CHANGING WHAT'S POSSIBLE

Reflection Insensitive Quantum Dot Lasers Grown on Silicon Substrates

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Frederic Grillot (U. Paris)

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Project Team

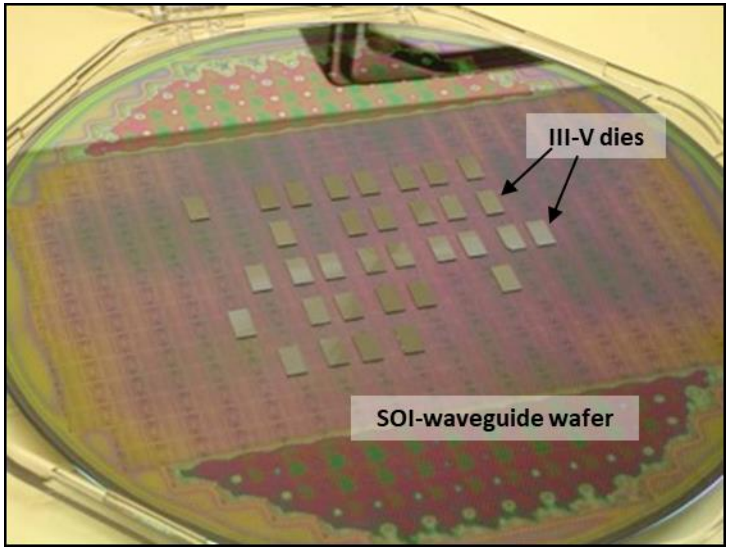
- **Silicon Photonics Research Group at UCSB**
  - State of the art equipment for the characterization and packaging of a wide range of semiconductor devices and optical communication systems
- **UCSB Nanofab**
  - >10,000 ft^2 of Class 100 and 1000 cleanroom space
  - Optical lithographic capability to 200 nm
- **UCSB Growth Facilities**
  - 30 years of pioneering MBE research
  - 9 MBE systems with two dedicated to III-Vs
- **California Nanosystems Institute**
  - Advanced material characterization tools
  - ECCI, TEM, AFM, XRD, SIMS, atom probe

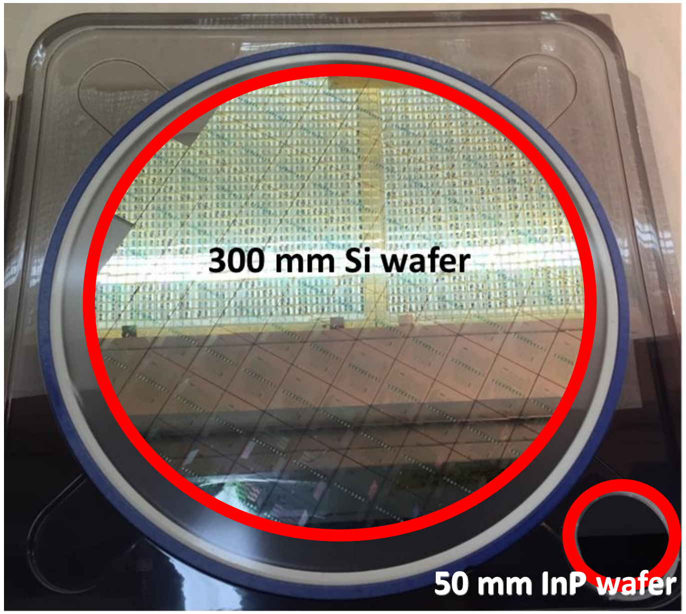
Collaborators

- **Frederic Grillot, ParisTech**
  - Laser dynamics, feedback stability
- **Robert Herrick, Intel Corp.**
  - Laser reliability and aging
- **Matteo Meneghini, Univ. of Padova**
  - Laser reliability and aging
- **Weng Chow, Sandia**
  - Laser theory for linewidth enhancement factor and mode-locking

Achieve High Performance Epitaxial Lasers on Silicon

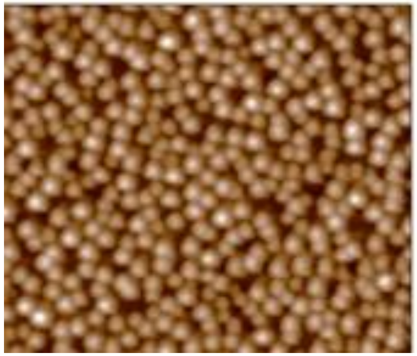
- **Leverage silicon manufacturing infrastructure**
  - Photonics in CMOS foundries
  - Economical, high integration density photonic circuits
- **Indirect bandgap necessitates III-Vs for lasers**
  - Heterogeneous integration: high cost, limited scalability
  - **Epitaxial growth: low cost, scalable with Si wafer size**

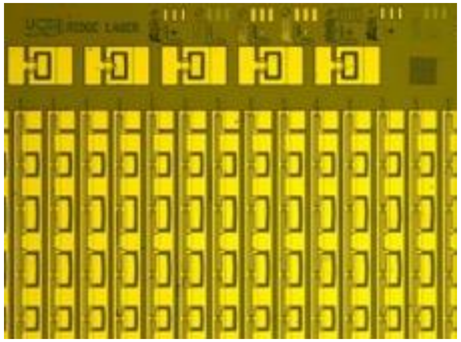


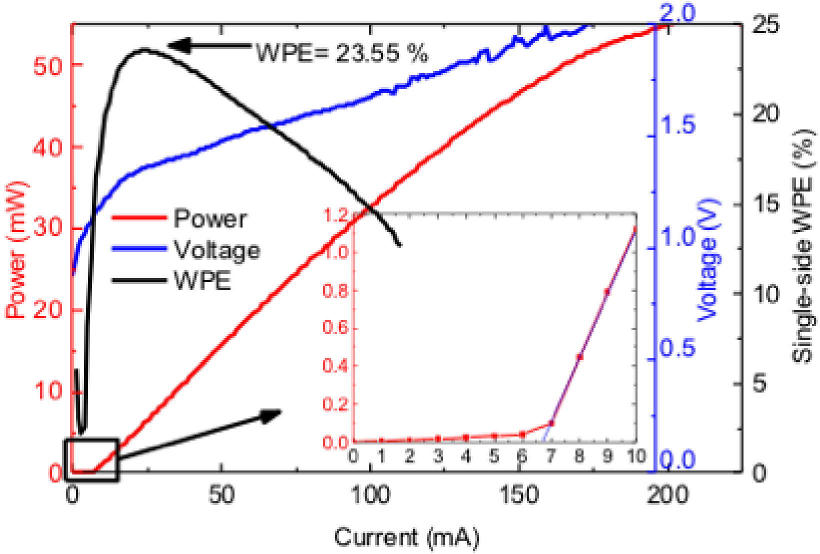


Why Quantum dot lasers?

- ☐ Lower threshold
- ☐ Higher temperature operation (220C)
- ☐ Lower diffusion length (enables smaller devices
- ☐ **Less sensitivity to defects (important for growth on Si)**
- ☐ **Lower linewidth enhancement factor-narrower linewidth**
- ☐ **Lower reflection sensitivity**



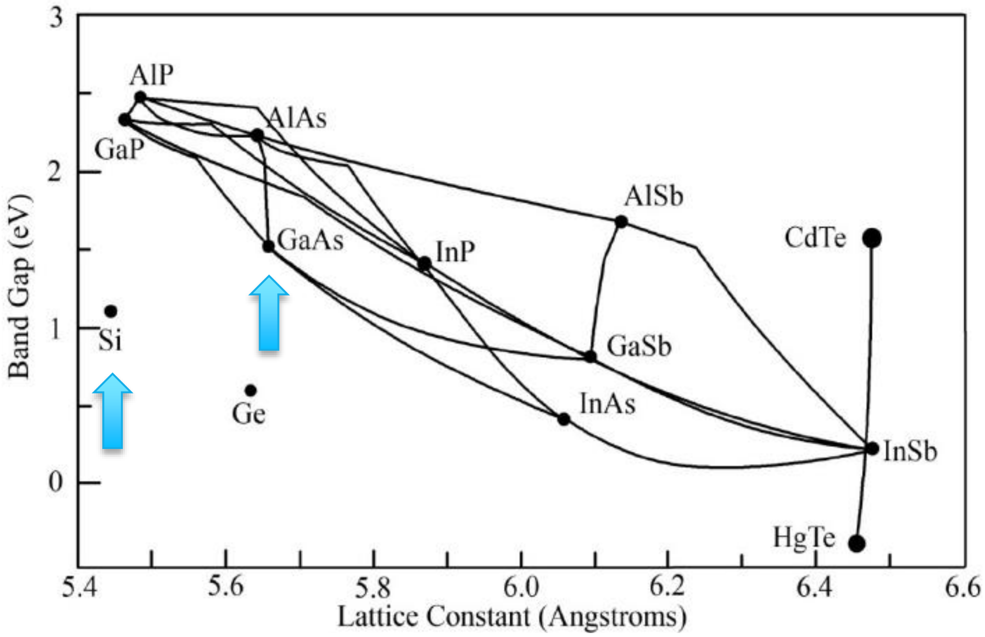




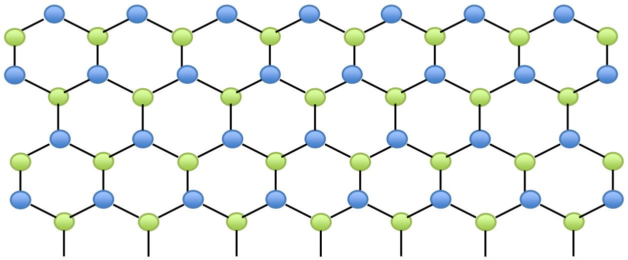
[1] Jung et al. ACS Photonics (2017)

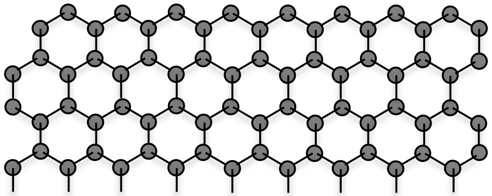
Heteroepitaxial Challenges

- **Crystal lattice mismatch**
  - High density of dislocations, antiphase domains
- **Thermal expansion mismatch**
  - Cracking, residual strain, dislocations



Bulk GaAs: $a = 0.565$ nm

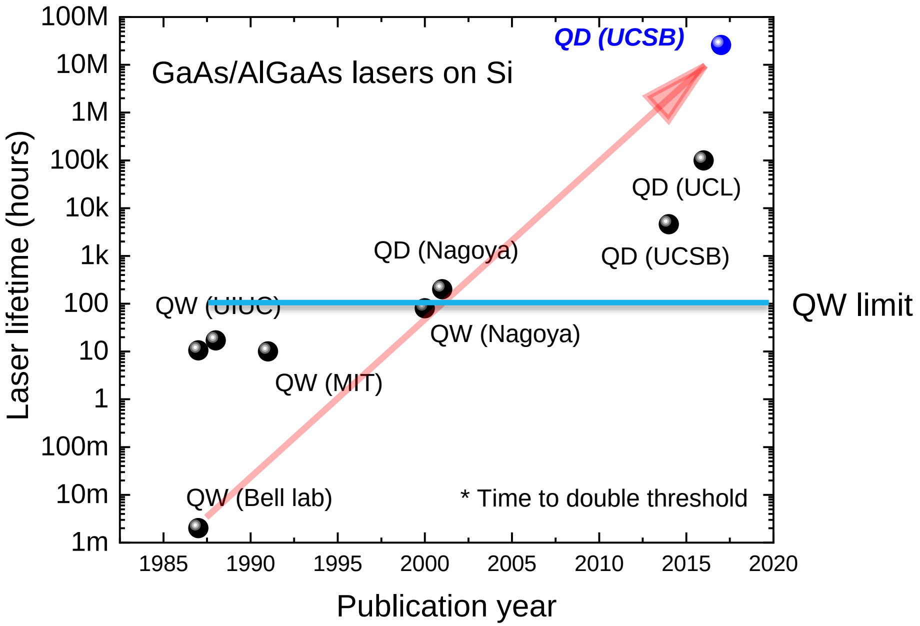


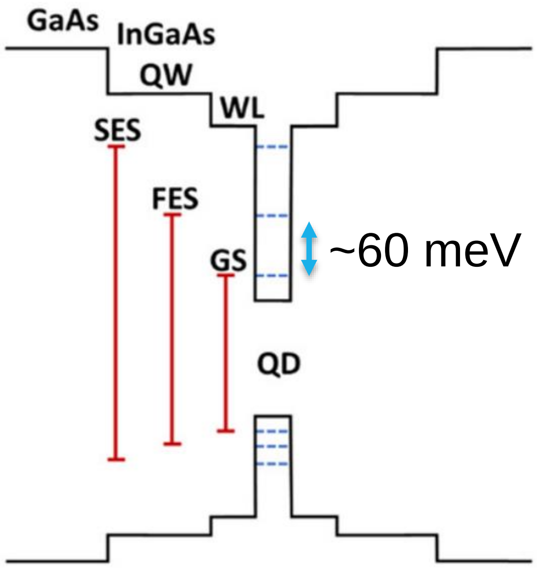


Bulk Si: $a = 0.543$ nm

Quantum Dots Enable High Performance

- **III-V/Si laser research has existed for 30 years**
  - Most reliable QW/Si laser has ~200 h lifetime for GaAs/Si materials
- **Quantum dots represent breakthrough for high performance on Si**
  - >10 M hour lifetime at 35C
  - Ultrashort (500 nm) in-plane diffusion lengths



