A Tutorial on Silicon Heterogeneous Integrated Photonic Integrated Circuits: From Data Centers to Sensors

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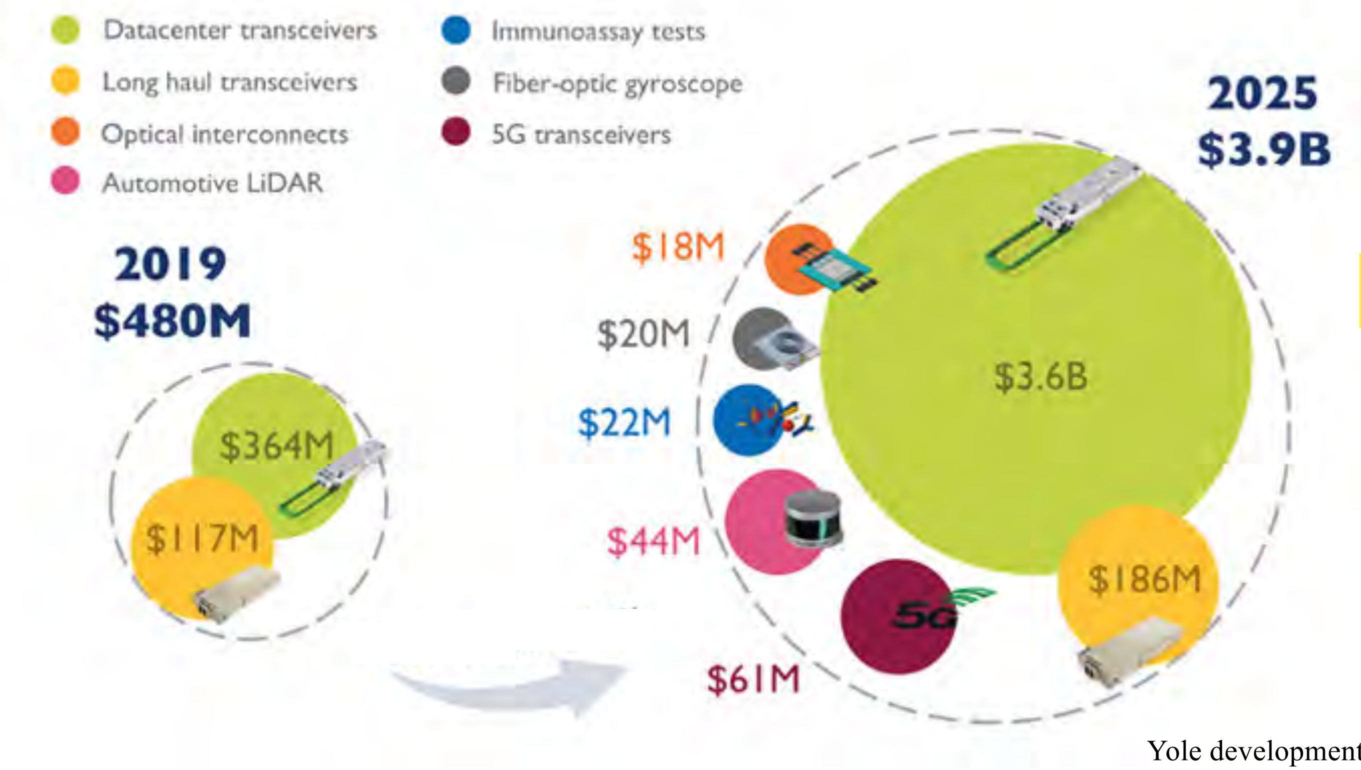
Outline

- Economic drivers: high volume applications
- Laser integration platforms
- Narrow linewidth lasers
- Comb generation:
  - Mode locked lasers
  - Nonlinear combs
- Conclusions

The silicon photonic market

Silicon photonics 2019-2025 market by applications



Yole development

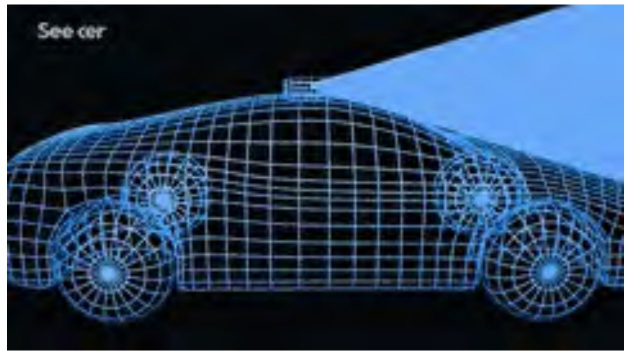
8x in 6 years

Applications are mainly limited within communications!
The scope of silicon photonics is still quite small!

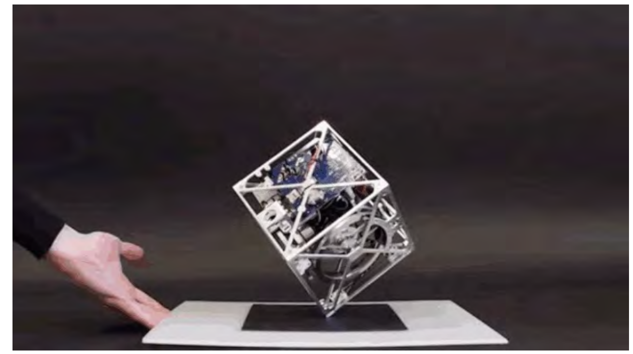
High Volume Silicon Photonic Applications

Datacom/Telecom

LIDAR

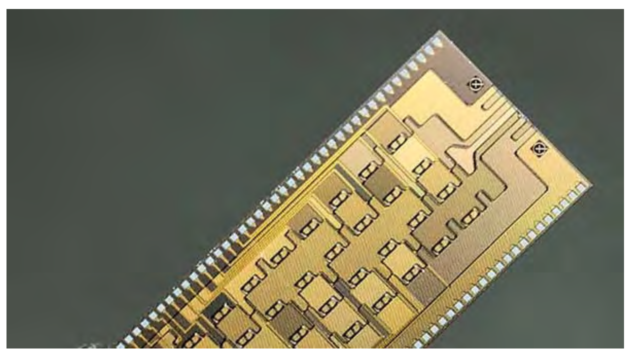


Optical Gyroscopes

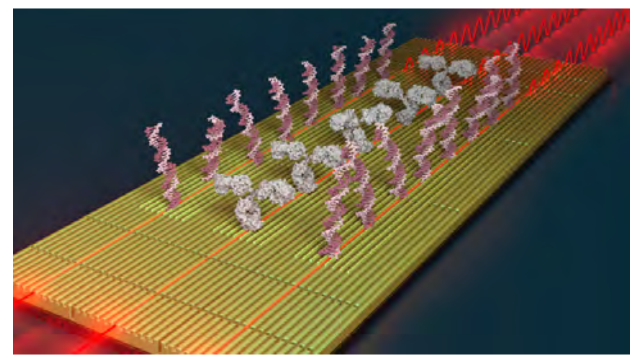


AR/VR

Optical and Quantum Computing



Biosensors for glucose, oxygen,…



Lasers in telecommunications

Data traffic volume requirements are continuously rising.

Laser applications

- Datacenter optical interconnects
- Long-haul optical transceivers

Global mobile network data traffic

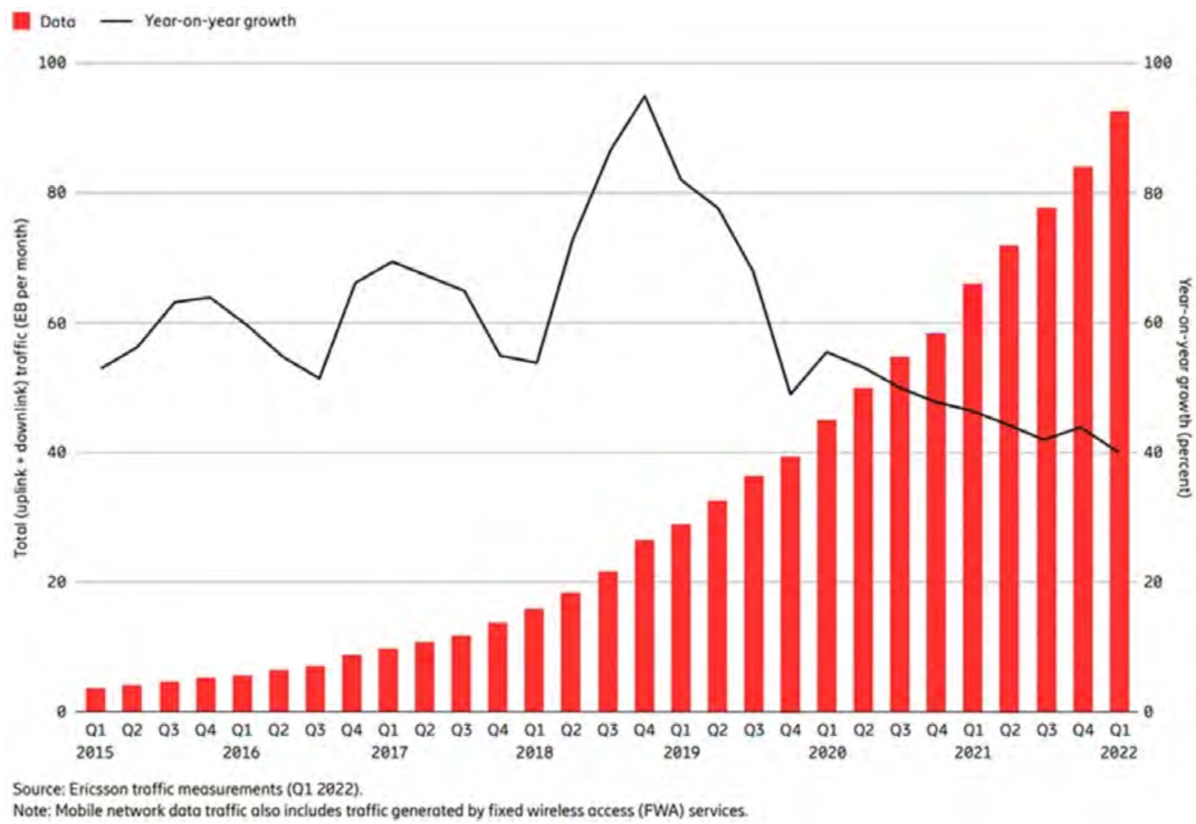


Image: Intel

S. Mzekandaba, Itweb (2022), "Worldwide mobile data traffic growth doubles in two years."

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Power Consumption of Data Centers Growing Rapidly

Skybox, Prologis Plan Massive 600-Megawatt Data Center Campus in Austin

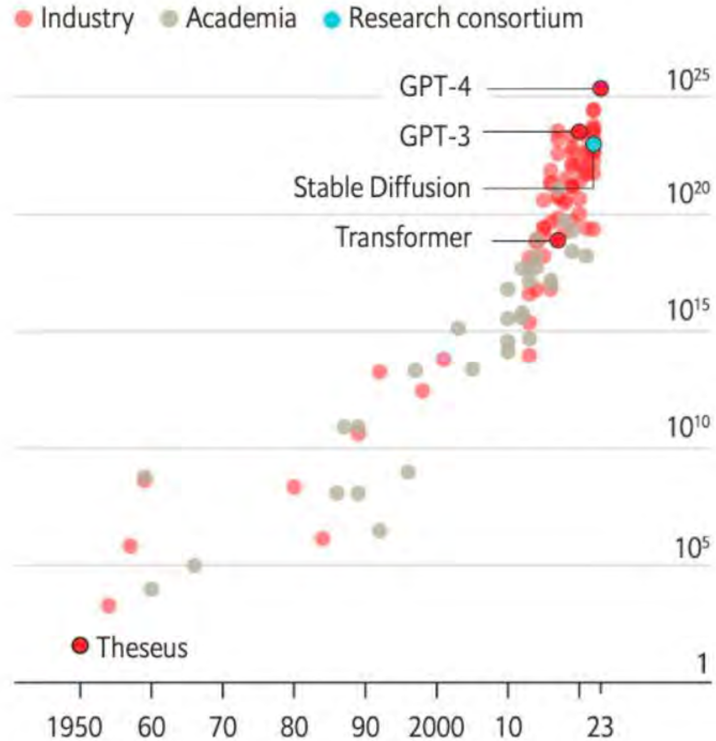
Skybox Datacenters and Prologis plan to build a massive 600-megawatt campus near Austin, Texas which will offer up to 4 million square feet of data center space.

An illustration of the Austin PowerCampus planned by Skybox Datacenters and Prologis in Hutto, Texas.

