TECH talks 2019

# High performance lasers on Si

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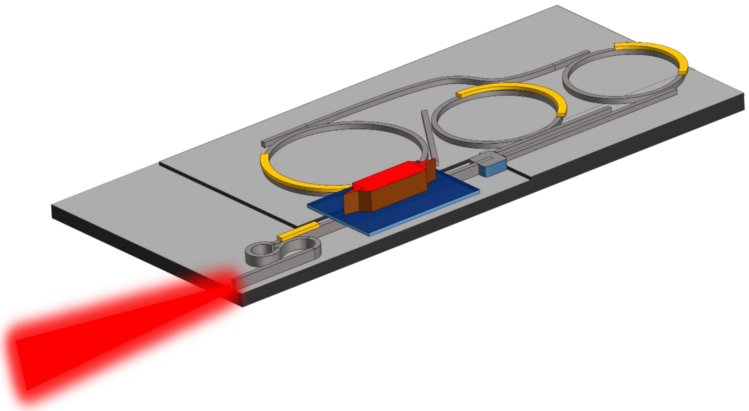
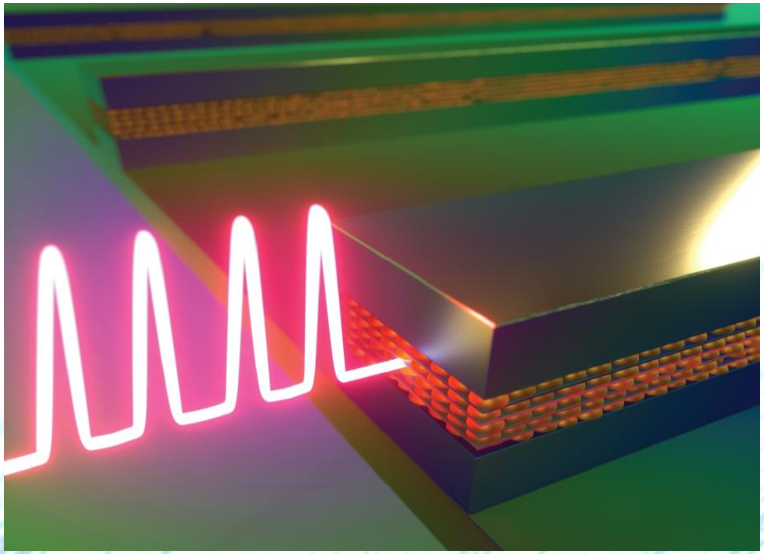
# Outline

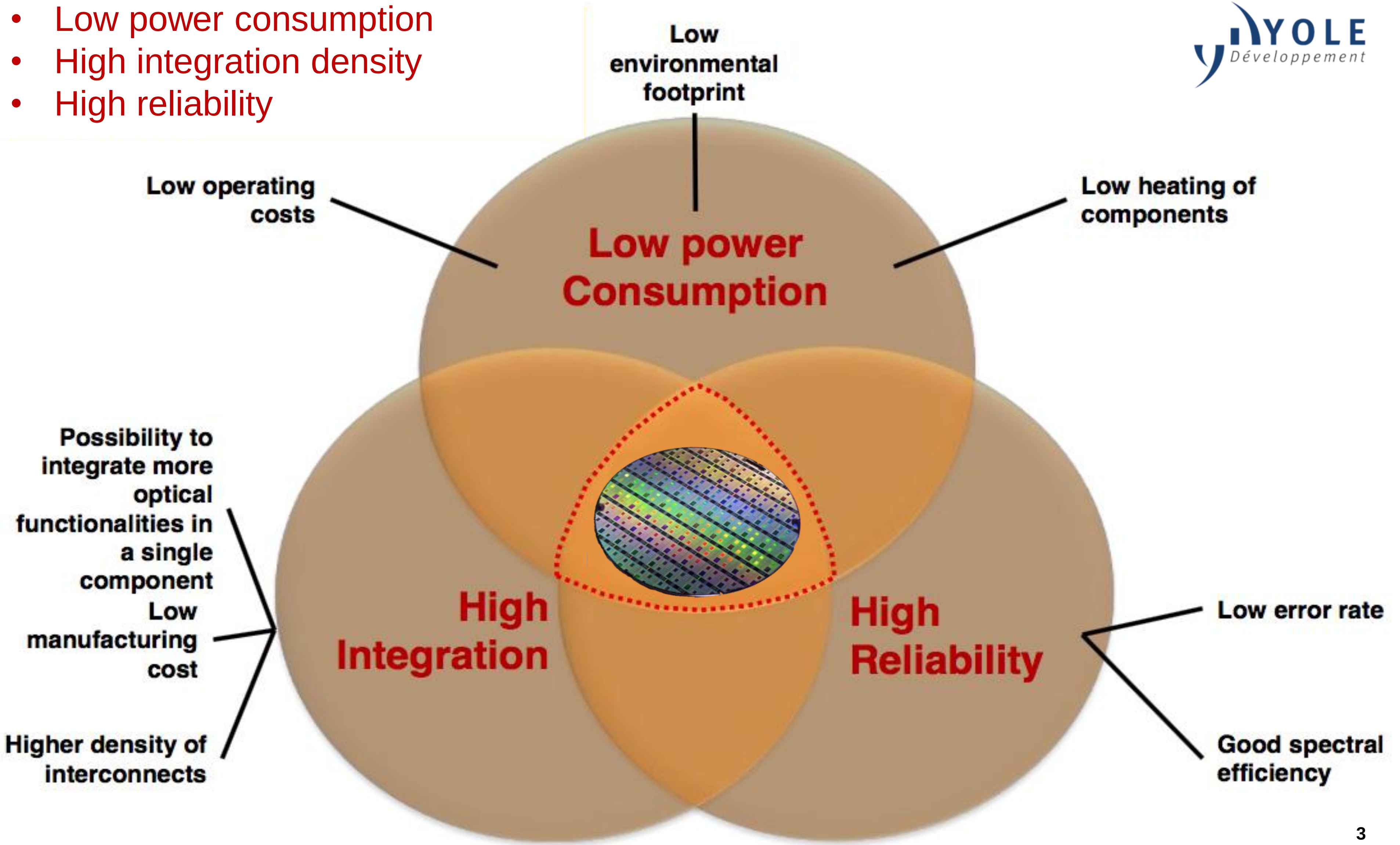
- Motivation
- Heterogeneous integration
  - Sub-kHz optical linewidth lasers
- Direct epitaxial growth
  - Low-noise high-channel-count comb lasers
- Summary