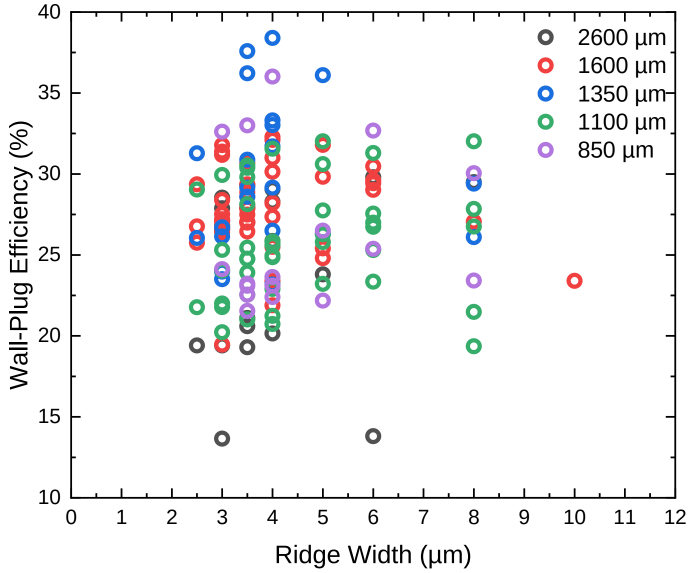


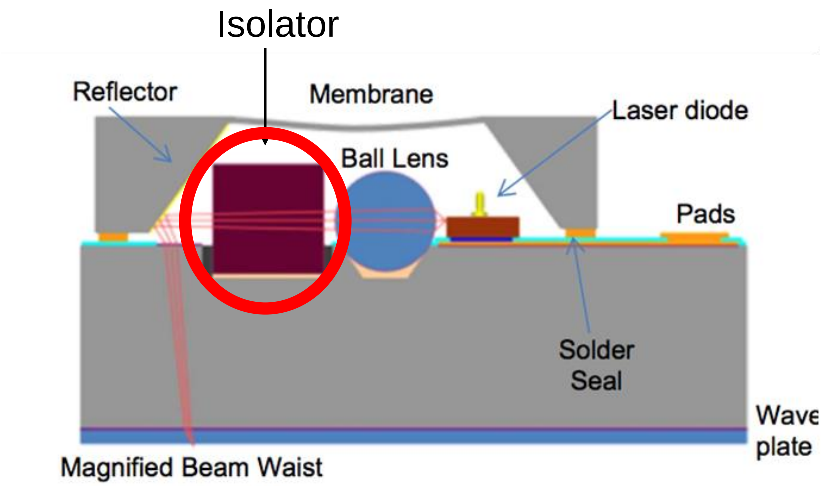
Advanced Capabilities

- **High temperature operation**
- **Sidewall insensitive**
  - Small footprint
- **High performance mode-locked lasers**
  - Ultrafast gain recovery, high four-wave mixing
- **Ultralow linewidth enhancement factor**
  - Narrow linewidth
  - Reflection insensitivity

Applications

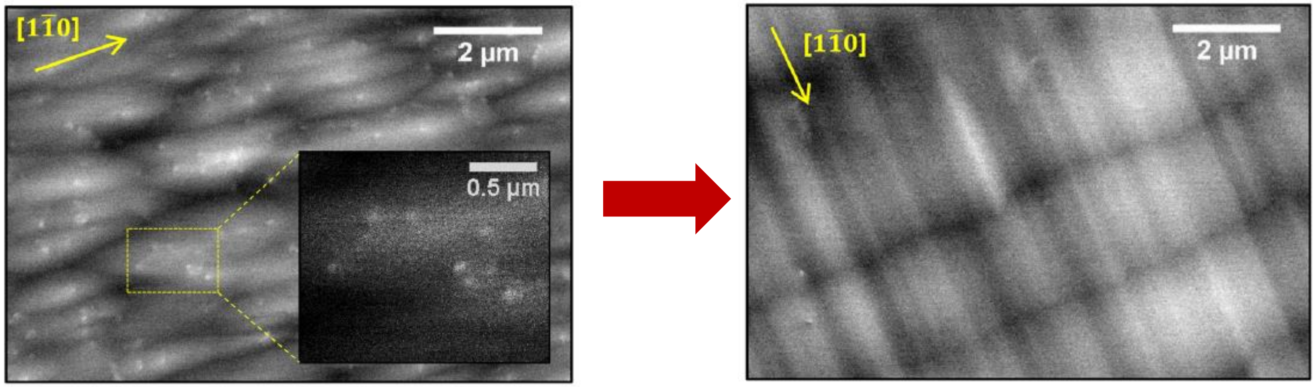
- **Low cost, small footprint, efficient transmitters**
  - Datacenters, HPC, LIDAR, etc.
- **Isolator-free Lasers**
  - Save cost and footprint

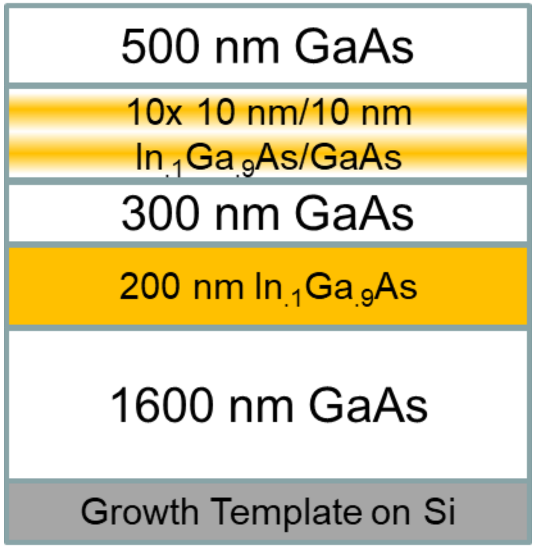




Optimized III-V/Si Templates

- **Thermal cycling and defect filter layers**
  - Antiphase domain free on-axis (001) Si
  - 7×10^6 cm^{-2} dislocation density
- **Ongoing optimization → 2×10^6 cm^{-2}**




500 nm GaAs

10x 10 nm/10 nm In$_{.1}$Ga$_{.9}$As/GaAs

300 nm GaAs

200 nm In$_{.1}$Ga$_{.9}$As

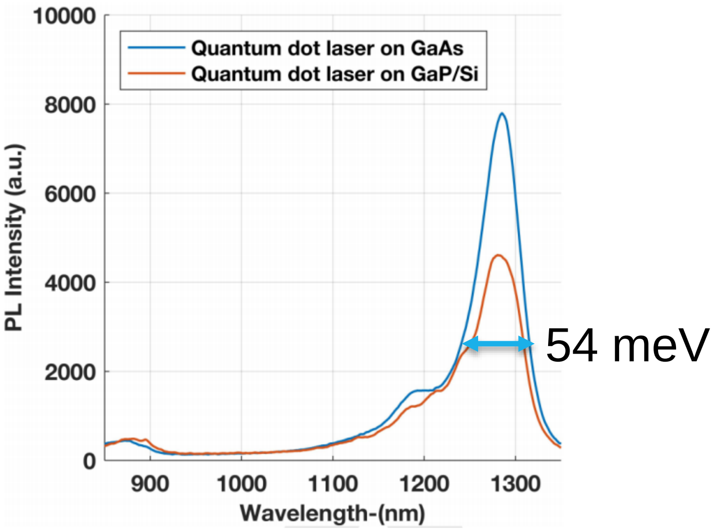
1600 nm GaAs

Growth Template on Si

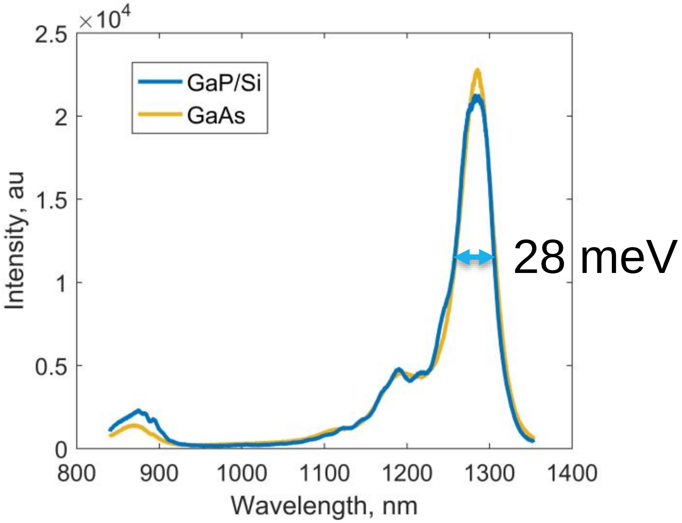
Optimized Quantum Dot Active Region

- **InAs dots in $In_{.15}Ga_{.85}As$ well**
  - O-band emission achievable from ~1260-1320 nm
- **Inhomogeneously broadened gain spectrum**
  - Dots form via self-assembled growth
  - Large, coupled parameter space to optimize

Before Optimization



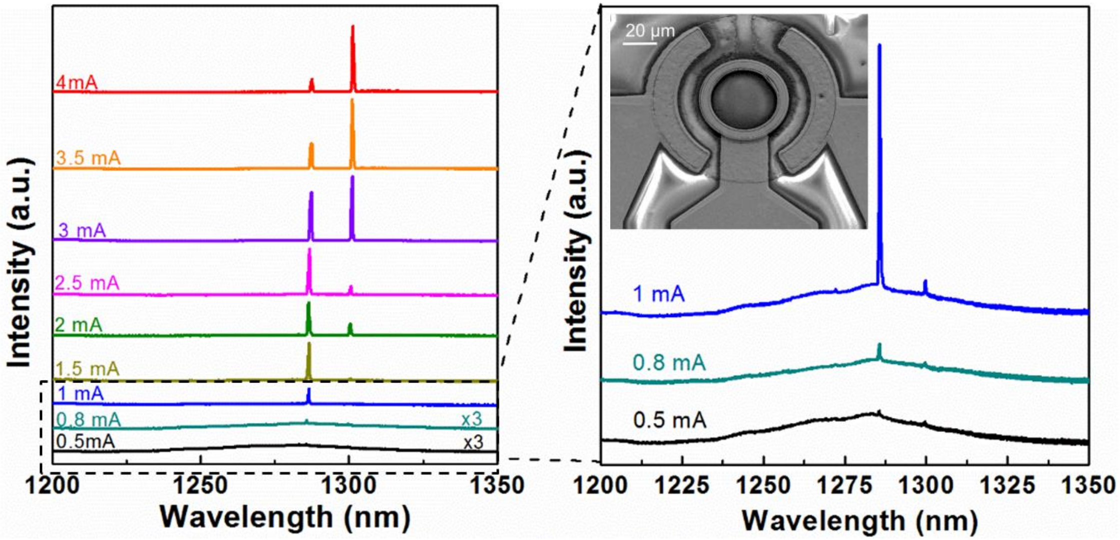
After Optimization

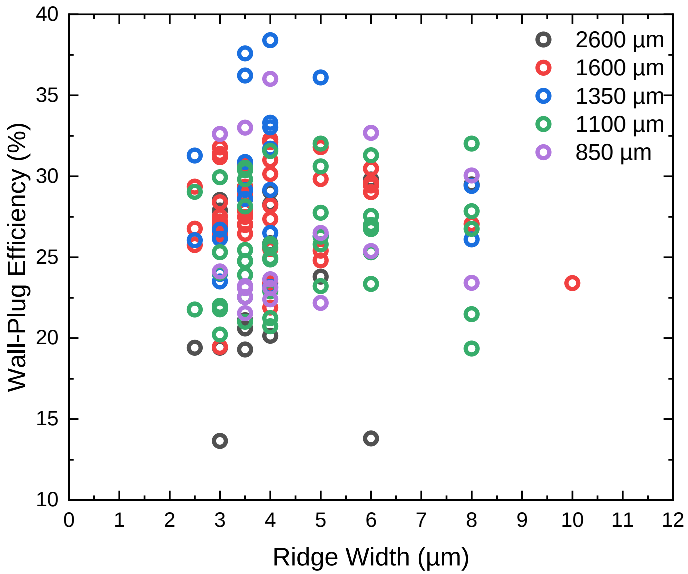


CHANGING WHAT'S POSSIBLE

Highly Efficient Lasers

- **Small-footprint microring cavities**
  - Sidewall insensitive
  - Sub-milliampere threshold current
- **High wall-plug efficiency Fabry-Perot lasers**

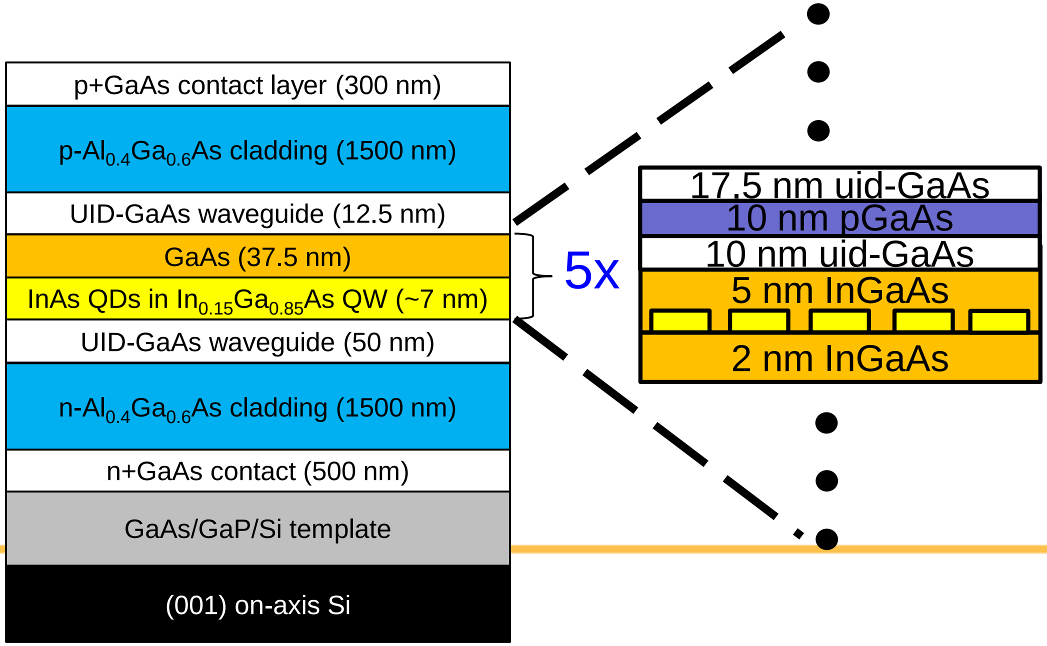




Y. Wan, et al., Optica, 4, (2017).

P-type Modulation Doping

- **Band offsets leave holes weakly confined in dots**
  - Add active region doping to offset thermalization
  - ~10-30 holes per dot
- **Significantly increases gain, differential gain**
  - Critical to high temperature reliability & low linewidth enhancement factor
  - Costs higher threshold, lower slope efficiency, ~10-20% WPE



p+GaAs contact layer (300 nm)

p-$Al_{0.4}Ga_{0.6}As$ cladding (1500 nm)

UID-GaAs waveguide (12.5 nm)

GaAs (37.5 nm)

InAs QDs in $In_{0.15}Ga_{0.85}As$ QW (~7 nm)

UID-GaAs waveguide (50 nm)

n-$Al_{0.4}Ga_{0.6}As$ cladding (1500 nm)

n+GaAs contact (500 nm)

