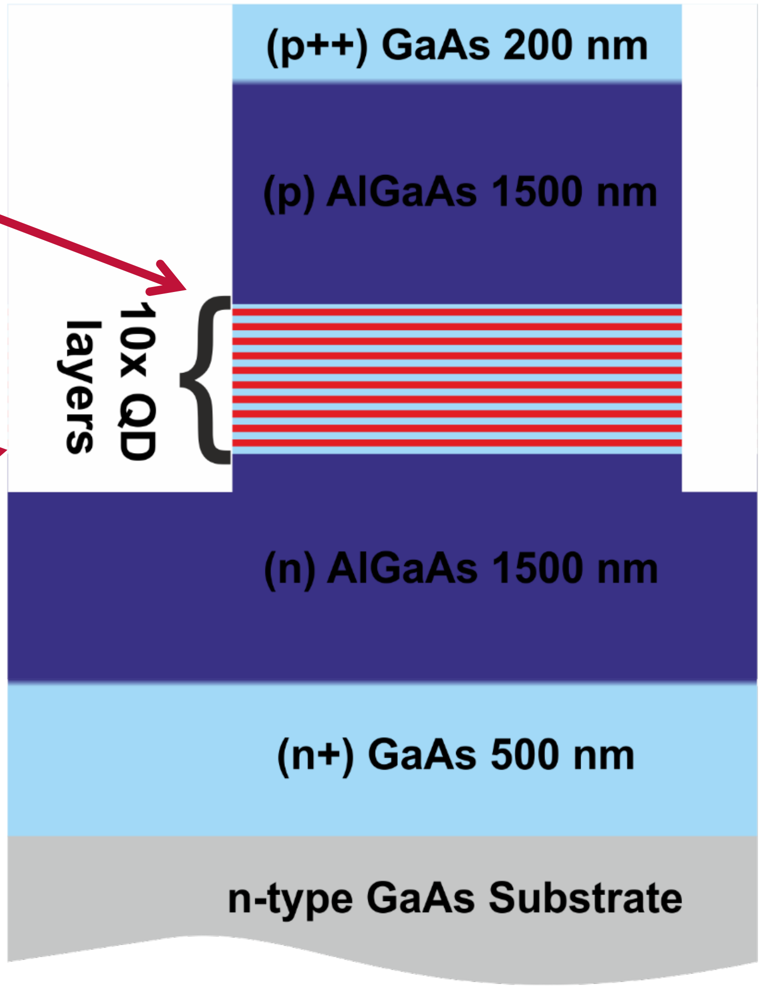
Transfer of stimulated emission?

InAs/GaAs QD lasers

Epi-layer Structure (MBE)

Etching through active region

Dot density of 3~5 $x10^{10}$ cm^{-2}



A.R. Kovsh et al., J. Cryst. Growth, Vol. 251, pp. 729-736 (2003)