Faster, higher, more calculations

Computing power used in training AI systems

Selected systems, floating-point operations, log scale

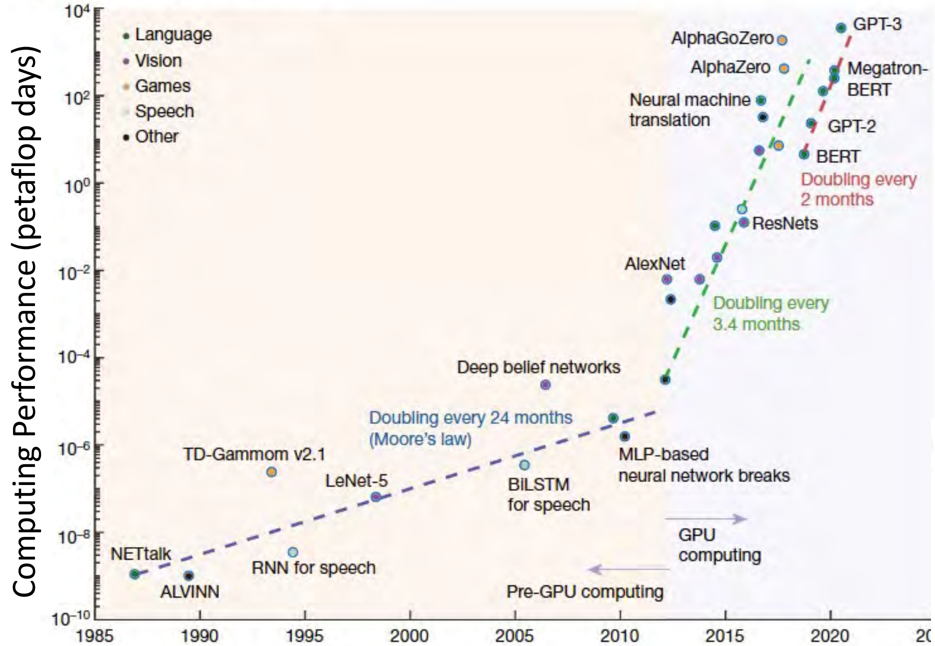


Sources: Sevilla et al., 2023; Our World in Data

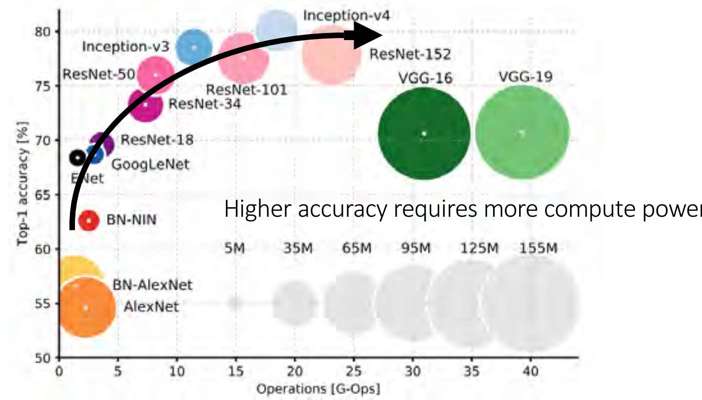
175-hectare, 600MW data center campus proposed outside London in Havering

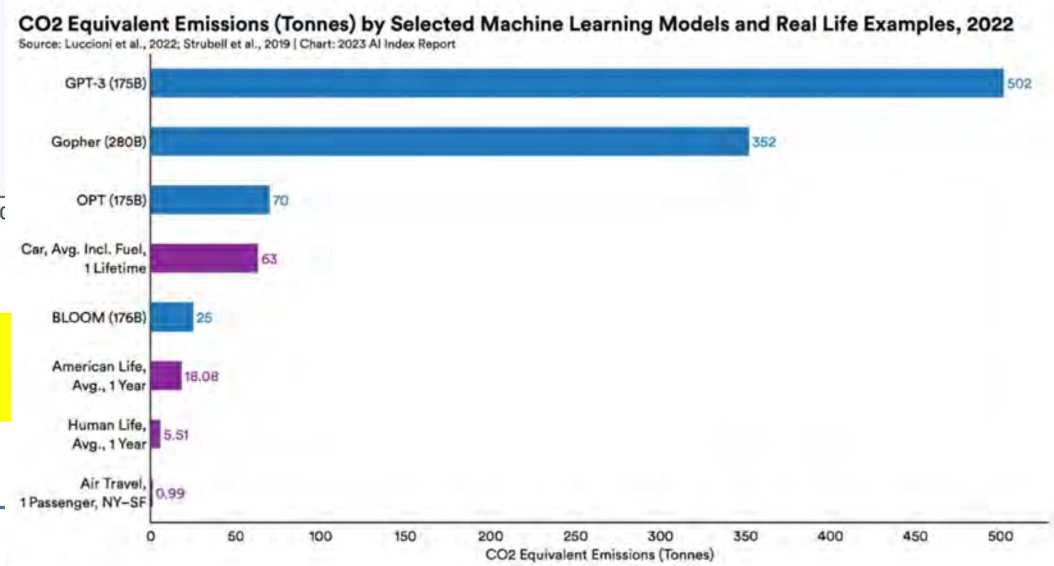
RISING DEMAND FOR AI AND COMPUTE POWER

Number of programs which use deep learning has *doubled* every 3.4 months, much faster than Moore's Law



Mehonic et al., "Brain-inspired computing needs a master plan"





Silicon Photonics can improve efficiency
Quantum Dot Lasers may be key for higher efficiency

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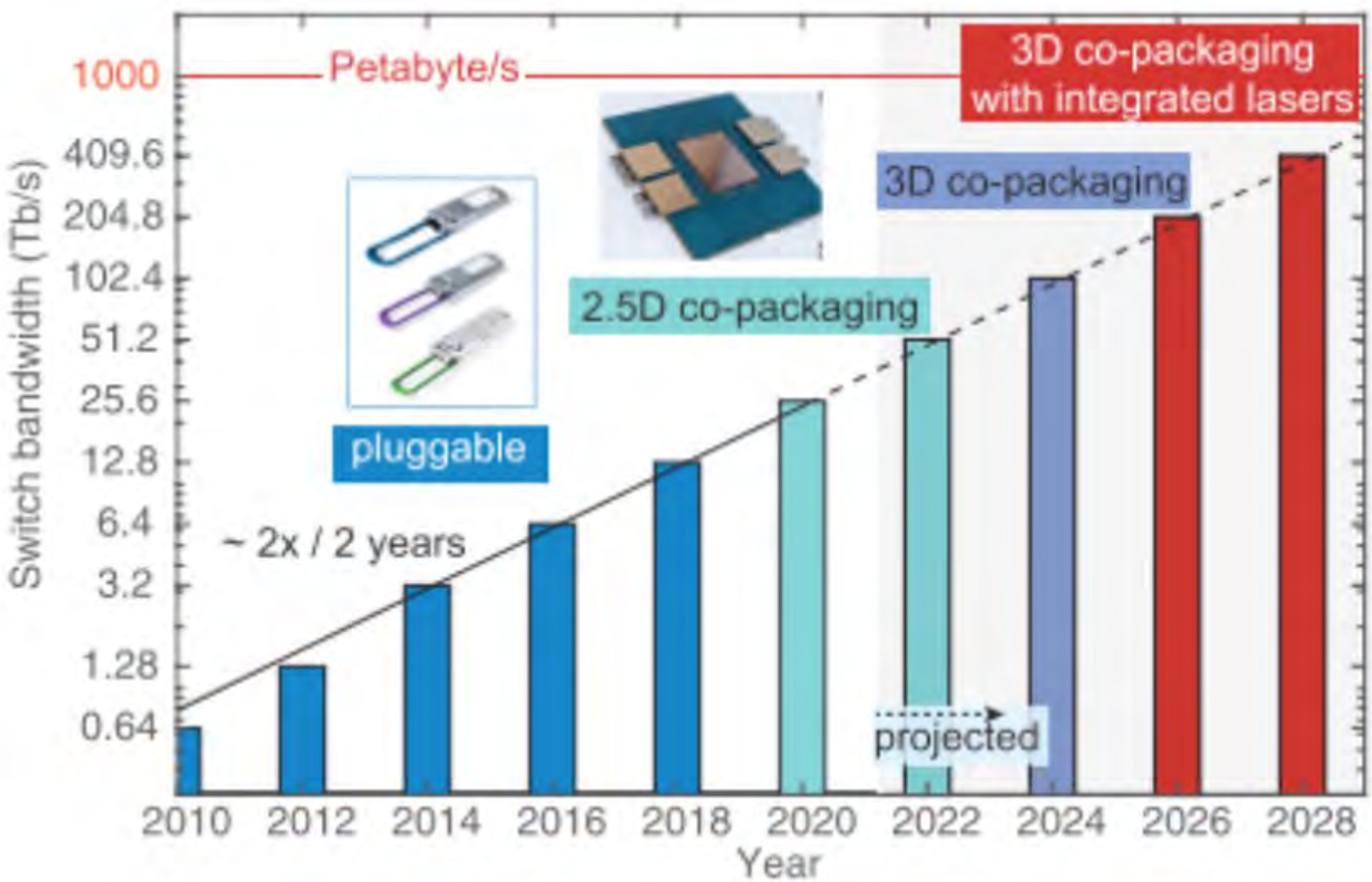
Abbas, Ali, et al. "Micro Activities Recognition in Uncontrolled Environments," *Applied Sciences* (2021).

Switch bandwidth evolution



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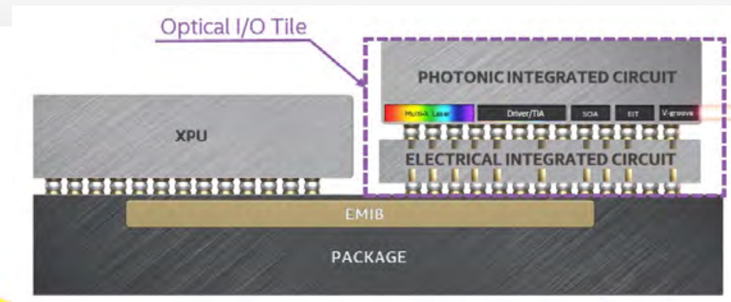
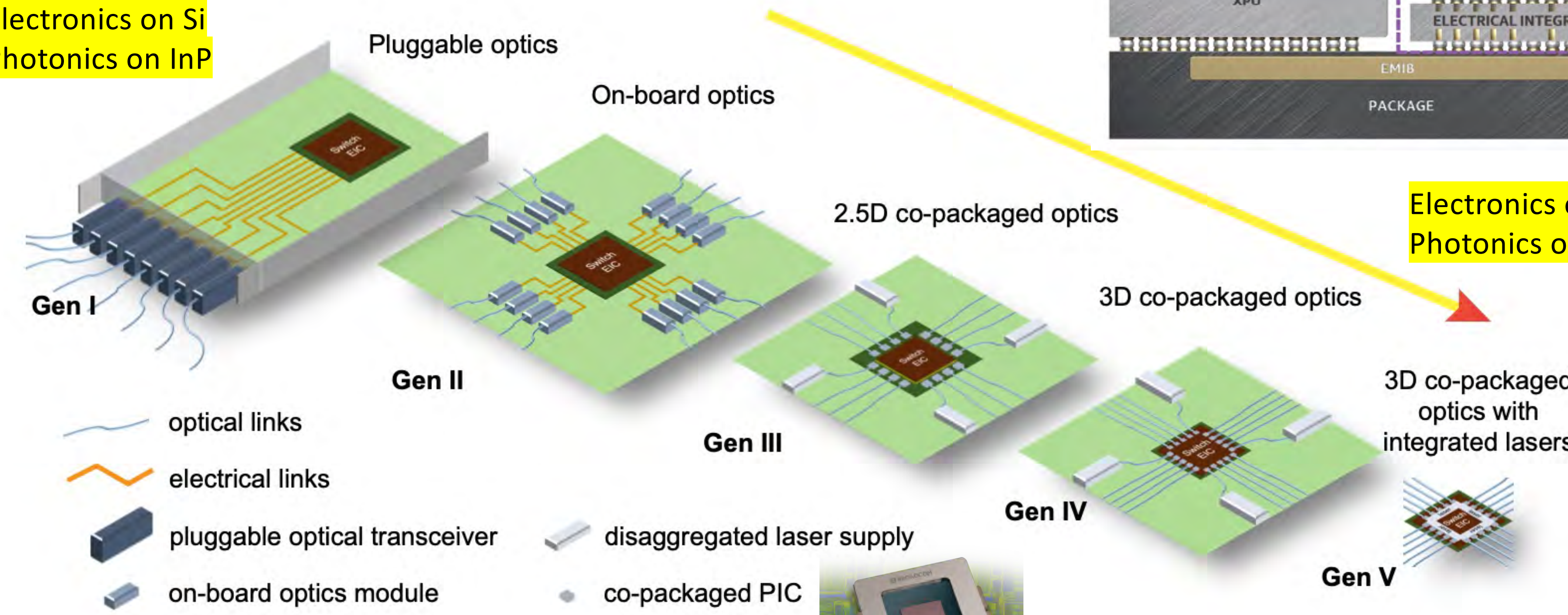
Economic Driver: Merging Photonics and Electronics

Electronics on Si
Photonics on InP



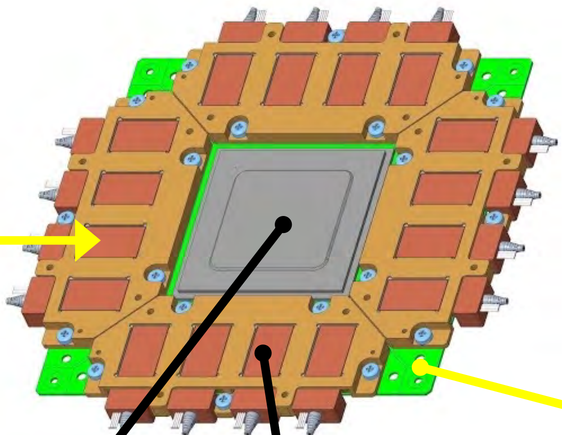


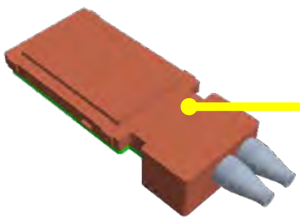
Electronics on Si
Photonics on Si

Margalit, Xiang, Bowers, Bjorlin, Blum, and Bowers, "Perspective on the Future of Silicon Photonics and Electronics", Applied Physics Letters, (2021)

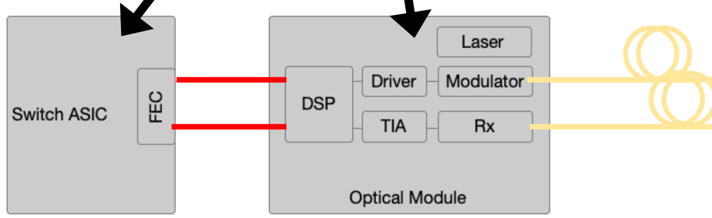
Co-packaged Optics – enabling lower power designs