GaAs/GaP/Si template

(001) on-axis Si

5x

17.5 nm uid-GaAs

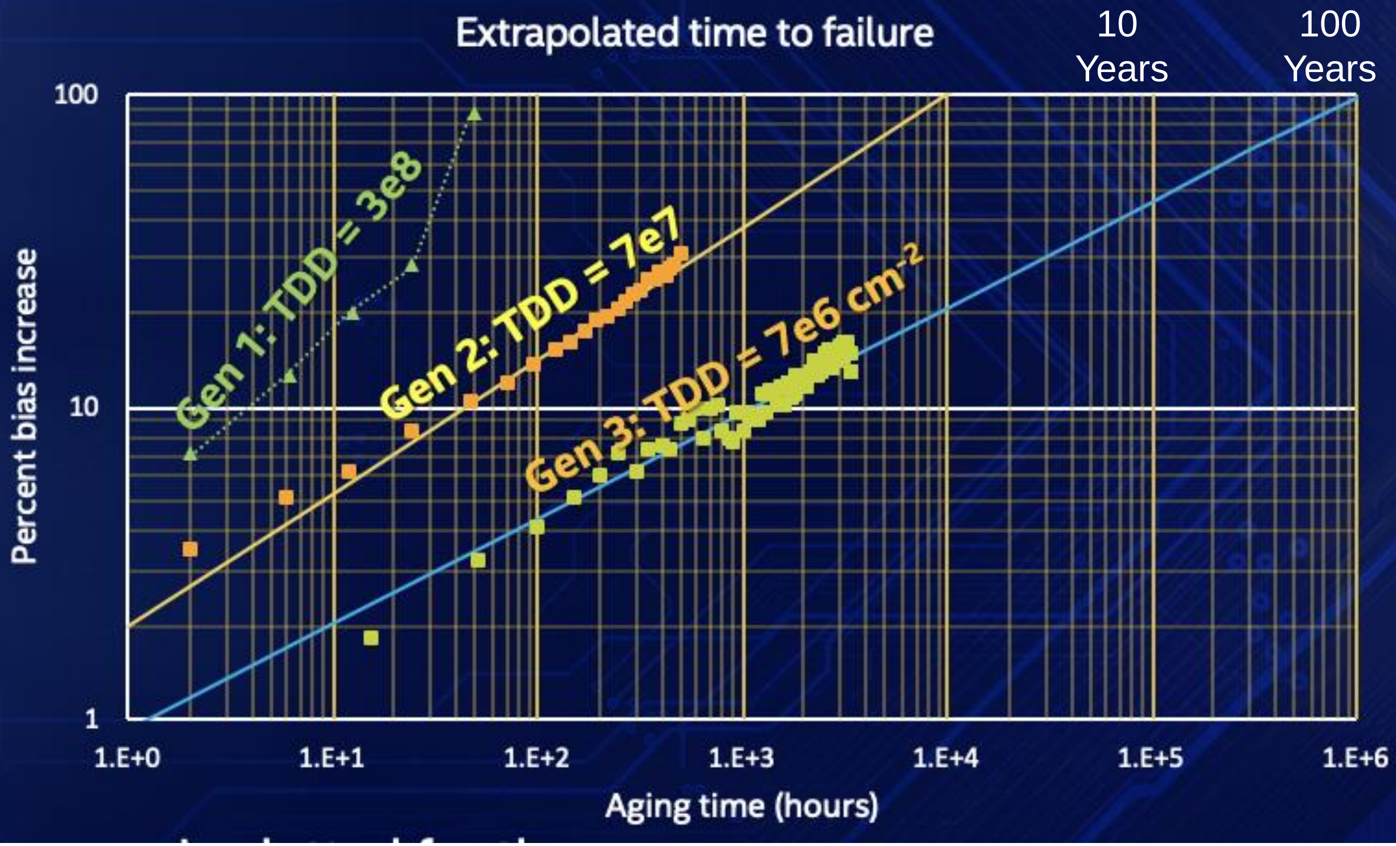
10 nm pGaAs

10 nm uid-GaAs

5 nm InGaAs

2 nm InGaAs

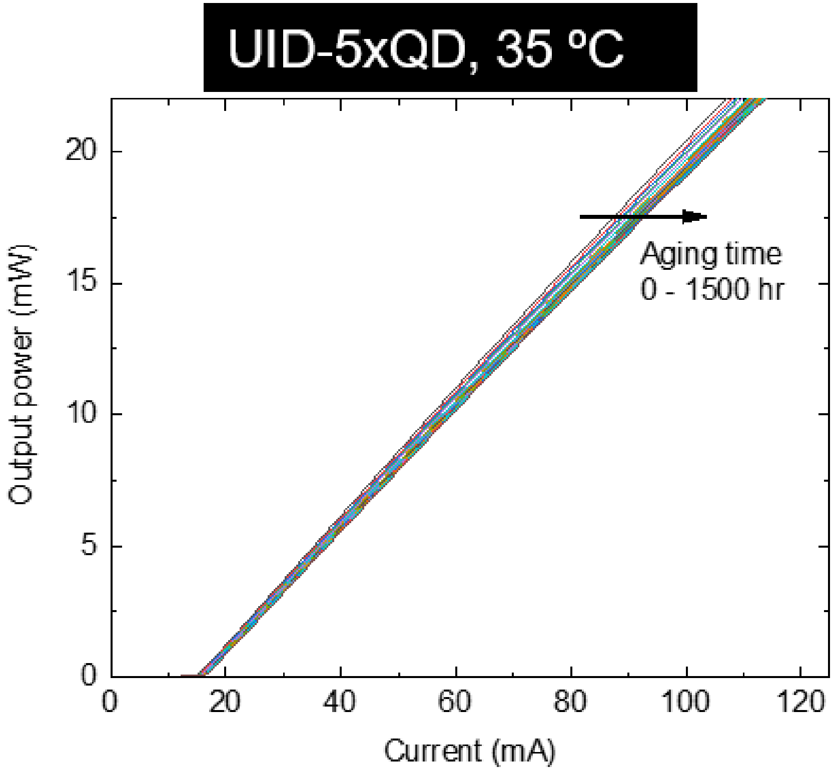
COMPARISON OF 3 RELIABILITY TESTS AT 35C

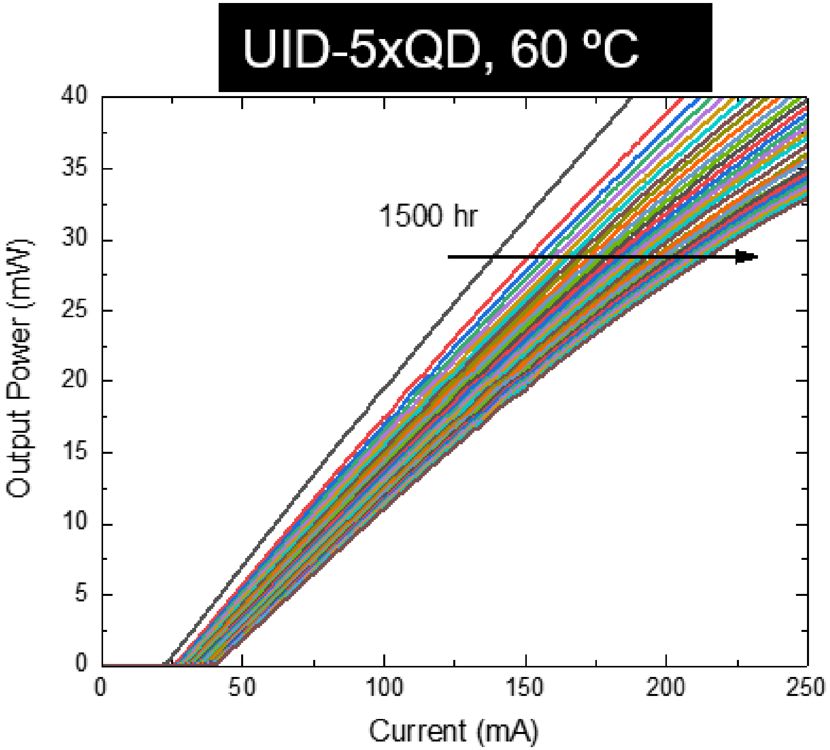


Herrick et al.(Intel, UCSB) OFC 2019

Reliability at 60ºC

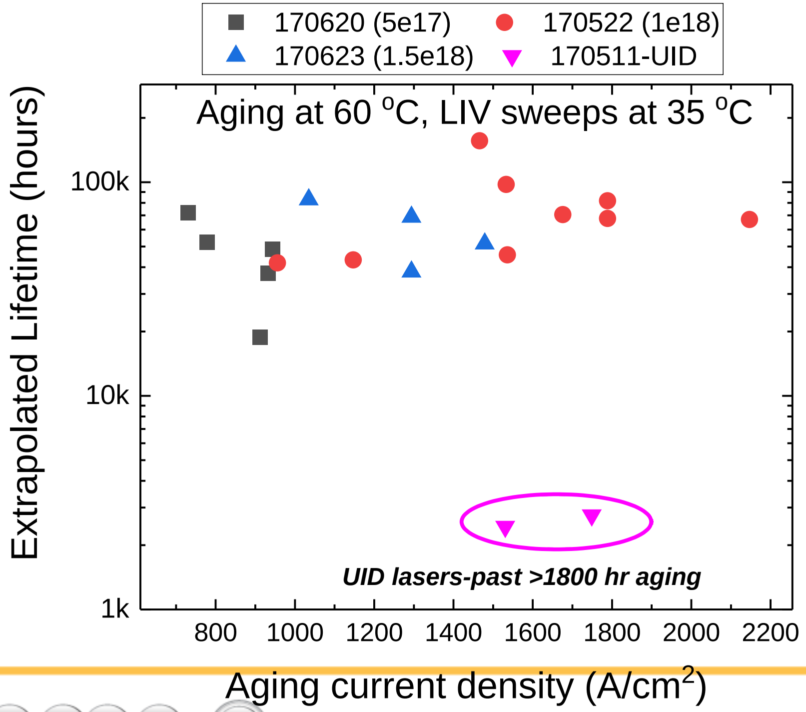
- Need reliable operation at elevated temperatures
- Datacenters & HPC applications at 60-80ºC or higher
- First aging test at 60 °C shows lifetime of **~2500 hours**

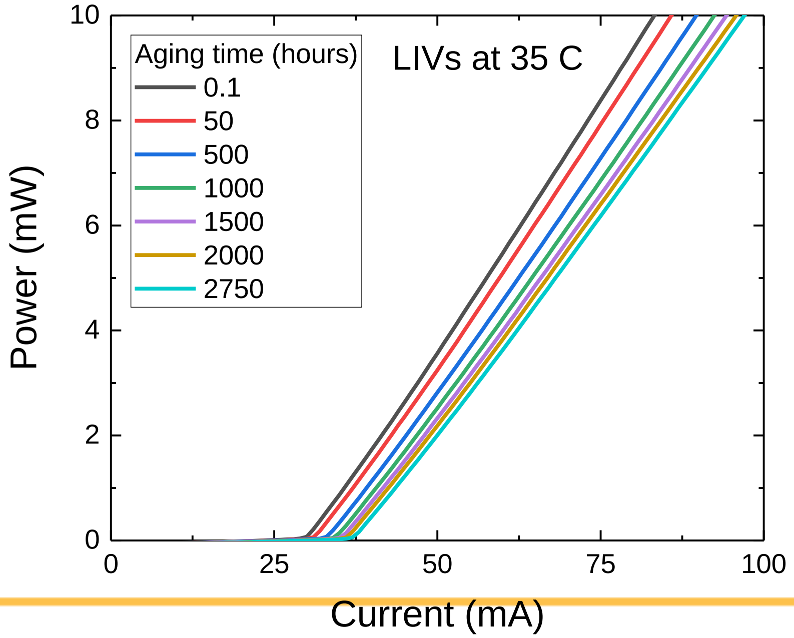

UID-5xQD, 35 ºC


UID-5xQD, 60 ºC

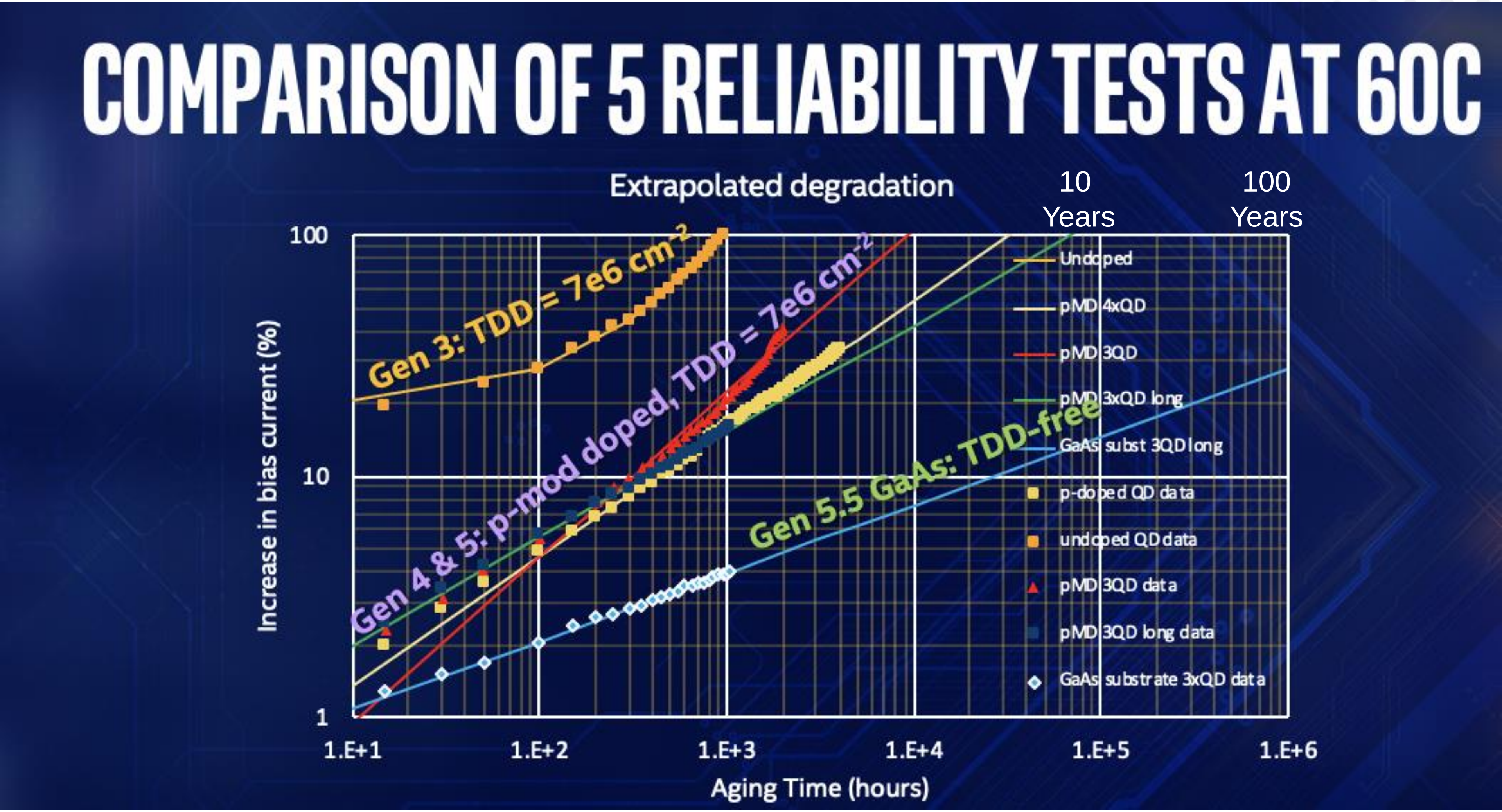
Summary of 60 C Reliability (300-hour)

