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EPITAXIAL QUANTUM DOT LASERS GROWN ON SILICON FOR ISOLATOR-FREE OPERATION IN PHOTONIC INTEGRATED TECHNOLOGIES

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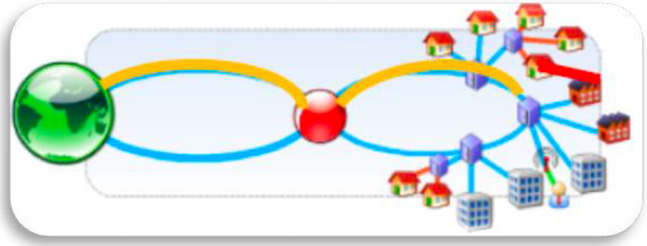
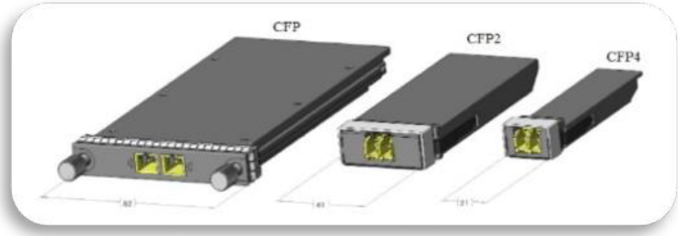
SILICON PHOTONICS APPLICATIONS

TELECOM

- **> 10 km**
  - Metro & Access



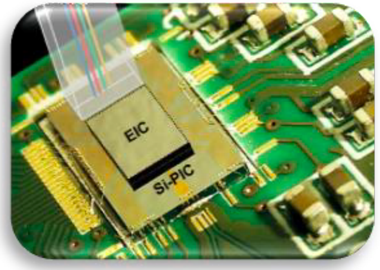
- **1.5 µm**
  - Transceivers modules



DATACOM

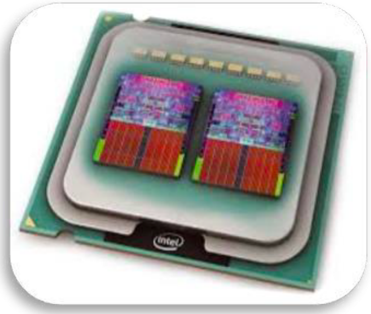
- **1m – 10 km**
  - Routers & switches

- **1.3 µm**
  - Rack-to-rack
  - Board-to-board

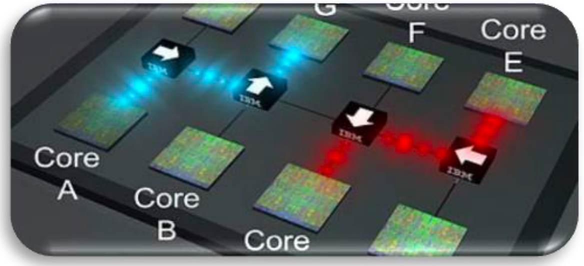


COMPUTERCOM

- **< 1m**
  - Photonics integrated circuits



- **1.3 µm**
  - Transceivers on chip

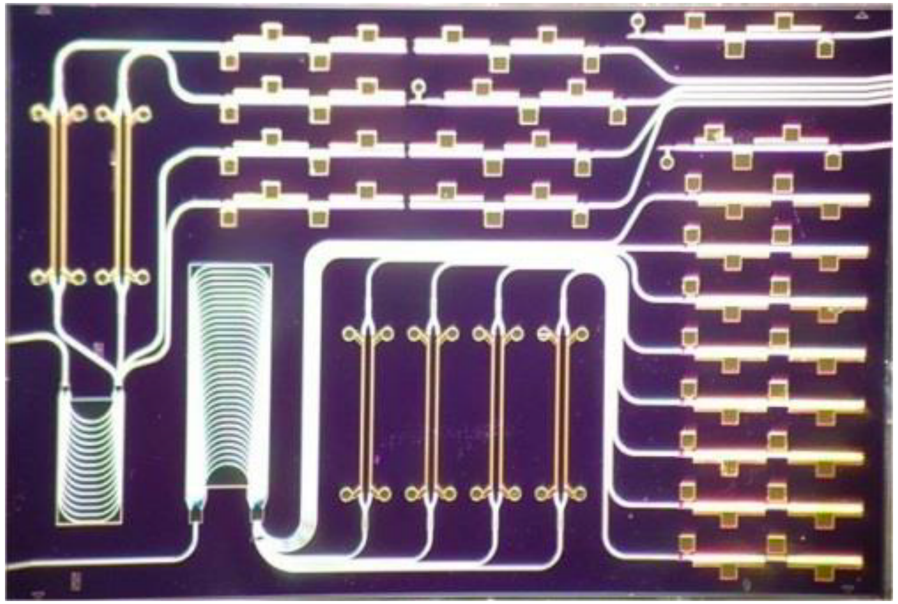


PHOTONICS INTEGRATED TECHNOLOGIES

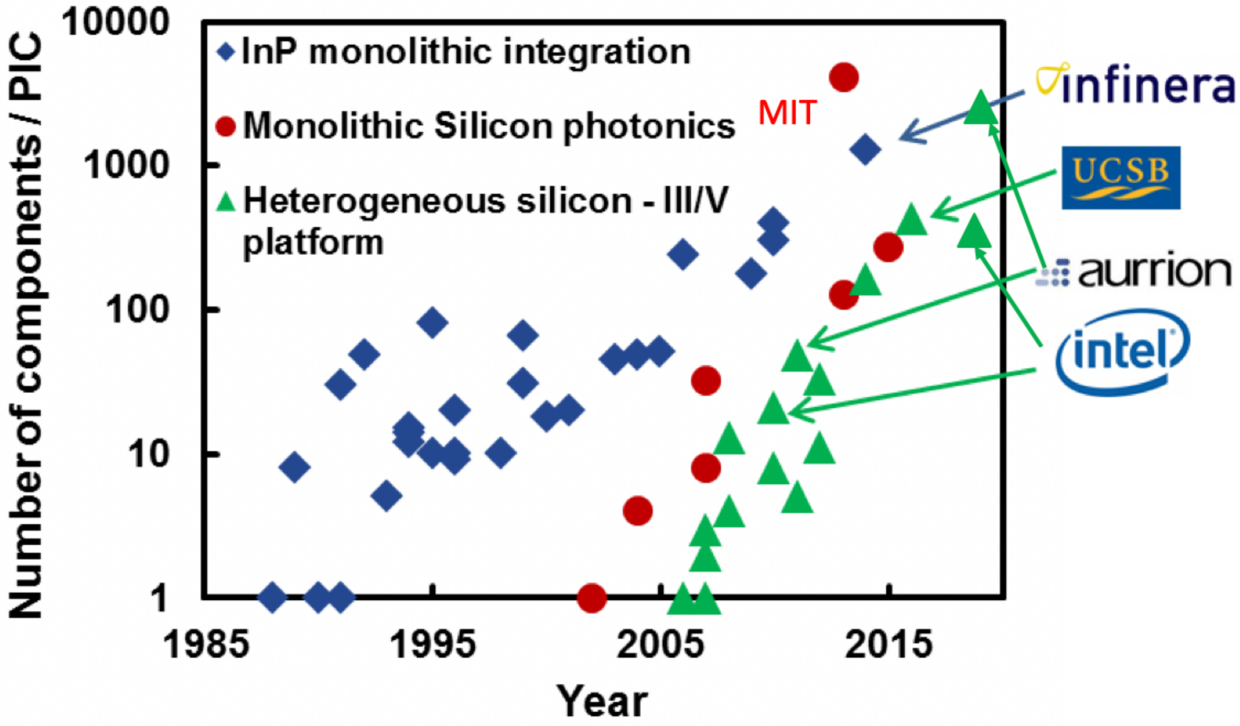
Photonics Integrated Circuits on silicon