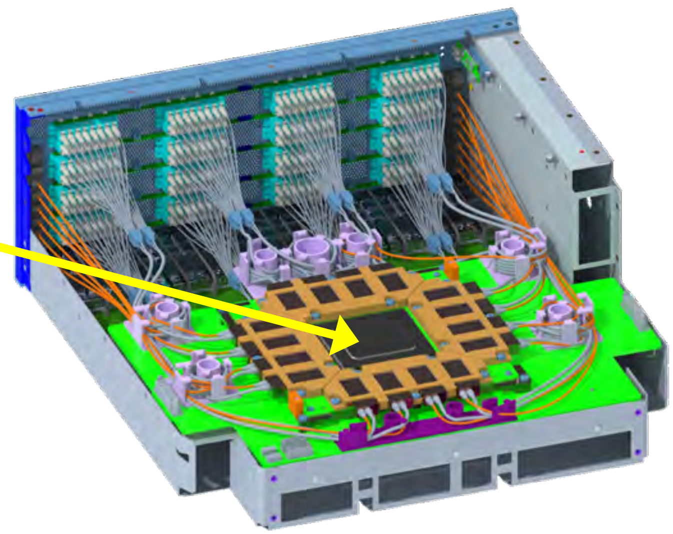
51T Switch + CPO Optics Assembly





3.2T CPO Optical Module

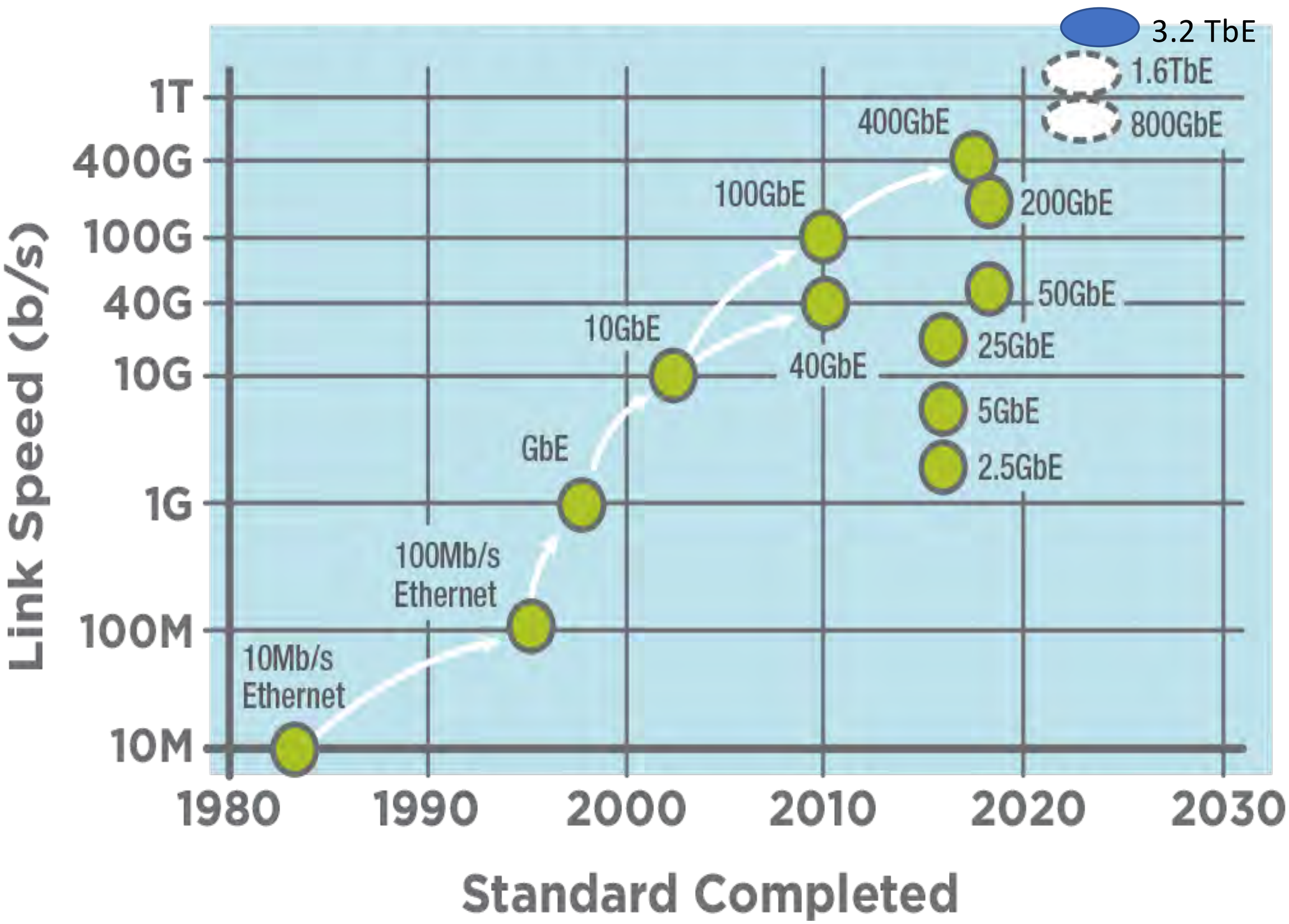




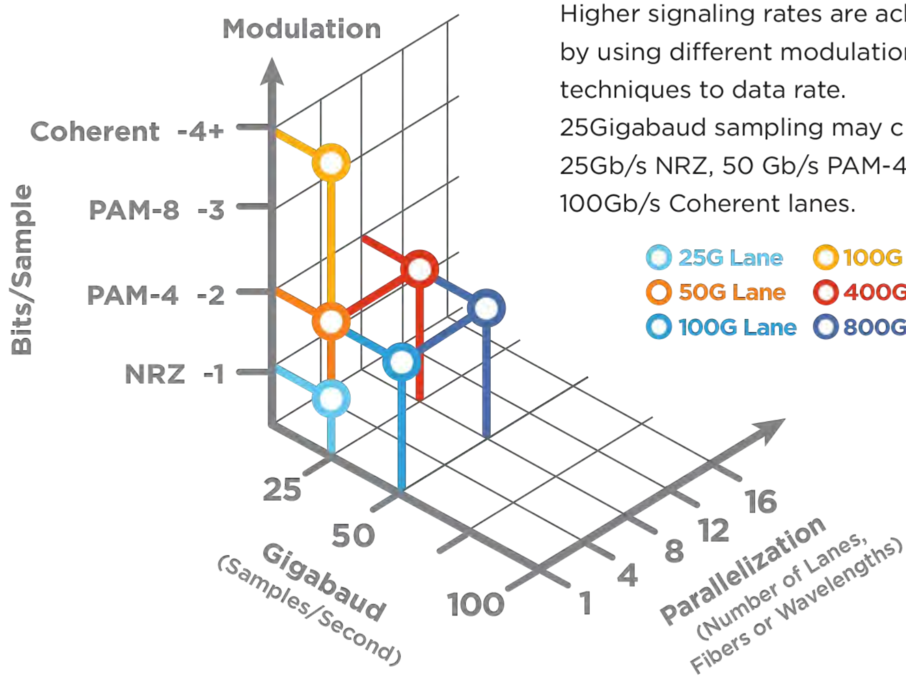
System Rear View

3.2 Tps per module: Combs of many wavelengths required

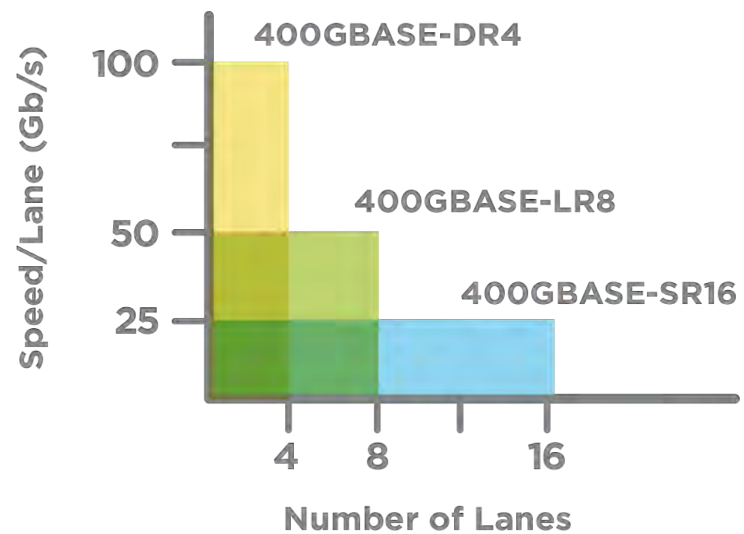
ETHERNET SPEEDS



The Path to Higher Capacity



Higher signaling rates are achieved by using different modulation techniques to data rate. 25Gigabaud sampling may create 25Gb/s NRZ, 50 Gb/s PAM-4 or 100Gb/s Coherent lanes.



Integration is key: N wavelength x P fibers =3NP devices
8 wavelengths x 4 fibers x 3 = 96 devices

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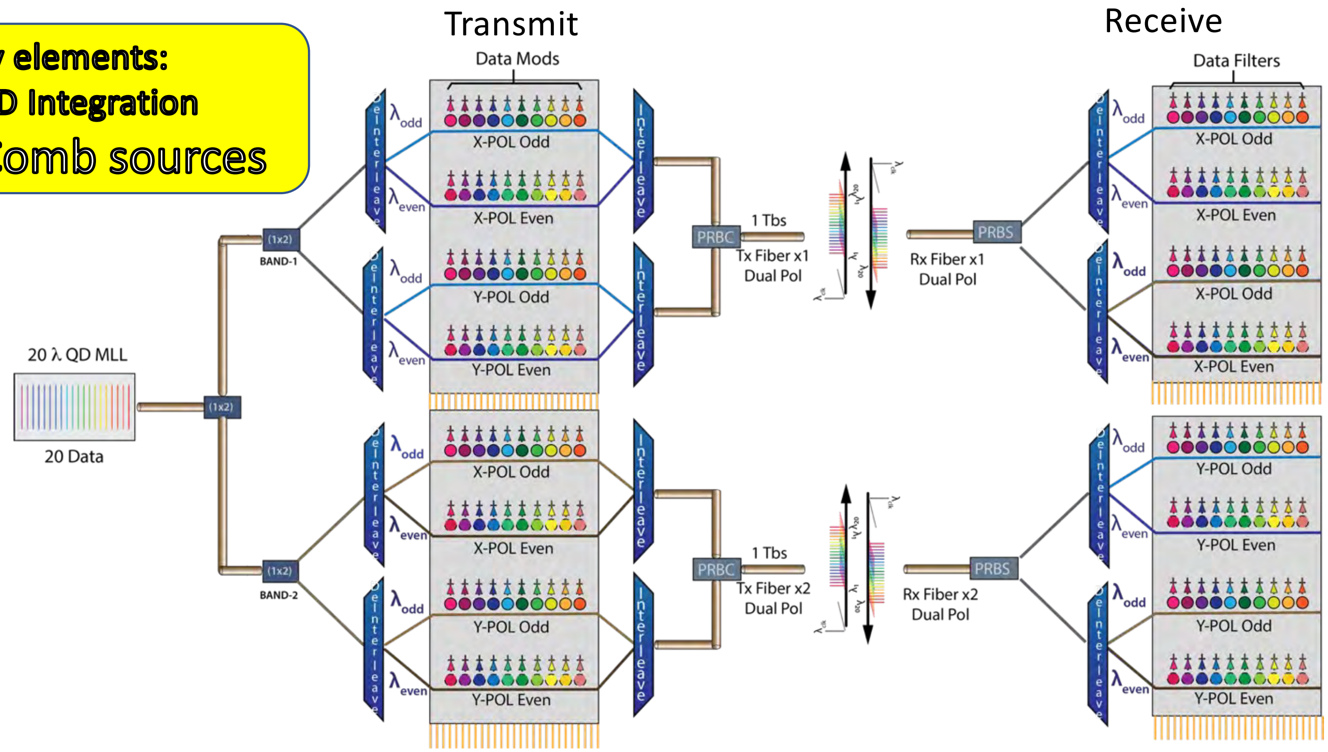
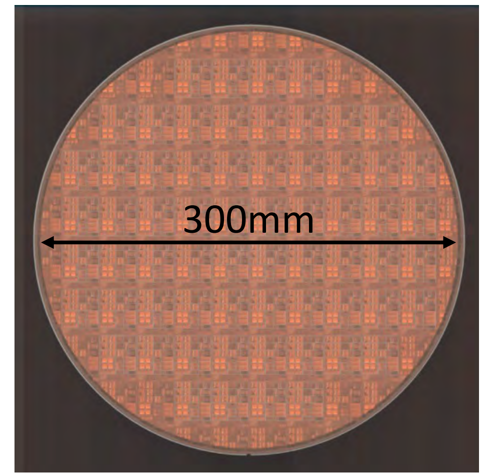
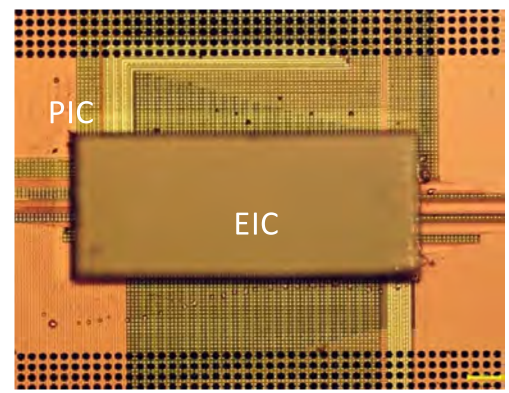
NEXT ETHERNET ERA ethernet alliance

UCSB/AIM/AP/Ciena:
1 Tbps link with 0.5 pJ/bit efficiency

Key elements:
3D Integration
Comb sources







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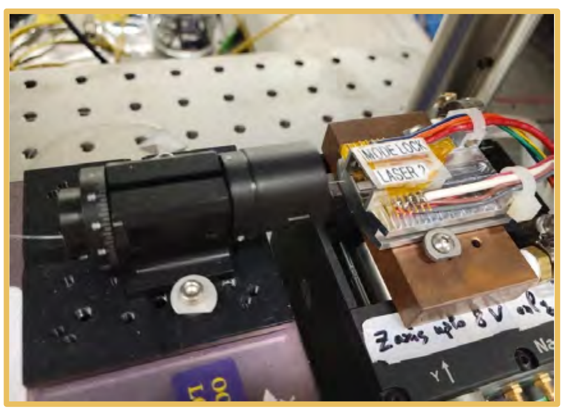
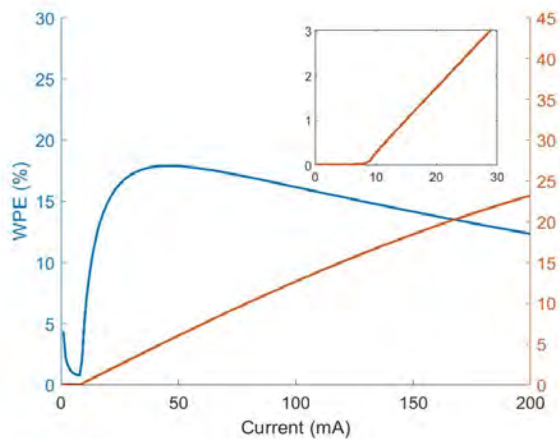
OFC W6A.3: A. Malik, et al. “Low power consumption silicon photonics datacenter interconnects enabled by a parallel architecture”, OFC (2021).