- Varied p-doping levels in active region
  - P=5e17 cm^{-3} to p=1.5e18 cm^{-3}
- Highly improved lifetimes from 60°C aging
  - >>10,000 hours extrapolated lifetime





Still Defect Limited

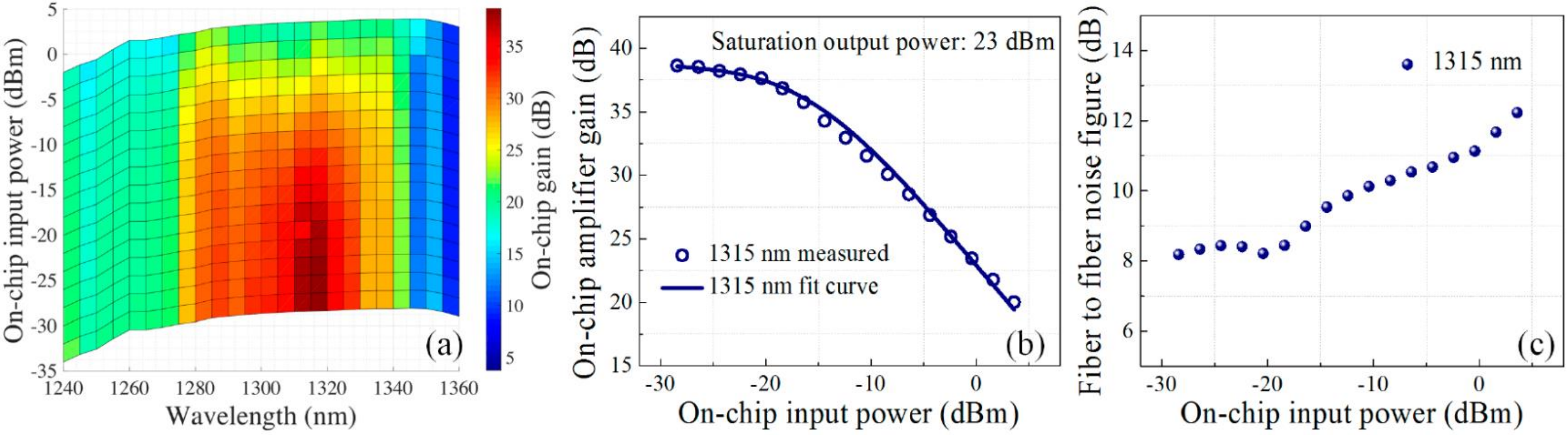


COMPARISON OF 5 RELIABILITY TESTS AT 60C

Herrick et al.(Intel, UCSB) OFC 2019

High Performance Optical Amplifiers

- Columbia Enlitened Project
- 39 dB ground state gain (>20 dB at 70°C)
- Noise figure as low as 6.1 dB
- Wall-plug efficiency up to 20%

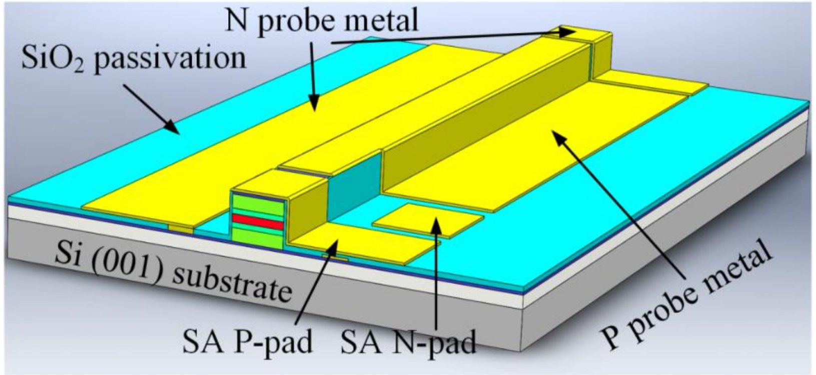


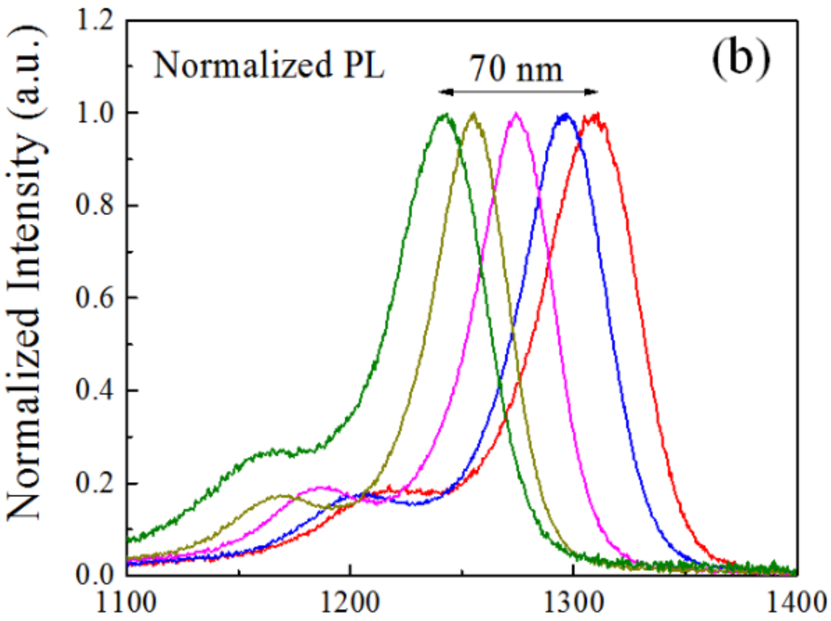
I_{gain} = 750 mA, T = 20°C, L = 5000 µm, tapered width 5 µm → 11 µm

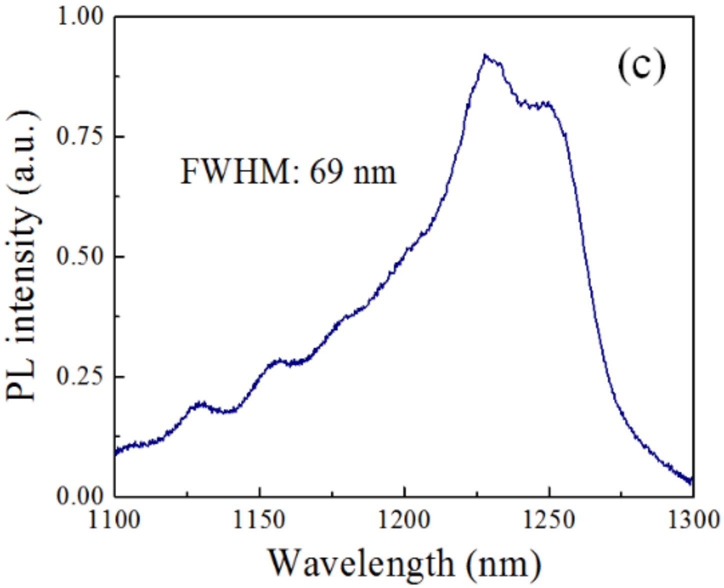
S. Liu, et al., ACS Photonics, 6, 2523-2529 (2019).

Mode-Locked Combs for Data Transmission

- **Quantum dots uniquely suited to MLLs**
  - Ultrafast gain/absorber recovery
  - Broad, engineerable gain bandwidth



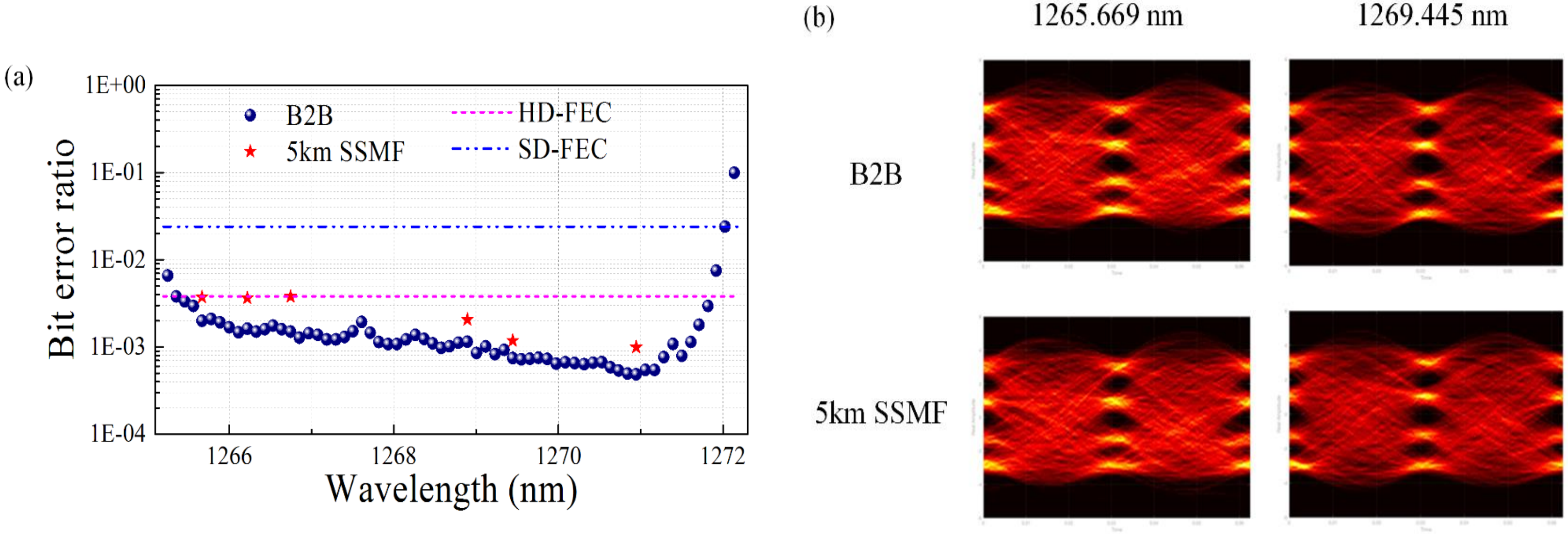




S. Liu, et al. Optica, 6(2), 2019

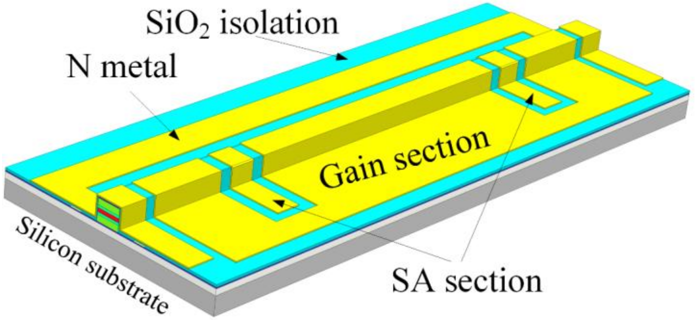
4.1 Tbps from Single Laser

- **64 channel, 32 Gbaud Nyquist pulse shaped PAM-4**
- **61 channels below HD-FEC, 64 below SD-FEC**
- **4.1 Tbps**

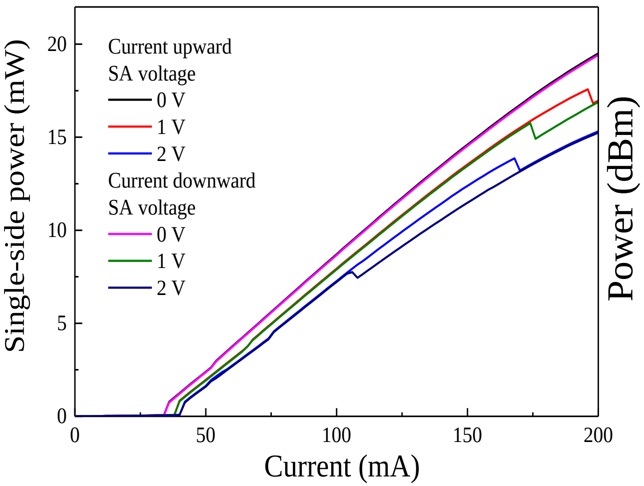


100 GHz Colliding Pulse MLL

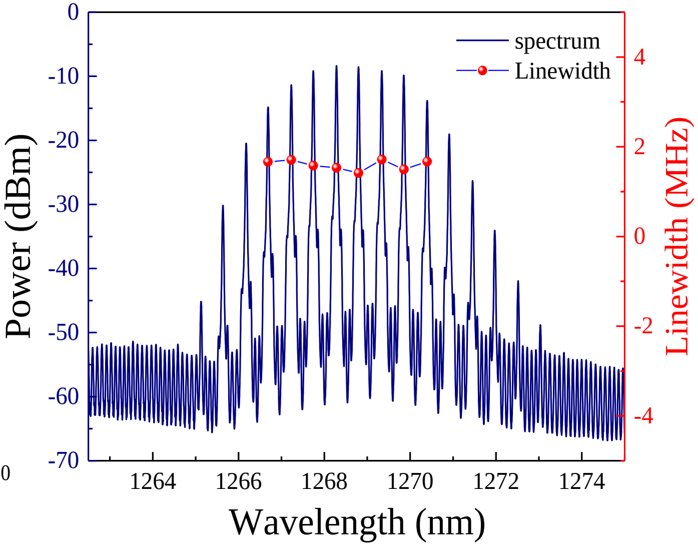
- **5^{th} harmonic design**
- **Wide mode-locking range**
  - < 2.5 ps and >8 dB pulse-contrast ratio