- CMOS compatible
- Low cost, high integration density, small footprint

WDM



Courtesy of PICs4ALL

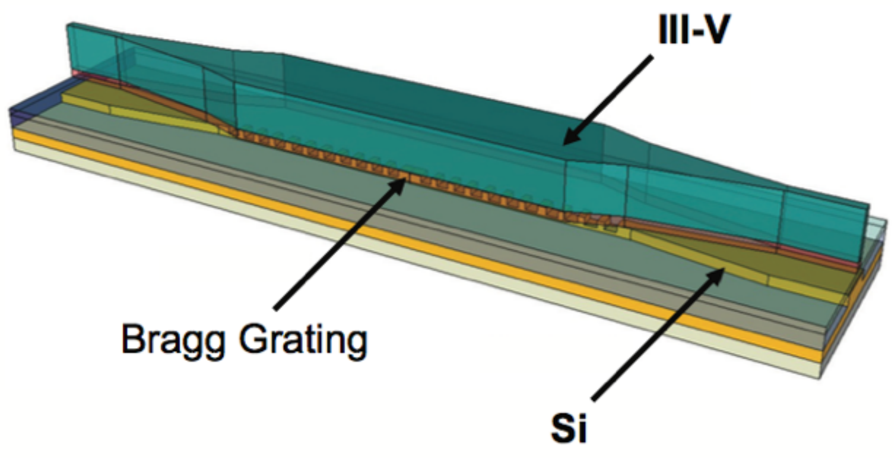


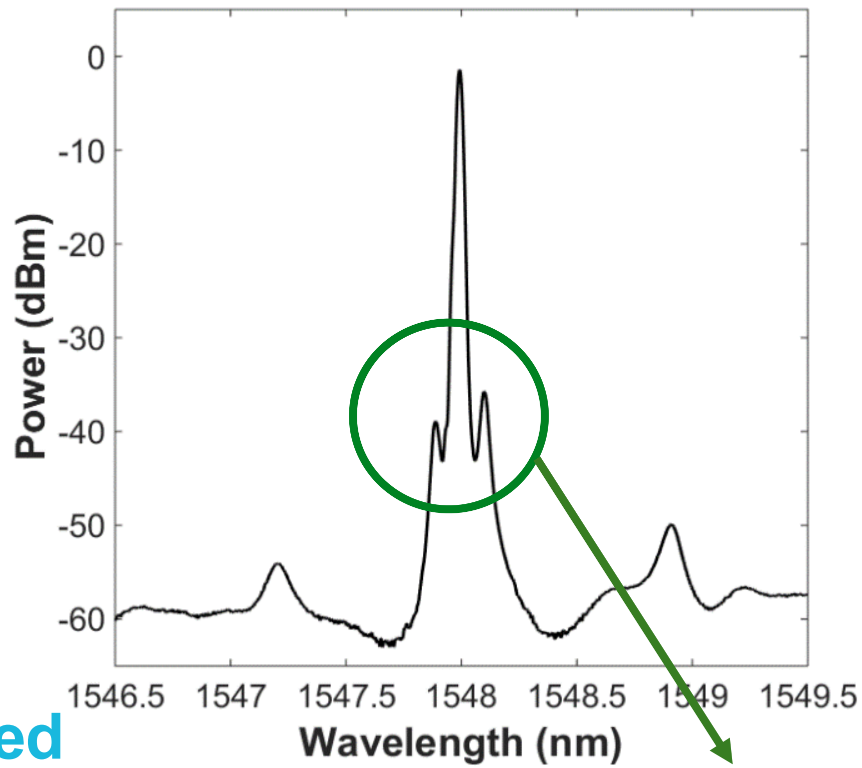
Refs: J. Norman et al., APL Photonics 3, 030901, 2018

CHALLENGES IN SILICON PHOTONICS

Hybrid III-V/Si lasers

- ➢ Reflections due to the various interfaces between the active/passive transitions
- ➢ Sub-cavities in the silicon waveguide





Oscillations due to parasitic reflections

On-chip optical isolators are expensive

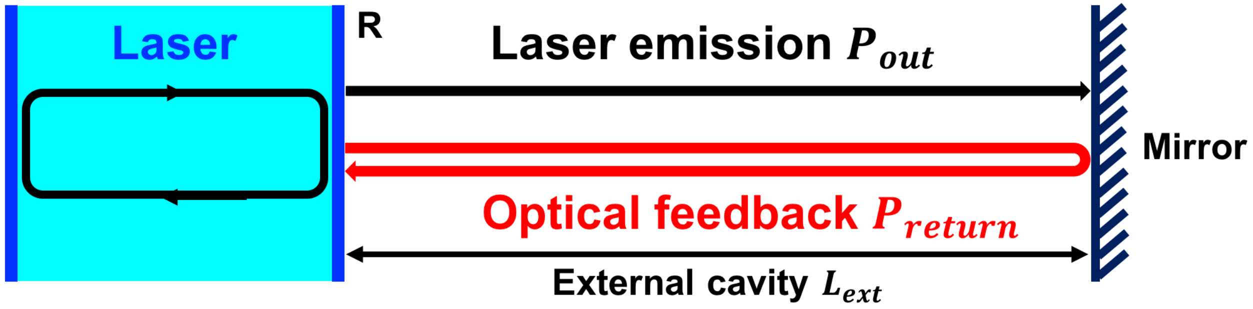
Isolator-free optical transmitters are required

Refs: G. Duan et al., IEEE J. Sel. Top. Quantum Electron, vol.20, No.4, 2014
K. Schires et al., IEEE J. Sel. Top. Quantum Electron, vol. 22, No. 6, 2016

OUTLINE

1. External optical feedback
2. InAs/GaAs QD laser studied
3. Feedback and dynamic properties
4. Conclusion

EXTERNAL OPTICAL FEEDBACK



Lang & Kobayashi Model :

$$\frac{d\tilde{E}(t)}{dt} = \left\{\frac{1}{2}(1 + i\alpha_H)\left[\Gamma G_N(N(t) - N_{tr}) - \frac{1}{\tau_p}\right] + i\omega_0\right\}\tilde{E}(t) + \kappa\tilde{E}(t - \tau_{ext})$$

Key parameters :

- Feedback strength : $r_{ext} = P_{return}/P_{out}$
- Cavity coupling factor : $C_l = \frac{1-R}{2\sqrt{R}}$
- Long-delay: $f_{RO} \times \tau_{ext} > 1$

$$\boldsymbol{\kappa} = \frac{1}{\tau_{in}} 2C_l\sqrt{r_{ext}}$$

Feedback coefficient

Refs: J. Ohtsubo, Semiconductor Lasers (3rd Ed.), Springer, 2013
K. Petermann, Laser Didde Modulation and Noise, Kluwer Academic Publishers, 1988

SENSITIVITY TO OPTICAL PERTURBATIONS

- **Coupling coefficient:**

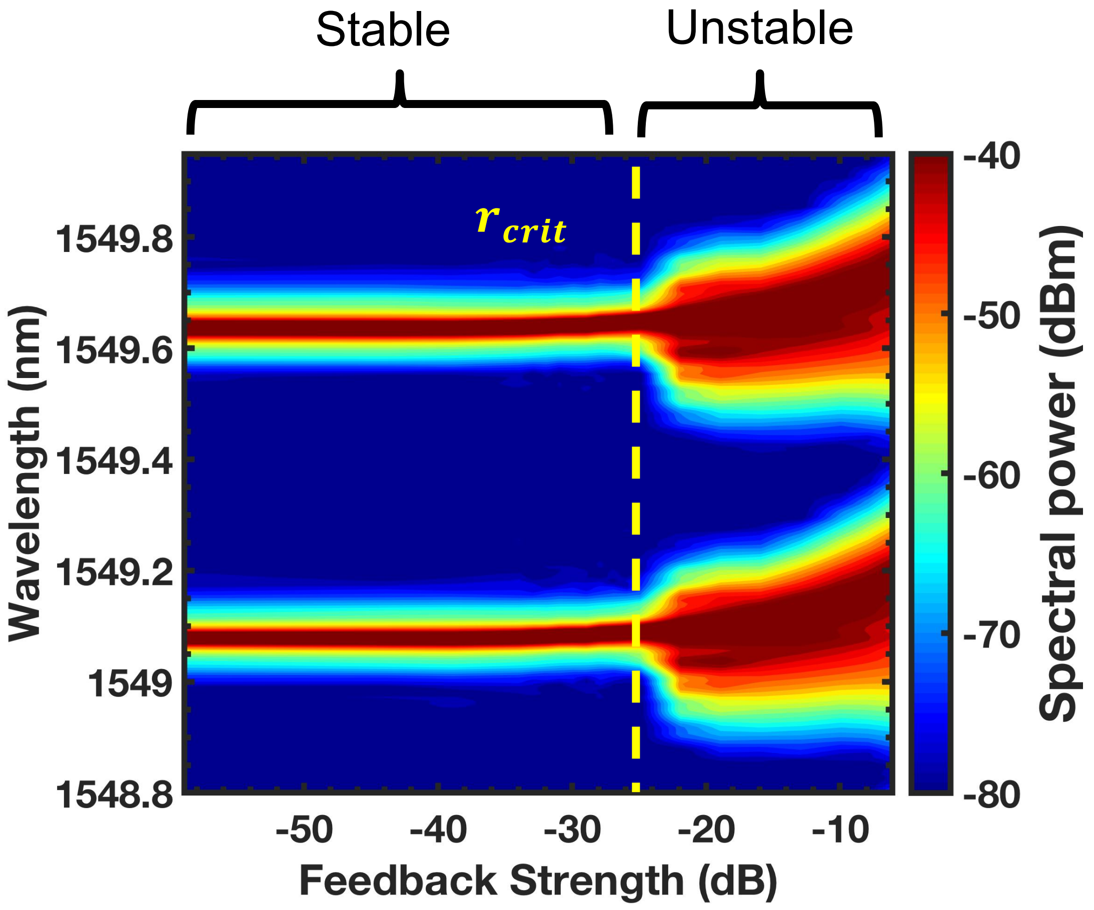
$$C = \omega\tau_{ext}\frac{1}{Q}\sqrt{1+\alpha_H^2}\sqrt{r_{ext}}$$