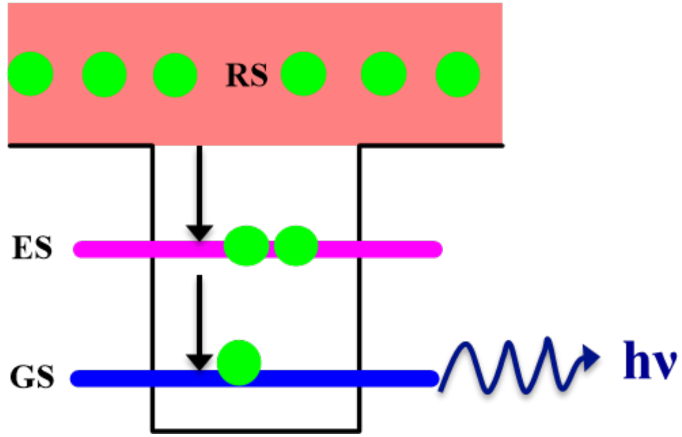
Output characteristics

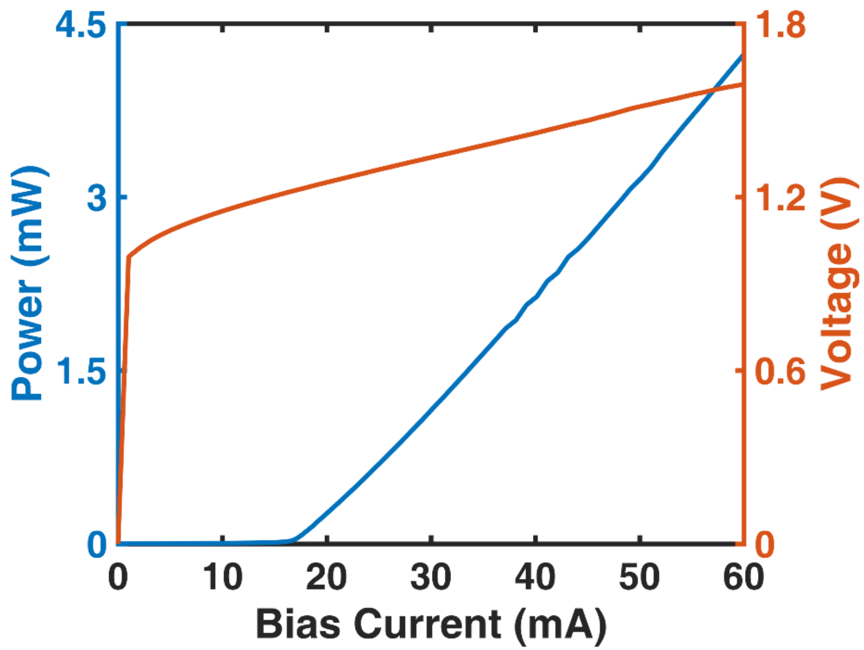
GS lasing line only

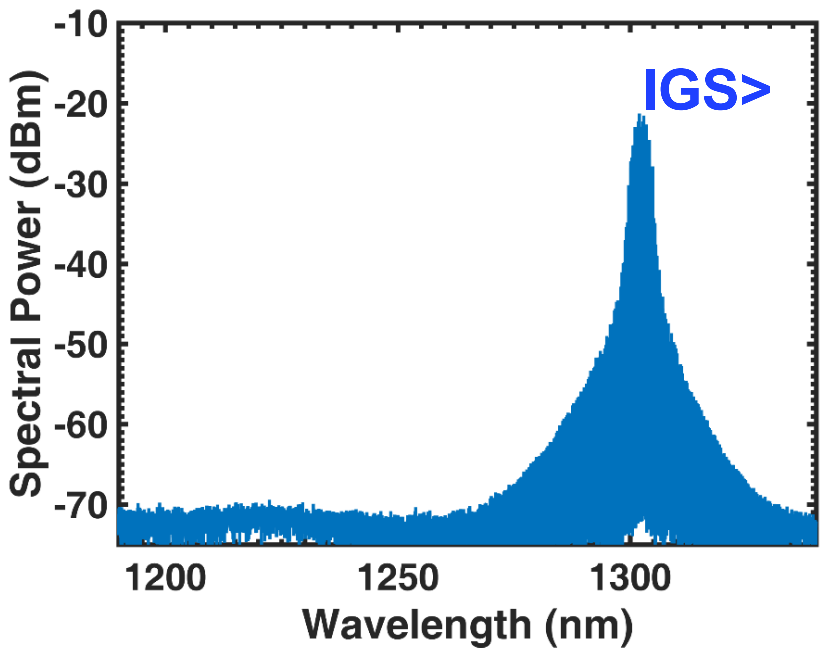
RWG : L × W = 1000 µm × 2 µm