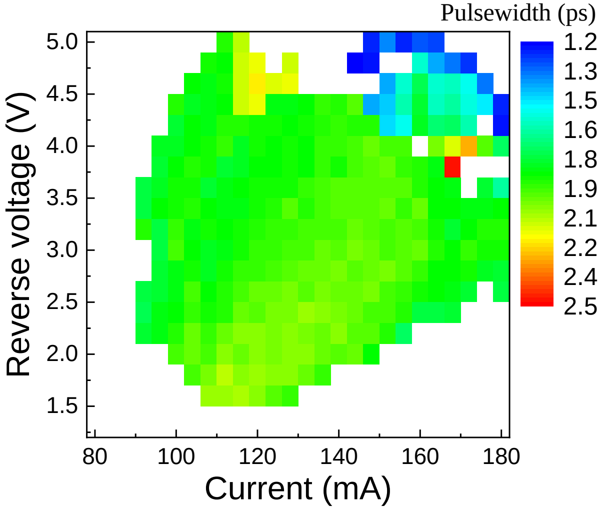
L–I curve



I_{gain} = 144 mA, V_{SA} = - 3.3 V

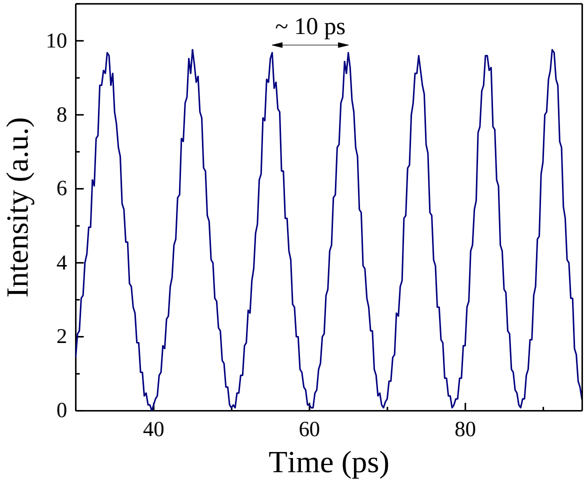


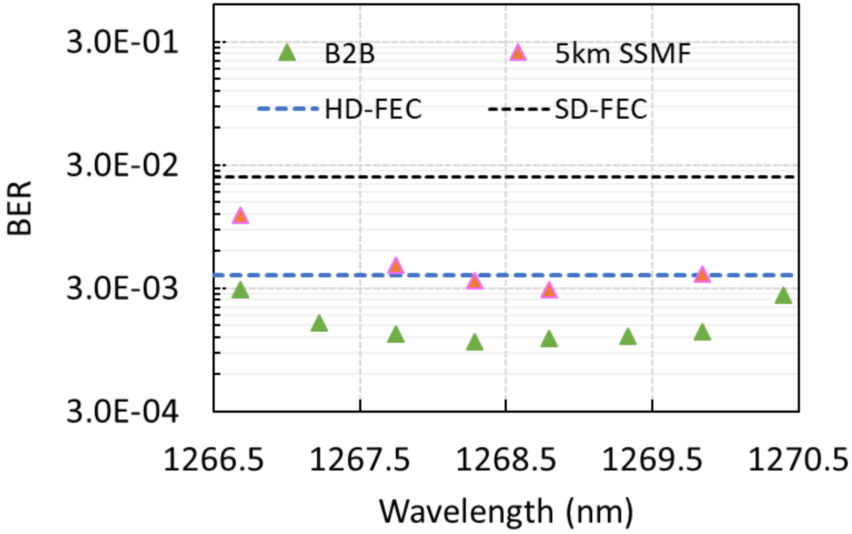
Pulsewidth mapping

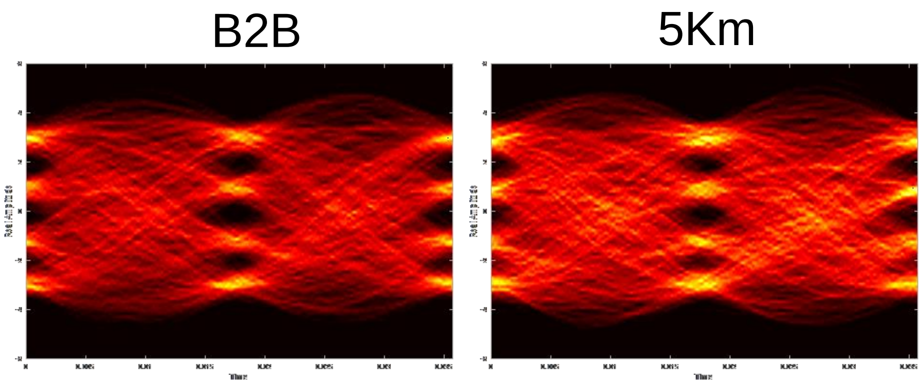


0.9 Tbps from Single Laser at 100 GHz

- **8 channels w/56 Gbaud Nyquist pulse shaped PAM-4**
- **Autocorrelator confirms 100 GHz**





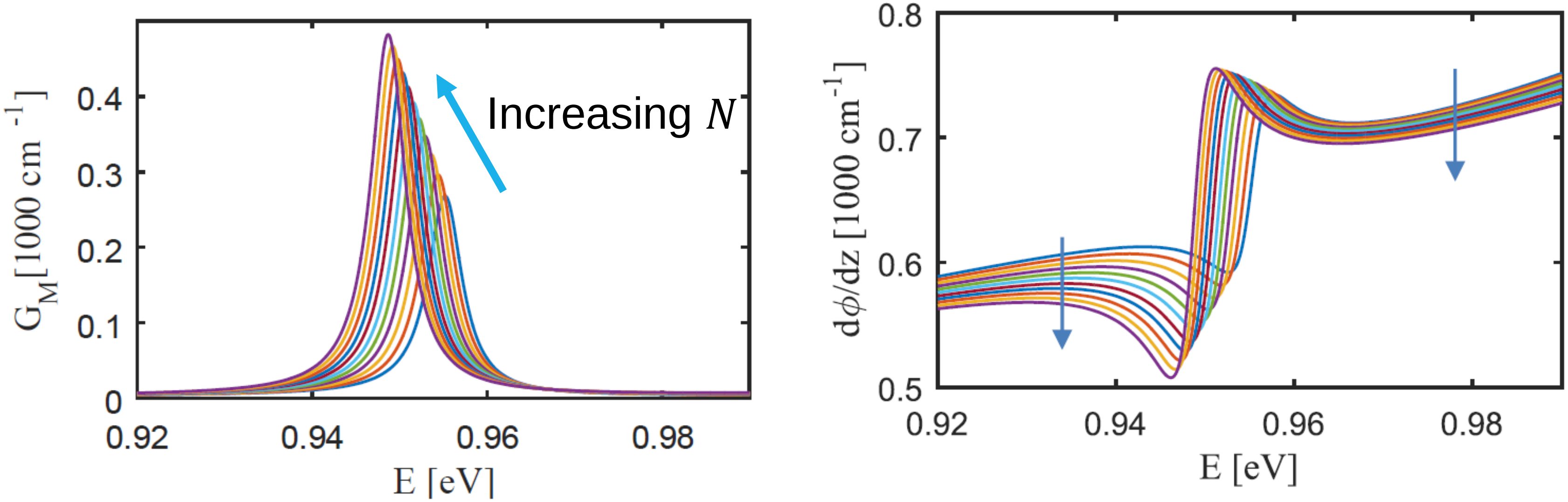


Wavelength =1268.794 nm

Quantum Dots for Low Linewidth Enhancement Factor

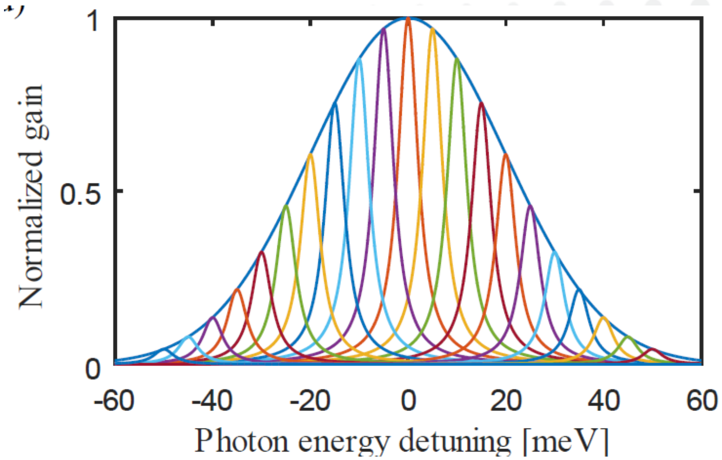
- **Quantum dots have inherently low LEF**
  - Symmetric density of states
  - Identically zero from Kramers-Kronig

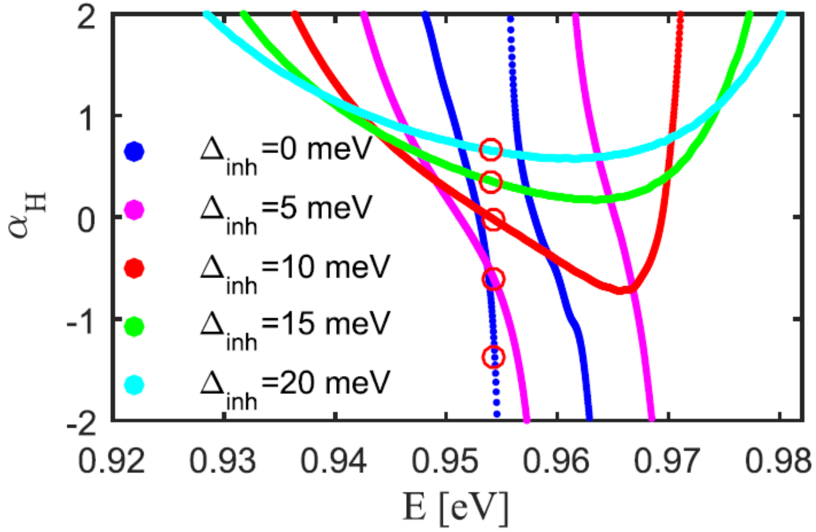
$$\alpha_H = -\frac{\frac{d(d\phi/dz)}{dN}}{\frac{d(G_M)}{dN}}$$

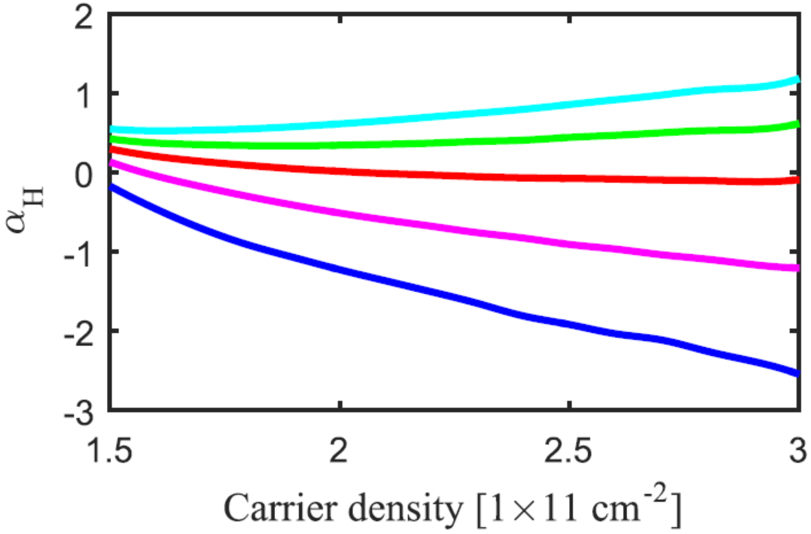


Inhomogeneous Broadening Increases LEF

- **Dot sub-populations overlap**
  - Low alpha at gain peaks, high at tails
- **Also depends on carrier density**
  - Many-body effects



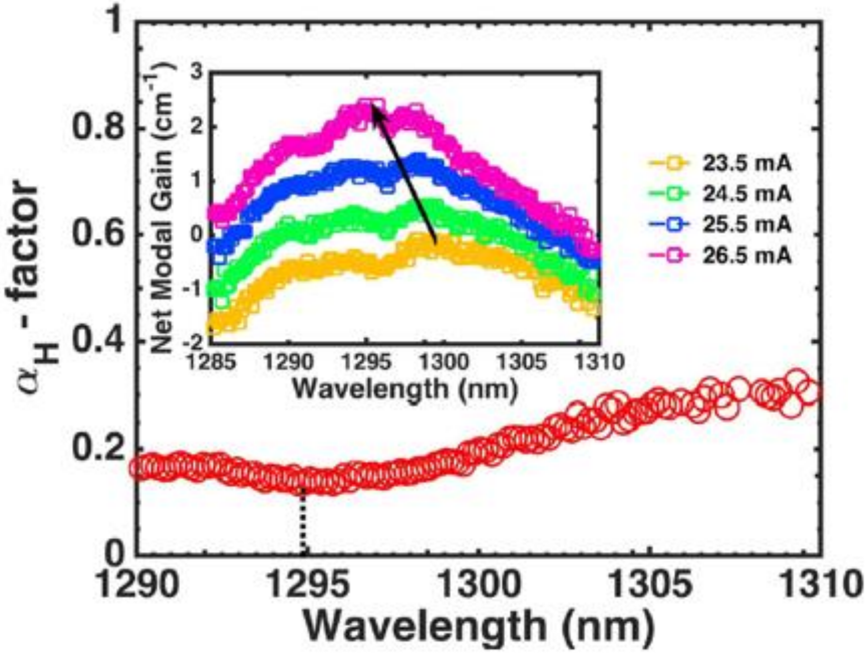


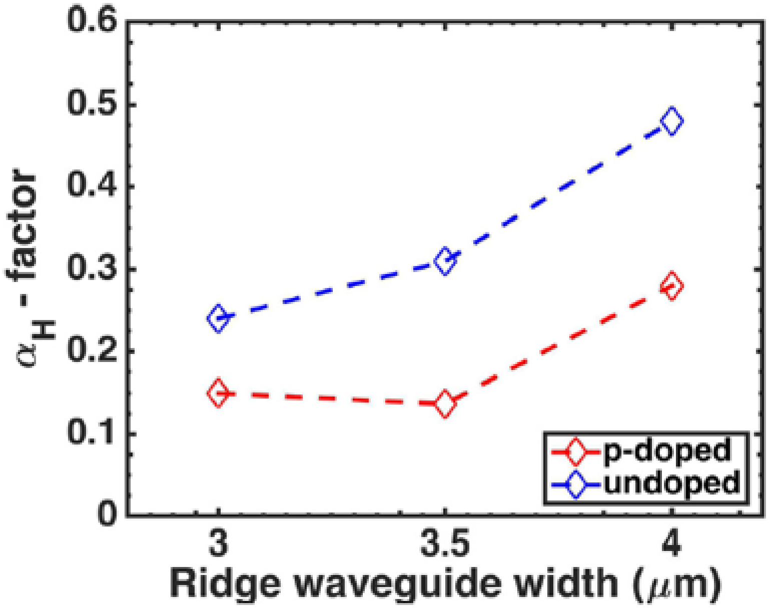


Experimental Ultralow Linewidth Enhancement Factor

- **Alpha factors of QD Si lasers show ~0.15 with p-doping**
  - Quantum wells typically ~3-5

$$\alpha_H \equiv -\frac{dn/dN}{dn_i/dN} = -\frac{4\pi}{\lambda}\frac{dn/dN}{dg/dN} = -\frac{4\pi}{\lambda a}\frac{dn}{dN}$$