- **Quality factor:**

$$\boxed{Q} = \frac{\omega}{\nu_g\alpha_{loss}}$$

- **Critical feedback level:**

$$r_{crit} = \frac{\tau_{in}^2\boxed{\gamma^2}}{16C_l^2}\left(\boxed{\frac{1+\alpha_H^2}{\alpha_H^4}}\right)$$

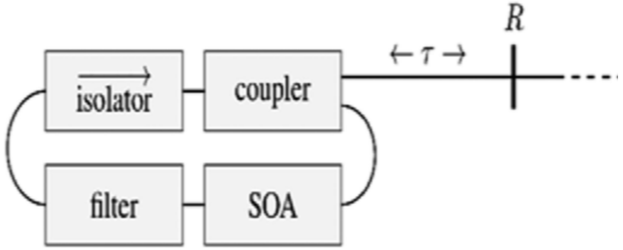


- **Maximum feedback ratio for a stable operation into a communication system**

Ref: H. Huang, Ph. D. thesis, Télécom Paristech, 2017

FEEDBACK-INSENSITIVE SEMICONDUCTOR LASERS

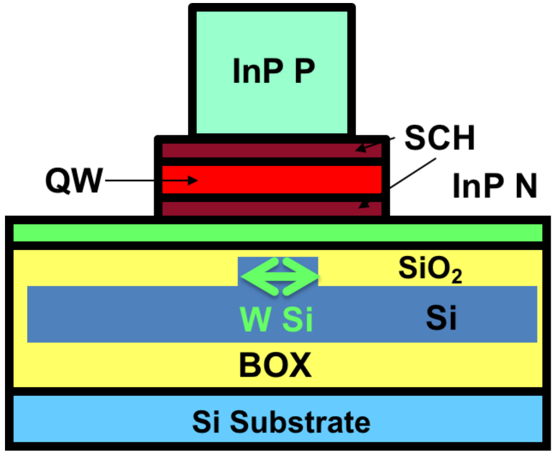
- **Ring lasers with intracavity optical isolator**
  - Complex device

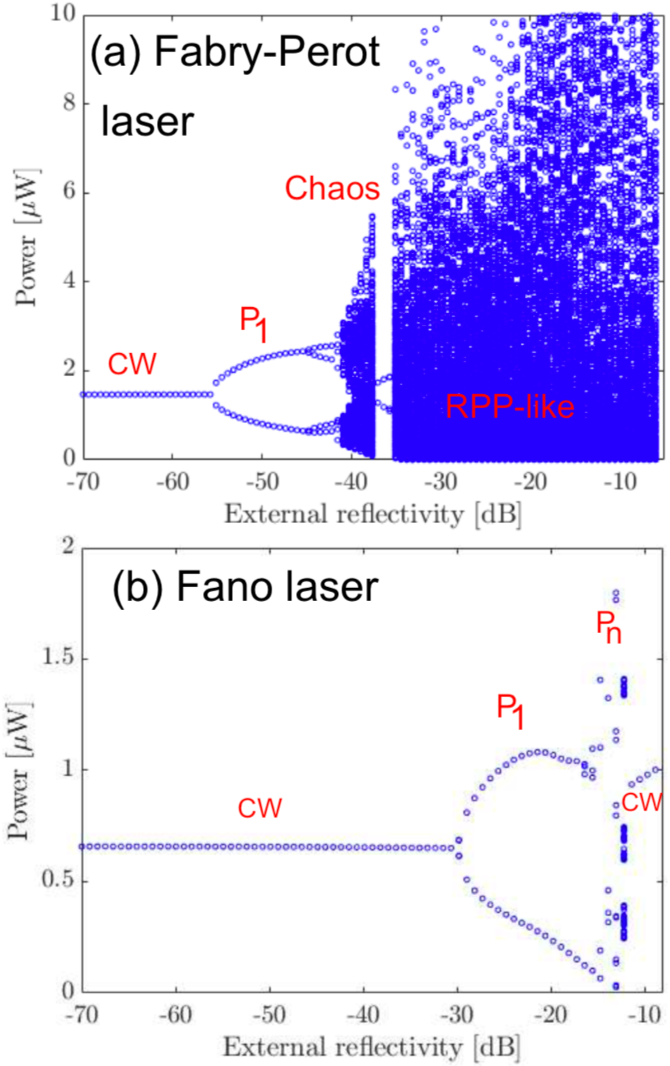


- **Photonic crystal based nano-lasers**
  - Limited output power

- **High coherence lasers**
  - High Q-factor (>10^6)
  - Long photon lifetime

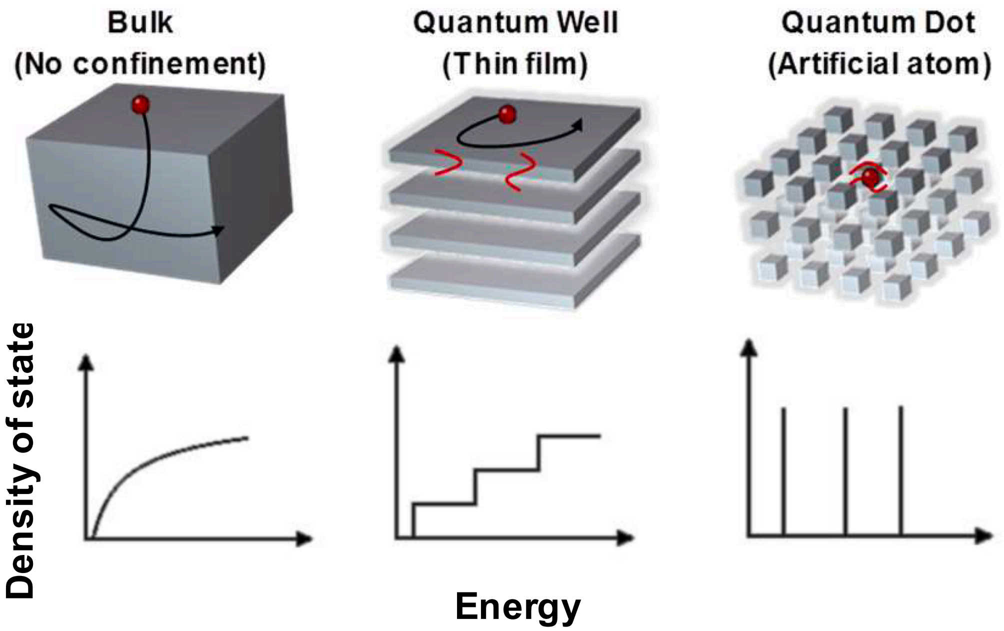
- **QD lasers on silicon**
  - Low α_H-factor
  - High damping
  - Single state dynamics

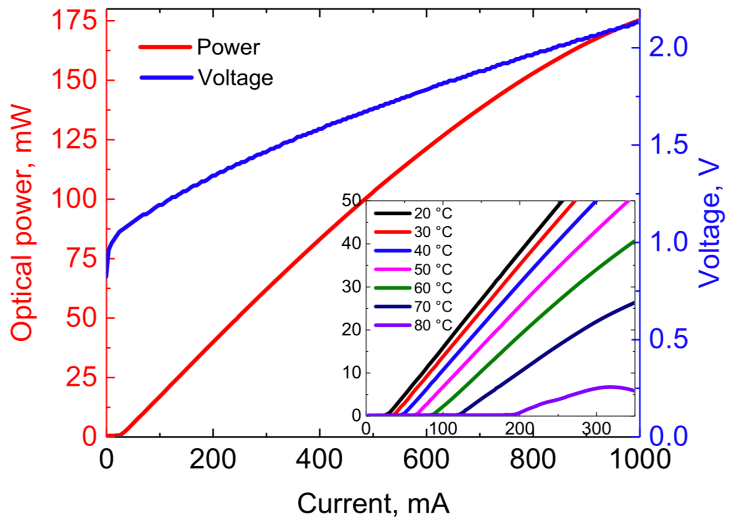


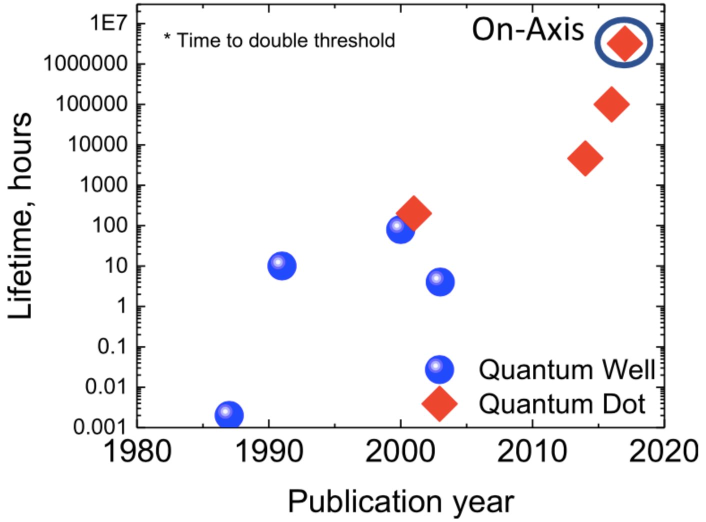


Refs: T. Rasmussen et al., arXiv: 1906.06923v1, 2019
D. Lenstra et al., IEEE Journal of Selected Topics in Quantum Electronics, Vol. 25, No.6, 2019