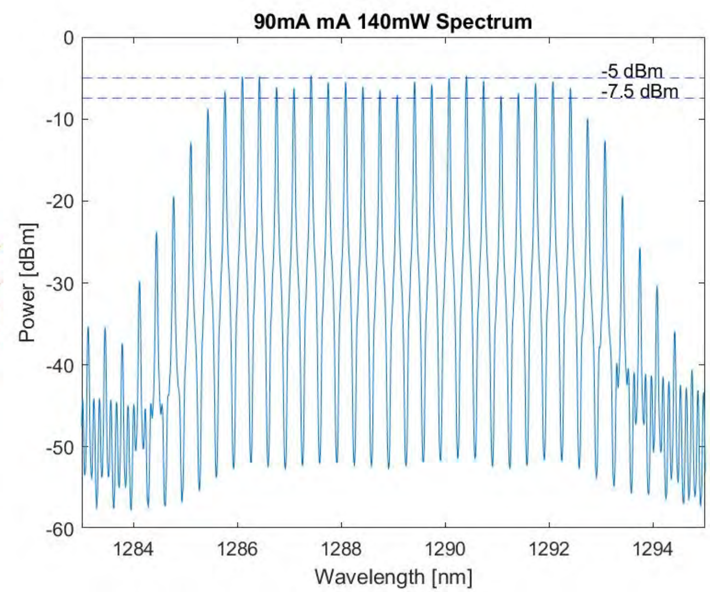
Passive Quantum Dot Mode Locked Lasers with Saturable Absorbers 60.0 GHz, 140 mW with -5 to -7 dBm/line

Advantage of **Quantum dot** mode locking:
1) Higher FWM allows better locking and even self mode locking (no saturable absorber)
2) Lower linewidth enhancement factor results in reduced reflection sensitivity (no isolator required)

- 2.5 dB Flatness
- 21 lines
- Exactly 60.0 GHz spacing
- 140 mW total electrical power







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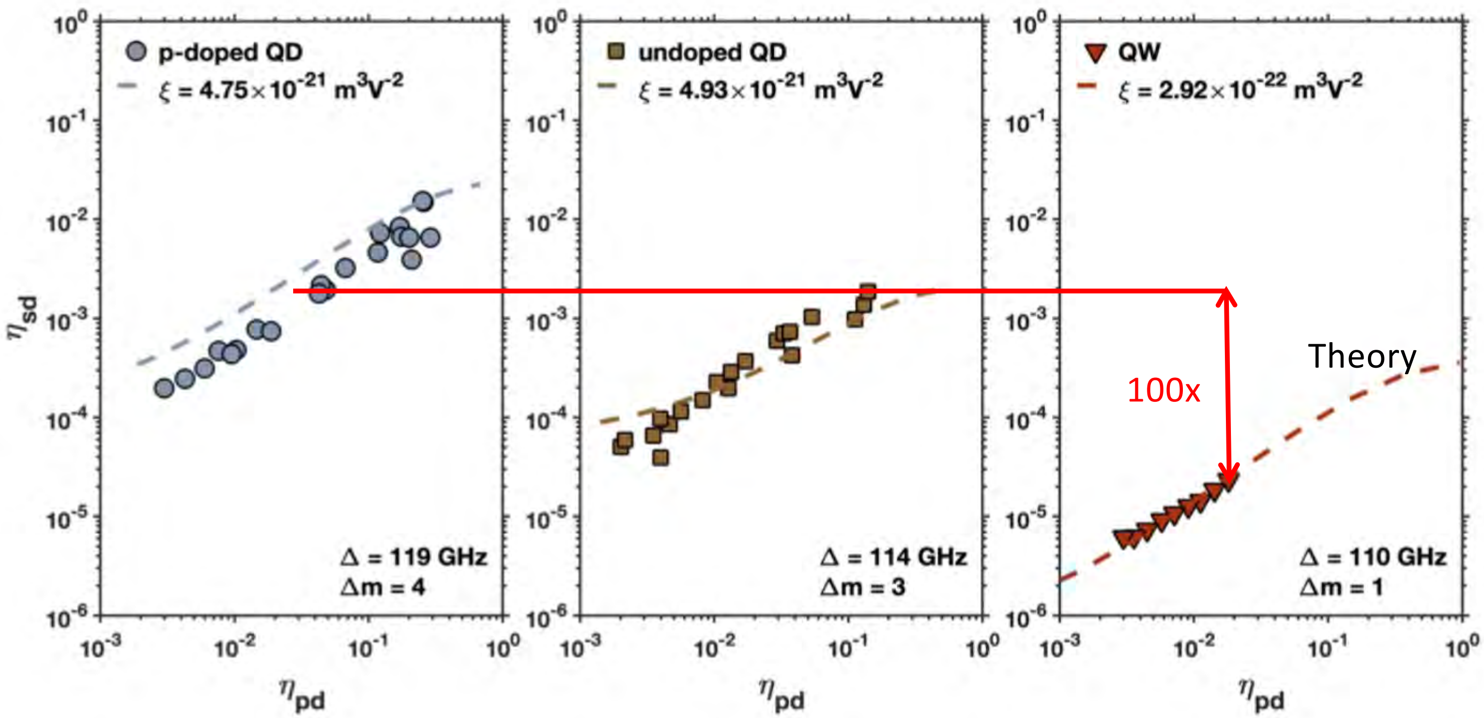
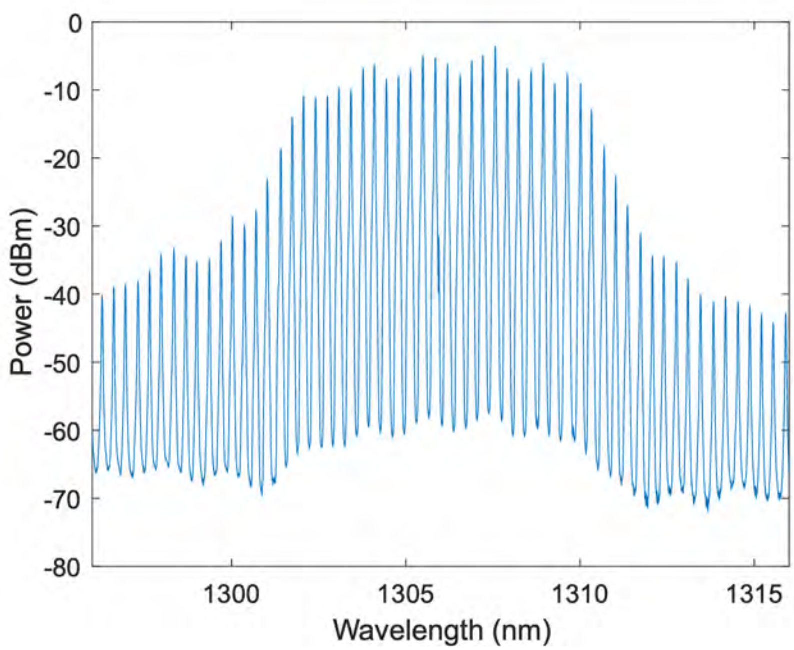
100x FWM in QDs Drives Magic Mode Locking:

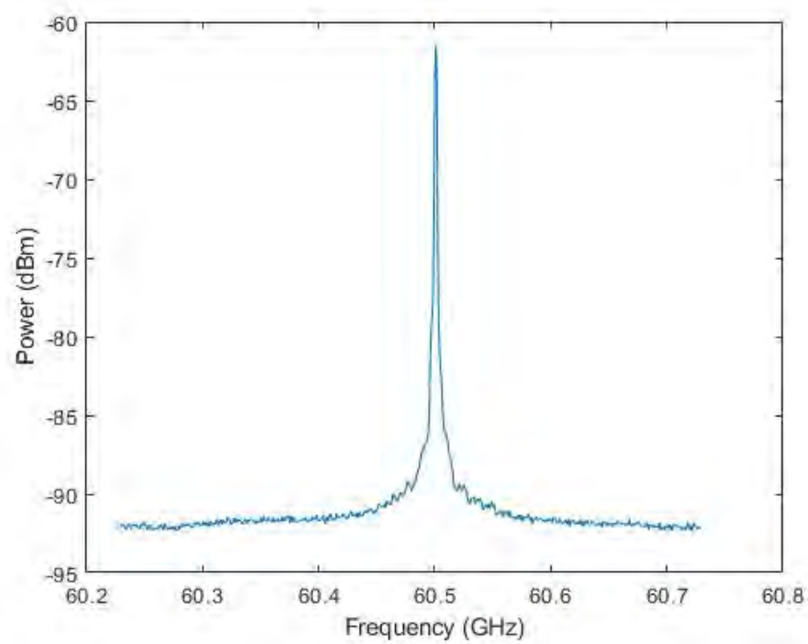
- Removing saturable absorber increases the wall plug efficiency
- We have observed magic mode locking due to four wave mixing
- Theory for FWM in good agreement with measurements.



Duan…Chow, Bowers, Grillot, "Four-wave mixing in 1.3 µm epitaxial quantum dot lasers directly grown on silicon" Photonics Research (2022).

Magic mode locking: Single Section Mode Locking





Comb Generation Using Nonlinear materials

Materials	$\chi^{(2)}$ [pm/V]	$\chi^{(3)}$ [cm^2/W] n_2	Refractive index @1550nm	Bandgap (nm)	Integration with active devices
$LiNbO_3$	26	5.3×10^{-15}	~2.14	310	No
SiO_2	-	2.2×10^{-16}	~1.44	137	No
Si_3N_4	-	2.5×10^{-15}	~2	238	No
Ta_2O_5	-	6.2×10^{-15}	~2	320	No
AlN	1	2.3×10^{-15}	~2	205	No
SiC	12	1×10^{-14}	~2.7	383	No
Si	-	6.5×10^{-14}	~3.4	1100	Indirect
GaAs (AlGaAs)	180	2.6×10^{-13}	~3.4	570-873	Direct
InP	263	1.1×10^{-13}	~3.2	922	Direct

Why (Al)GaAs?

- High nonlinear coefficients
- High refractive index (~3.4)
- Compatible with active devices
- Tunable bandgap to avoid TPA at telecom bands

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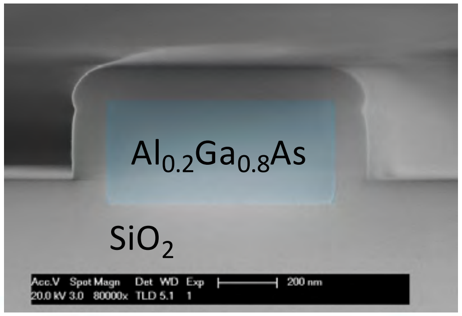
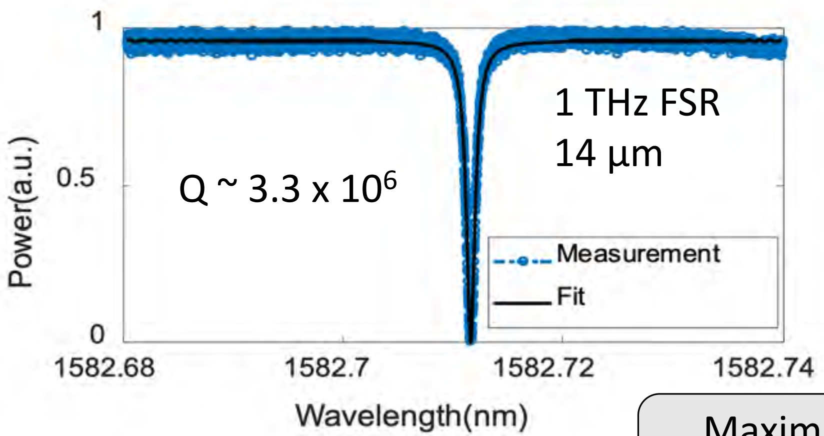
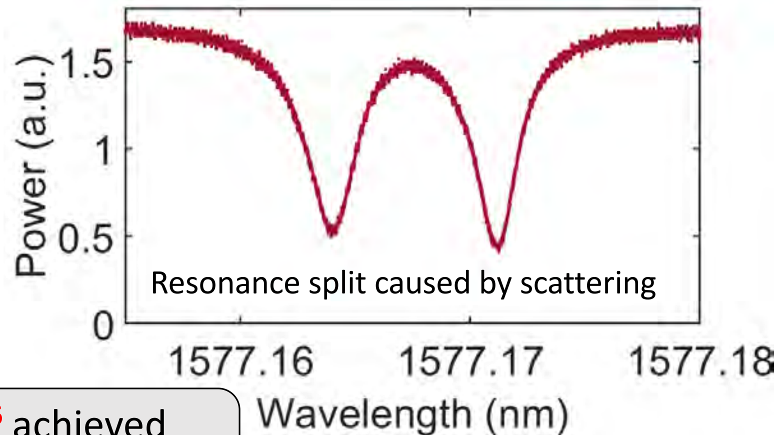
Comb Generation (Al)GaAs on insulator platform

(Al)GaAs on insulator platform

- High index contrast: footprint, power intensity, geometry tailoring
- Low loss
- Integration compatible and scalable







Maximum Q > **3×10^6** achieved
Propagation loss < **0.2 dB/cm**

E. Stanton, L. Chang…J. Bowers, R. Mirin, APL Photonics (2020)
W. Xie, L. Chang, H. Shu…X. Wang, J. Bowers *et al. Opt. Express.* (2020)
L. Chang, W. Xie, H. Shu… X. Wang, K. Vahala, J. Bowers, *Nat. Com.* (2020)

Key: Passivation to reduce edge absorption
Low oval defect density, Scaling to 3”

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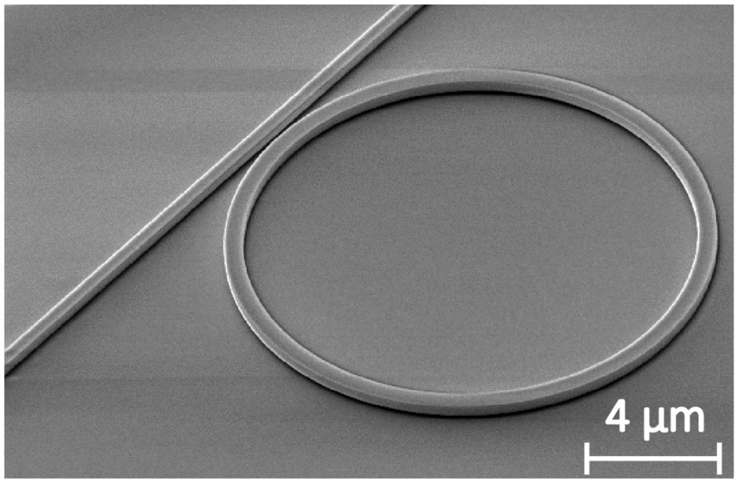
Ultra-low threshold Kerr comb generation

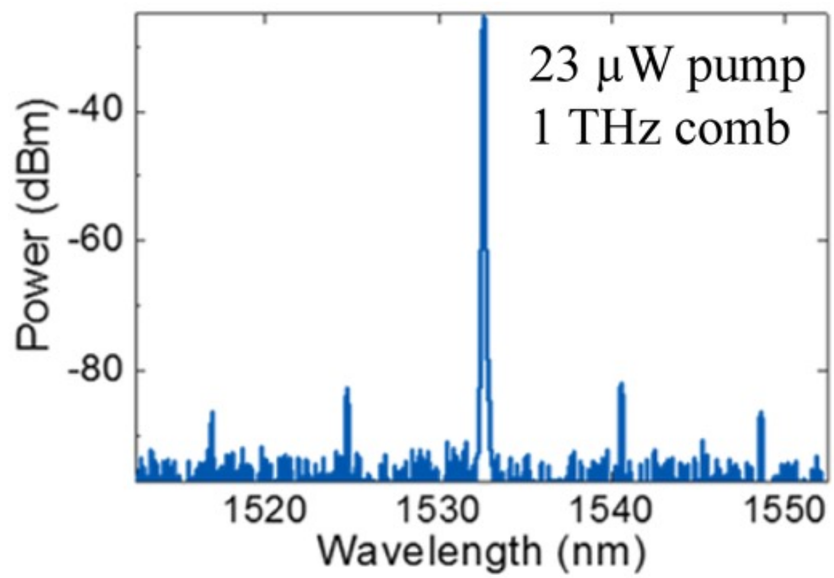


$$P_{th} \approx 1.54(\frac{\pi}{2})\frac{1}{\eta}\frac{n}{n_2}\frac{\omega}{D_1}\frac{A}{Q_T^2}$$

Si_3N_4: n_2=**2.5 × 10^{-15}** cm^2/W, A ~ **1.5** μm^2
(Al)GaAsOI: n_2=**2.6 × 10^{-13}** cm^2/W, A ~ **0.25** μm^2
AlGaAsOI reduces the Power by **20** times!