Threshold current ~16.5 mA RT

Gain peak @1300 nm







H. Huang et al. AIP Advances, Vol. 6, pp. 125114, (2016)

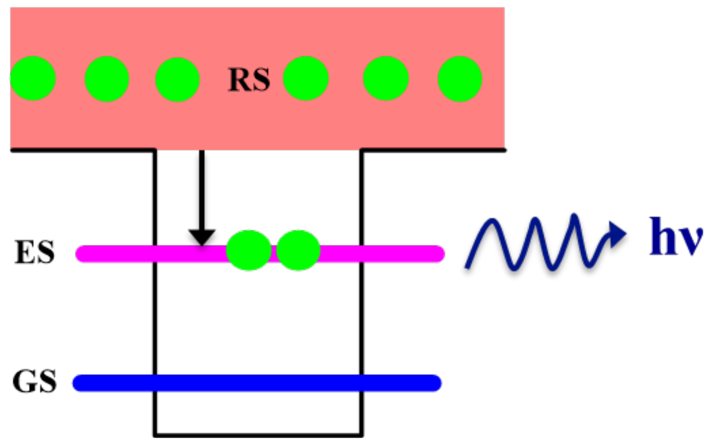
Output characteristics

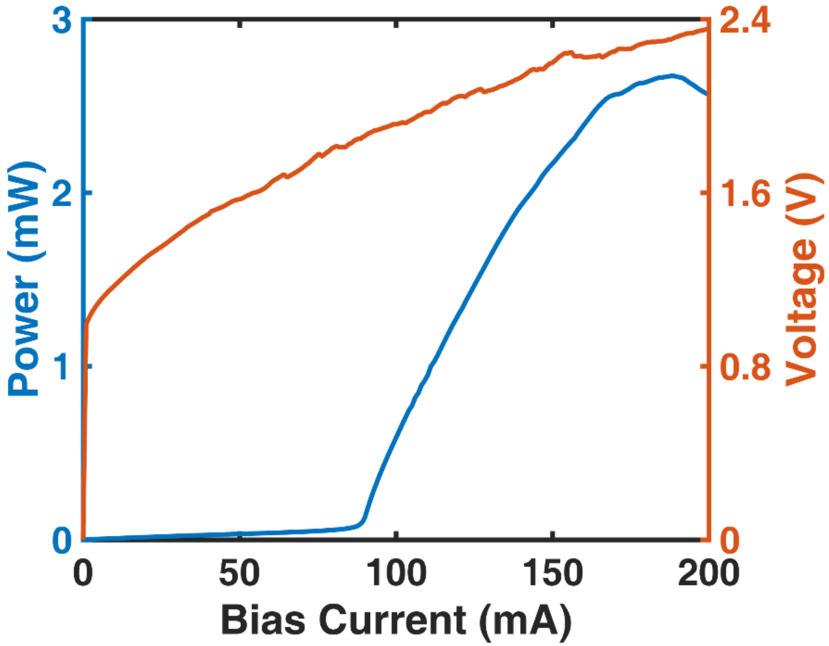
ES lasing line only

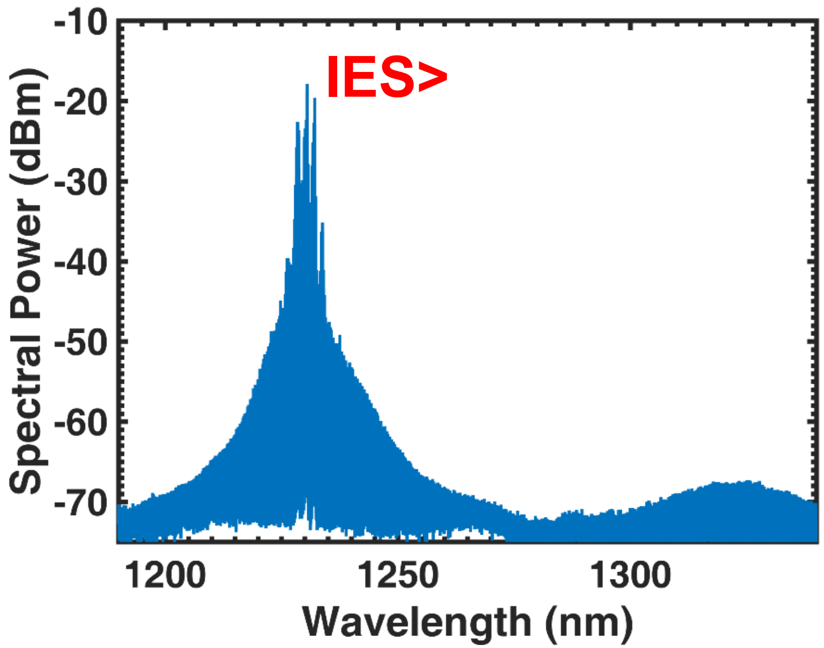
RWG : L × W = 1000 μm × 2 μm

Threshold current ~ 88.5 mA RT

Gain peak @1220 nm