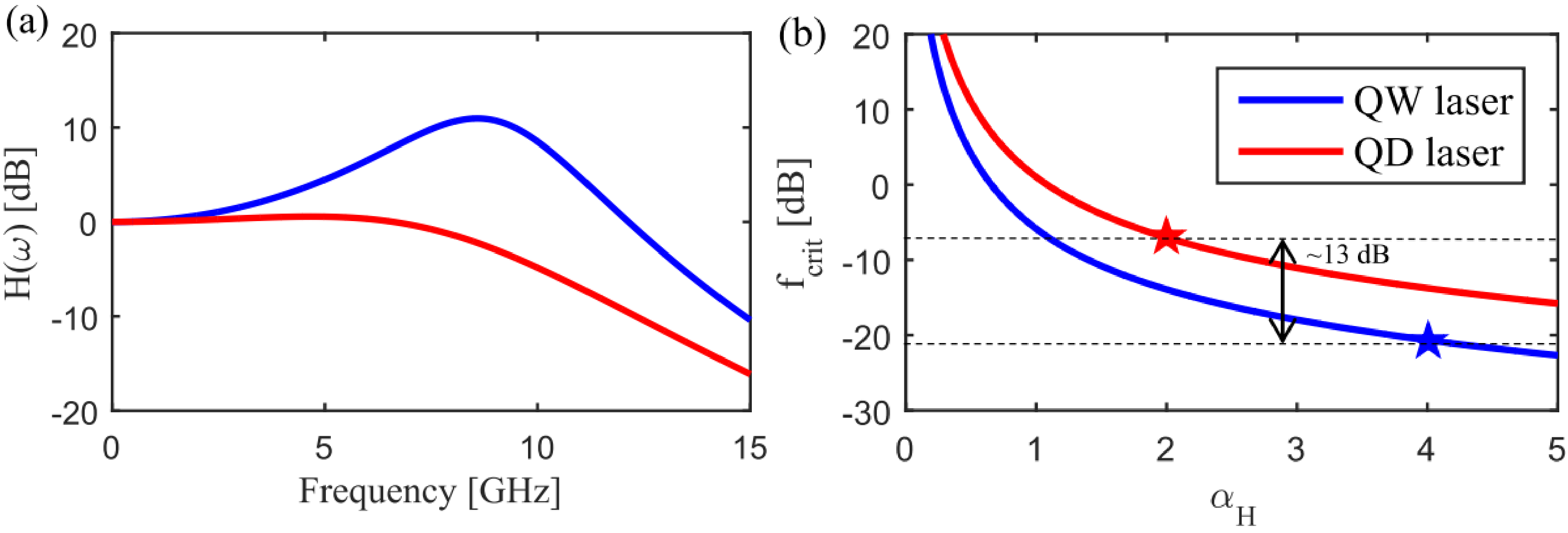


Jian Duan *et al.* APL 2018

High Critical Feedback Level

- **High damping and low α_H yield high feedback tolerance**

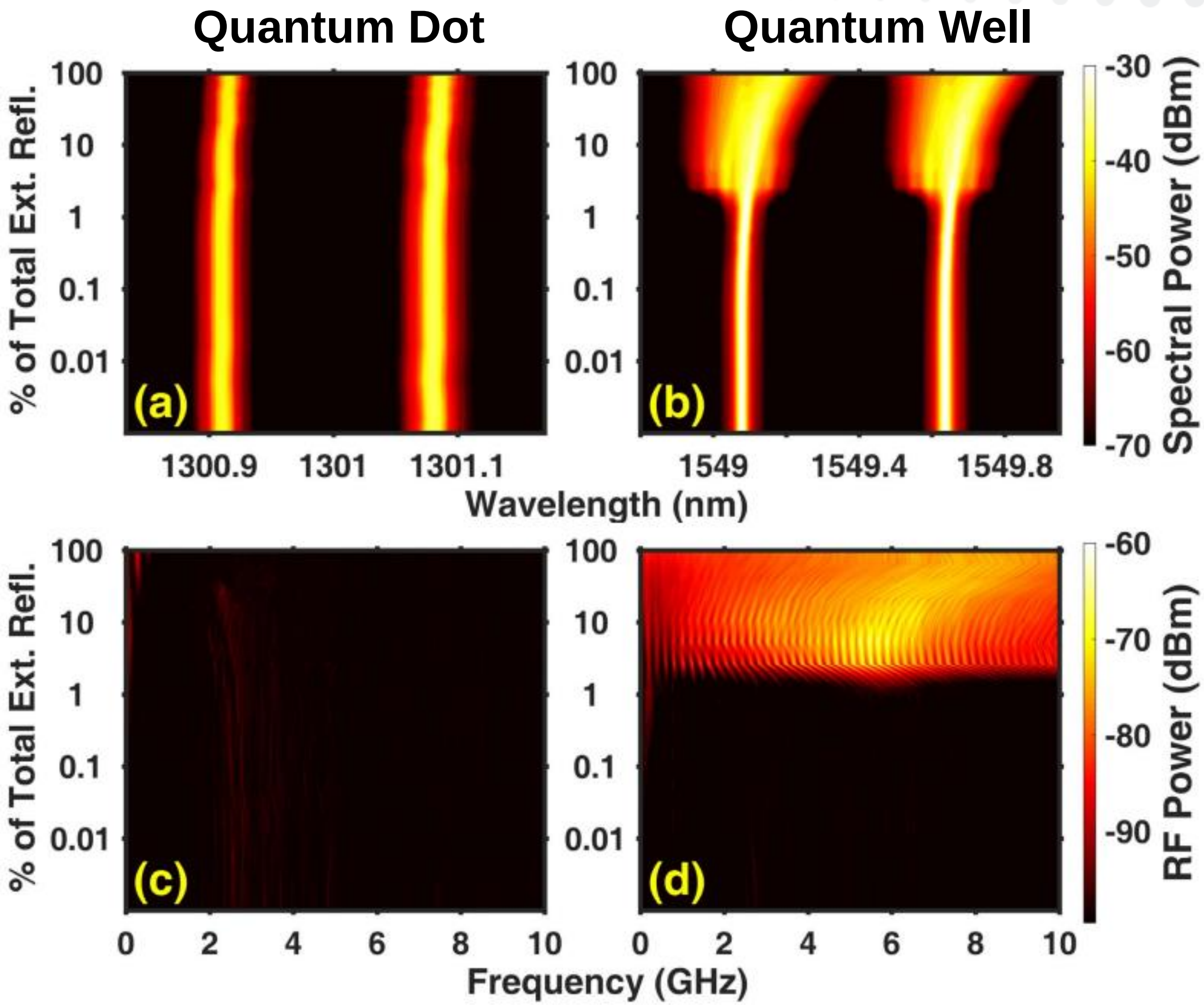
$$f_{ext}\Big|_{crit} = \frac{\tau_L^2}{16C_e^2}(Kf_R^2+\gamma_0^2)\left[\frac{1+\alpha_H^2}{\alpha_H^4}\right]$$



Zhang, et al. J. Sel. Top. Quant. Electron. 25(6), 2019.

Feedback Insensitive Operation

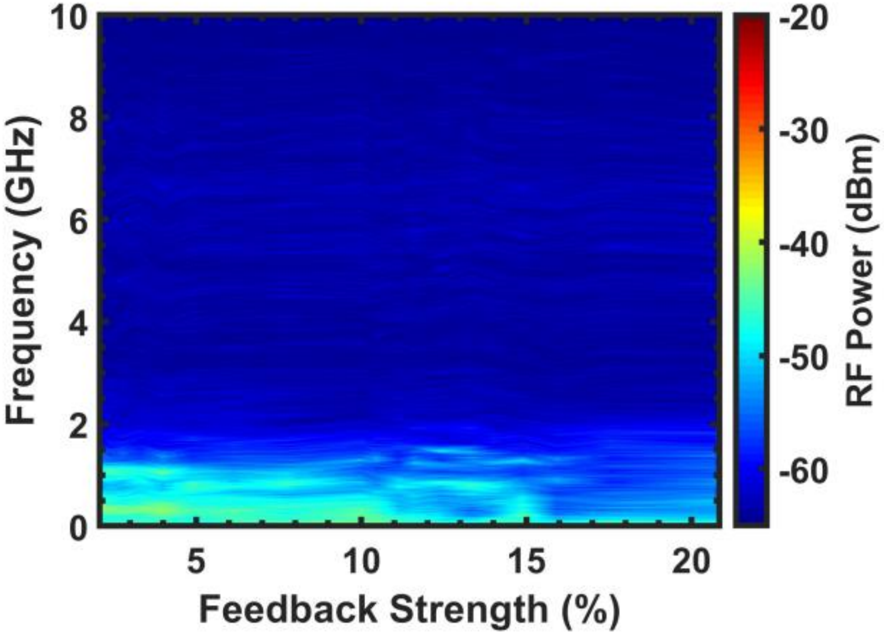
- **7 m feedback**
- **Bias at 3×I_{th}, up to 100% back-reflection (-10% tap)**
- **Quantum dot device perfectly stable**
- **Quantum well undergoes coherence collapse at < 2%**



J. Duan, *et al.*, Photon. Technol. Lett. 2019

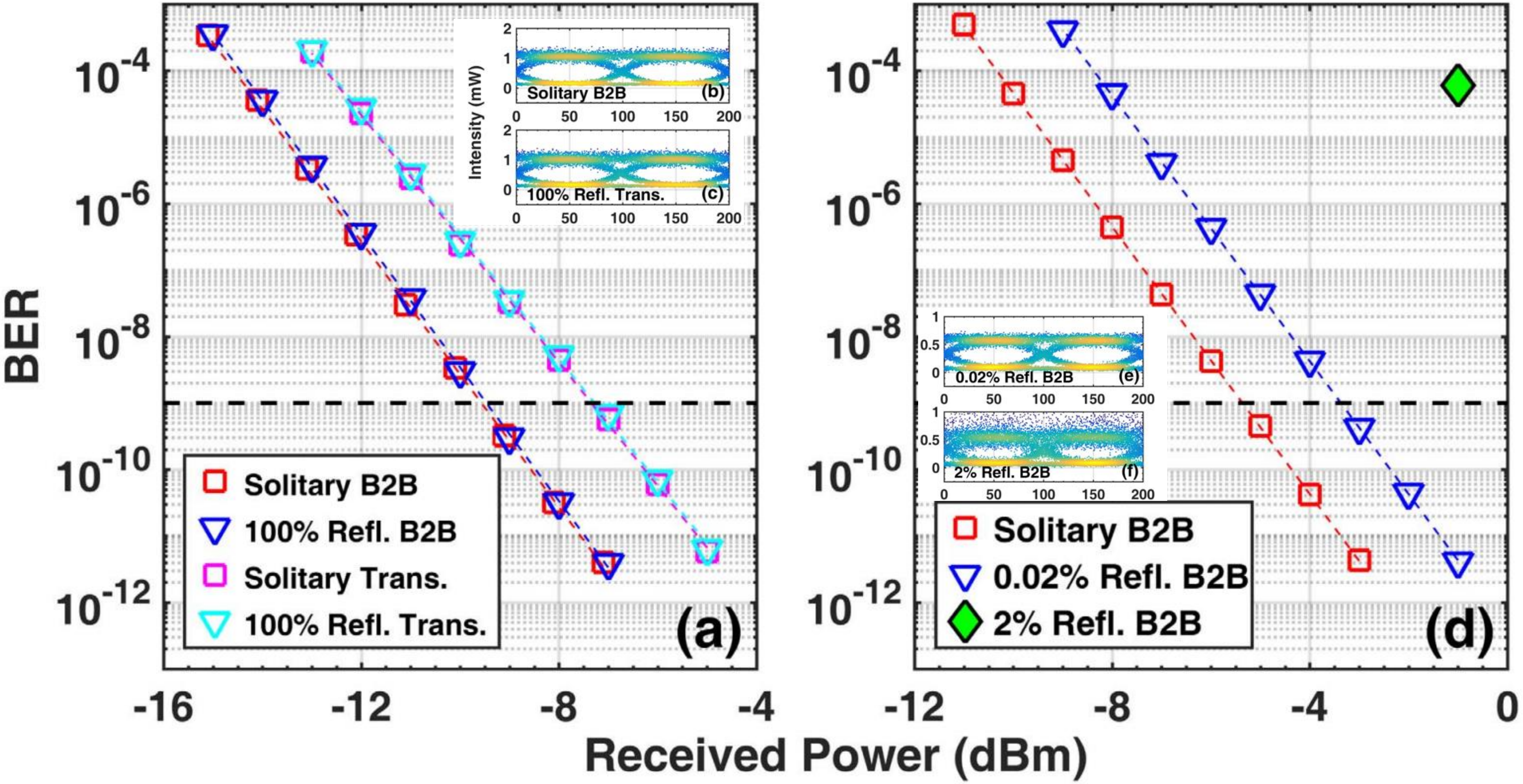
Short-Cavity Regime

- **P-doped laser stable in short cavity regime:** $\frac{f_{RO}}{f_{ext}} = \frac{3\text{ GHz}}{5\text{ GHz}} < 1$
- **Movable mirror**
  - Feedback up to 20.8% (coupling limited)
  - Cavity length 3 cm