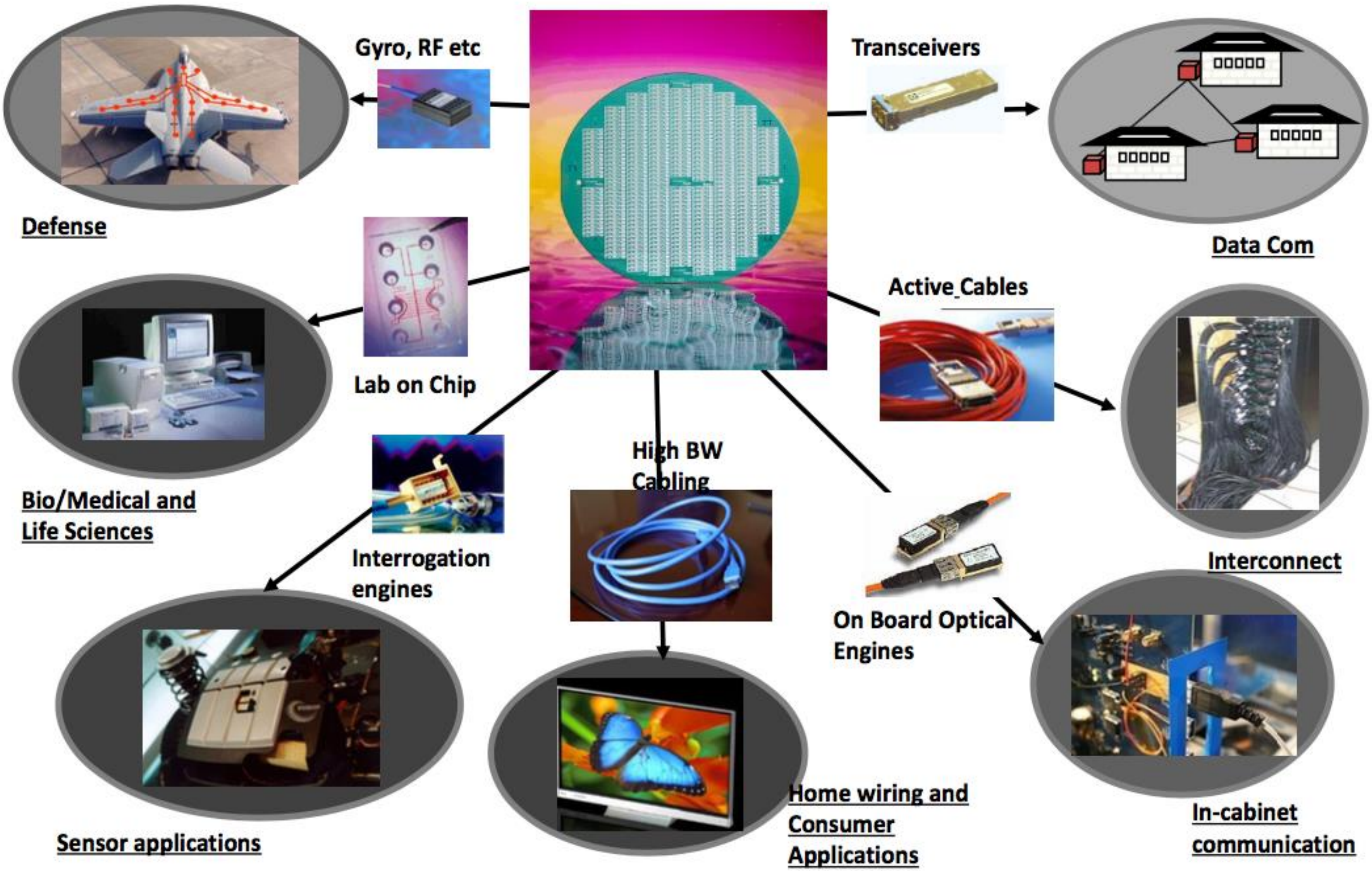
# Advantages of Si photonics

- Low power consumption
- High integration density
- High reliability



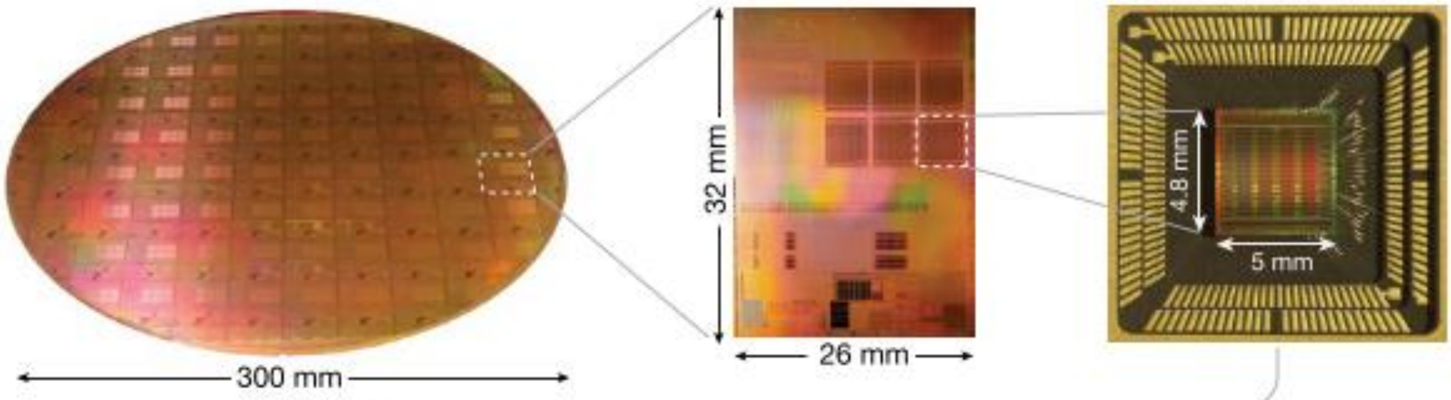
# Many applications of Si photonics

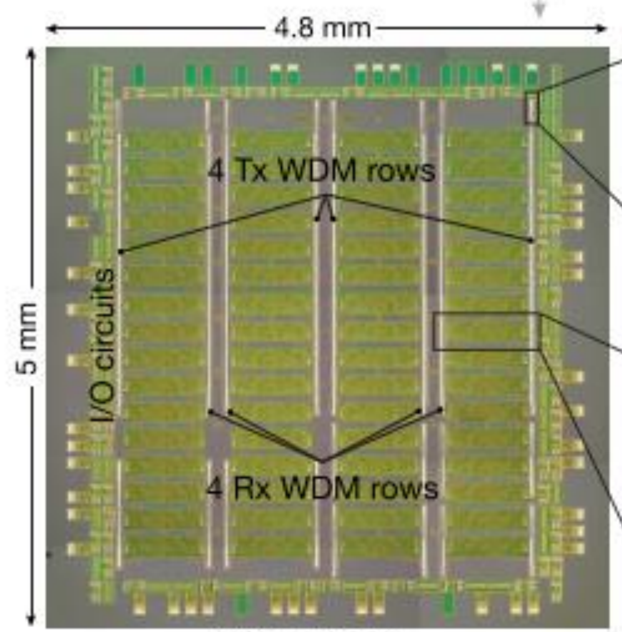
From Jean Louis Malinge



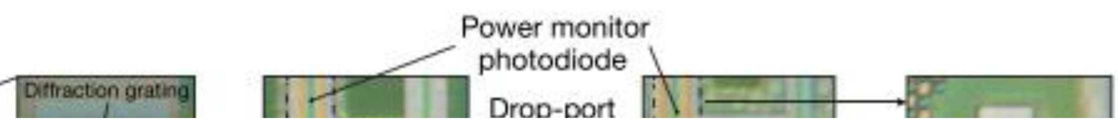
# SiPh already in a 300mm fab

## First 65nm bulk CMOS wafers with working photonics and transistors!

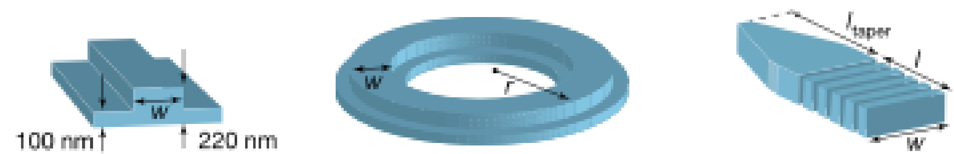



WDM chiplet




Passive components (specifications at 1,300 nm)

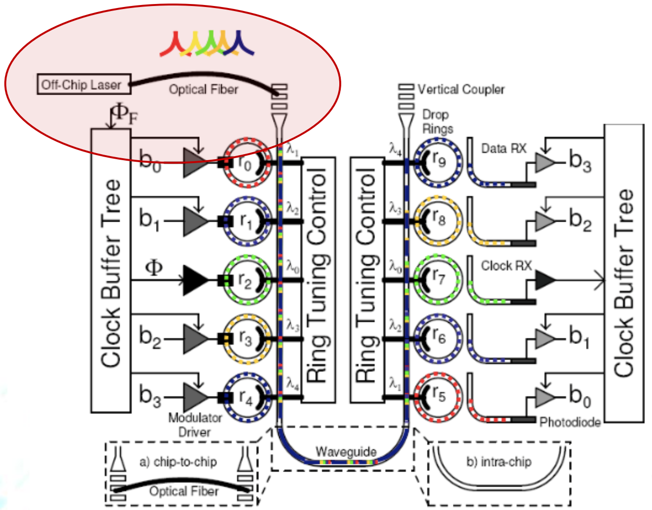



| | Propagation loss | Intrinsic Q | Coupling loss |
|---|---|---|---|
| Partial flow | 8–15 dB $cm^{-1}$ | 19,000–31,000 | 4.2 dB |
| Full flow | 21–27 dB $cm^{-1}$ | 10,000–19,000 | 5.2 dB |
| Dimensions | $w$ = 400 nm | $w$ = 400 nm $r$ = 7.5 μm | $w$ = $l$ = 8 μm $l_{taper}$ = 250 μm |

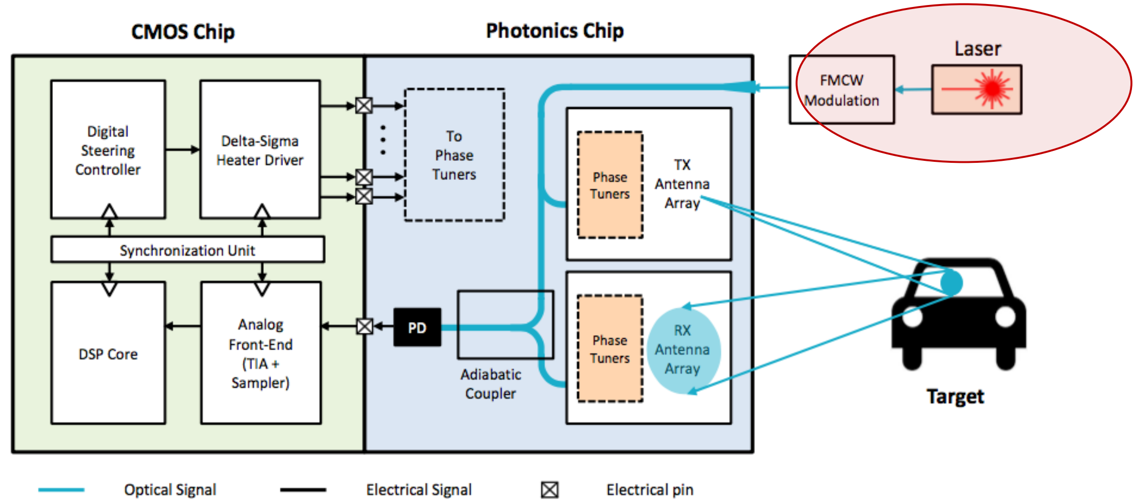
Single Tx/Rx channel macro

A. Atabaki, S. Moazeni et al. Nature, April 2018

# The biggest limitation of Si photonics

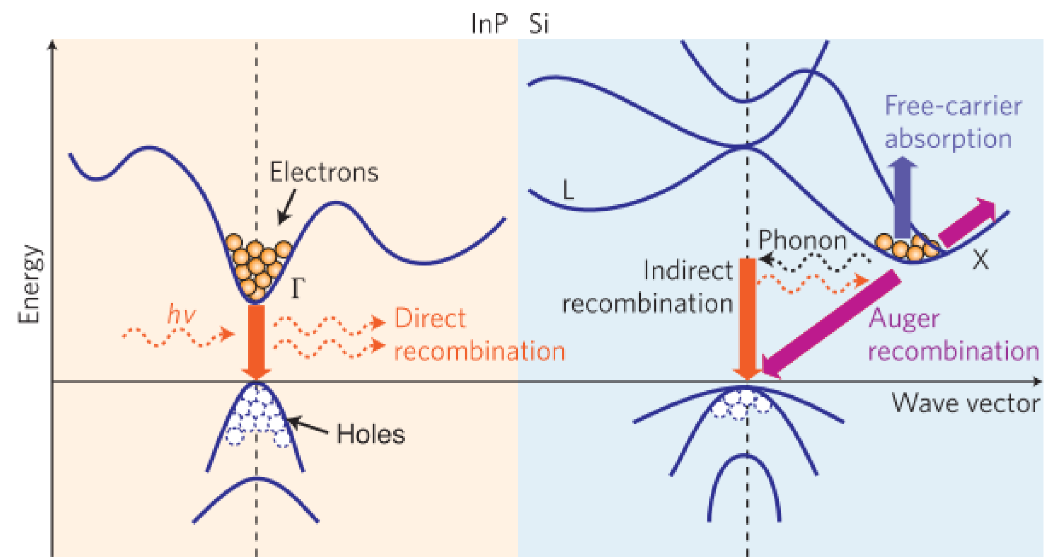



Integrated photonic interconnects



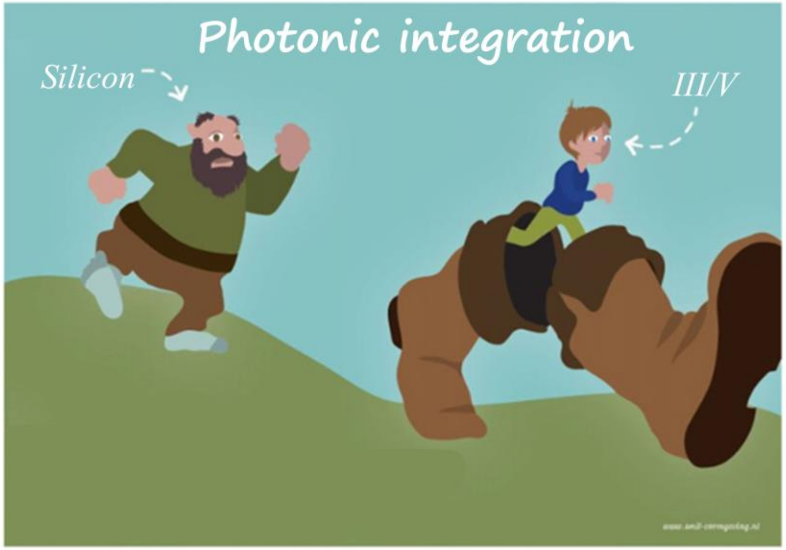

FMCW LIDAR – System Architecture

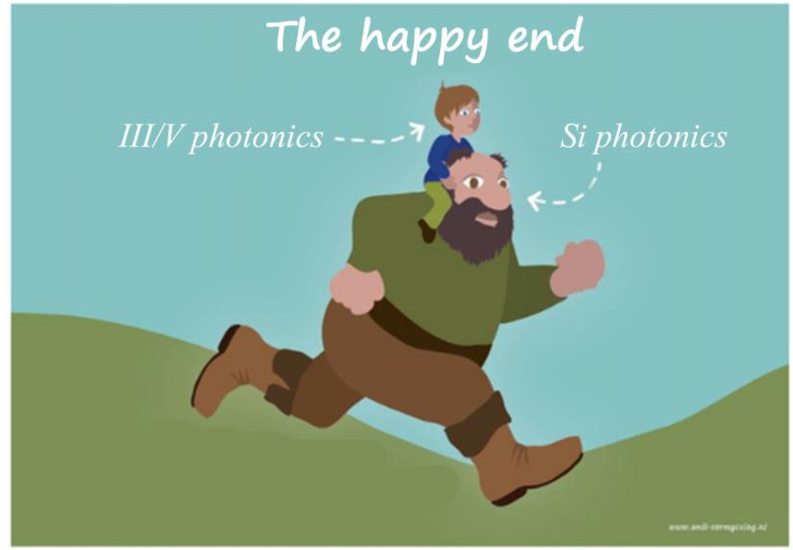
Indirect bandgap nature limits silicon to realize efficient light sources on-chip!