~20 μW threshold for 1 THz comb

- **100** times lower than previous III-V semiconductor platforms
- **10** times lower than state of the art dielectric platform



W. Xie, L. Chang, H. Shu…X. Wang, J. Bowers *et al. Opt. Express.* (2020)
L. Chang, W. Xie, H. Shu… X. Wang, K. Vahala, J. Bowers, *Nat. Com.* (2020)

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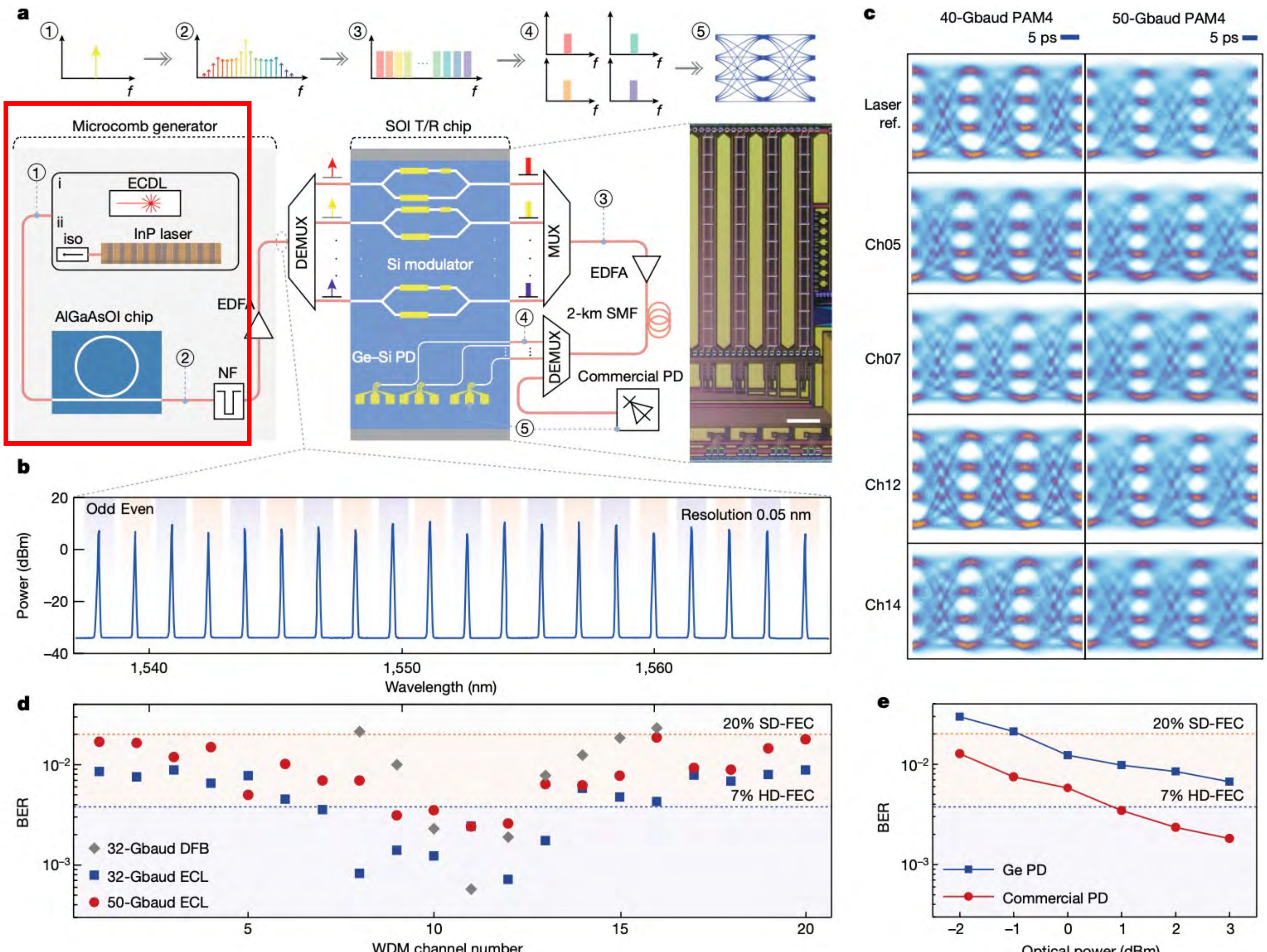
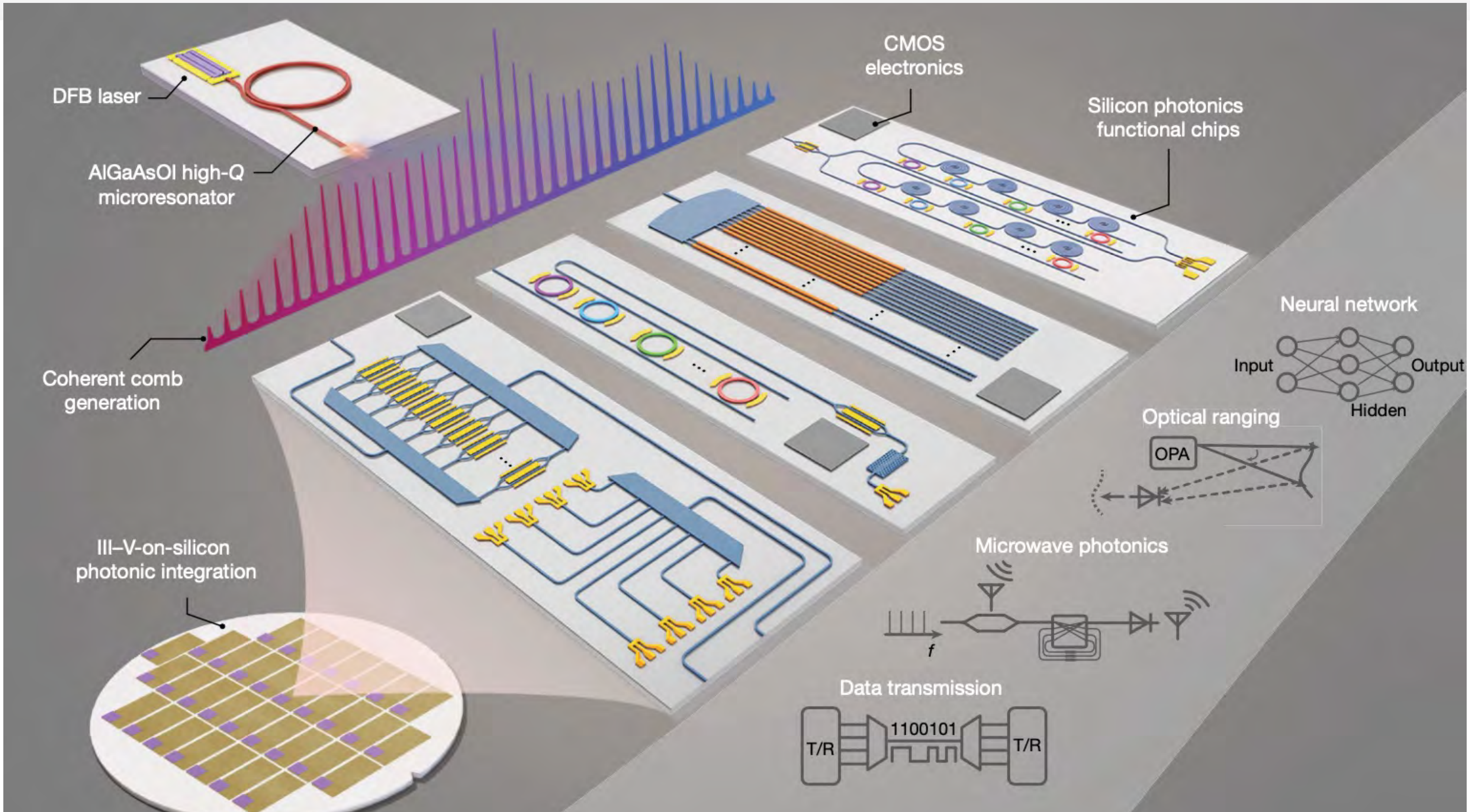
DWDM Comb Experiment

- 2 Tbps
- 20 wavelengths
- PAM-4
- 50 Gbaud



UCSB H. Shu et al., “Microcomb-driven silicon photonic systems” Nature (2022)

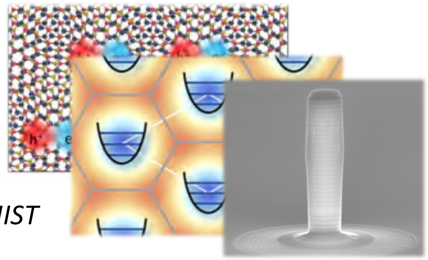
Major Applications of Comb Sources



H. Shu et al., "Microcomb-driven silicon photonic systems" Nature (2022)

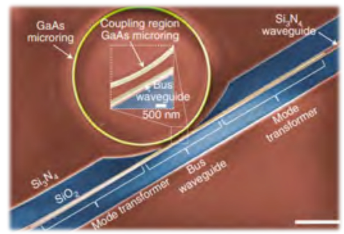
Si Quantum photonic integrated circuits

Quantum dots



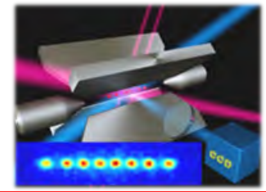
NIST

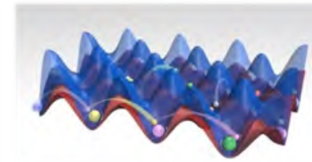
Nonlinear devices



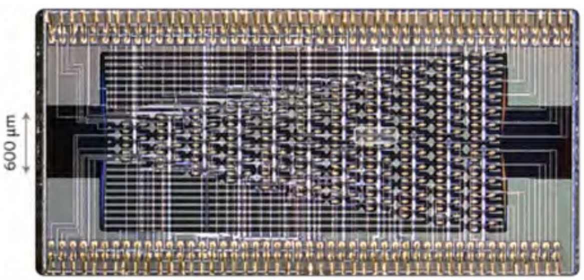
K. Balram, et al. Nat. Photonics 2016

Atoms/Ions

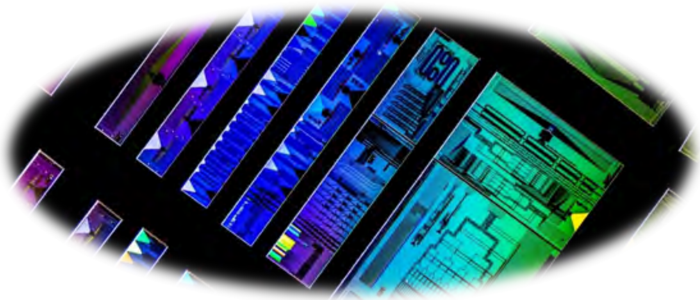




Computation

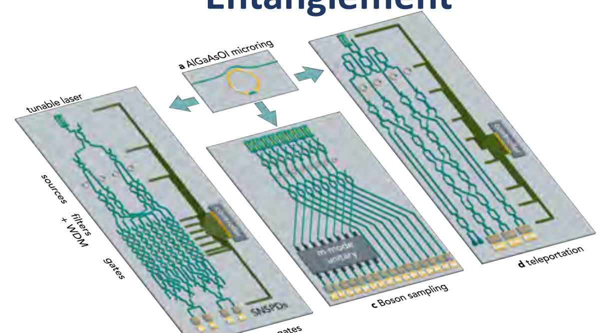


N. C. Narris, et al. Nat. Photonics 2017



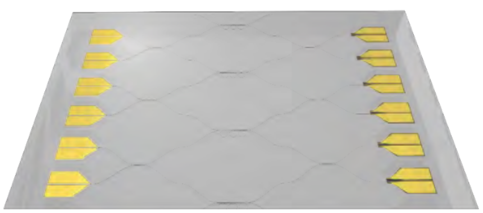
MIT Lincoln lab

Entanglement



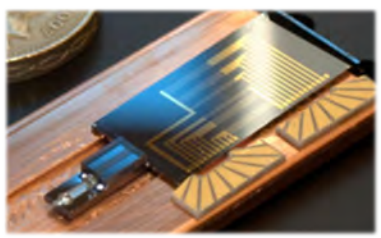
Moody, Bowers, AVS Quantum Science, 2020.
Steiner, Moody Bowers, Optica 2023

SNSPD



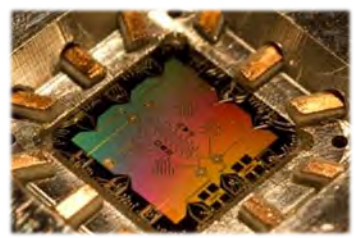
NIST 2018

Hybrid integration



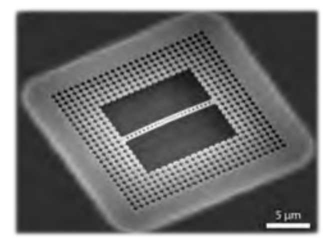
E. Murray, et al. Appl. Phys. Lett. 2015