INAS/GAAS QD DIRECTLY GROWN ON SILICON







Advantageous for laser devices

- Low cost
- Power efficient
- High thermal stability
- Long device lifetime

Refs: J. Norman et al., APL Photonics 3, 030901, 2018
K. Nishi et al., IEEE J. Sel. Top. Quantum Electron., vol. 23, no. 6, 2017

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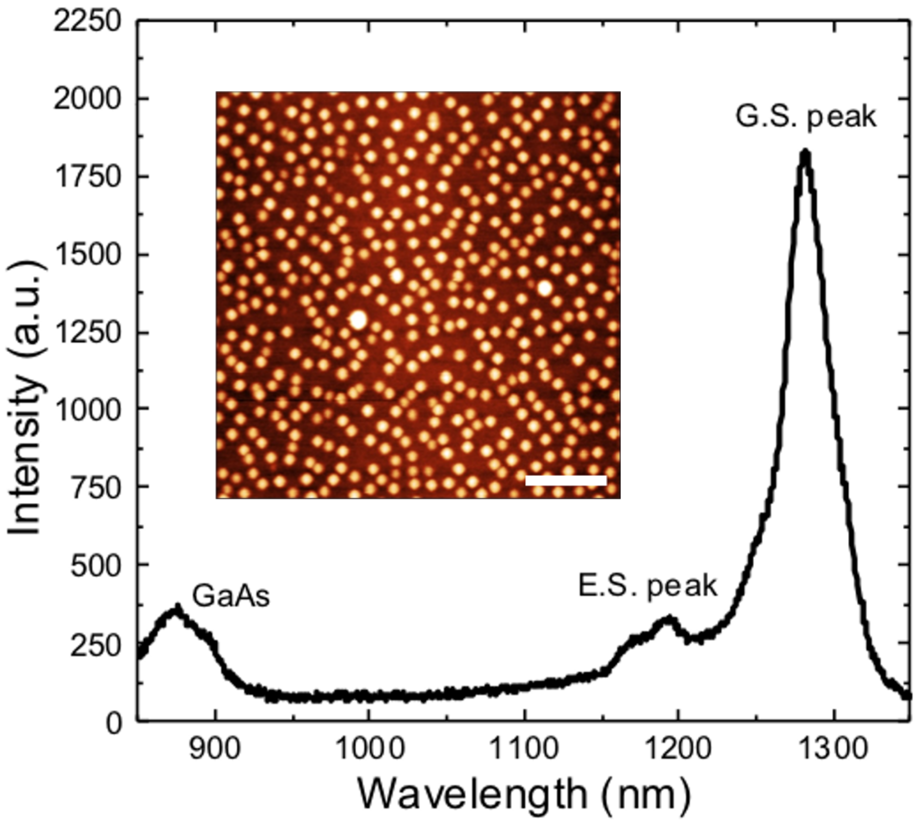
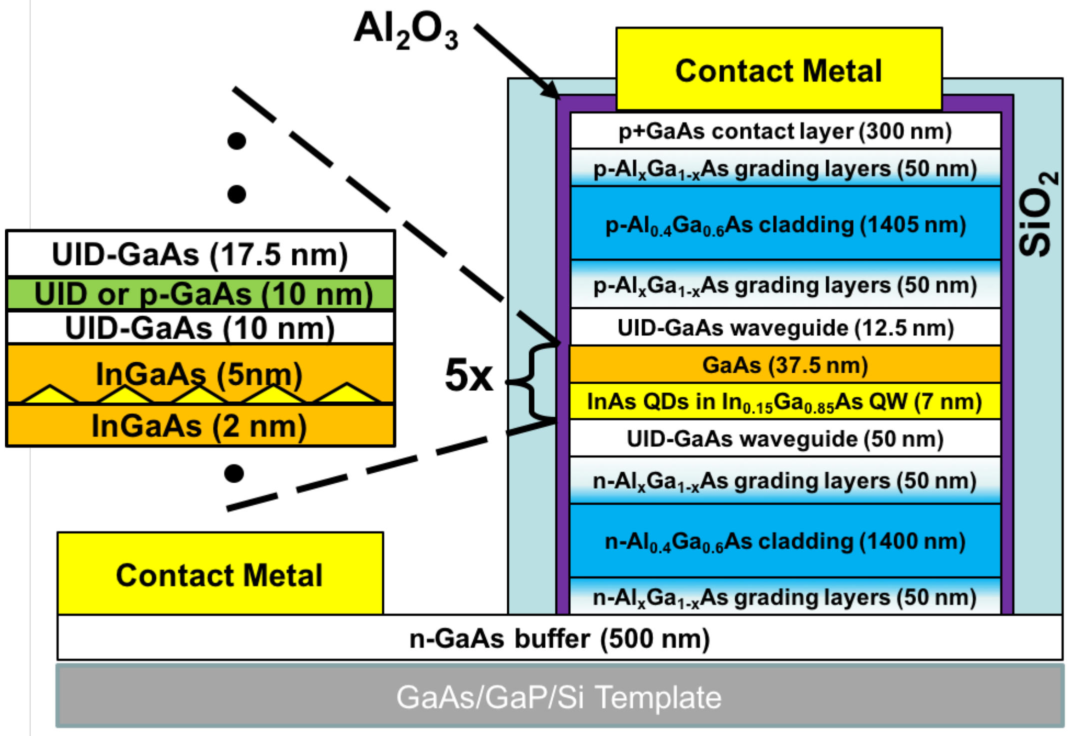
DEVICE STUDIED (I)

QD FP lasers epitaxially grown on silicon

- L: 1.1 mm; RWG: 4 µm
- 5 dot layers
- Dot density: 5 x10^{10} cm^{-2} per layer
- Inhomogeneous width ~ 15 meV

UCSB





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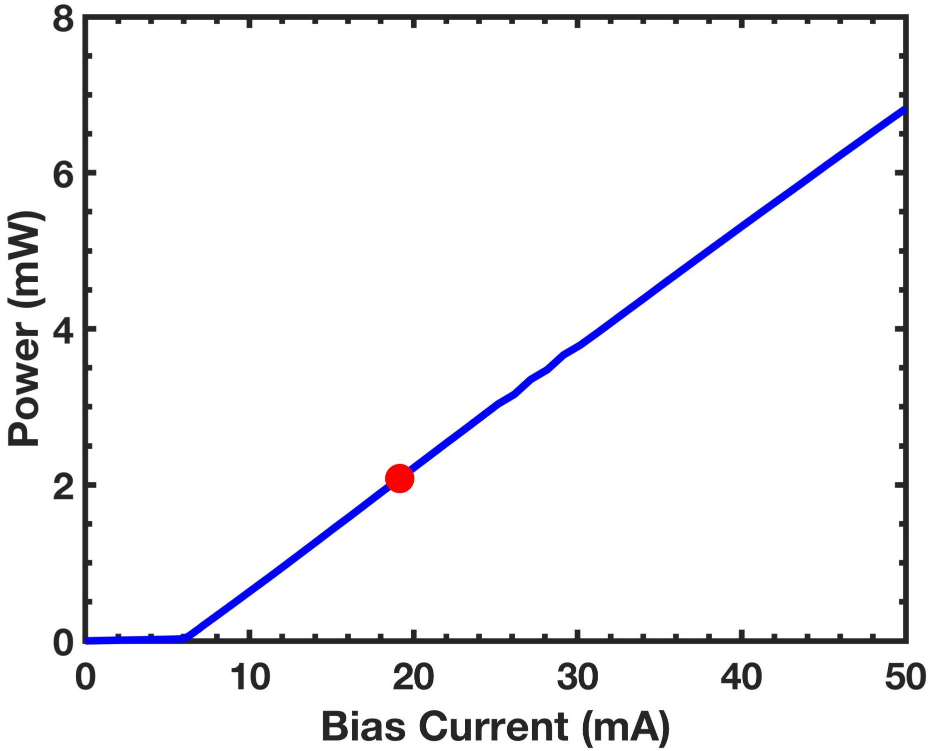
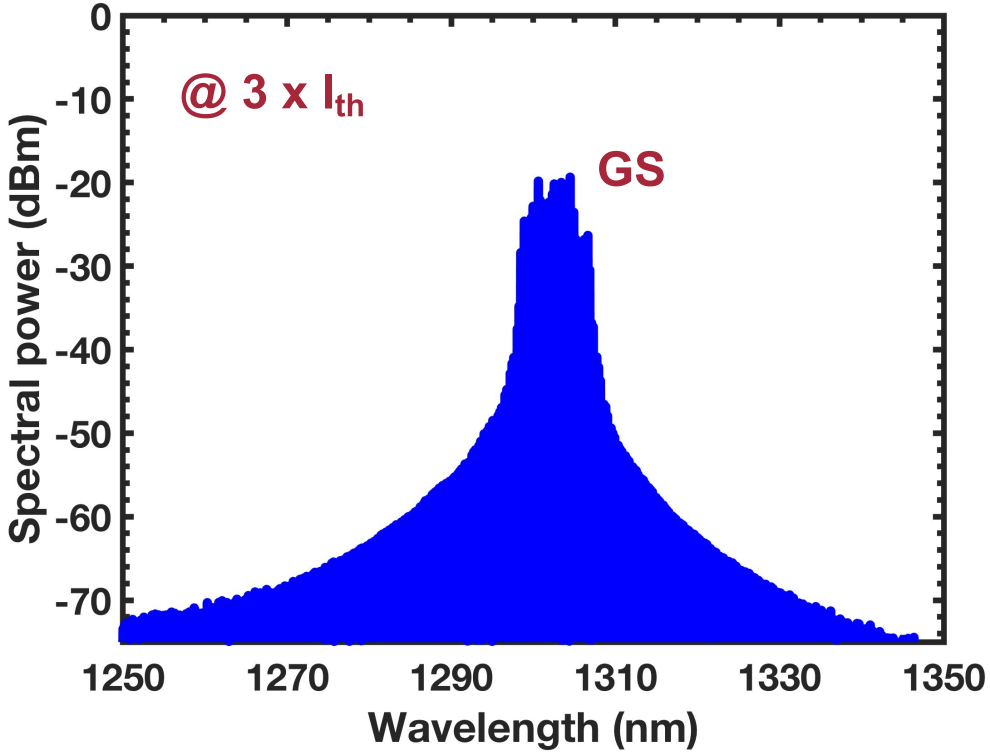
DEVICE STUDIED (II)