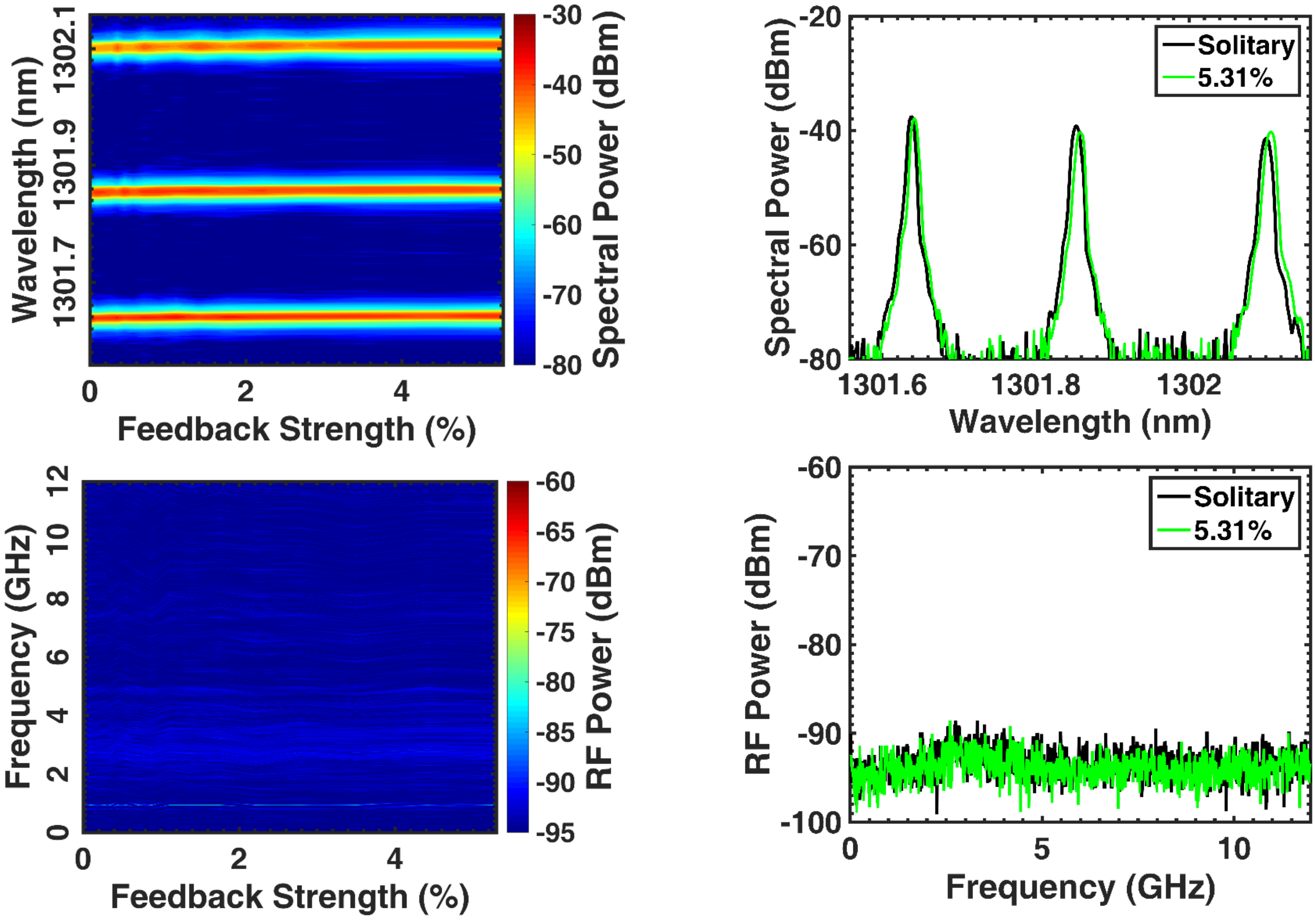




H. Huang et al. AIP Advances, Vol. 6, pp. 125114, (2016)

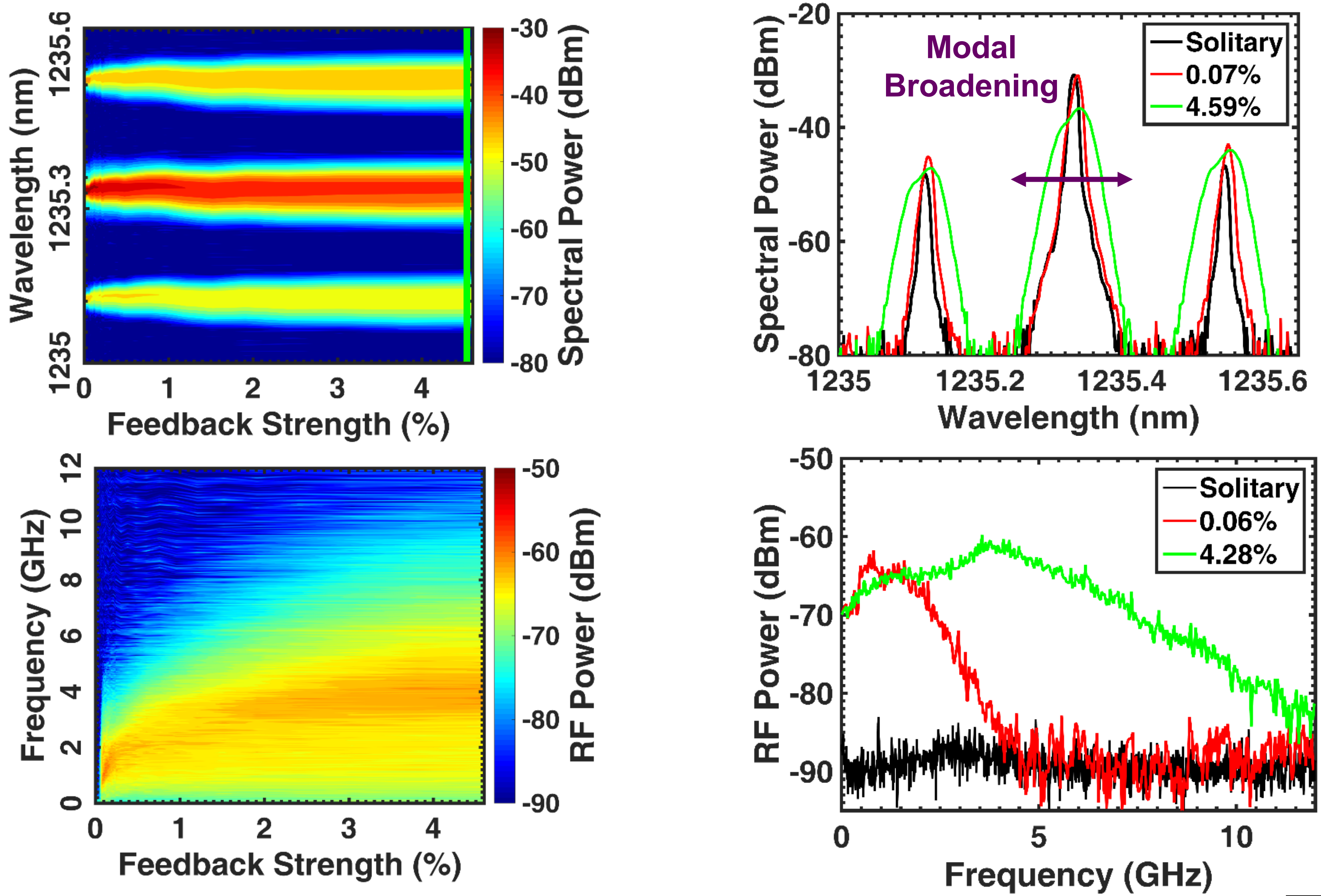
Chaos-free transmitter

GS QD laser at 1.5 x I_{th} (long delay, 7 m)