D. Liang, J. Bowers, Nature photonics, 2010

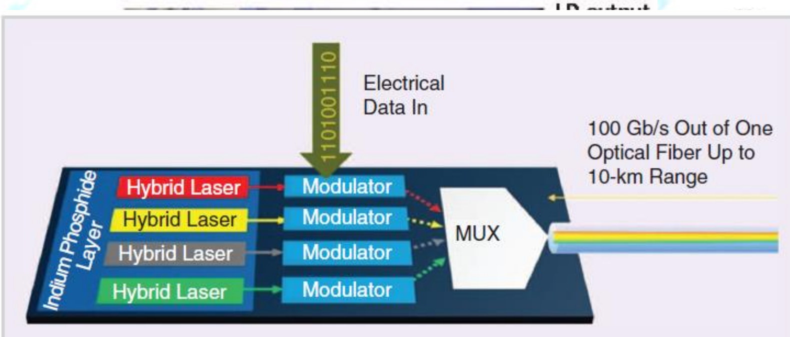
# Efficient ways to generate light on Si

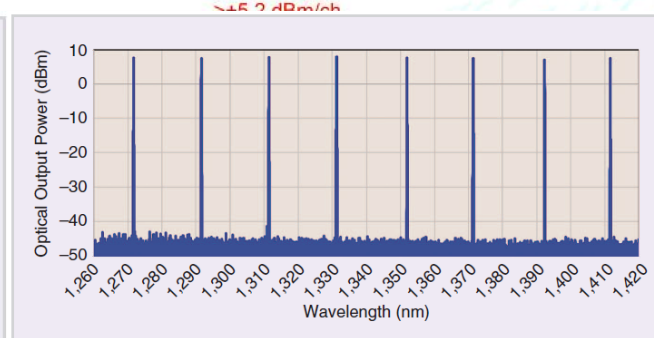



M. Smit, et al, Semicond. Sci. Technol., 2014

- Mature light source technology
  - Flip chip bonding
  - Heterogeneous wafer bonding




Wavelength (nm)

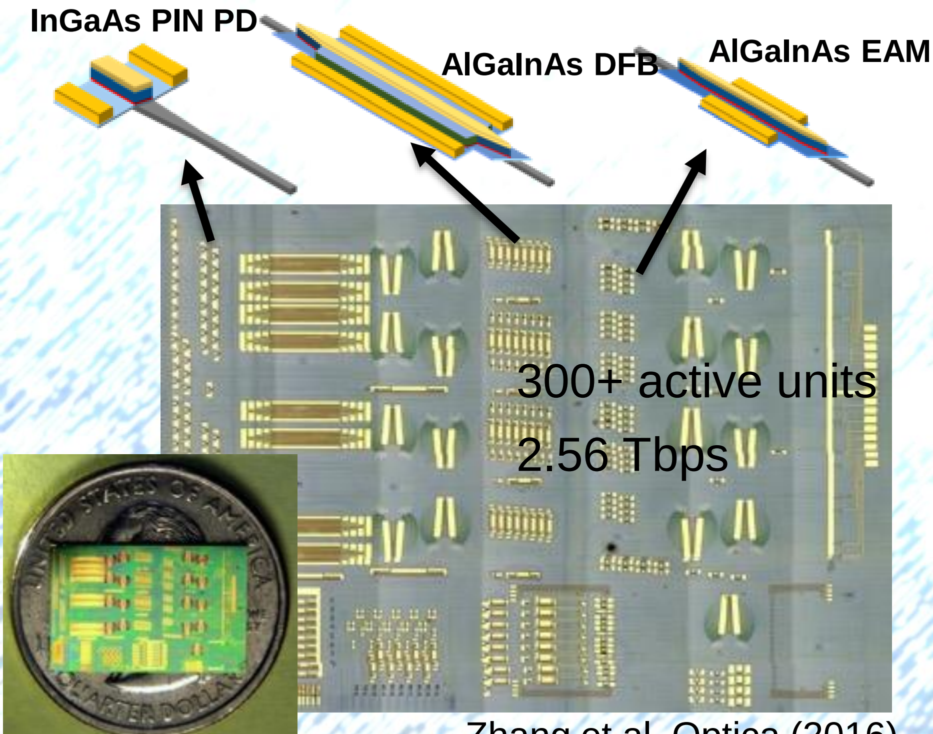
R. Jones *et al.*, *IEEE Nanotechnology Magazine*, April 2019.

S. Tanaka *et al.*, *ECOC*, Cannes, 2014.

# Current status of the heterogeneously integrated lasers on Si

UCSB · III-V lab · intel · Juniper Networks · AIM photonics · Ghent University · Caltech · NTT · hp · cea leti

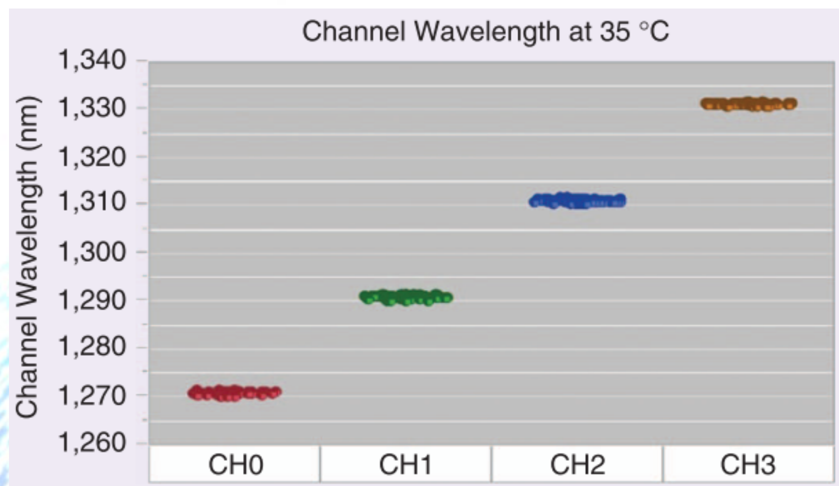
## UCSB largest integration demonstration




Zhang et al. Optica (2016)

## Intel ships the Si transceiver to the market

using their own commercial 300-mm wafer fabrication process.



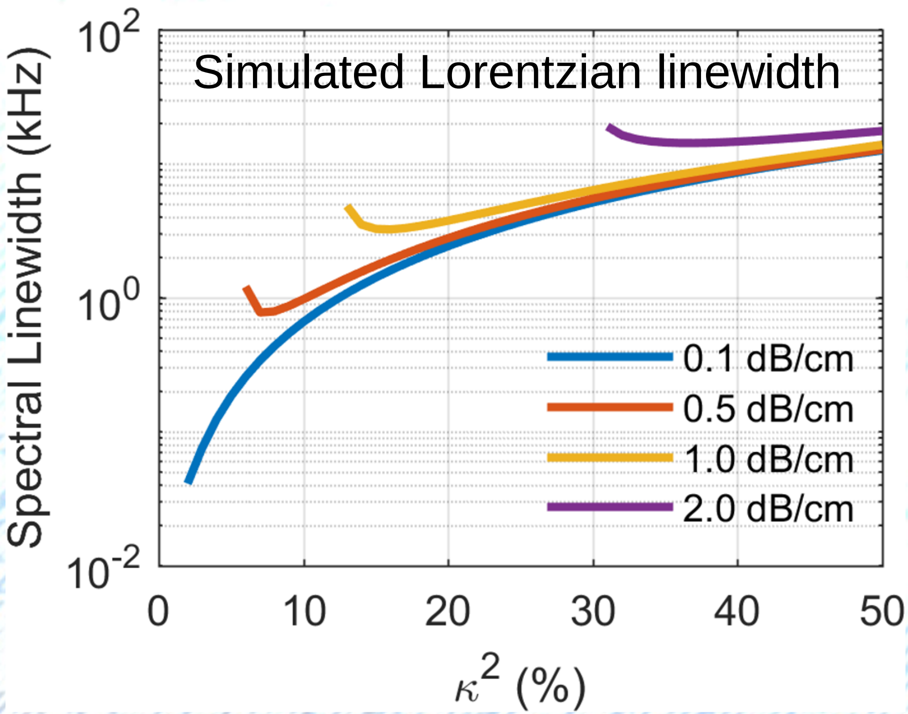

R. Jones *et al.*, *IEEE Nanotechnology Magazine*, April 2019.

# Further improvement in terms of optical linewidth

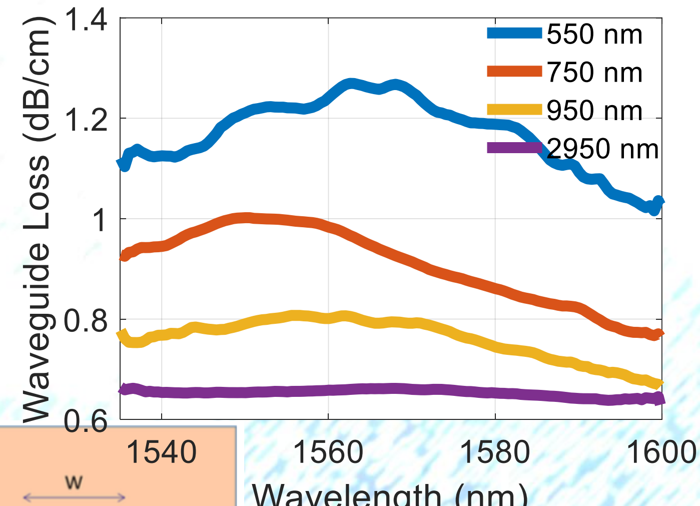
Modified Schawlow Townes Henry linewidth equations:

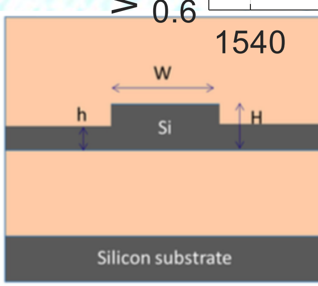
$$\Delta v_0 = \frac{q\omega^2 n_{sp}}{2Q^2 (I - I_{th})}(1+\alpha^2)$$

- Increase $Q$ – cold cavity quality factor, governed by the internal loss
- Reduce $I_{th}$
- Reduce $n_{sp}$, $\alpha$




Measured Data on 231 nm Etched WG

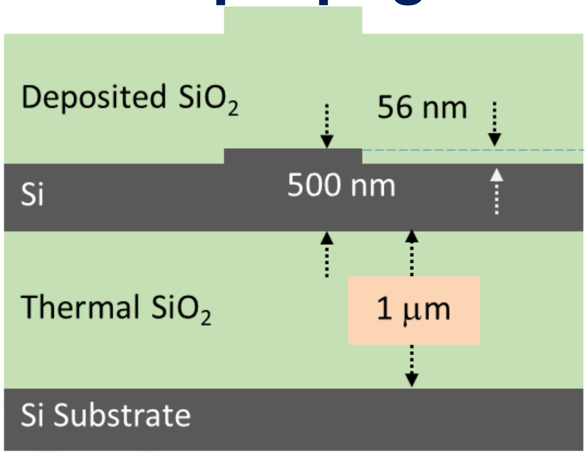


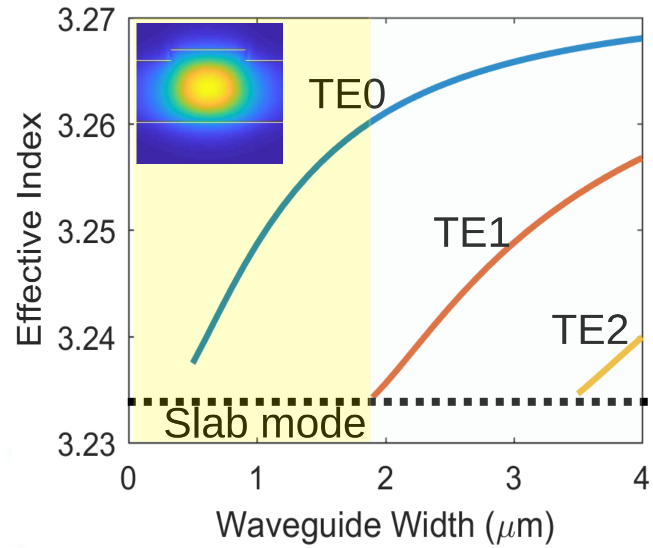




500 nm thick SOI platform

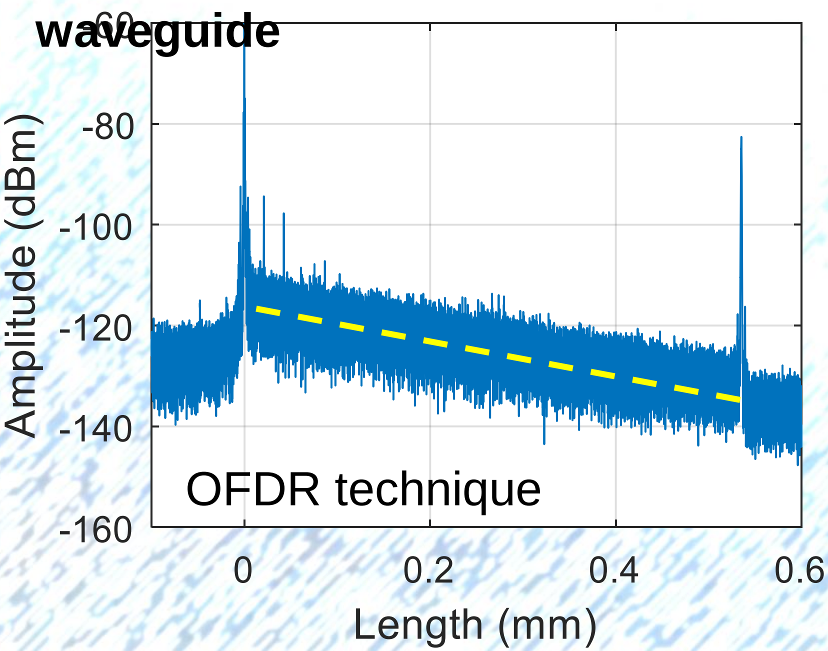
Minh Tran, et al, Applied Sciences, 2018