QD FP lasers epitaxially grown on silicon

- Threshold current : 6 mA @ 20°C
- Gain peak : 1.3 µm (GS)
- No ES (single state lasing)

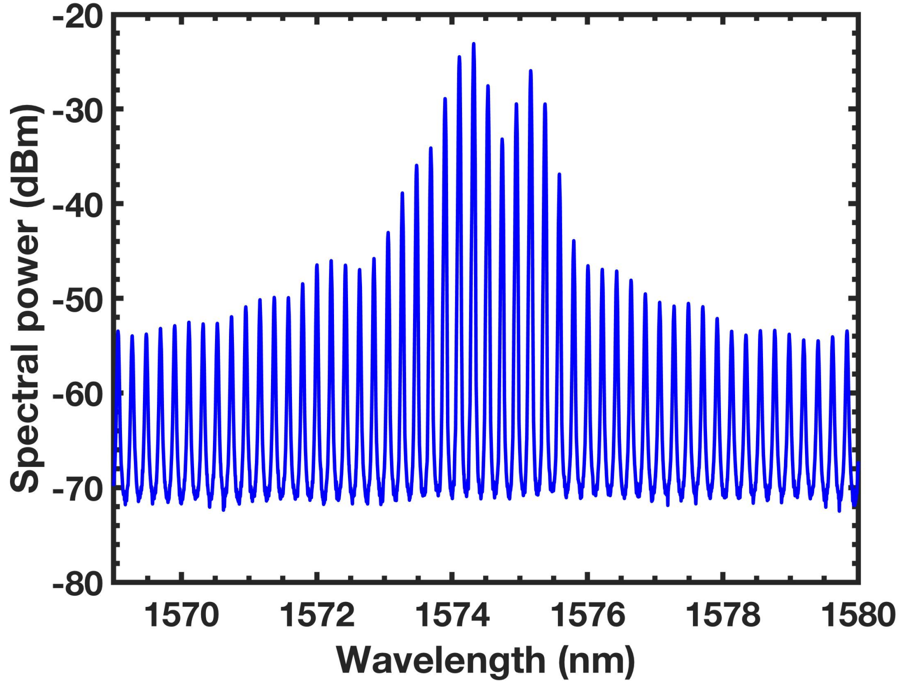


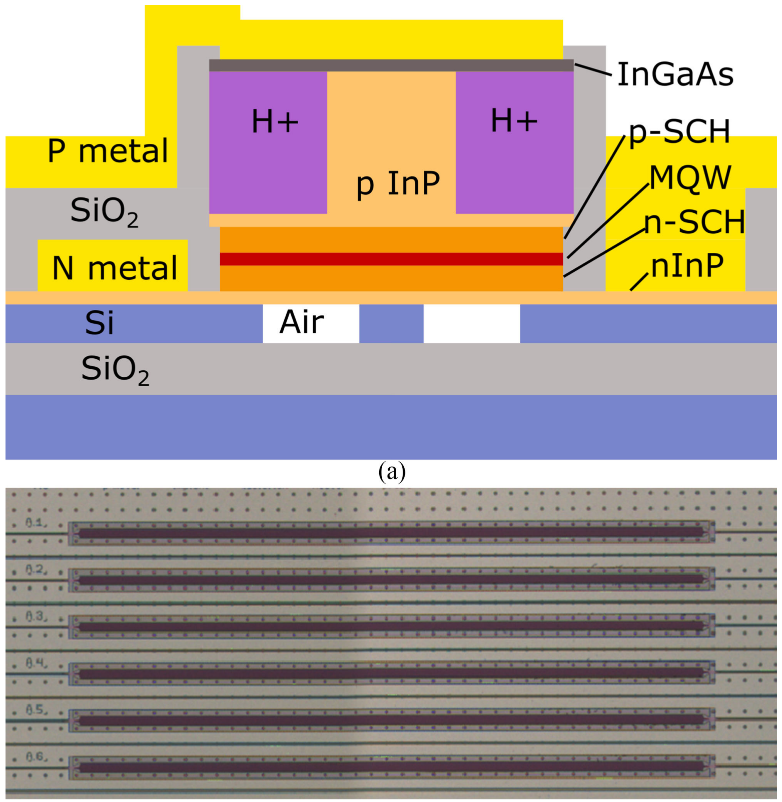


DEVICE STUDIED (III)

Hybrid III-V/Si QW lasers

- L: 1.5 mm; RWG: 4 µm
- 7 InAlGaAs QWs
- Threshold current : 36 mA @ 20°C
- Gain peak : 1.5 µm



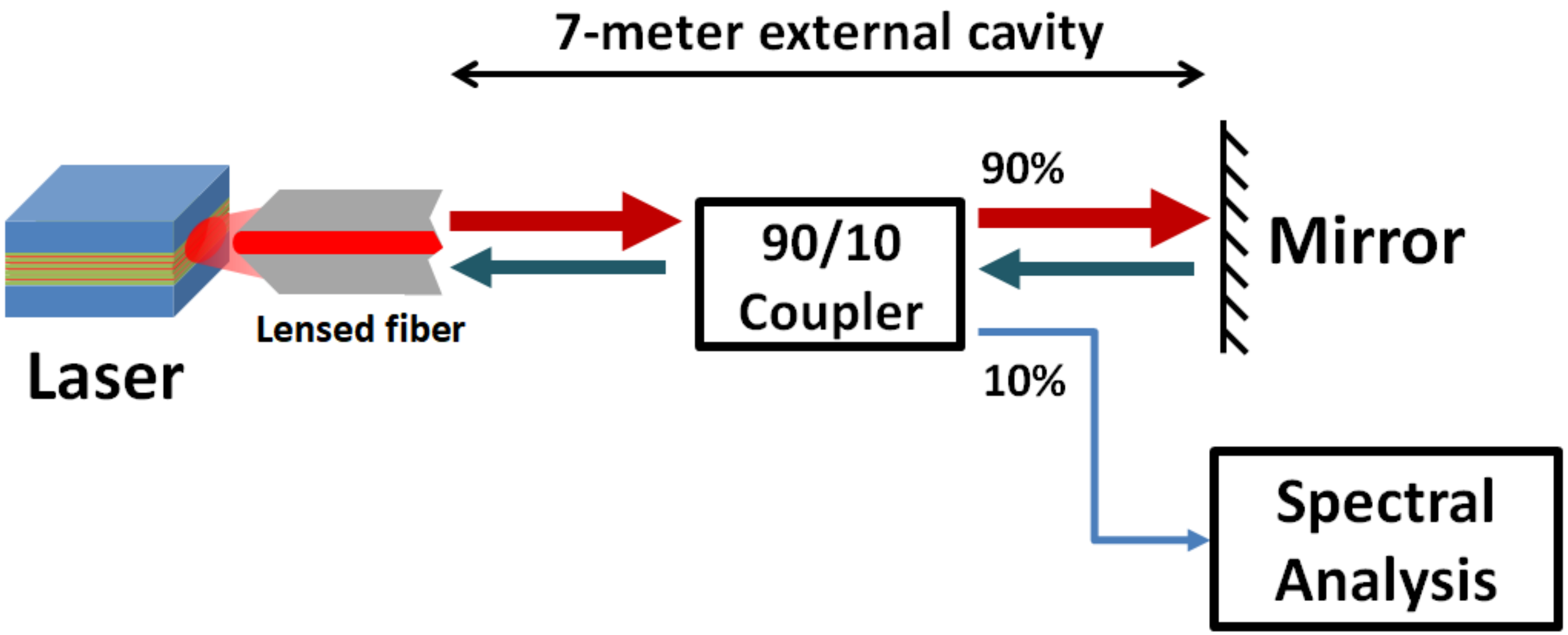


(a)