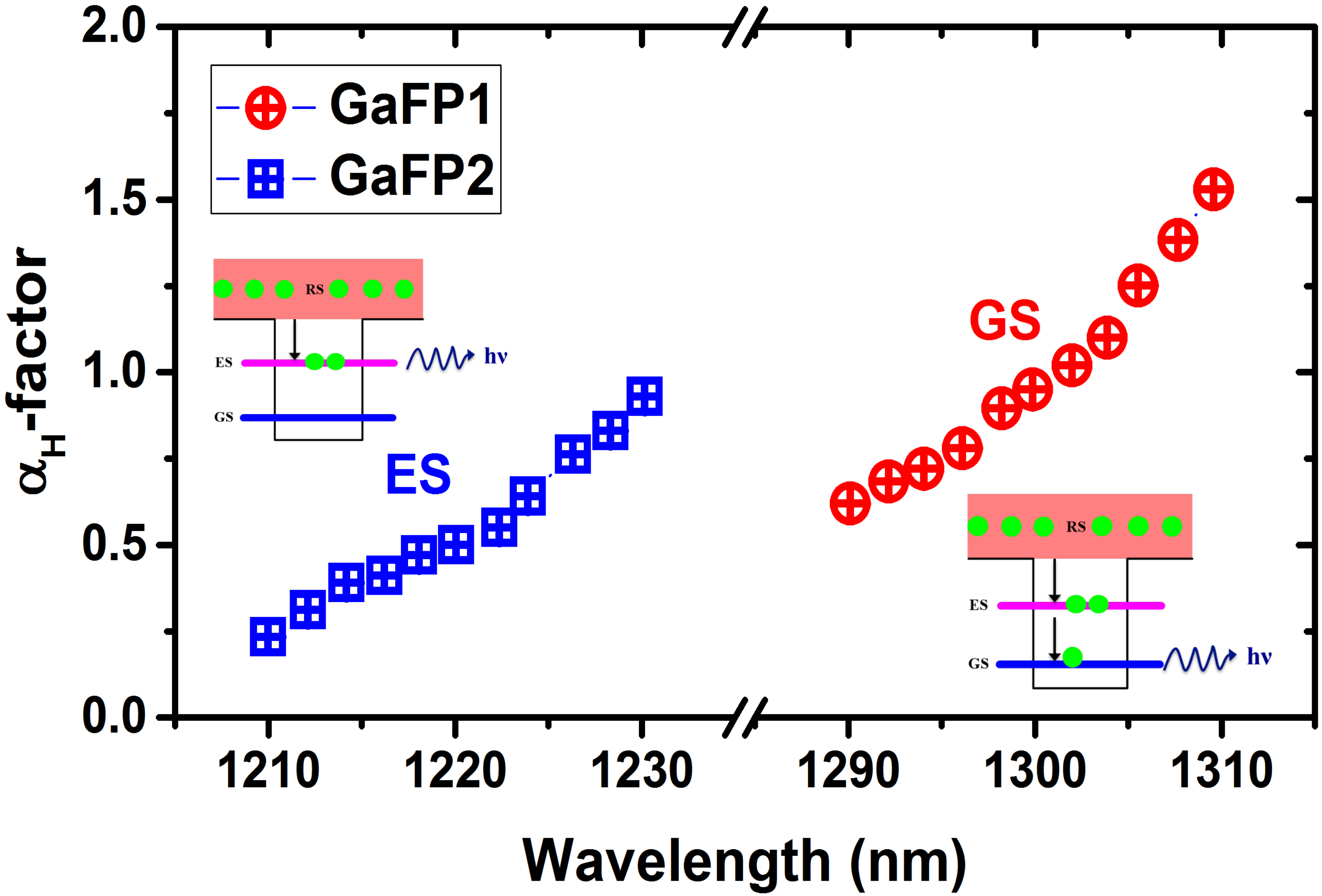


Broadband chaos

ES QD laser at 2 x I_{th} (long delay, 7 m)



αH-factor



H. Huang et al., AIP Advances, Vol. 6, pp. 125114, (2016)

Peculiar features

GS QD laser;

Overdamped oscillator due to strong vertical coupling (quasi-class A like)

ES QD laser;

Underdamped oscillator with small vertical coupling (class B like)

Laser	GS		ES	
Bias	$1.5 \times I_{th}$	$2 \times I_{th}$	$1.5 \times I_{th}$	$2 \times I_{th}$
r_{crit}	$> 6\%$	$> 6\%$	0.5%	0.04%
α_H	1	1	0.5	0.5
τ_{int}	$21\ ps$	$21\ ps$	$21\ ps$	$21\ ps$
C_l	0.6	0.6	0.6	0.6
γ	$> 18\ GHz$	$> 18\ GHz$	$1.6\ GHz$	$0.6\ GHz$