Superconducting



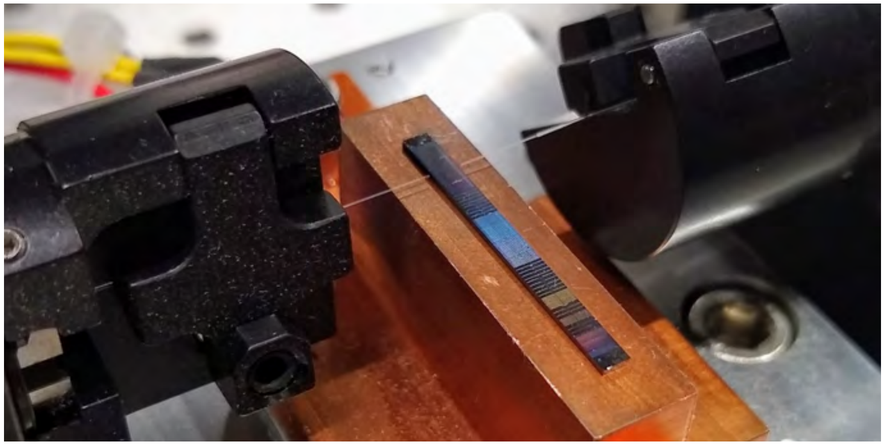
E. Lucero, UCSB

Acoustic

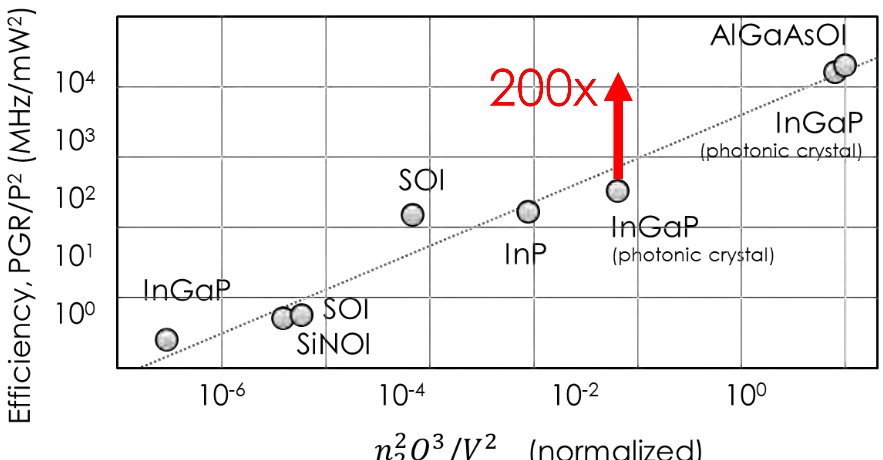


J. Chan, et al. Nature 2011

PHOTONIC QUANTUM COMPUTING: ULTRA EFFICIENT

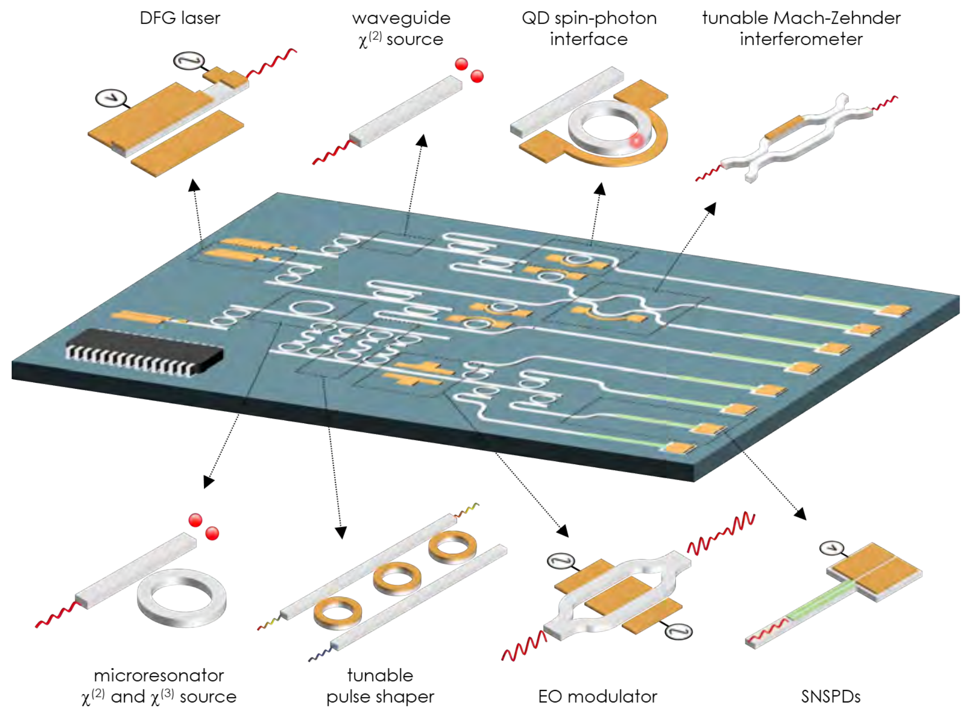


PRX Quantum **2**, 010337 (2021)



Efficient photonic circuits, lasers, quantum sources, and detectors are key enabling technologies for future computers, networks, and communications

Galan Moody
John Bowers



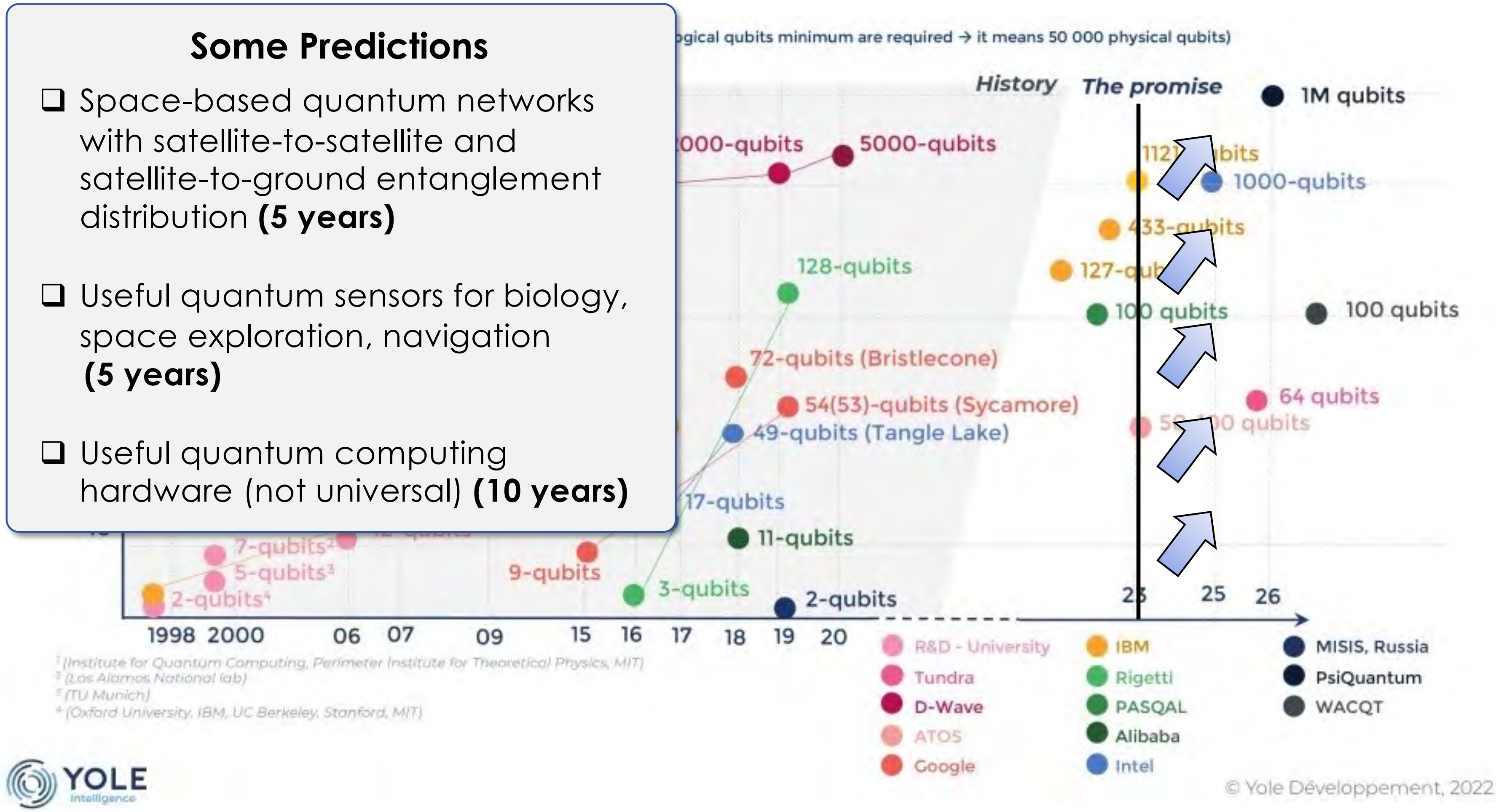
Moody, Bowers, AVS Quantum Science, 2020. Optica **10**, 917 (2023)

Looking Forward at the Next 5 to 10 Years

Moody

Some Predictions

- ❑ Space-based quantum networks with satellite-to-satellite and satellite-to-ground entanglement distribution **(5 years)**
- ❑ Useful quantum sensors for biology, space exploration, navigation **(5 years)**
- ❑ Useful quantum computing hardware (not universal) **(10 years)**



Photonic navigation

Incoherent

- Mode-locked laser
- Pulsed high-power laser
- Fast photodetector

Coherent

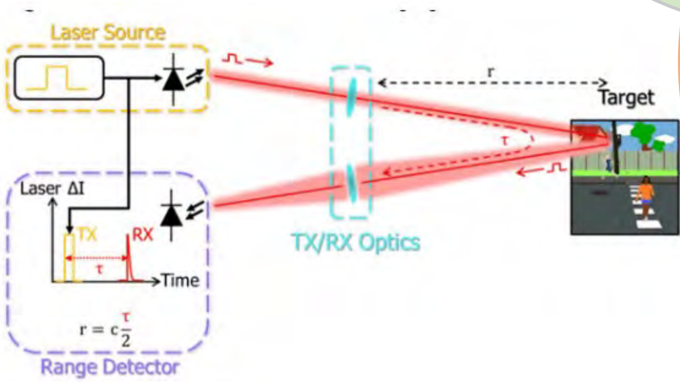
- Frequency-chirp DFB lasers
- Tunable lasers
- Narrow-linewidth lasers

LIDAR

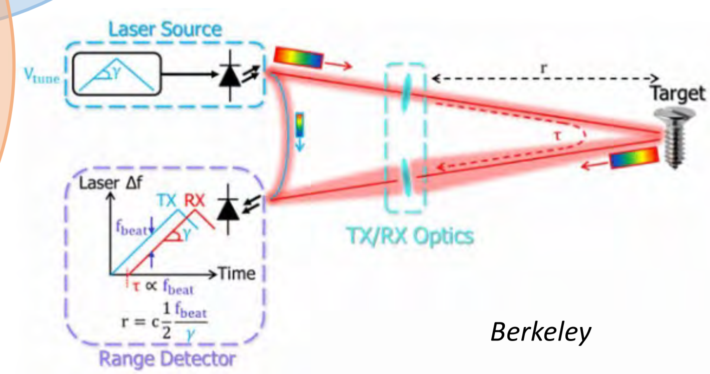
Others

- Optical parametric oscillator
- Rayleigh/Raman scattering
- Absorption spectroscopy