(b)

Ref: M. Davenport et al., IEEE J. Sel. Top. Quantum Electron, vol.22, No.6, 2016

STATIC OPTICAL FEEDBACK APPARATUS

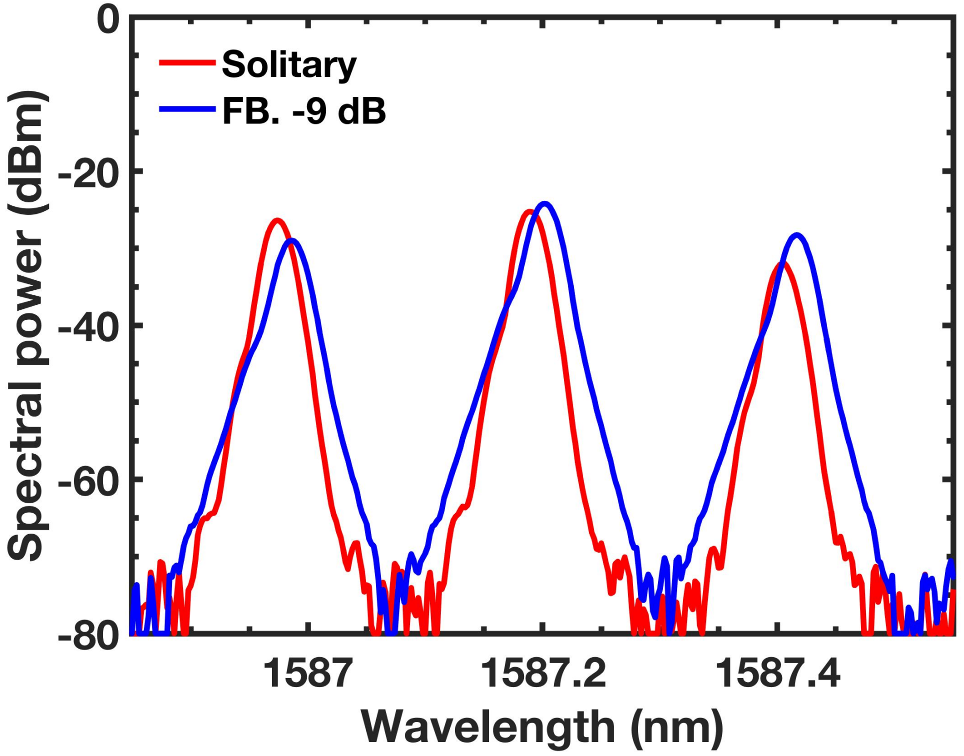


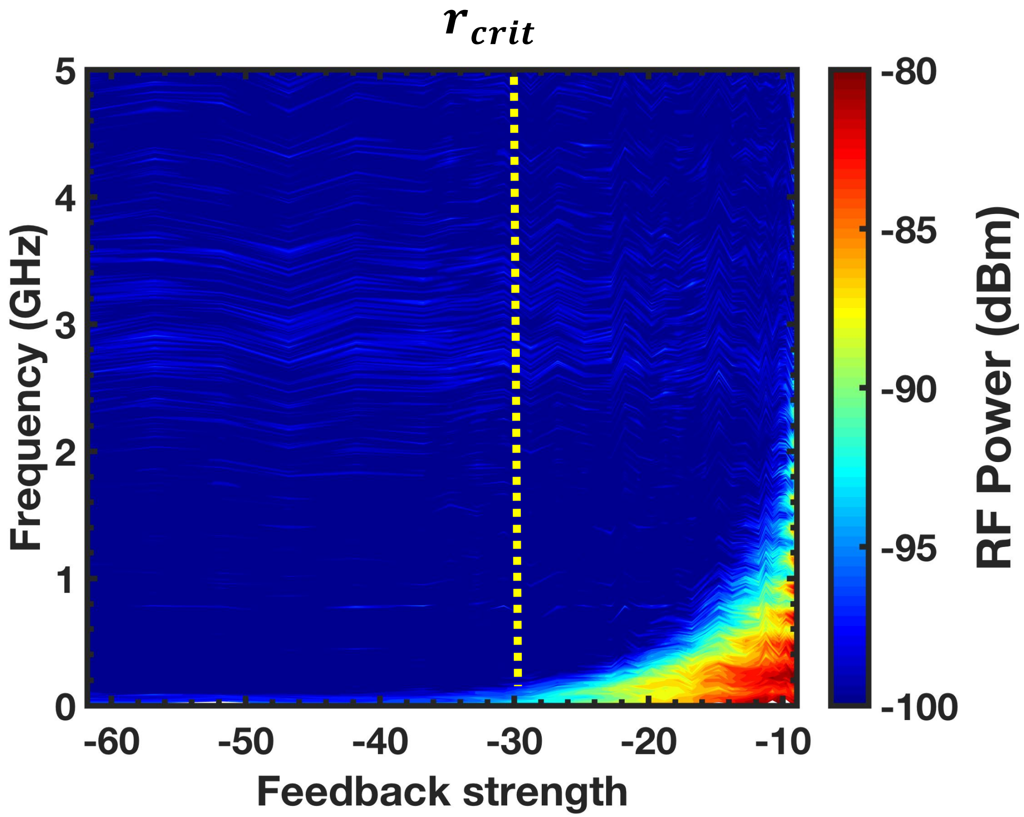
Experimental conditions :

- Laser @ 3xIth and 20^{O}C
- External cavity frequency : 14 MHz
- Largest maximum feedback ratio : -7 dB

HYBRID III-V/SI QW LASERS

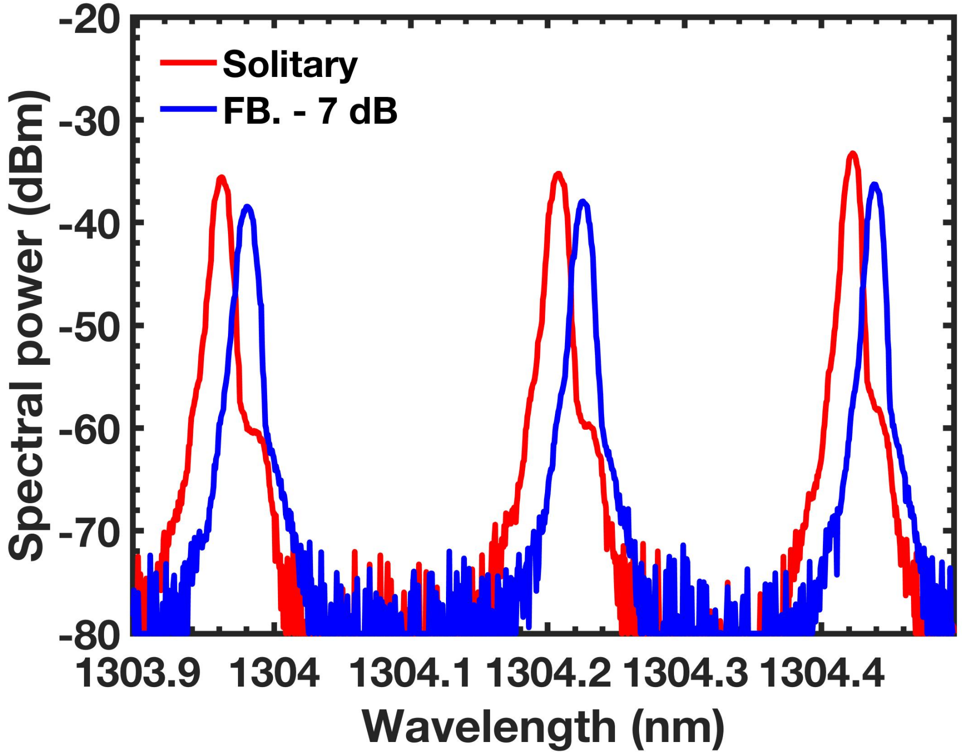
- Destabilization route with birth of spectral broadening and coherence collapse for a feedback strength beyond – 30 dB
- High feedback sensitivity problematic for PIC integration