Feedback Insensitive Transmission

Quantum Dot Laser **Quantum Well Laser**



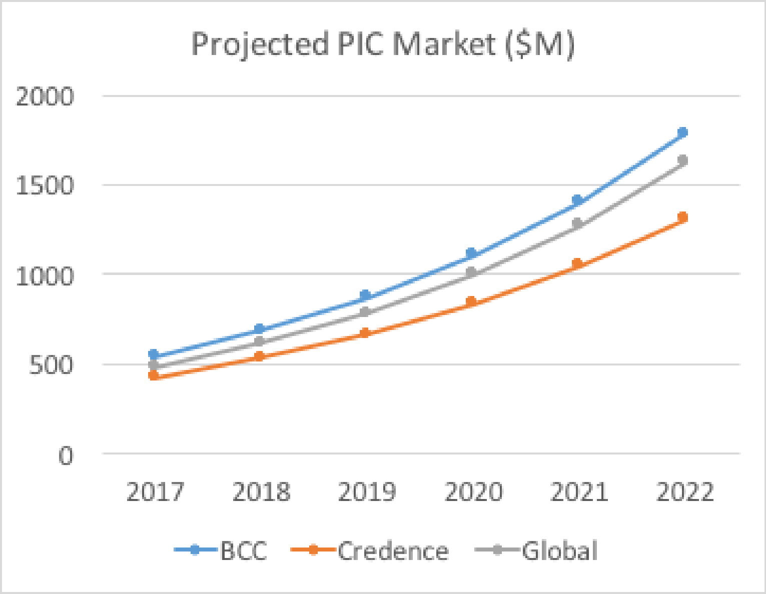
J. Duan, *et al.*, Photon. Technol. Lett. 2019

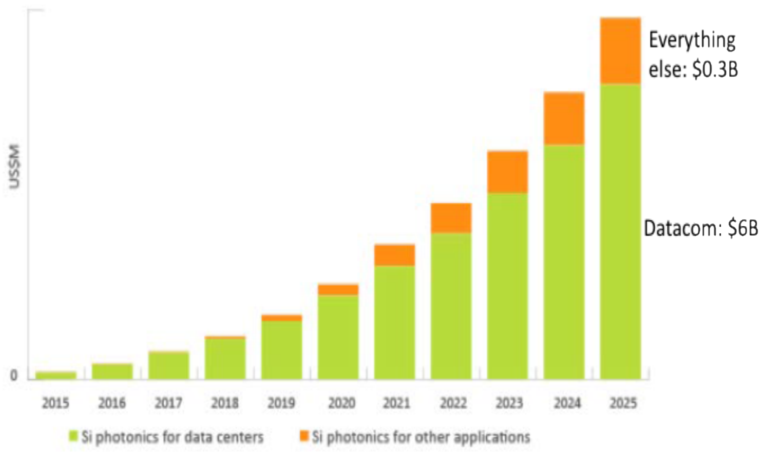
Future Prospects

- **Waveguide integration**
  - All-epitaxial photonic integrated circuits
- **>60°C reliability**
  - Need lower dislocation density
  - Native substrate devices reliable >80°C
- **Single-mode lasers**
  - Feedback insensitive, narrow linewidth DFBs
- **Achieve zero linewidth enhancement factor above threshold**
  - Careful engineering of threshold modal gain and inhomogeneous broadening

T2M – Market Opportunity

- **Silicon photonics market expected to grow to $2B by 2023**
  - Datacom projected 90% of market ($6B by 2025)
- **Major players:** Acacia (US): Luxtera (US), Intel (US), Cisco (US), Mellanox (Israel/US), Finisar (US), STMicroelectronics (Switzerland), Hamamatsu (Japan), IBM (US), Juniper (US), GlobalFoundries (US), Broadcom (US), Oclaro (US), NeoPhotonics (US), Ciena (US)

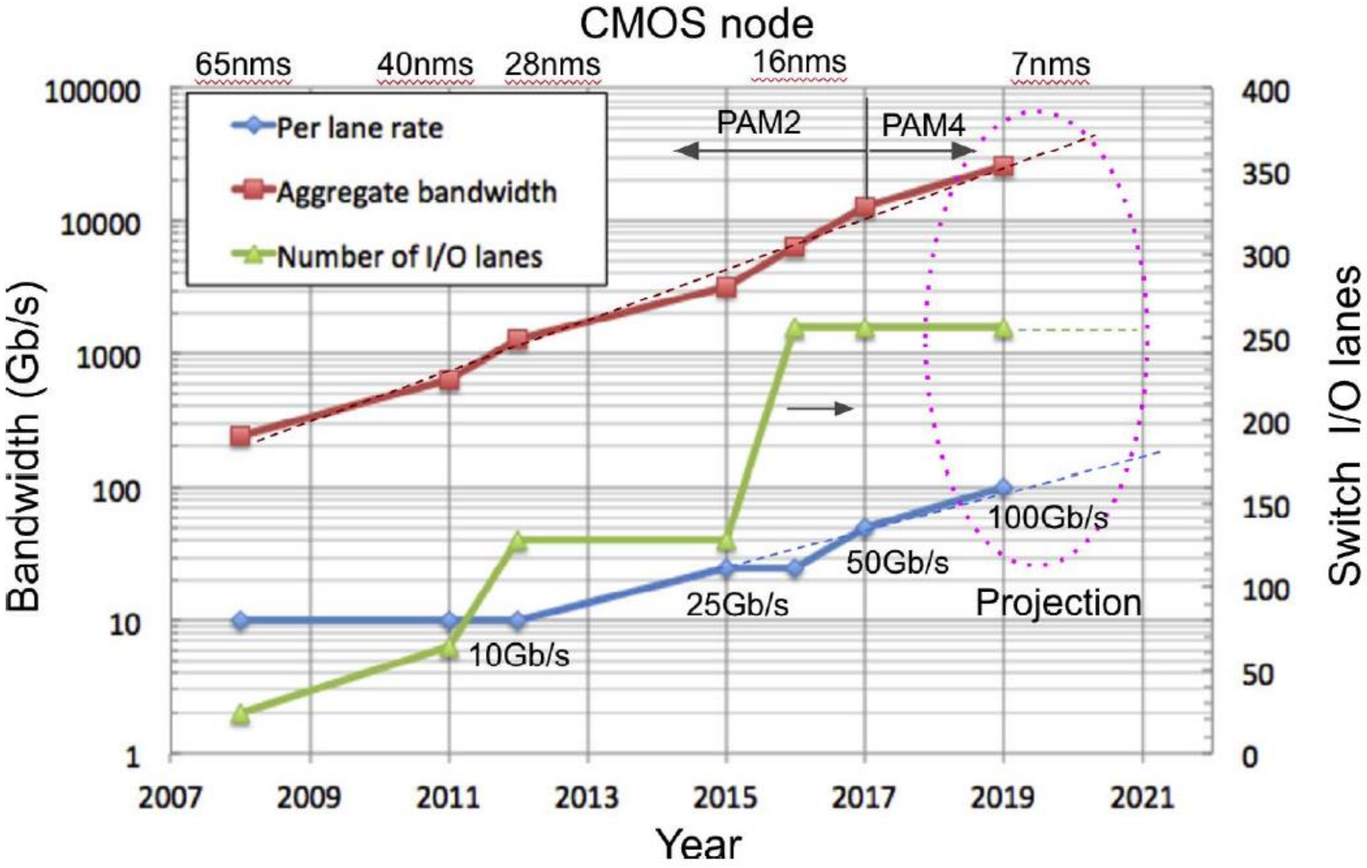

Projected PIC Market ($M)


Silicon photonics market forecast

(Source: Silicon Photonics for Data Centers and Other Applications 2016, October 2016, Yole Développement)

T2M – Market Opportunity

- **Google, Cisco want PAM4 format now**
  - Looking at QPSK (and higher-level modulation) in the future

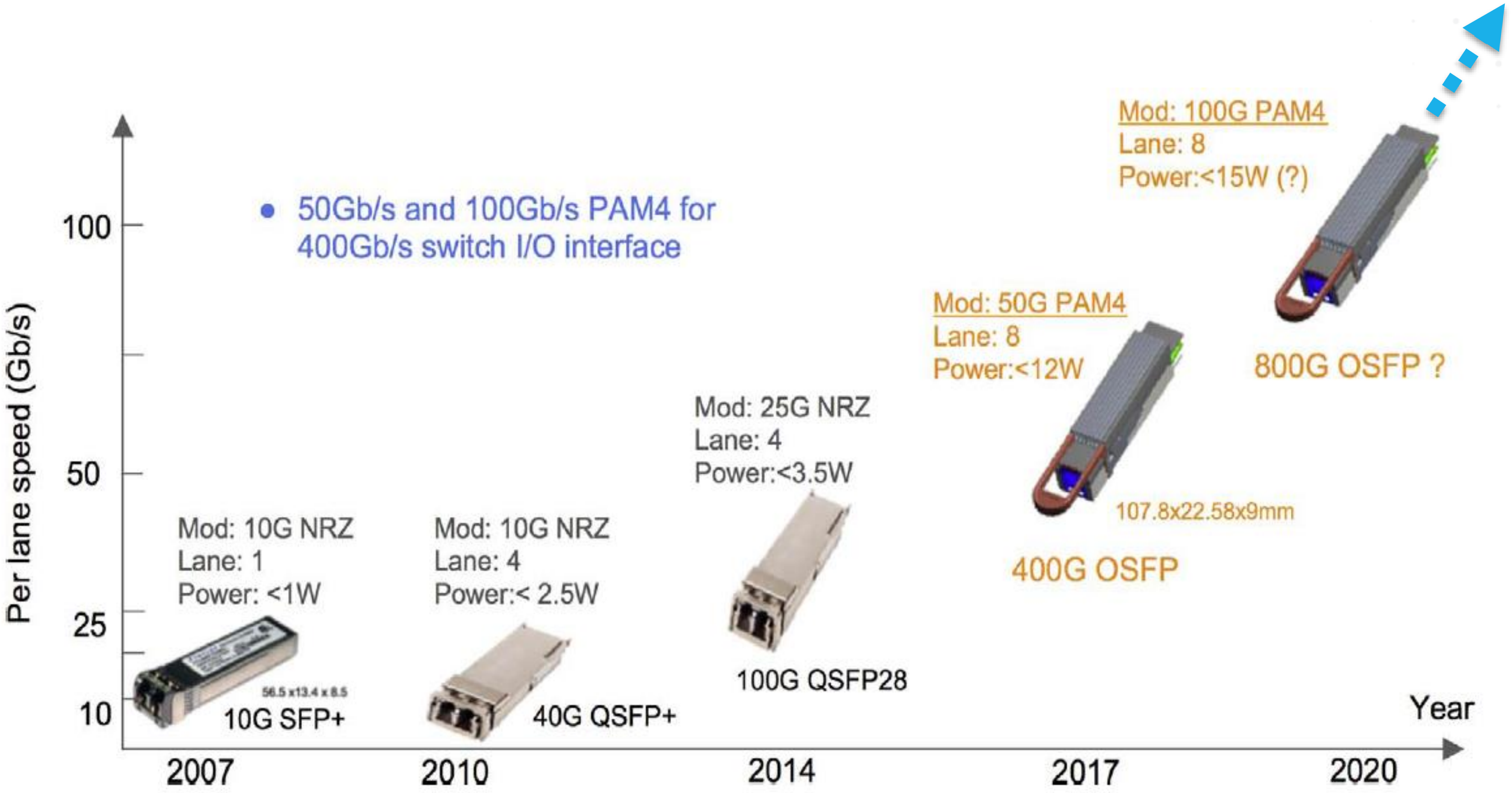


Datacenter Example– Google Interconnect

Scaling large data center interconnects…, Zhou 2017

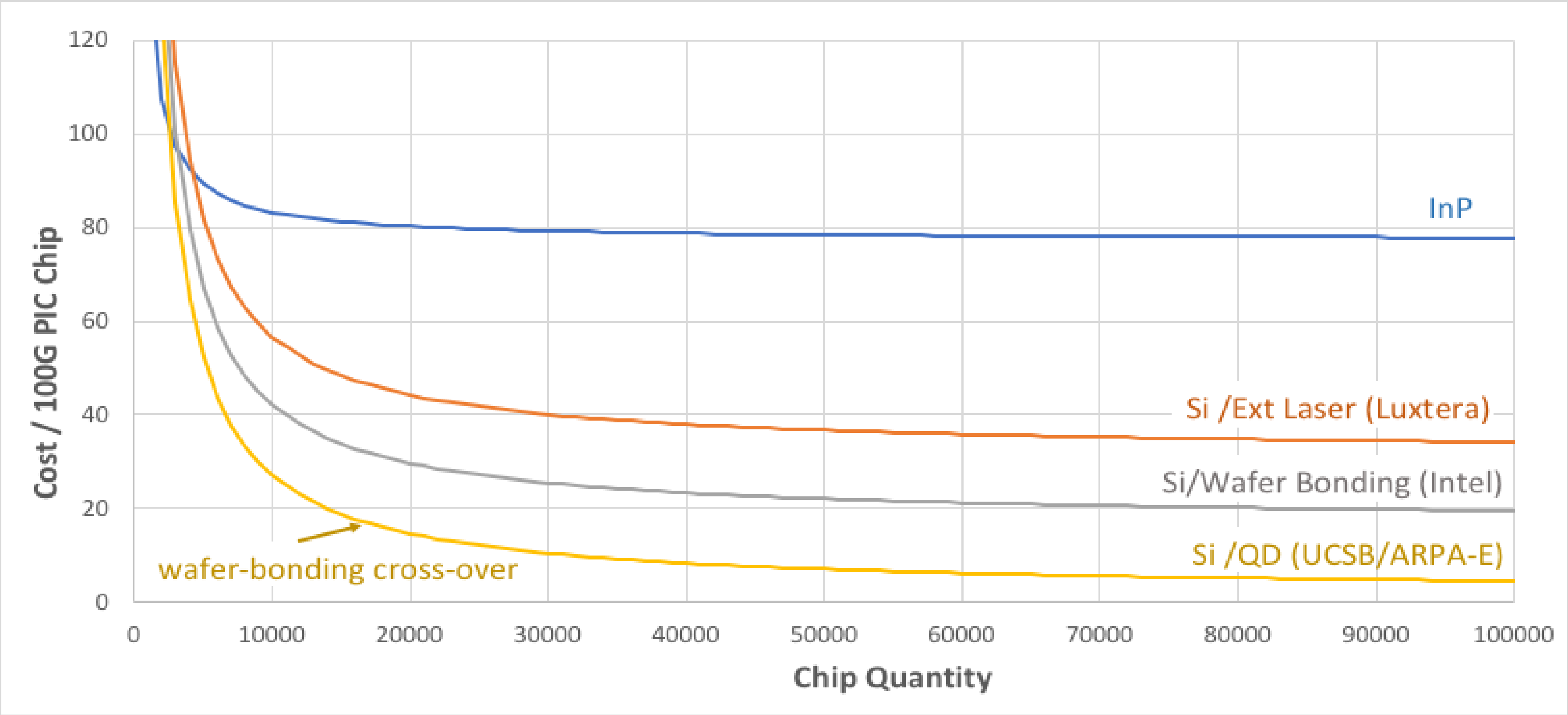
T2M – Datacom Market Opportunity

- **Facebook currently upgrading to 100 and 200 GB/s transceivers**
  - **Plans 400 GB/s, then 1600 GB/s**