TOF LIDAR

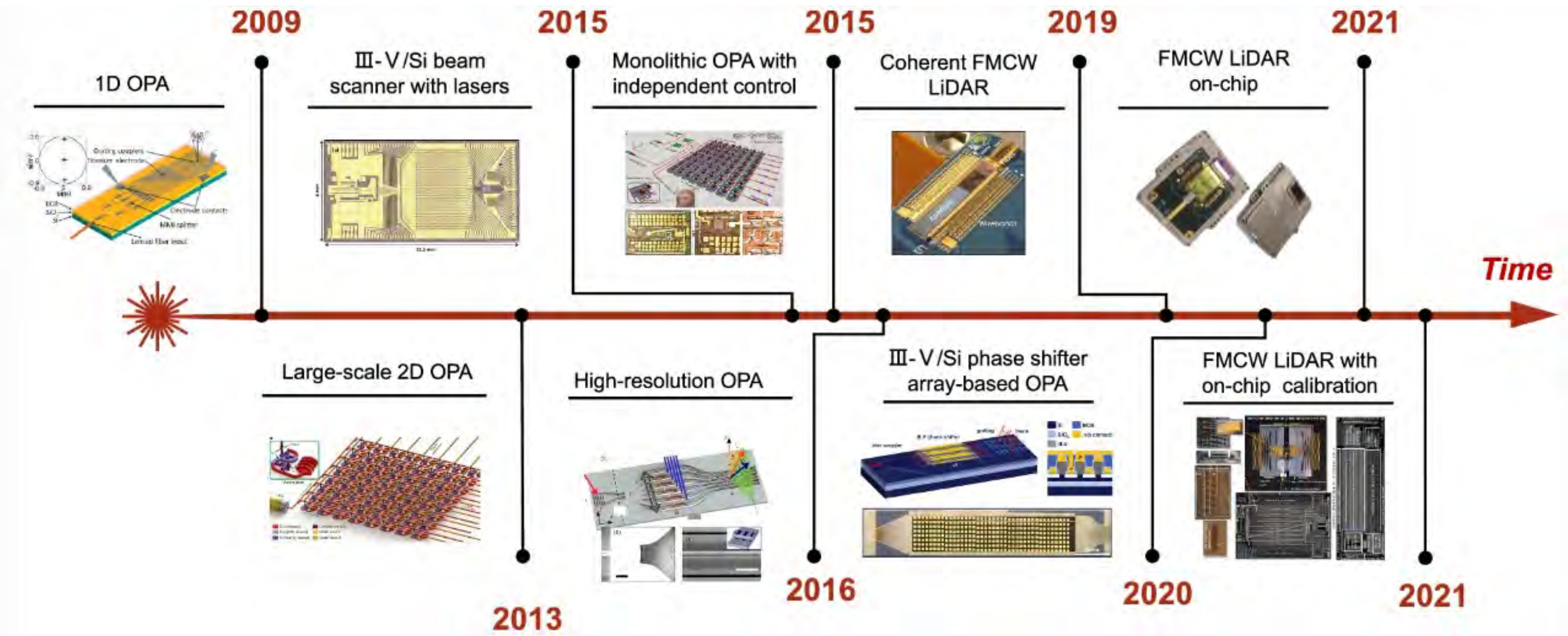


FMCW LIDAR



Berkeley

Silicon LIDAR

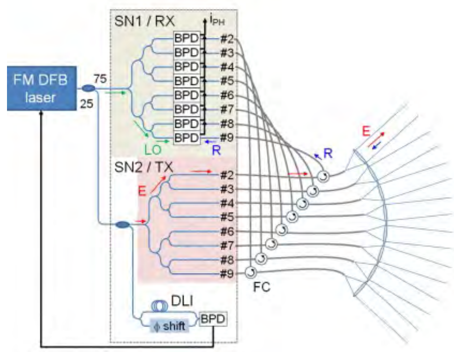


Zhou et al, eLight 2023

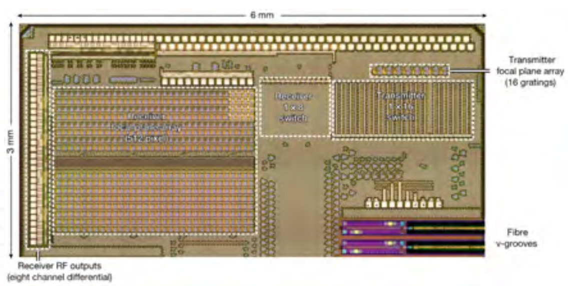
UCSB

On-chip coherent LIDAR system

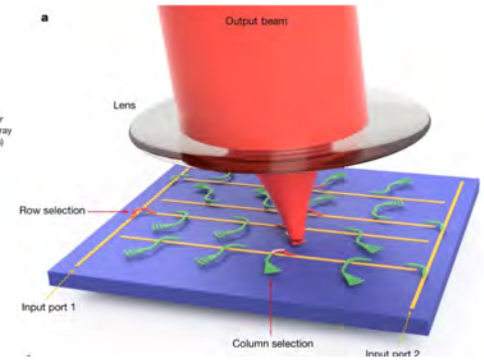
R & D



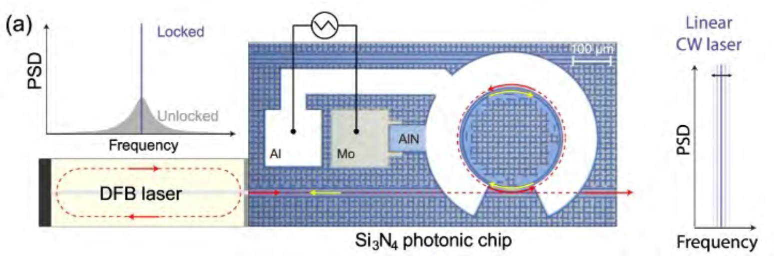
Thales, Tyndall, IMEC 2018



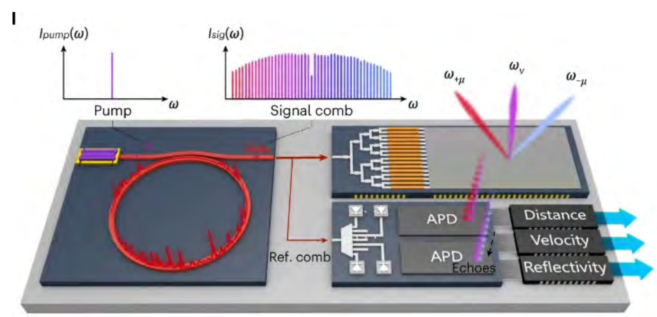
Pointcloud, Southampton 2021



Berkley 2022



EPFL 2022



PKU, UCSB 2023

Commercialized

ANALOG PHOTONICS

LUMOTIVE

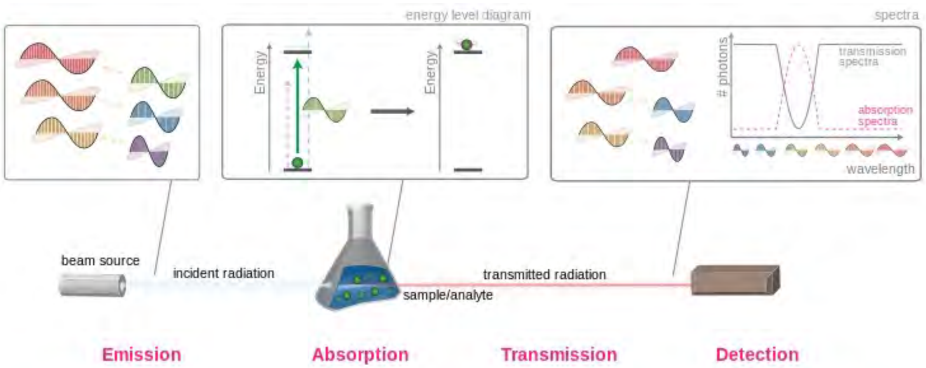
SOS LAB

TRILUMINA
Advancing Illumination to Sense Your World

Baraja

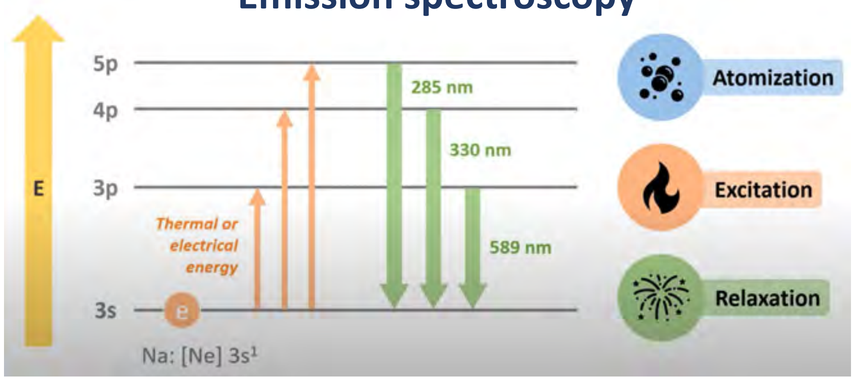
Photonic sensing technologies

Absorption spectroscopy



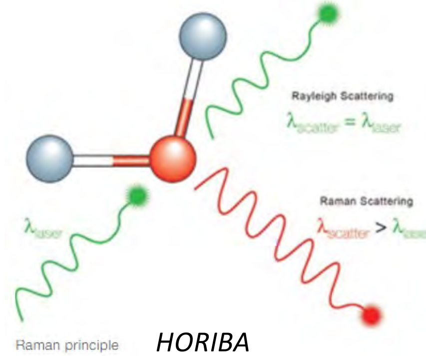
wiki

Emission spectroscopy



Youtube, Francis Chong

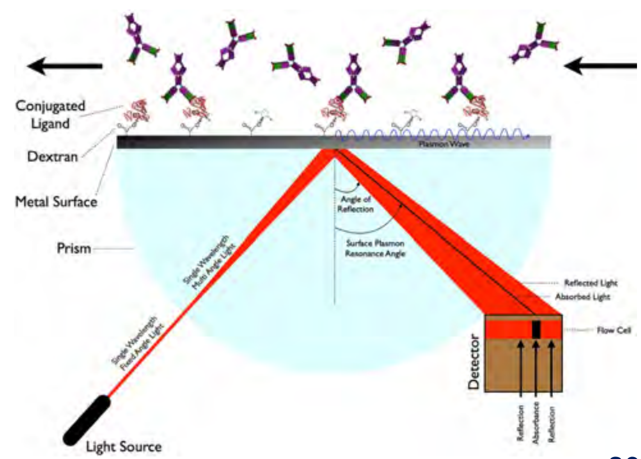
Raman spectroscopy



HORIBA

Key: Tunable laser

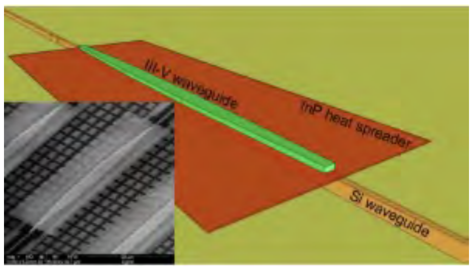
Surface plasmon resonance



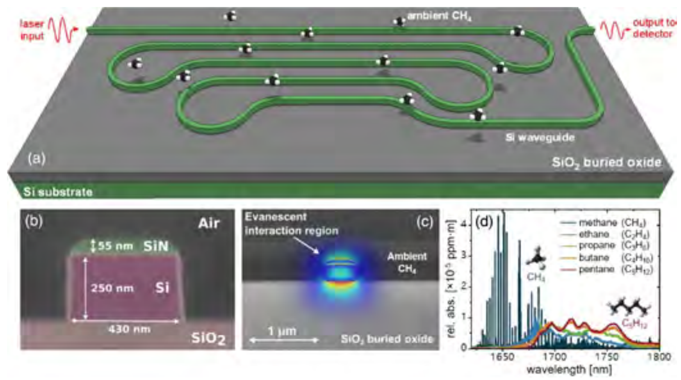
wiki

Silicon photonic sensors

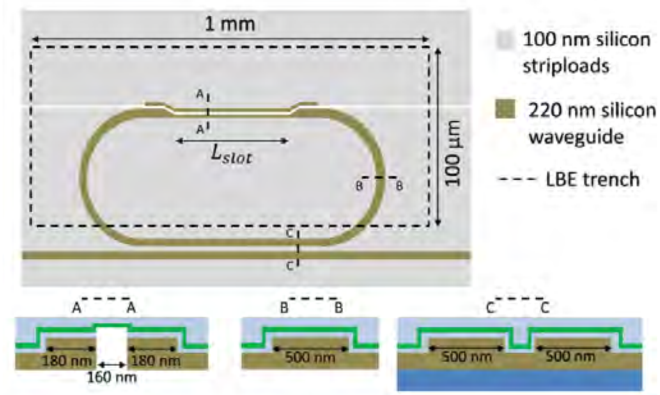
R & D



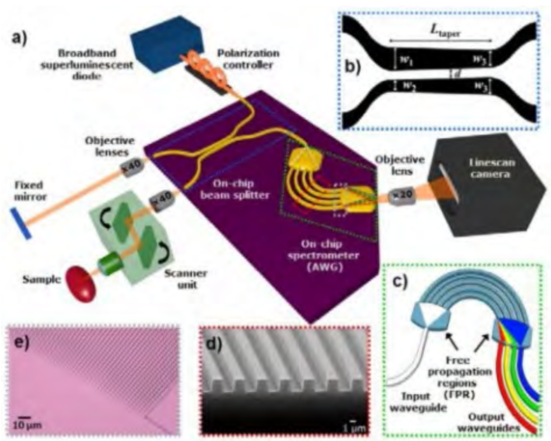
Ghent 2015



IBM 2017



IHP 2020



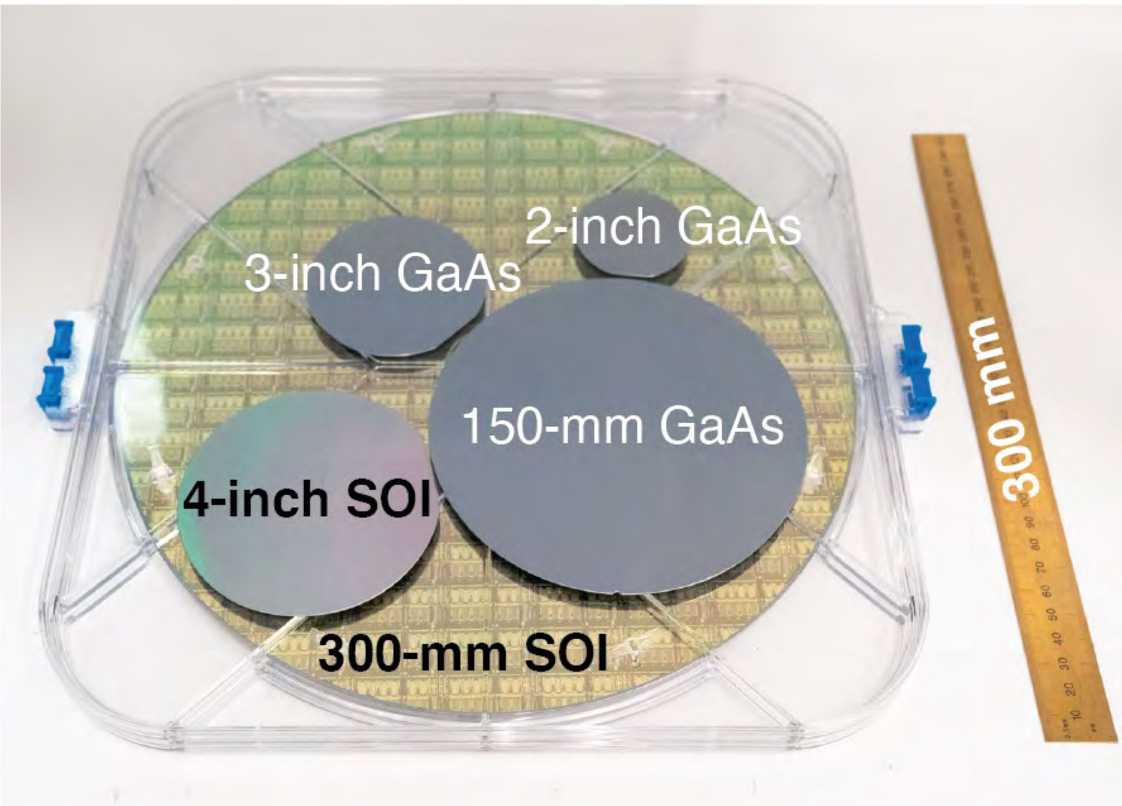
MIT 2017

Commercialized

Genalyte

SiPhox

300 mm Silicon Photonics

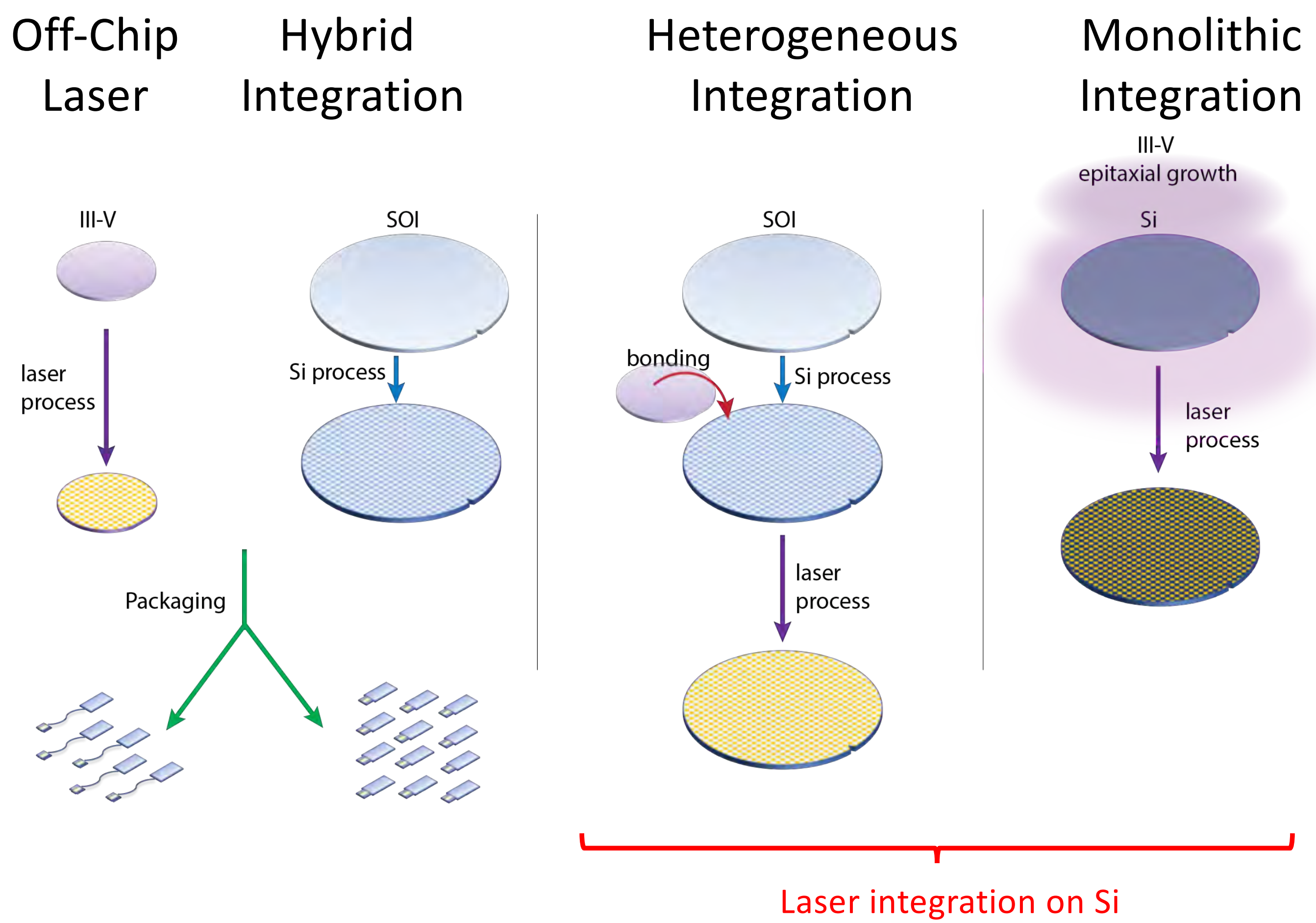


- Lower loss waveguides
- Cheap substrates
- Rapid scaling to high volume
- Most advanced CMOS processing
- Most advanced Packaging
- 3D EIC/PIC integration

UCSB

C. Xiang, et al., "High-Performance Silicon Photonics Using Heterogeneous Integration", *IEEE JSTQE,* 2022.

Advanced Silicon Photonics