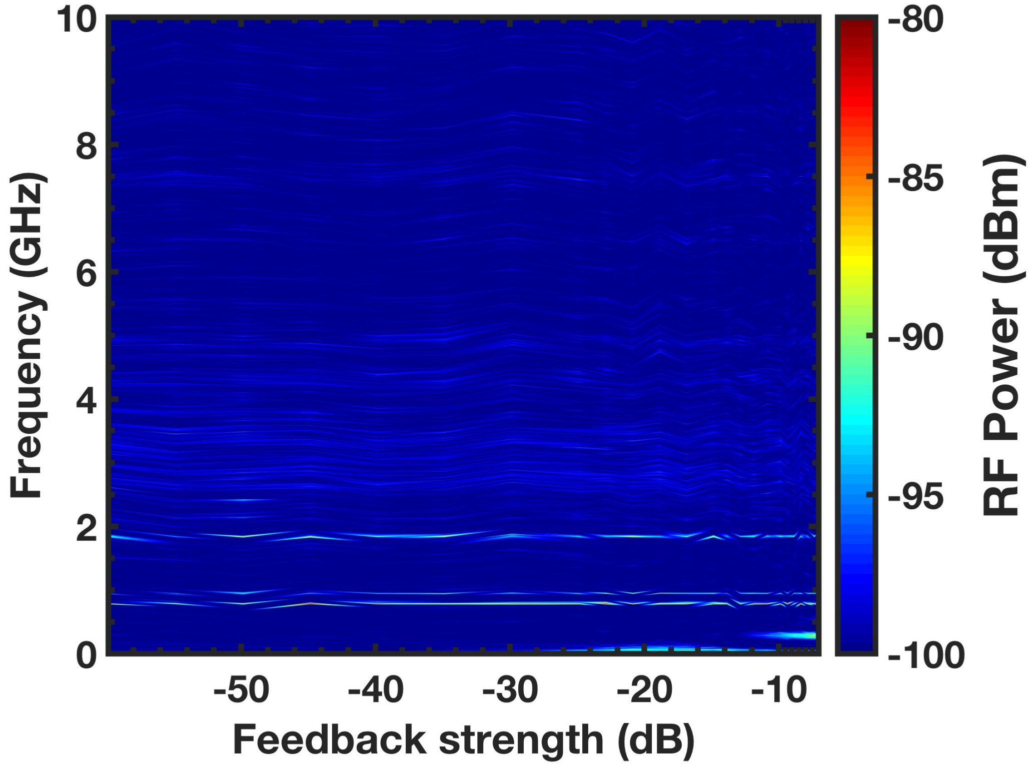


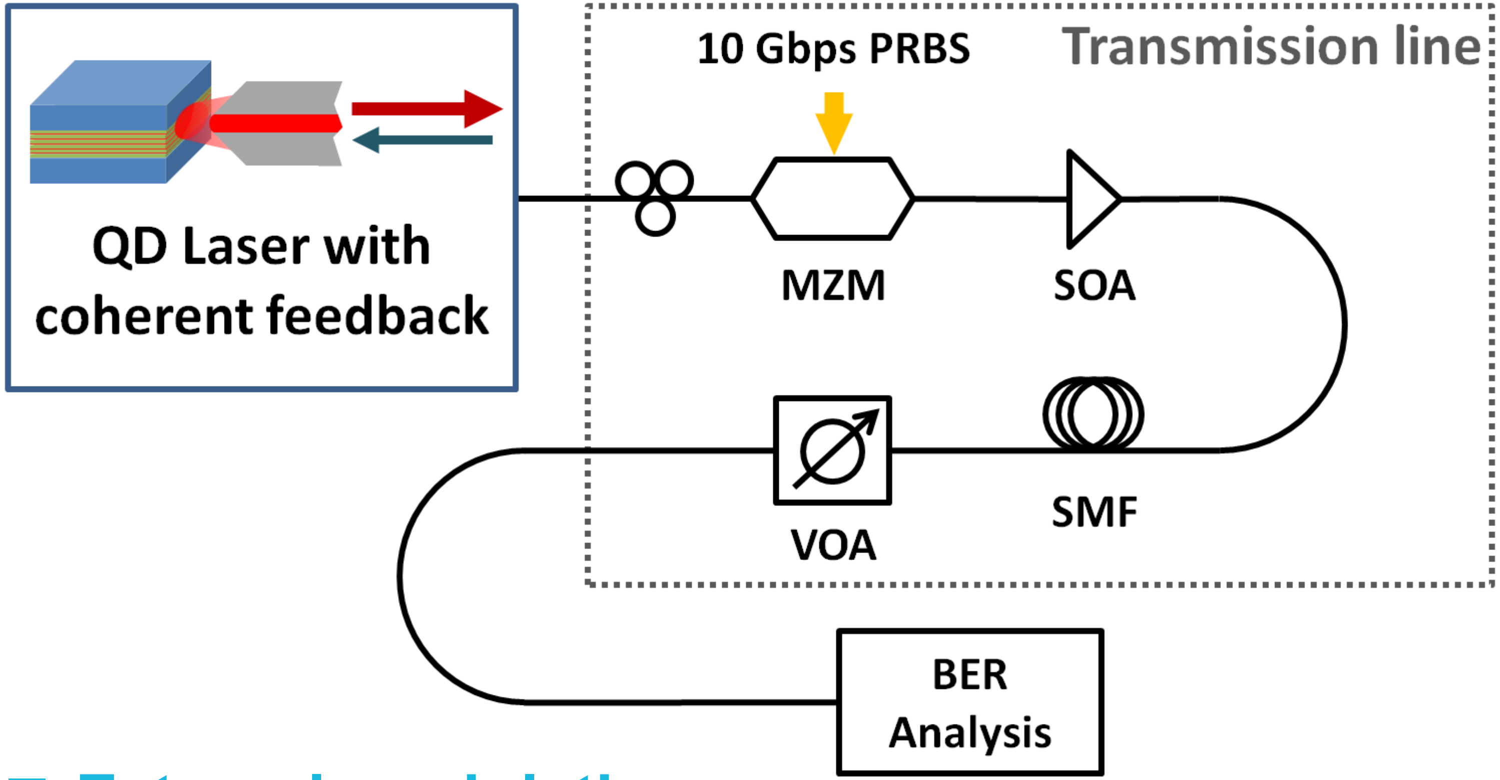


QD LASER ON SILICON

- No spectral instabilities and broadening
- No complex dynamics is observed even at the highest feedback strength of – 7 dB
- Complete reflection insensitivity achieved





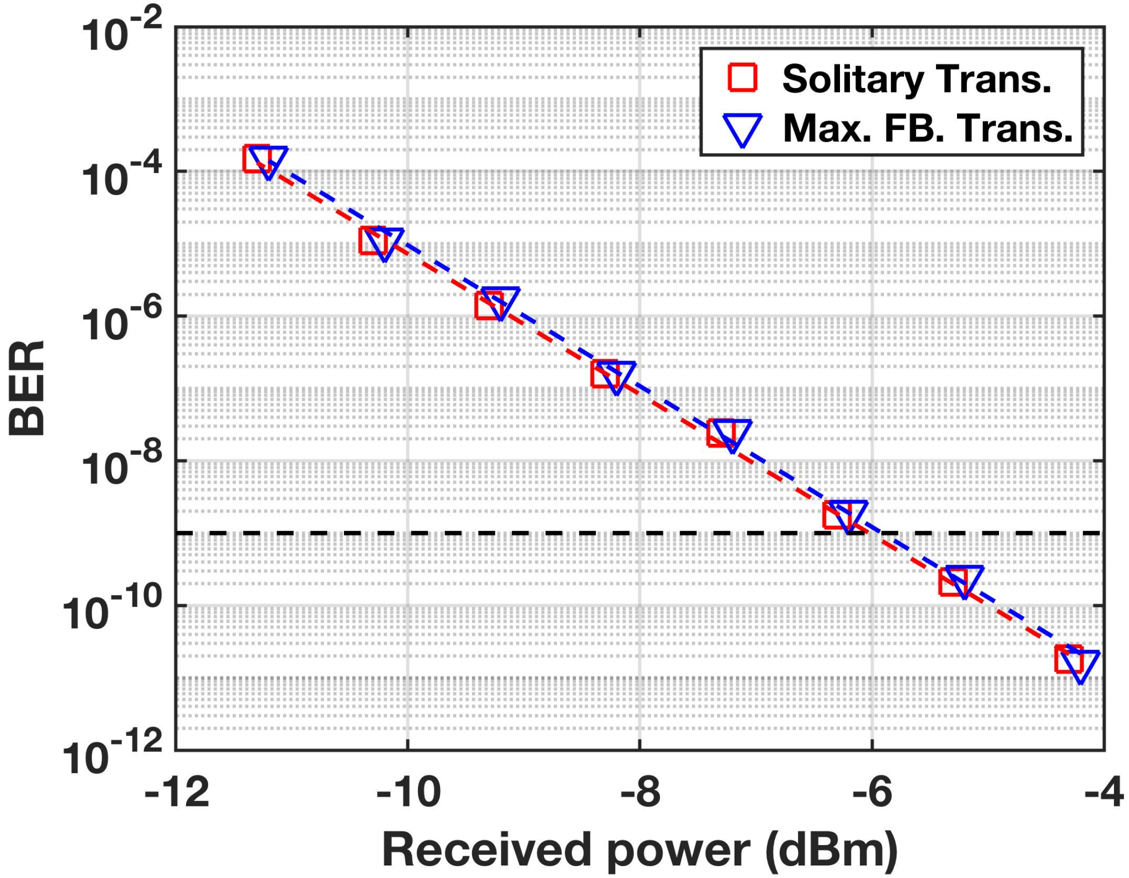


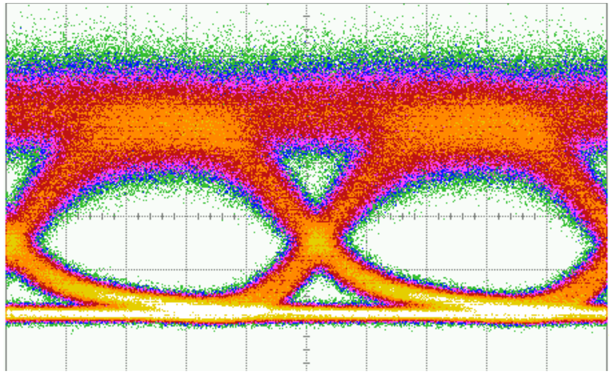
External modulation :