# 0.16 dB/cm propagation loss Si waveguide

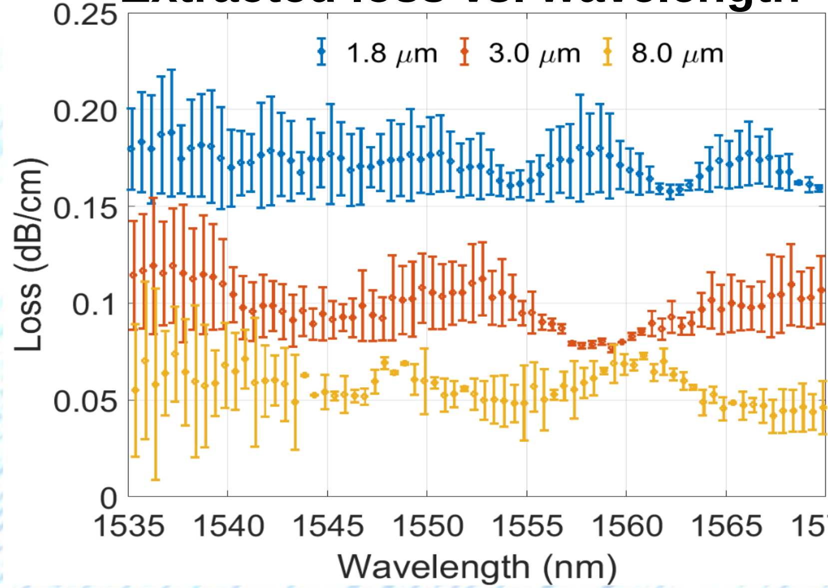



**Measured OBR trace of 1.8 um waveguide**



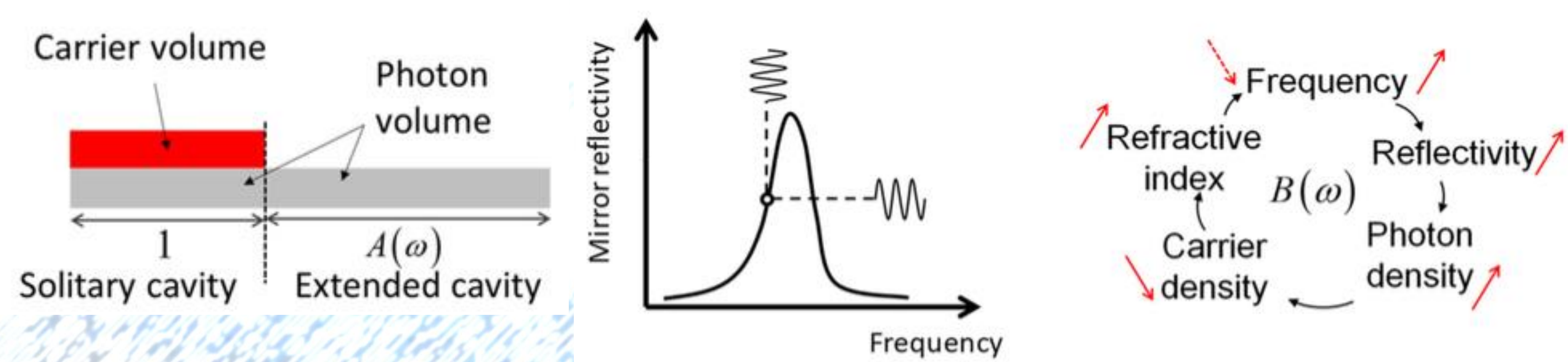

**Extracted loss vs. wavelength**



# One more step to improve the optical linewidth

$$\Delta\nu = \frac{\Delta\nu_0}{F^2} \qquad F = 1 + A + B \qquad A = -\frac{1}{\tau_{in}} \frac{d\varphi_{eff}(\omega)}{d\omega} \qquad B = \frac{\alpha_H}{\tau_{in}} \frac{d}{d\omega}\left(\ln\left|r_{eff}(\omega)\right|\right)$$

- Reduce $\Delta\nu_0$
- Increase A - Extended cavity length/ active length
- Increase B - Negative feedback effect (detuned loading)



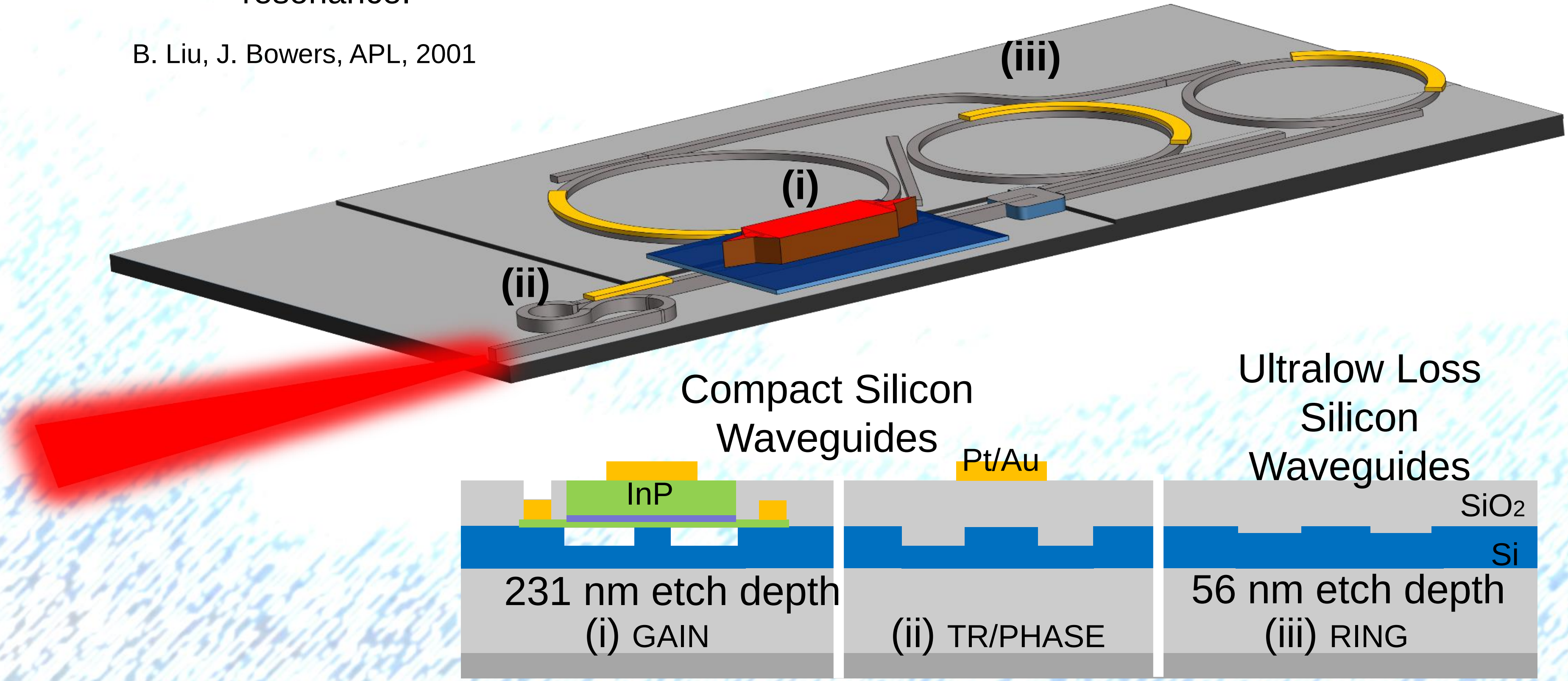

Minh Tran, PhD thesis, UCSB, 2019

# Ring Resonator Coupled Lasers

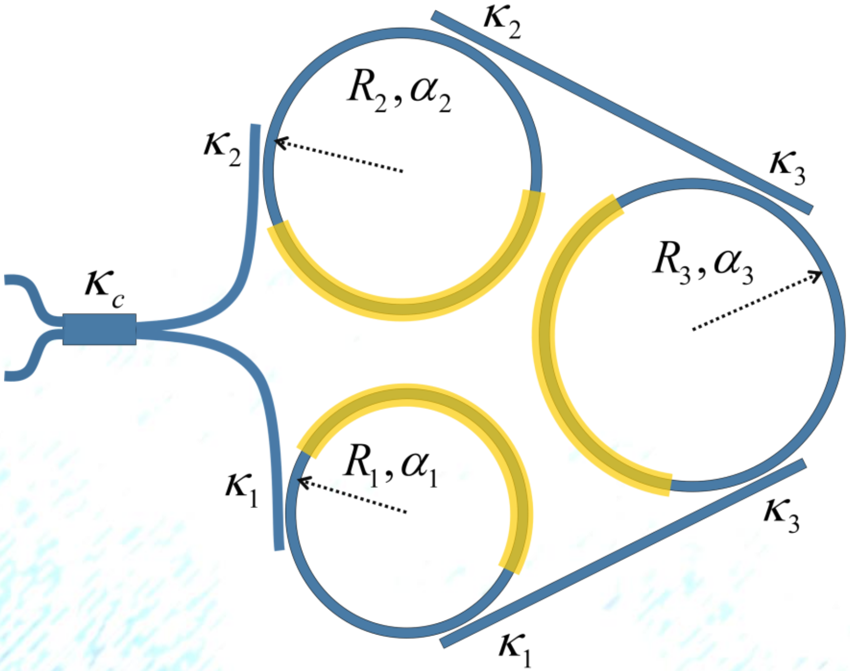
**Using rings inside the cavity benefits the linewidth in two ways:**

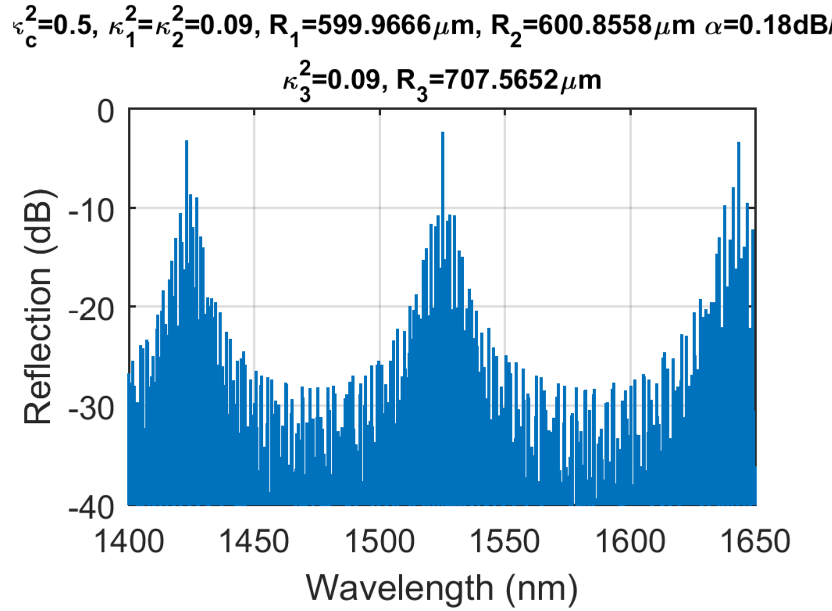
- **Resonance cavity length enhancement**
  - increasing the photon lifetime due to effective cavity length enhancement.
- **Negative optical feedback**
  - providing negative optical feedback by slight detuning from the ring (resonator) resonance.