H. Huang et al., AIP Advances, Vol. 6, pp. 125114, (2016)

Conclusions

QD lasers exhibit peculiar dynamical features originating from 3D quantization

→ **GS lasing: meaningful for isolator-free transmitter in short-reach networks**

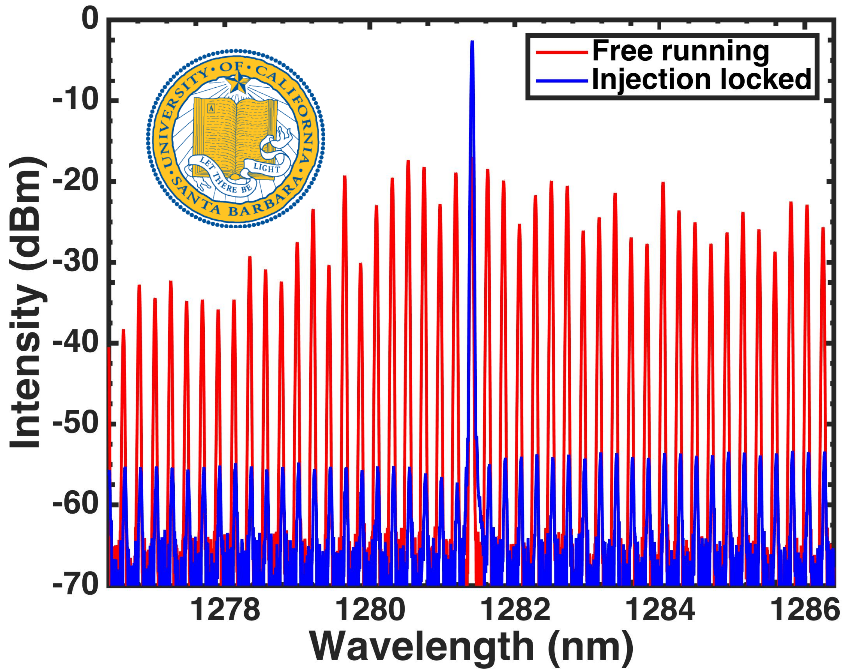
→ **ES lasing: essential for applications taking advantages of chaos such as chaotic lidars and random number generation**

→ **Dynamics of silicon lasers are very promising for PIC applications**

Further work will investigate optically injected silicon QD lasers

→ **Single mode transmitters**

→ **Integrated microwave photonics**



Thank you!