- @ 10 Gbps
- OOK PRBS $2^{31} - 1$
- 2 km transmission

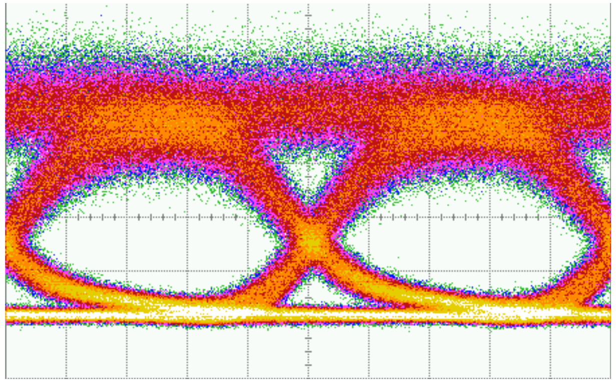
HIGH-SPEED EXPERIMENTS

- Excellent stability without any performance degradation





Solitary Trans.



Max. FB. Trans.

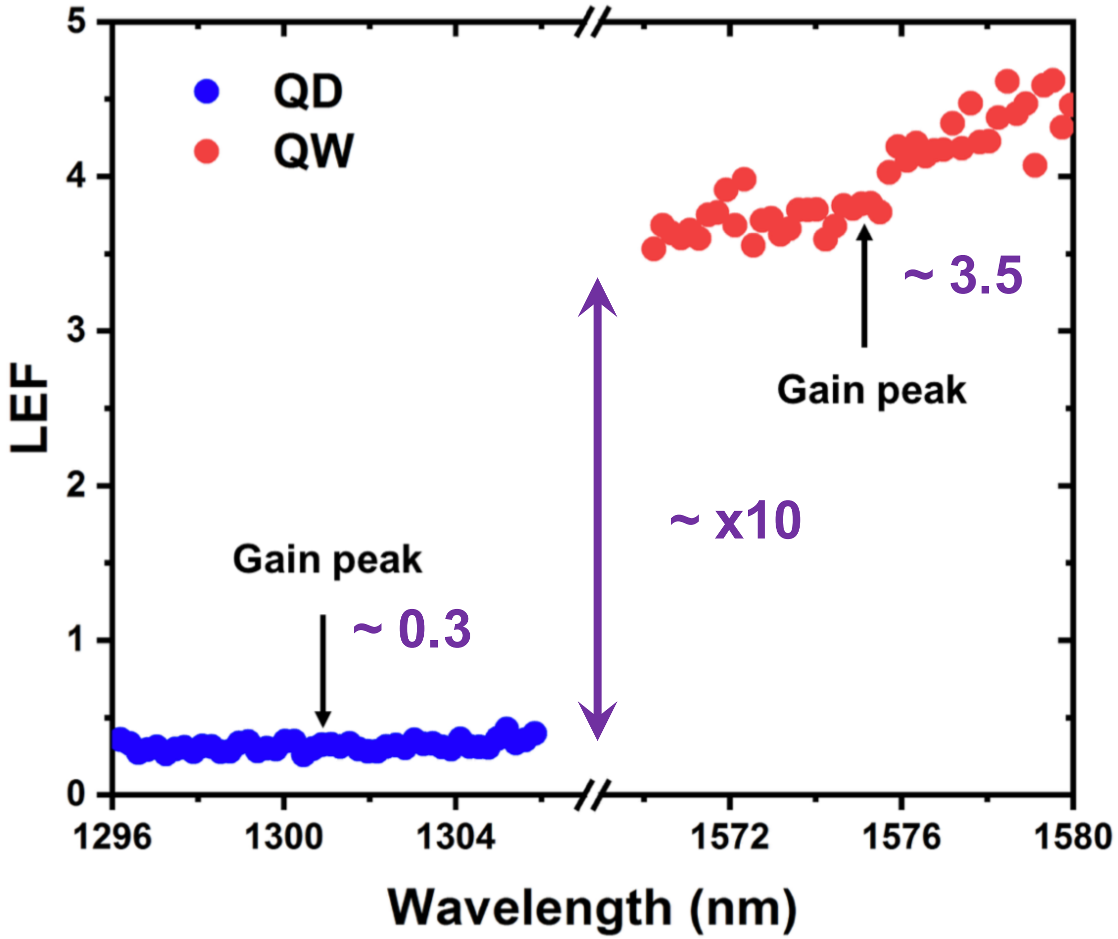
LINEWIDTH ENHANCEMENT FACTOR

■ Low α_H results from :

- ➢ Low threading dislocations: 7.3 x10^6 cm^{-2}
- ➢ Large QD size uniformity
- ➢ Emission on the sole GS

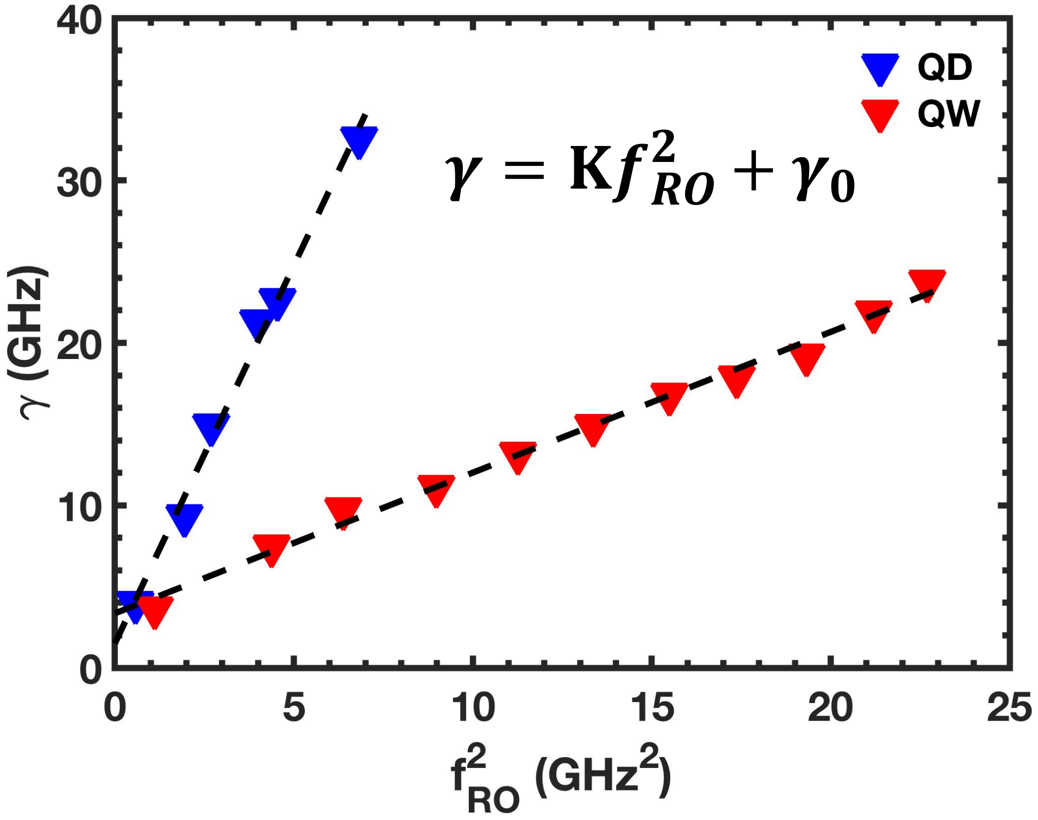
■ Stability criterion

$$r_{crit} = \frac{\tau_{in}^2 \gamma^2}{16 C_l^2} \left(\frac{1 + \alpha_H^2}{\alpha_H^4} \right)$$



DAMPING AND RELAXATION OSCILLATION

	K (ns)	γ_0 (GHz)	γ (GHz) @ 3×Ith
QW	0.9	3.4	15
QD	4.7	1.5	33



- **Stability criterion**

$$r_{crit} = \frac{\tau_{in}^2 \gamma^2}{16 C_l^2} \left(\frac{1 + \alpha_H^2}{\alpha_H^4} \right)$$

CONCLUSIONS & OUTLOOK

- QD lasers epitaxially grown on silicon exhibit a complete reflection insensitivity

- This unique feature mostly results from the narrow QD size dispersion and the absence of emission from higher energy level
  - Near zero α_H – factor
  - High damping

- Strong potential for isolator-free transmission in future silicon photonics systems

- Further investigation will focus on single mode lasers (DFB)

THANK YOU FOR YOUR ATTENTION !

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