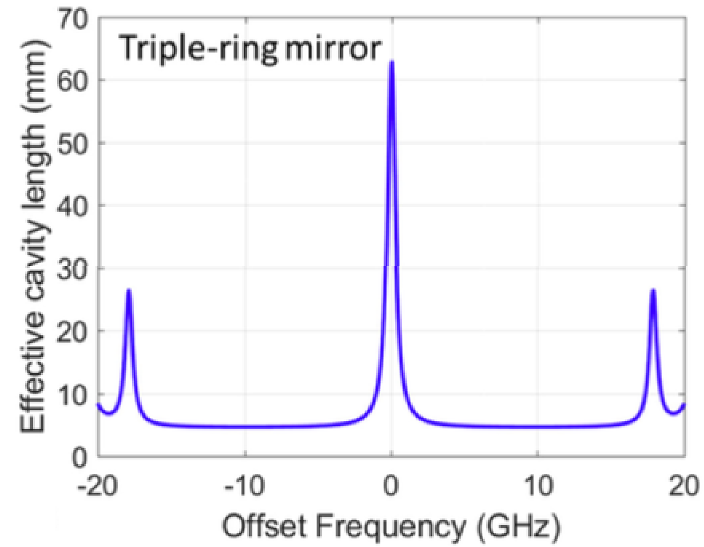
B. Liu, J. Bowers, APL, 2001



# Ring Resonator Coupled Lasers



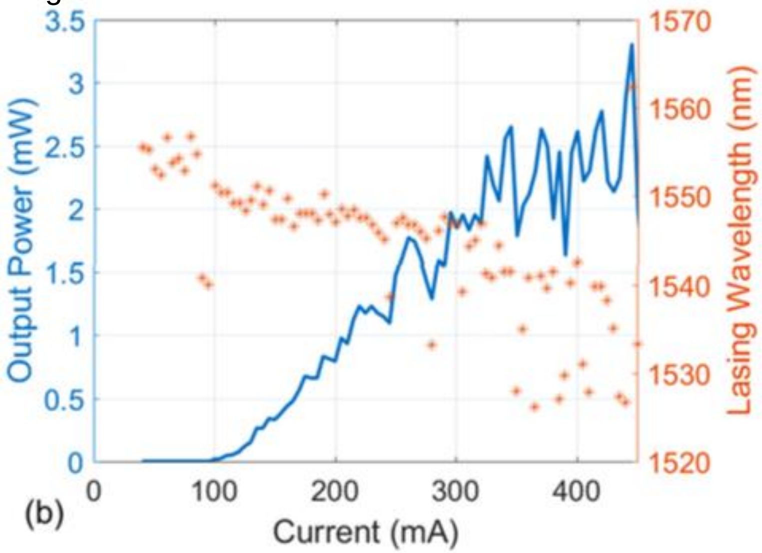



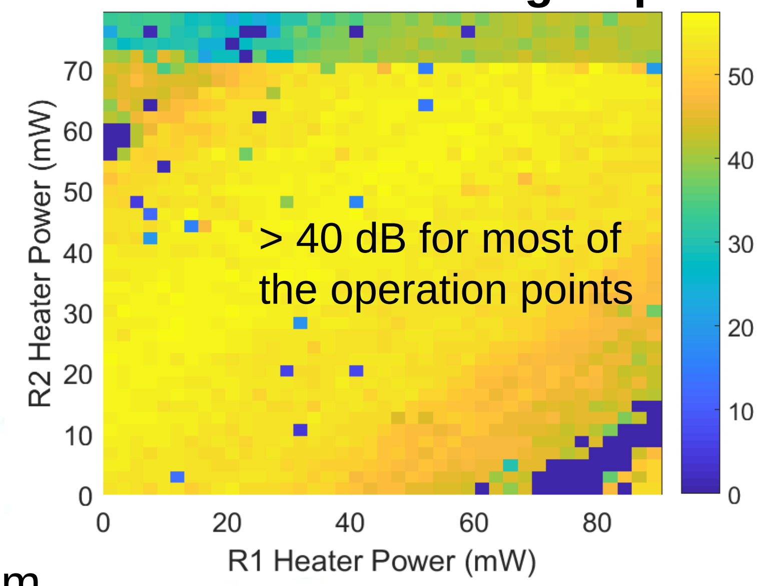

- Designed Vernier FSR = 114 nm
- ✓ Passive SMSR > 8 dB across the whole tuning range

# Laser performance characterization

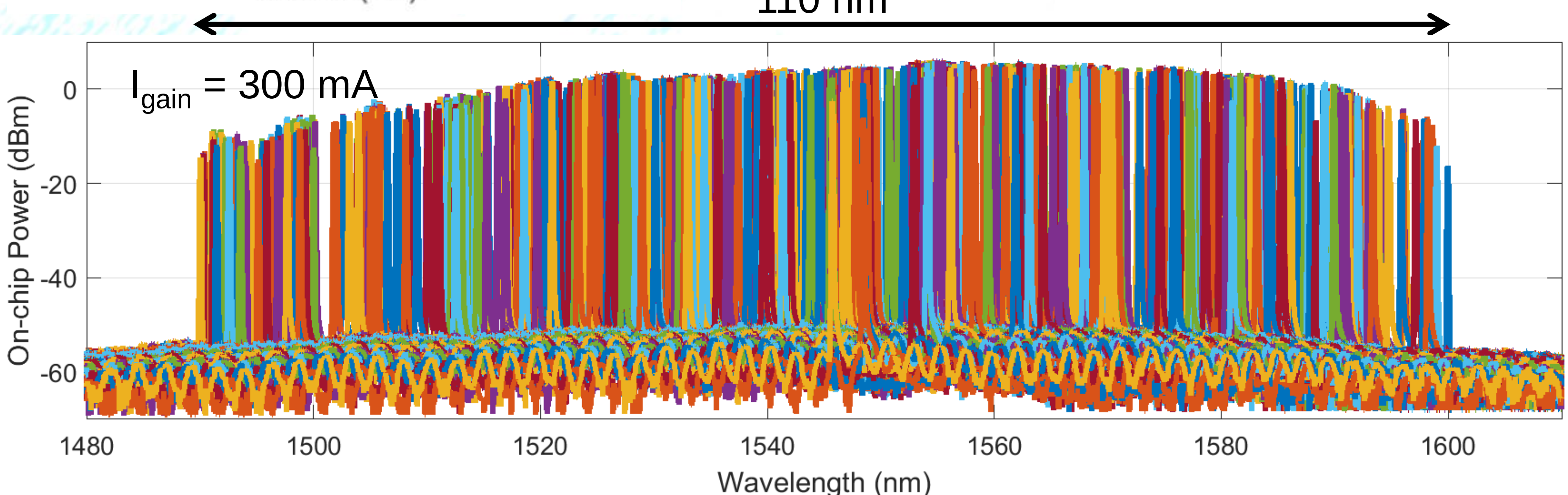
$T_{stage}$ = 20 ℃



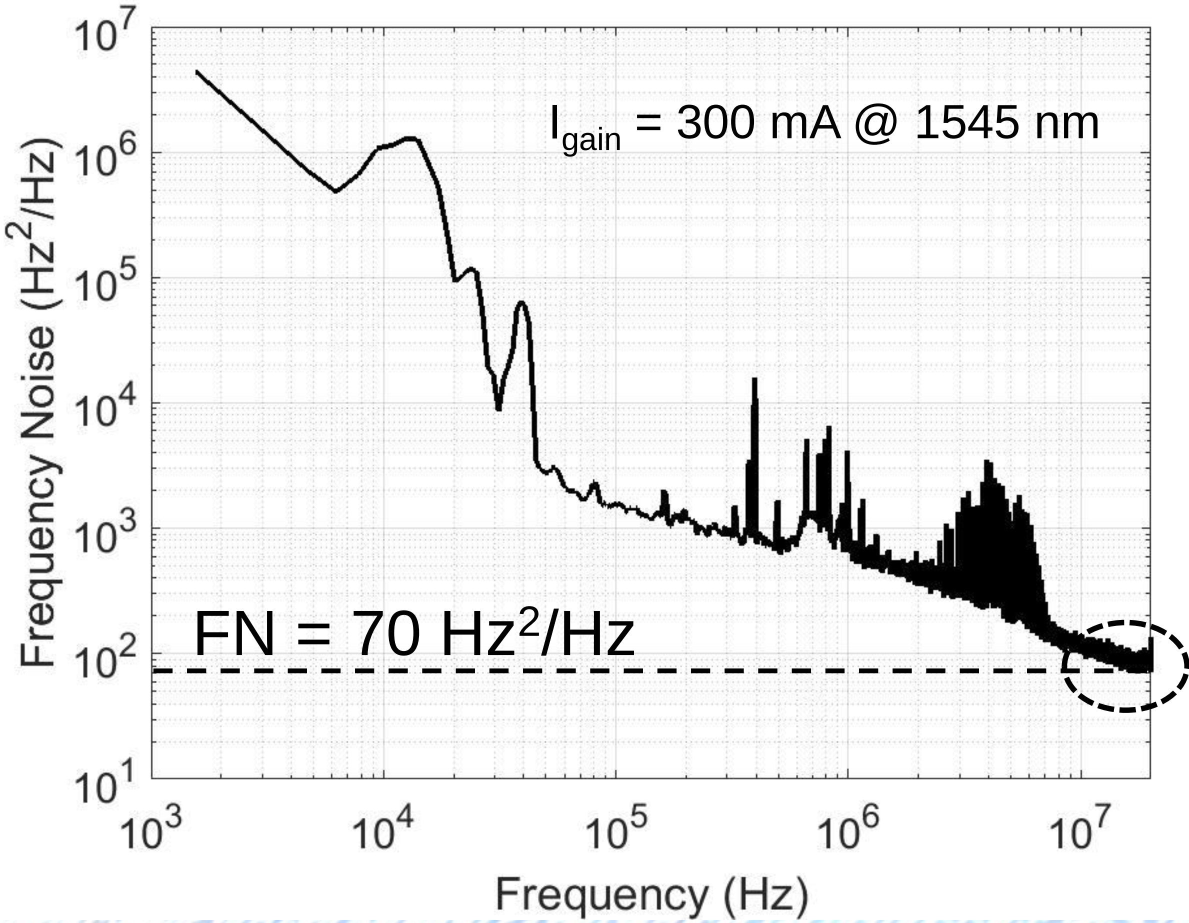

SMSR on Tuning Map




110 nm



# Frequency Noise and Lorentzian Linewidth

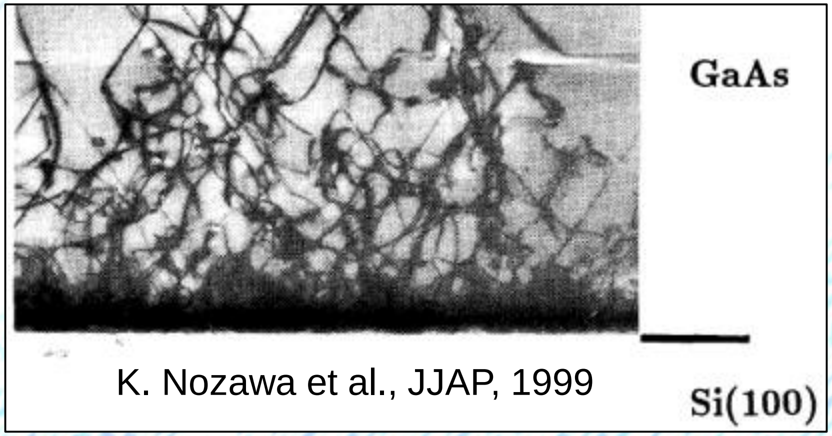



- Measurement setup is limited. The noise spectrum has not flattened at 20 MHz yet.
- Lorentzian Linewidth < **220 Hz !**

# Emerging light source technology by direct epitaxial growth

## Monolithic Growth is Difficult

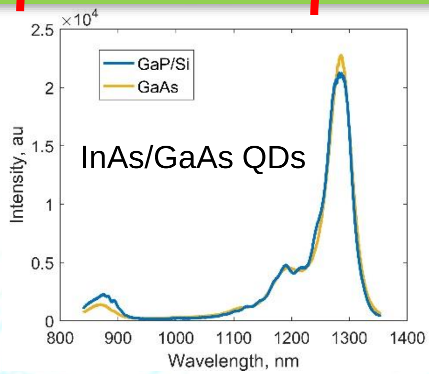
- Lattice constant mismatch
  - High density of dislocations, antiphase domains, stacking faults
- Thermal expansion mismatch
  - Cracking, residual strain at room temperature