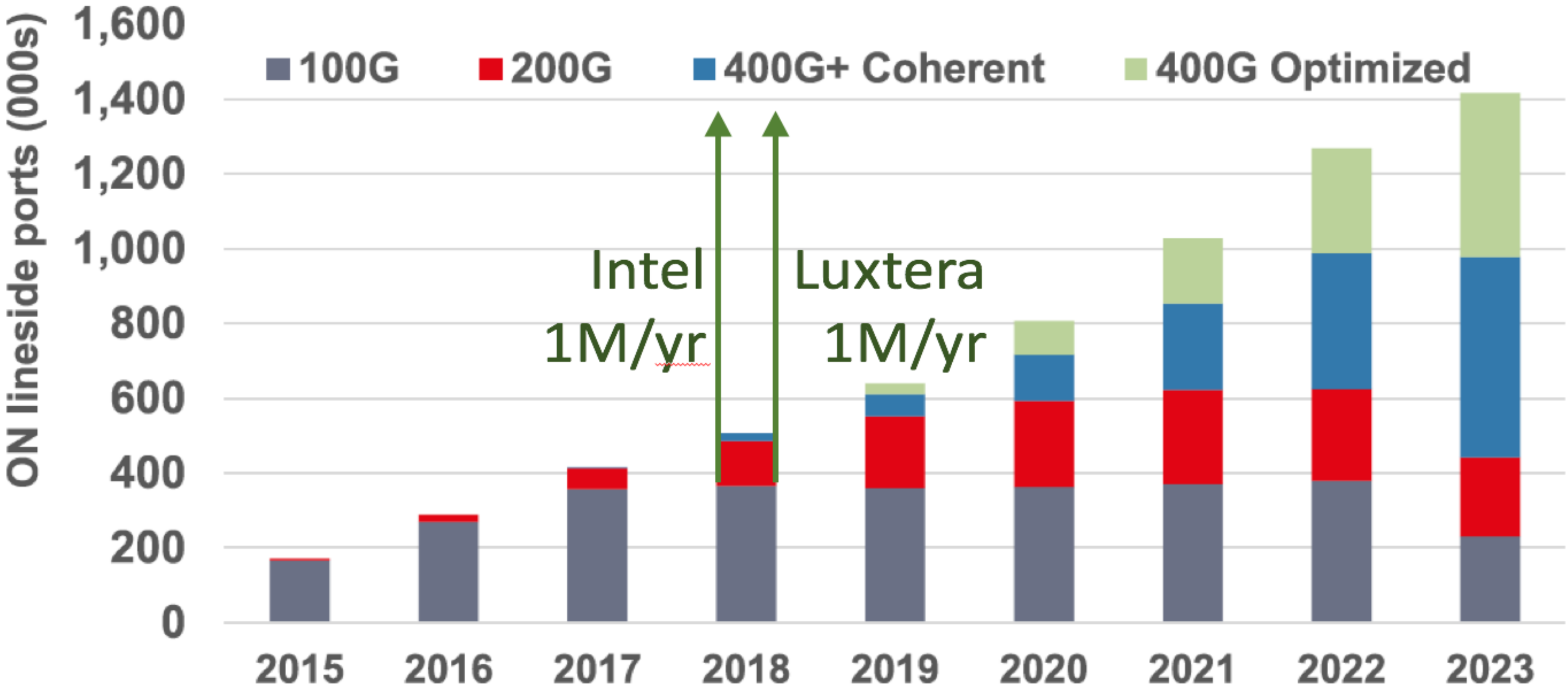
T2M – Cost Model

- **Silicon PIC/External Lasers (Luxtera)**
  - Laser: $8 + $7 alignment = $15
  - Isolator: $8 + $7 alignment = $15
  - Wafer fab = $22k
  - Mask cost (300mm) = $250k



T2M – Scalability

- **SiPh transceiver chips 5x cheaper than InP**
- **Transceiver market grew ~5x faster than expected**



Submitted IP

- **Three patent applications filed**
- **Integration of direct-bandgap optically active devices on indirect-bandgap-based substrates**
  - Methods of integrating epitaxial III-V devices with Si waveguides
- **Monolithic integrated quantum dot photonic integrated circuits**
  - Epitaxial III-V based approach to integration on silicon
- **Quantum dot lasers and methods for making the same**
  - Methods of growth for avoiding strain relaxation in the laser active region

Commercialization Prospects

- **Quintessent, Inc.**
  - New startup leveraging research from OPEN2015
- **Manufacturing semiconductor laser optical engines**
  - Advanced quantum dot materials and laser architecture for high bandwidth communications
- **Closed seed round and developing prototypes**

QUINTESSENT

Conclusion/summary slide

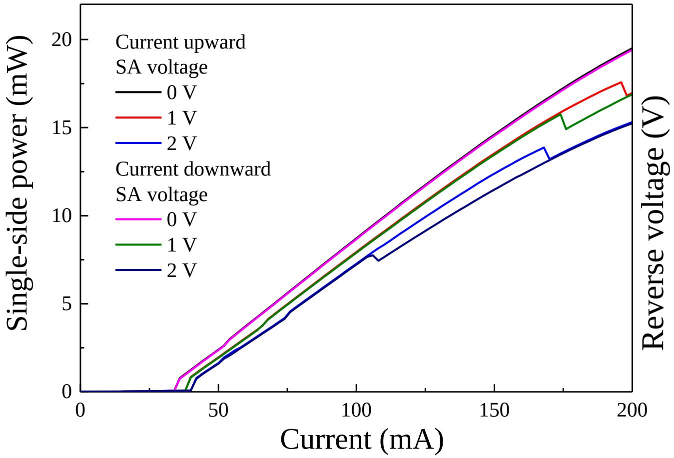
- Reduction in threading dislocation density from 7e6 cm^{-2} to 2e6 cm^{-2} in GaAs
- High performance QD FP laser on on-axis Si
  - Wall plug efficiency of ***38.4%***
- Reliability results at 60 °C aging tests
  - Extrapolated lifetime longer than ***>8 years***
- Efficient semiconductor optical amplifiers
- **4.1 Tbps** system demonstration from a single QD mode locked laser
- Reduction in subthreshold **linewidth enhancement factor to near-*zero*** in uniform p-doped QD laser
- Isolator-free transmitter demonstrated: ***zero errors with 100% reflection***
- ***Promising pathways to commercialization***

Supplementary Slides

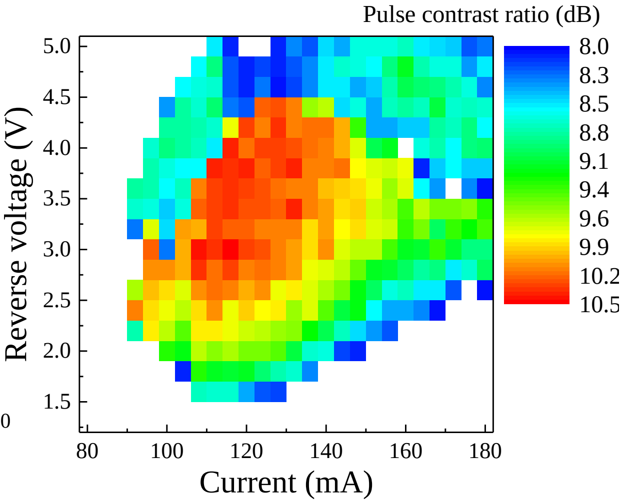
Mode-Locking Regime

- **Threshold current 34 mA (0 V SA) → 40 mA (-2 V SA)**
  - Series resistance ~4 Ω
- **Wide mode-locking range**
  - < 2.5 ps and >8 dB pulse-contrast ratio

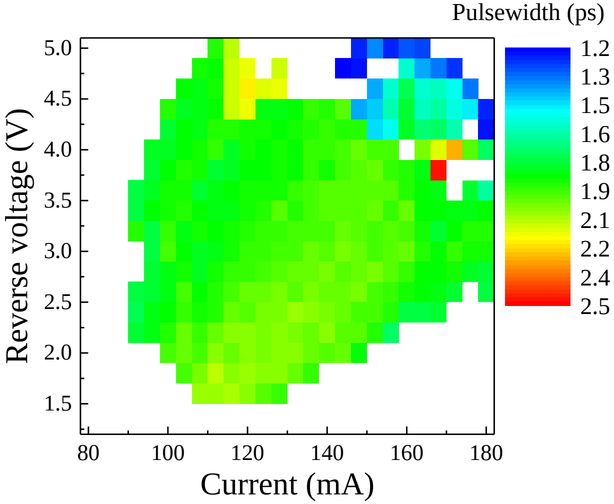
L – I curve



Pulse intensity contrast mapping

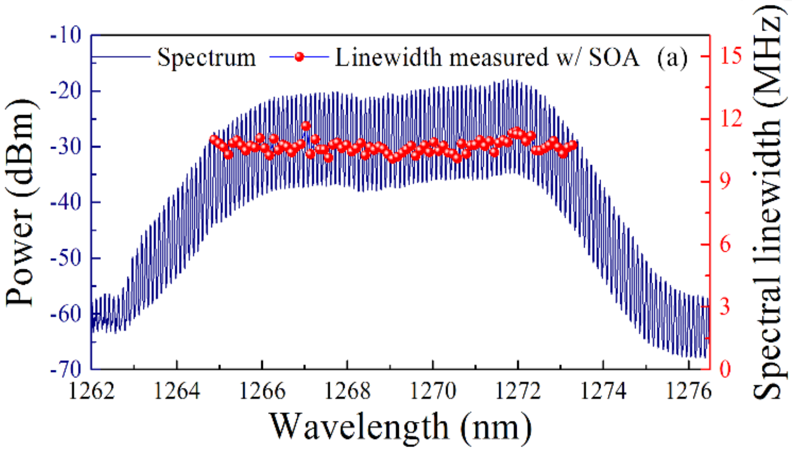


Pulsewidth mapping

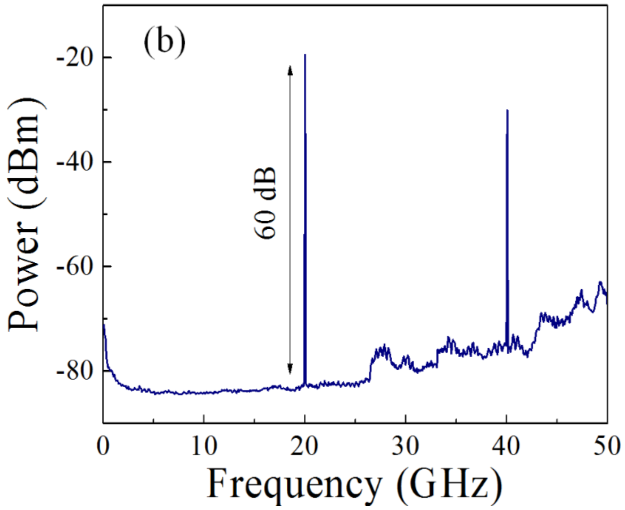


Excellent RF Performance

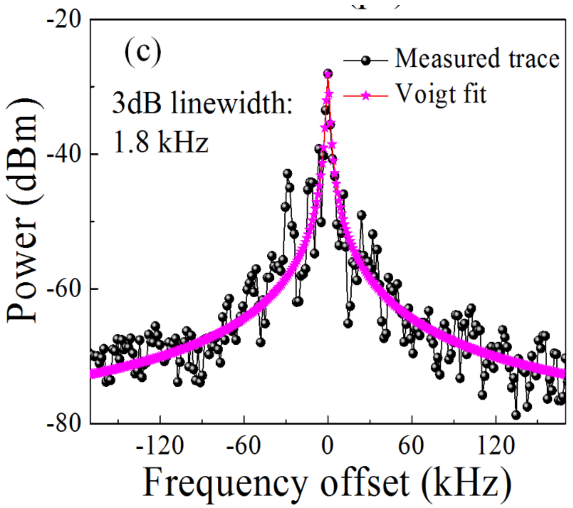
- **Broad, flat mode-locking regime**
- **1.8 kHz RF linewidth**
- **Record low timing jitter 82.7 fs**



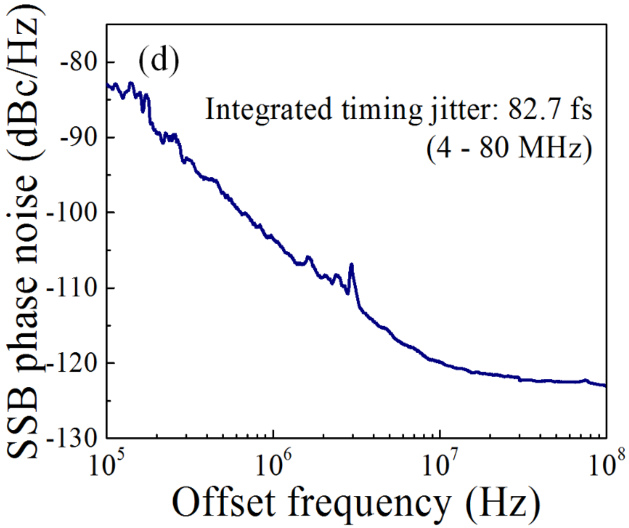
RF spectrum



RF peak with Voigt fit



SSB phase noise plot



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2. Marko *et al.* “Physical Properties of 1.3 μm InAs-Based Quantum Dot Laser on Silicon”, ISLC, 2018
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