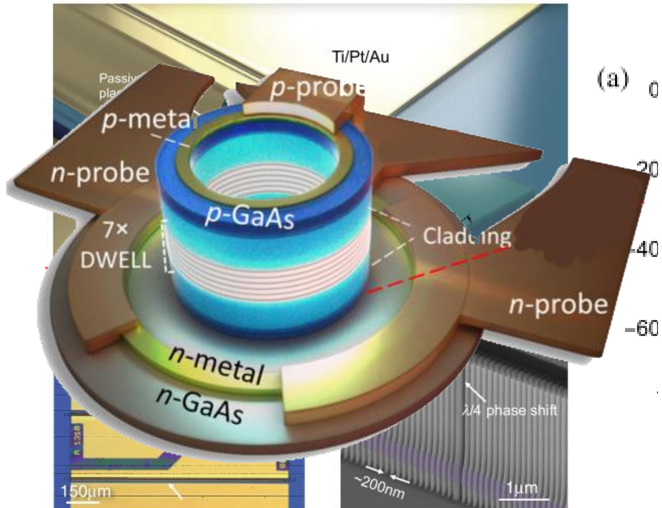



K. Nozawa et al., JJAP, 1999

# Tremendous progress in the last five years

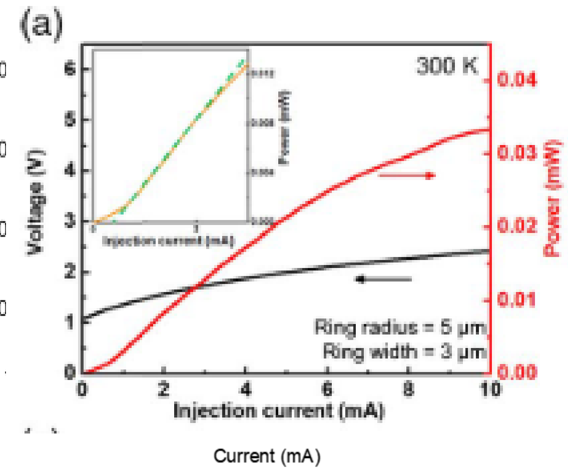
## Maturation of the Light Source

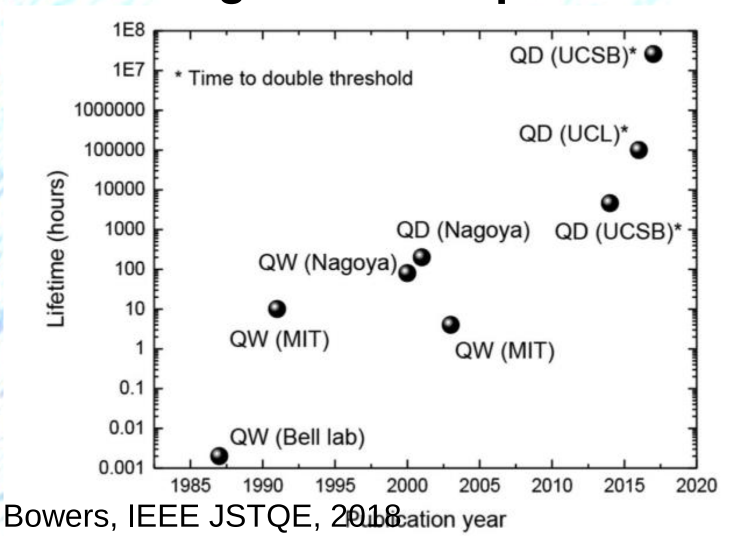

Y. Wan, et al, Optica, 2018

Y. Wang, et al, Optica, 2018

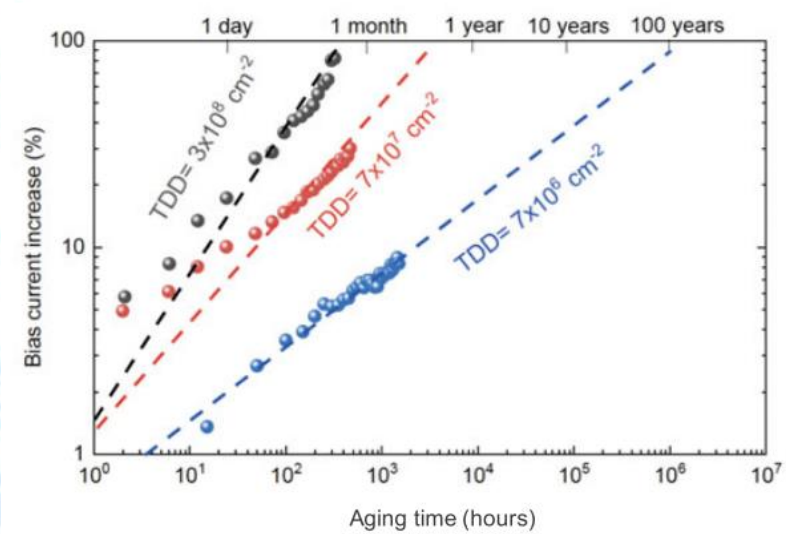



D. Jung, et al, ACS photonics, 2018

## Demonstrating Reliable Operation




A. Liu, J. Bowers, IEEE JSTQE, 2018



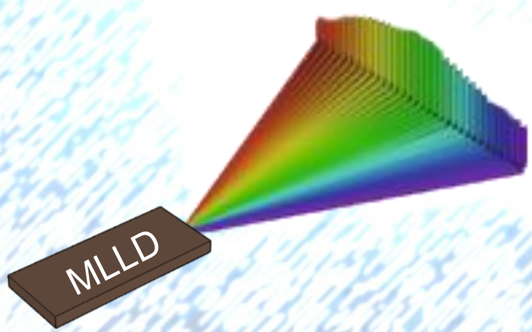
# Advantage of the quantum dots

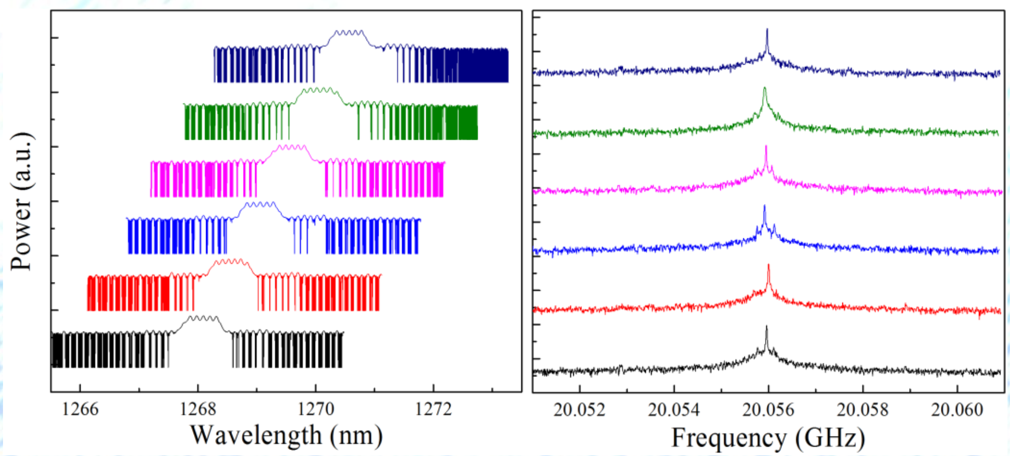
**Quantum dots have advantages over Quantum well or bulk material**

- ✓ inhomogeneously broadened gain spectrum
- ✓ ultrafast carrier dynamics
- ✓ superior temperature stability
- ✓ high saturation output power
- ✓ better back-reflection insensitivity
- ✓ low level of amplified spontaneous emission (ASE) noise

**Excellent material for making mode locked lasers!**

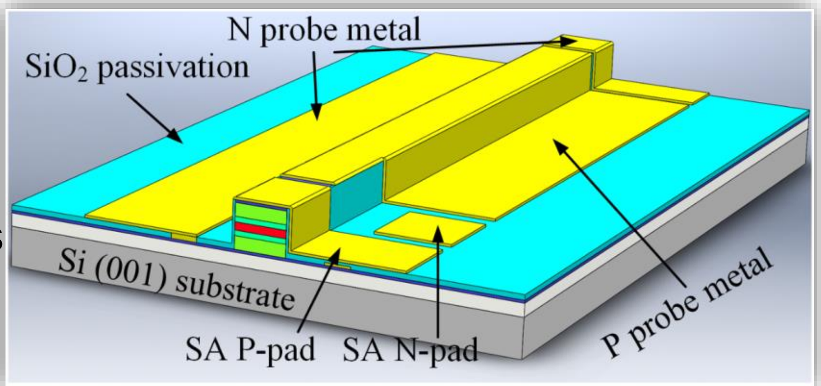
- ➢ **Simple structure to generate a wide coherent spectrum with a fixed channel spacing**

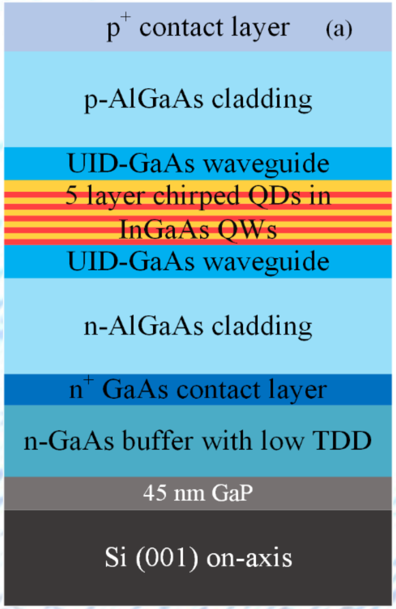


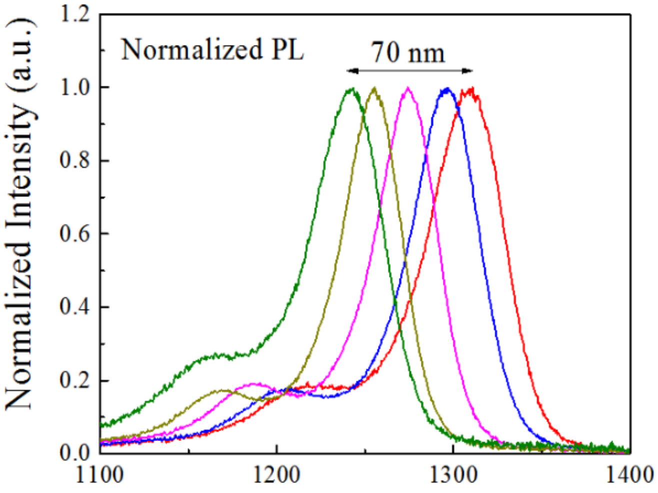



# Mode locked laser device design

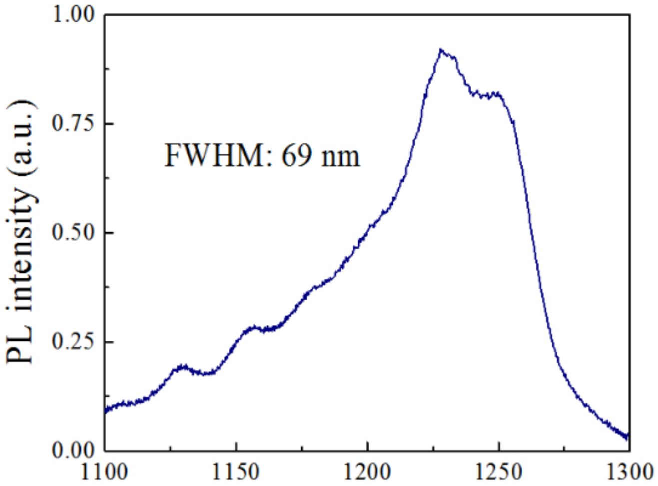
- Two section mode locked laser design
  - 3 µm ridge width
  - 2048 µm cavity length
  - SA section length is 14% of the total cavity length
- Active region: chirped five stacks of InAs QD layers
  - P modulation doped 5 x $10^{17}$ $cm^{-3}$ in the spacer layer
  - TDD as low as 7 x $10^{6}$ $cm^{-2}$
  - Chirped QD layers for broadened FWHM of 69 nm



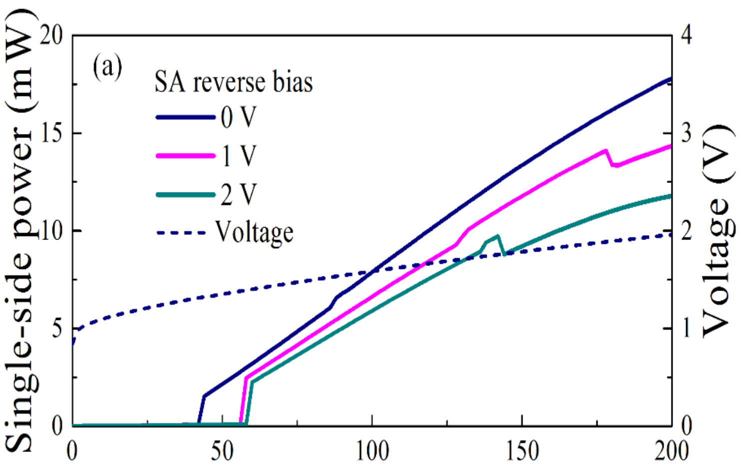

PL emission spectra of a single InAs DWELL layer with different InGaAs thicknesses in test run




PL spectrum of the material used.

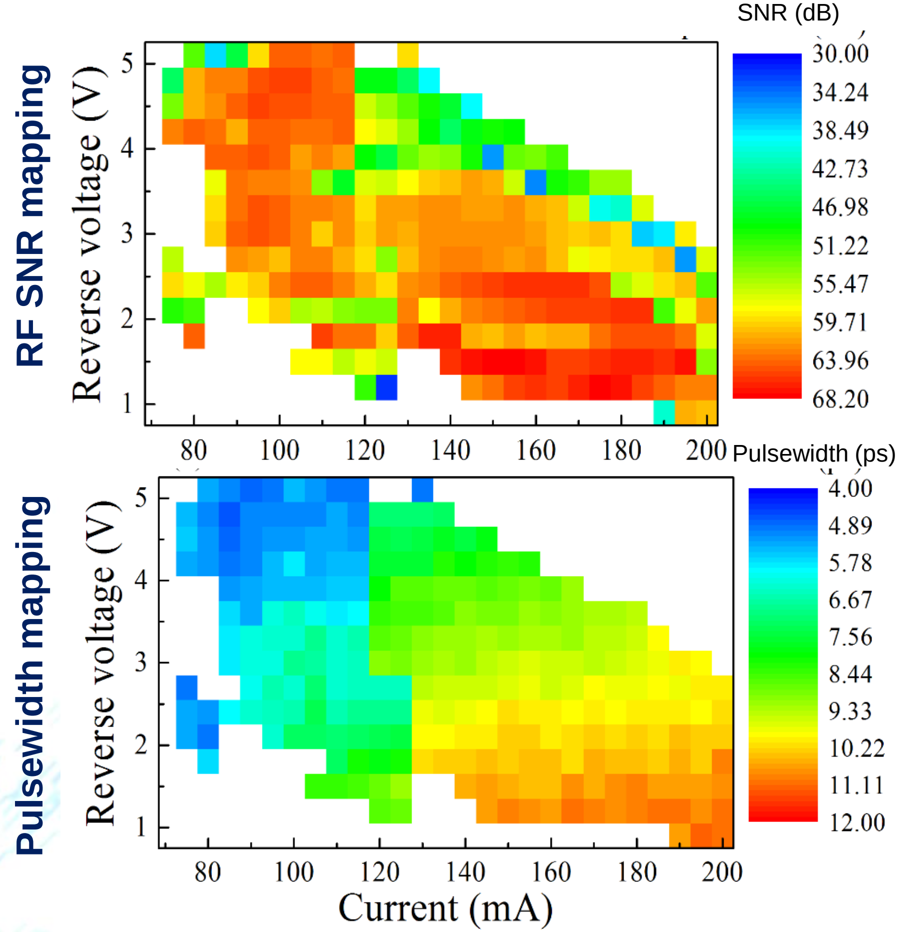
# Basic device performance

## L-I-V curve



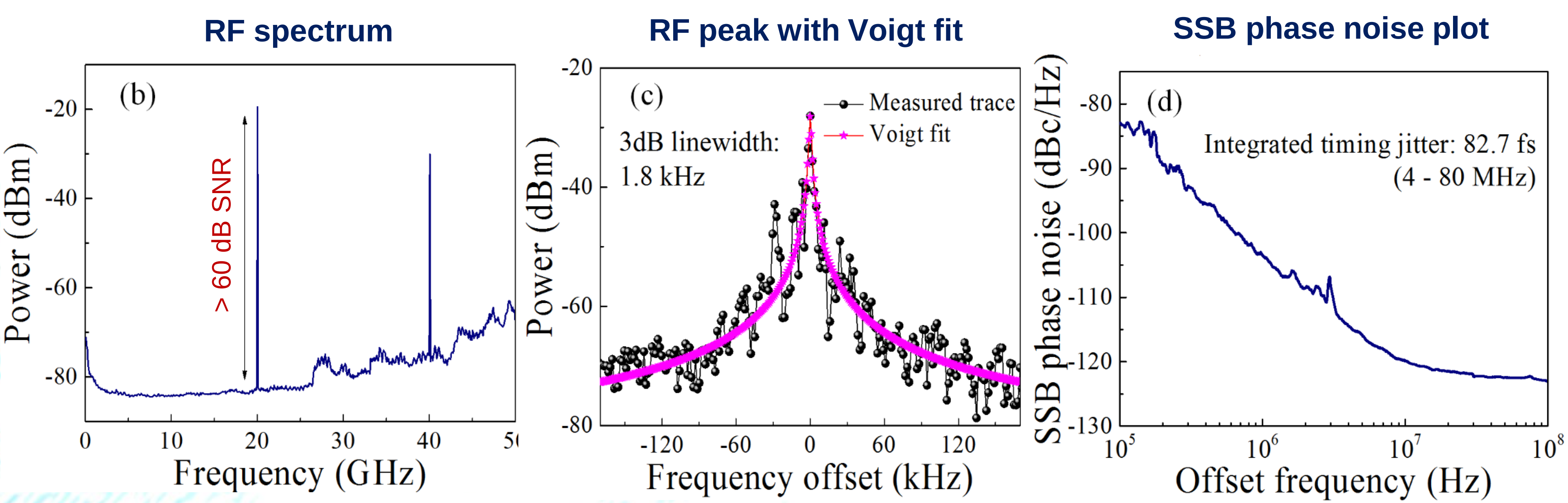

Current (mA)

- Threshold: increase from 42 mA to 58 mA as SA section reverse bias increase
- Series resistance: ~ 3.2 Ω



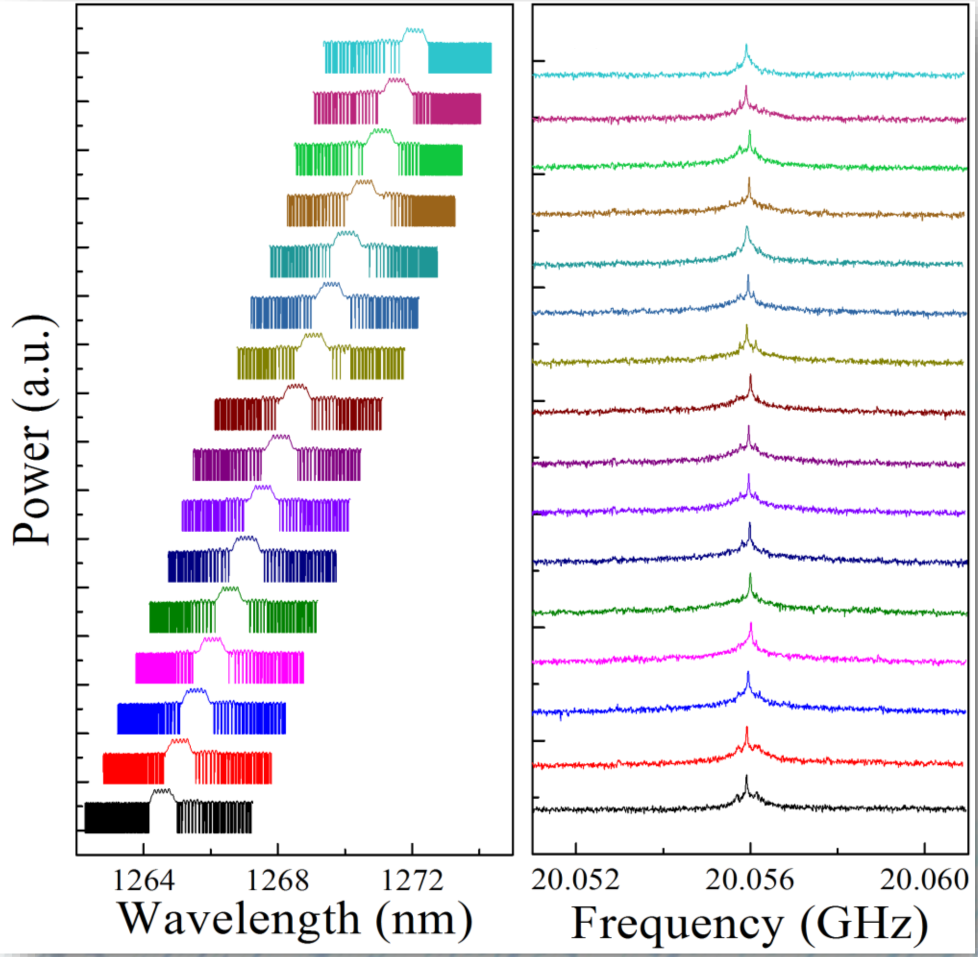

- Mode locking criterion: being restricted to fundamental frequency tone signal to noise floor (SNR) ratio larger than 30 dB with the pulse width narrower than 12 ps.
- Wide mode locking regime is demonstrated.

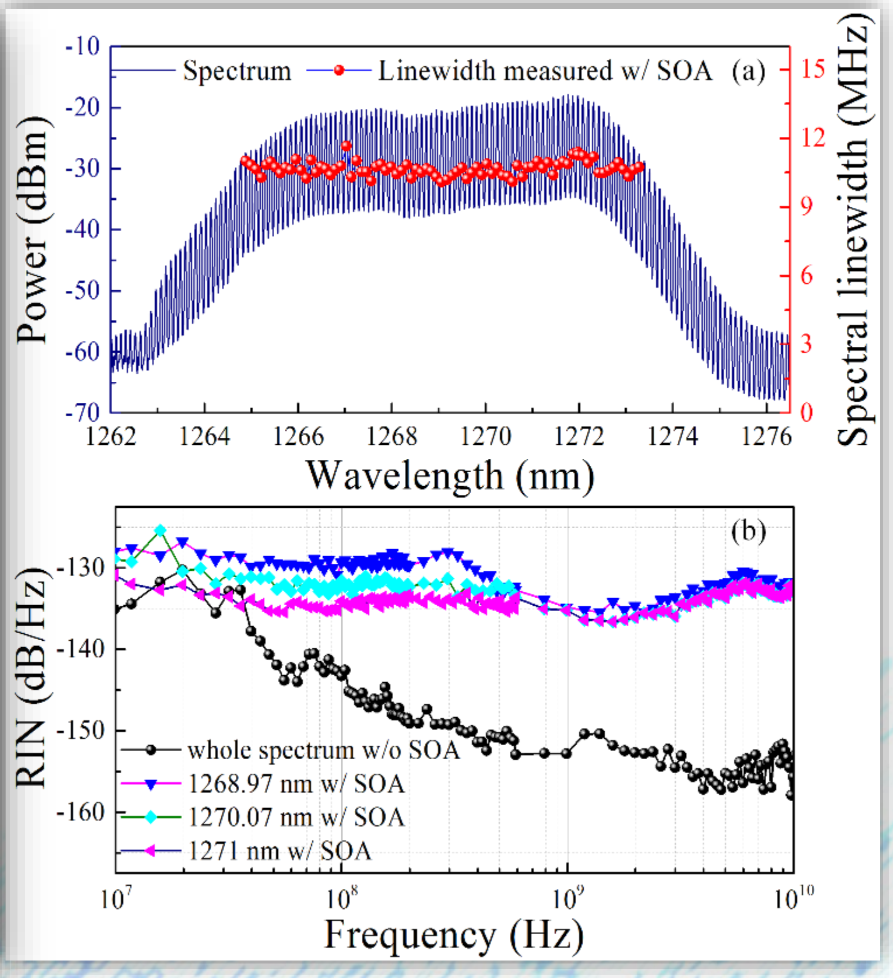
# Basic device performance




- A sharp fundamental RF tone at 20.02 GHz with a SNR of 64 dB and its higher-order harmonic can be clearly seen across the 50 GHz span, indicating very stable mode locking operation.
- The 3 dB RF linewidth is 1.8 kHz with a Voigt fit.
- The integrated timing jitter is 82.7 fs from 4 to 80 MHz of the ITU-T specified range, which is the lowest timing jitter ever reported to date for any passively mode-locked semiconductor laser diode.

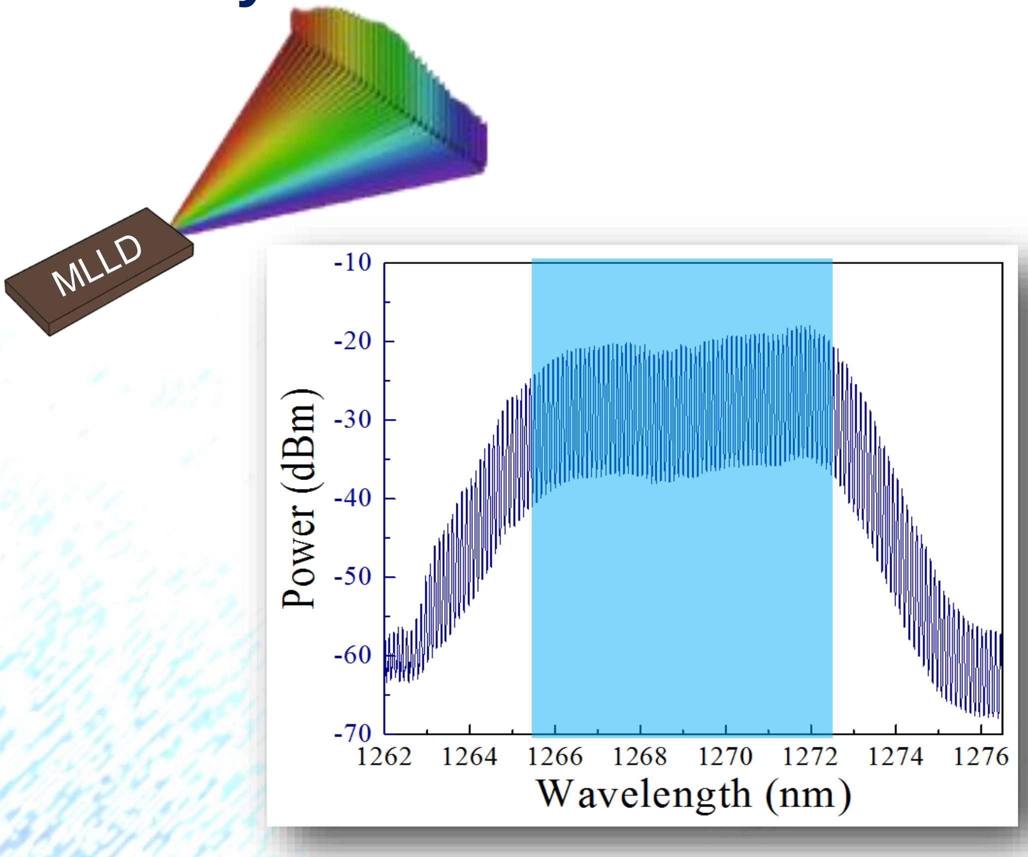
# Basic device performance



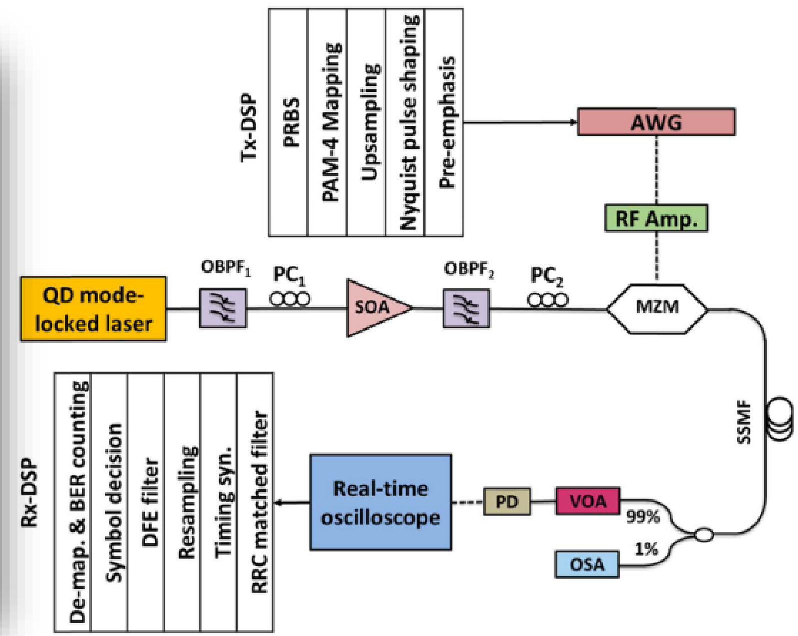




$I_{gain}$ = 180 mA, $V_{SA}$ = - 1.92 V

# PAM-4 system level transmission demonstration



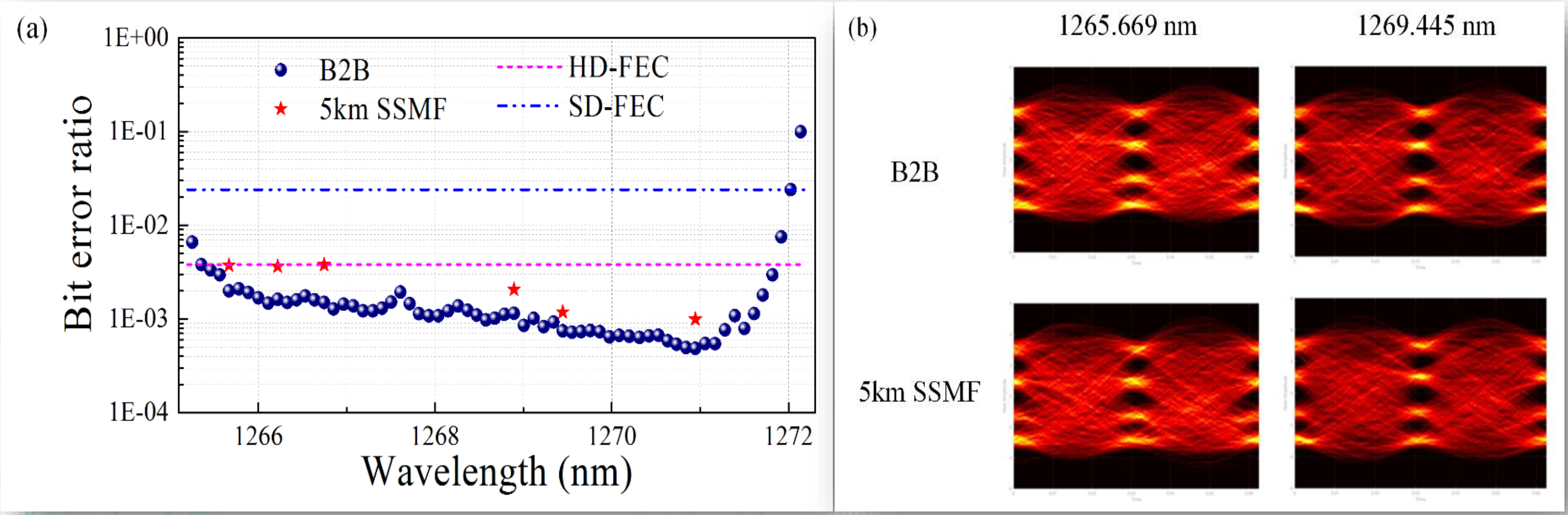

System-level PAM-4 transmission test setup




[1] X. Wu, S. Liu, D. Jung *et al.*, “Terabit interconnects with a 20-GHz O-band passively mode locked quantum dot laser grown directly on silicon”, OFC, 2019
[2] S. Liu, X. Wu, D. Jung et al.,” High-channel-count 20 GHz passively mode-locked quantum dot laser directly grown on Si with 4.1 Tbit/s transmission capacity”, Optica, 2019

# 4.1 Tbps 64-wavelength 32 Gaud PAM-4 Demonstration

**BER performance** **PAM-4 eye diagram**

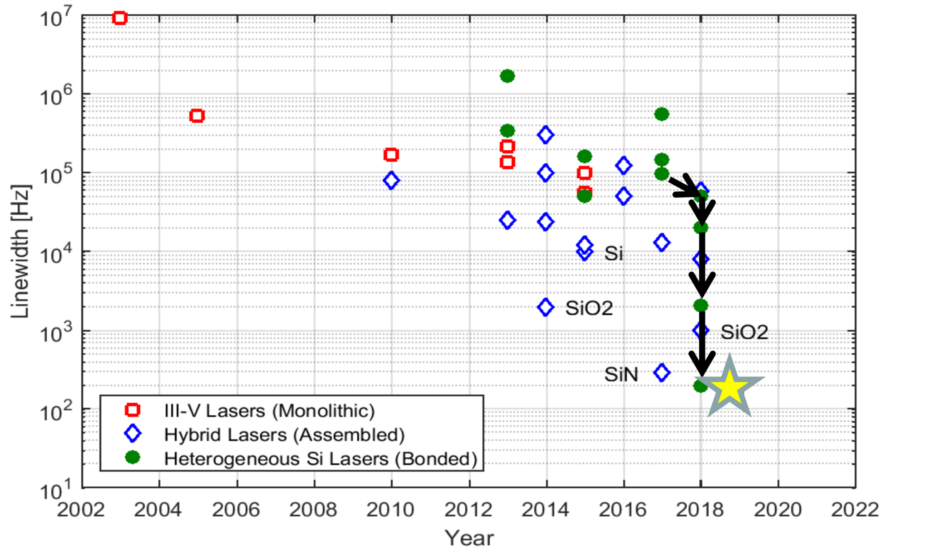



- 64 channels are utilized.
- 32 Gbaud Nyquist pulse shaped PAM-4 modulation format.
- With 61 channels below hard-decision FEC threshold and total 64 channels below soft-decision FEC threshold.
- An aggregate total transmission capacity is 4.1 terabits per second.

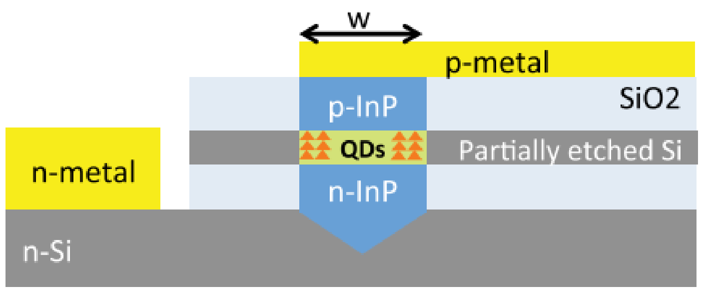
# Summary

- Integrated lasers on silicon can provide a high performance, low cost, mass production and high energy efficiency solution.

  ✓Record ultralow noise chip-scale semiconductor lasers
  ✓Record ultrawide wavelength tuning ranges for chip-scale lasers




- Epitaxial lasers are progressing fast.




The work was funded by ARPA-E, U.S. Department of Energy, under Award No. DE-AR0000843, ENLITENED program, DARPA under contract No. N66001-16-C-4017 and Morton Photonics DARPA STTR program #W911NF-16- C-0072. The authors would like to thank all the members in the group for useful discussions and contributions.