How to Integrate Lasers with Modulators, Photodetectors, Passives?



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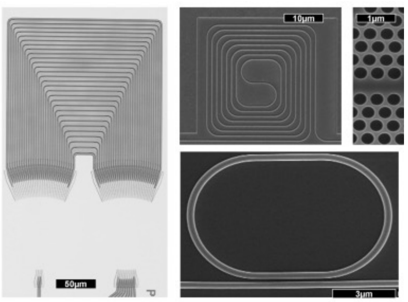
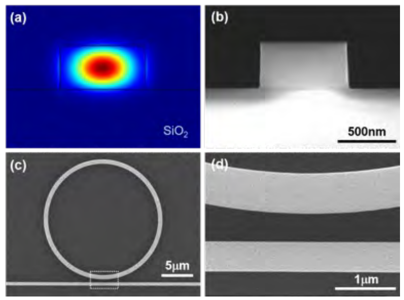
Heterogeneous Integration: Infrared to Visible

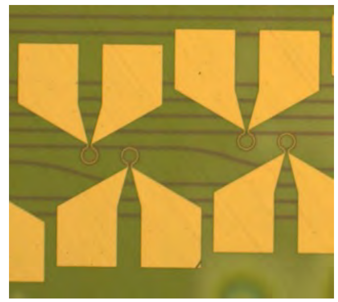
Passives:
Si, SiN/SiON/SiO_2



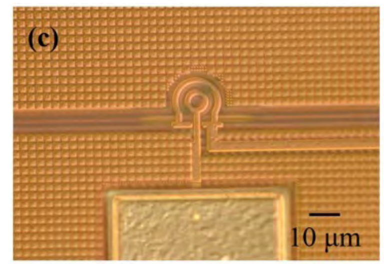
Nonlinear:
AlGaAsOI, $LiNbO_3$



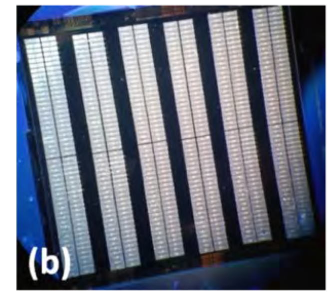
Isolator/Circulator:
Ce:YIG

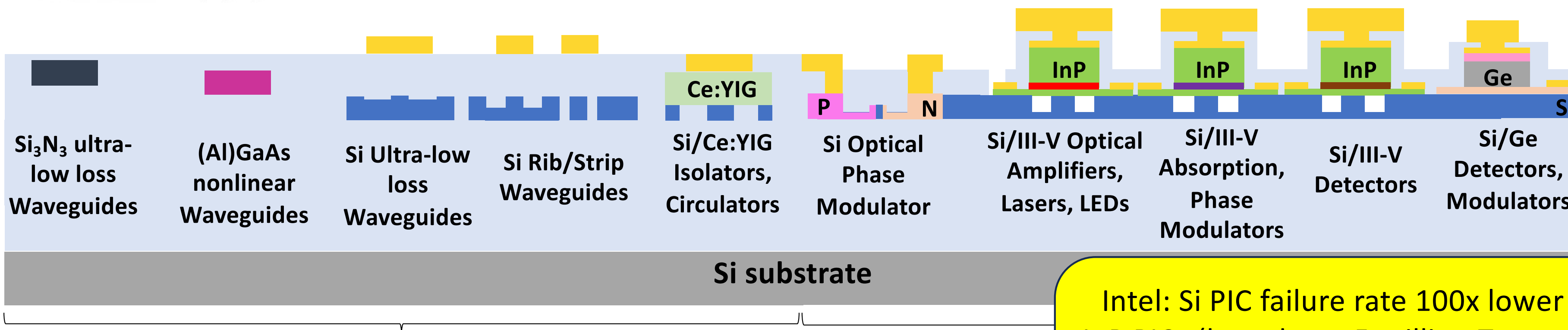


Actives:
Si, SiGe, InGaAsP



Gain:
GaN, GaAs, InP





Heterogeneous Passives

Hete

Intel: Si PIC failure rate 100x lower than InP PICs (based on >5 million Transceivers)

Why?

1) More integration is more reliable
2) No exposed III-V facets

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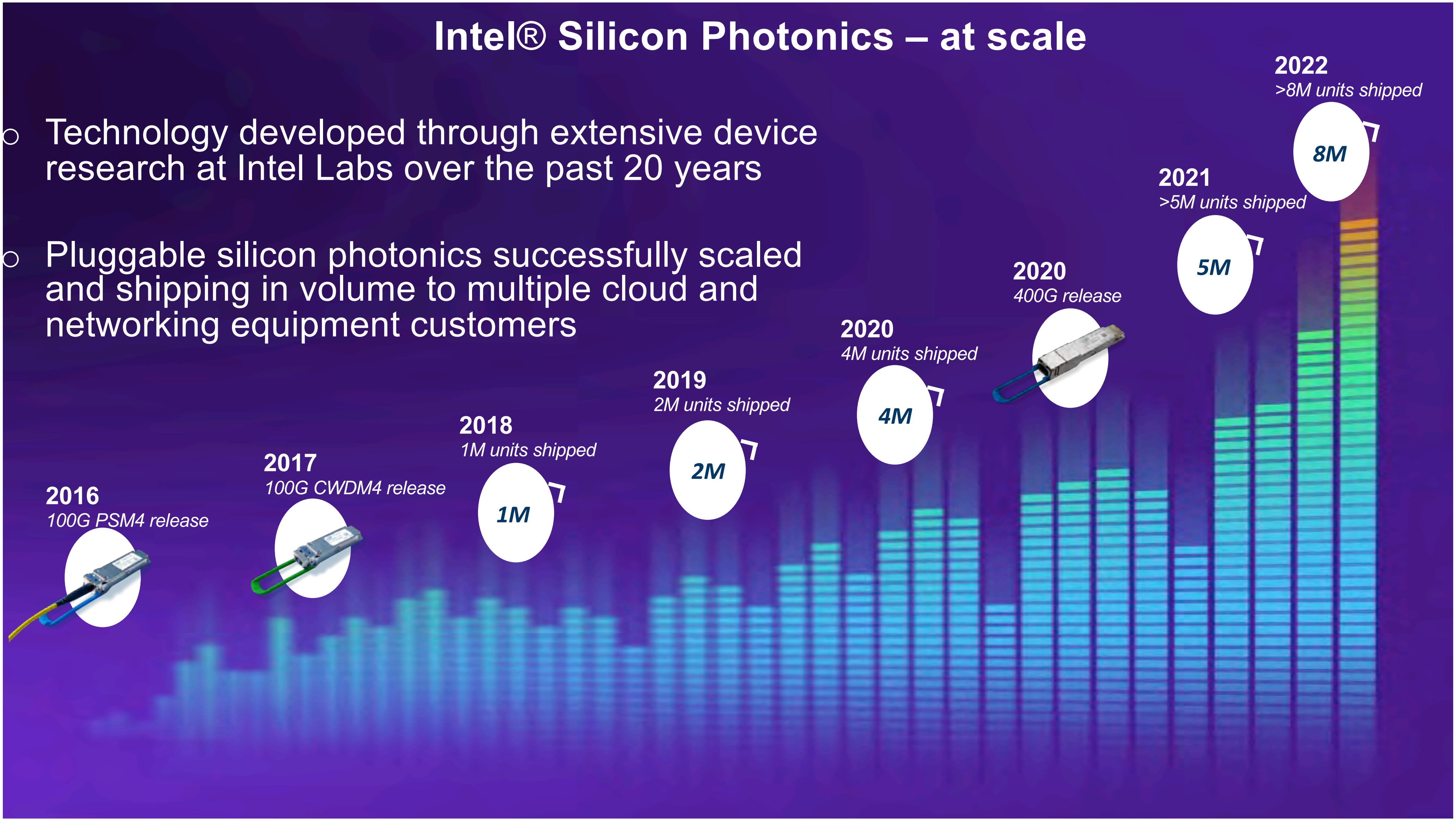
Komljenovic…Bowers, "Photonic Integrated Circuits Using Heterogeneous Integration on Silicon", *Proc.*

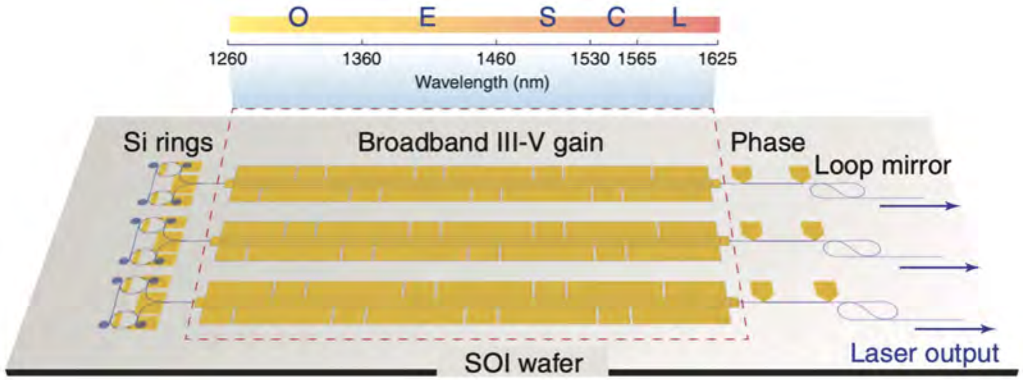
C. Xiang…Bowers, "High-Performance Silicon Photonics Using Heterogeneous Integration", *IEEE JSTQ*

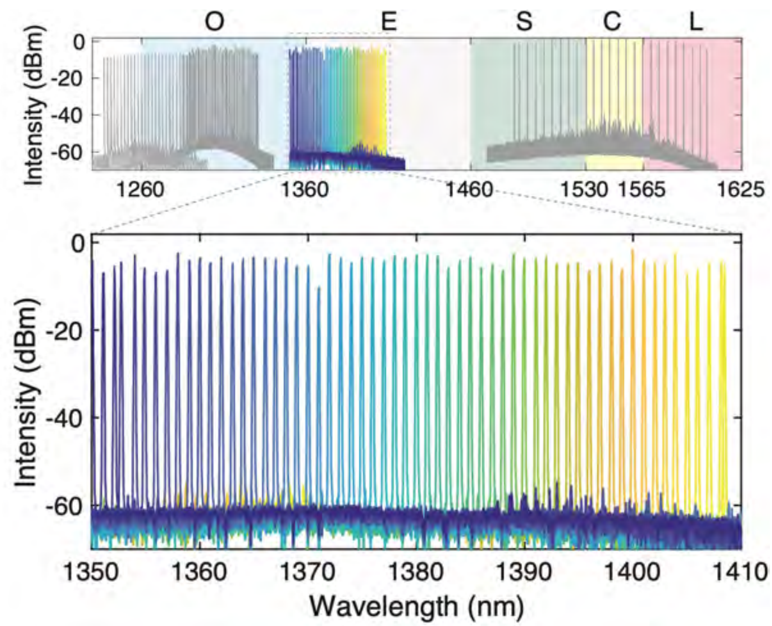


Intel® Silicon Photonics – at scale
Technology developed through extensive device research at Intel Labs over the past 20 years
Pluggable silicon photonics successfully scaled and shipping in volume to multiple cloud and networking equipment customers
2016
100G PSM4 release
2017
100G CWDM4 release
2018
1M units shipped
1M
2019
2M units shipped
2M
2020
4M units shipped
4M
2020
400G release
2021
>5M units shipped
5M
2022
>8M units shipped
8M

Heterogeneous Tunable Lasers Across O,E,S,C,L Bands

SOI (Si waveguides)



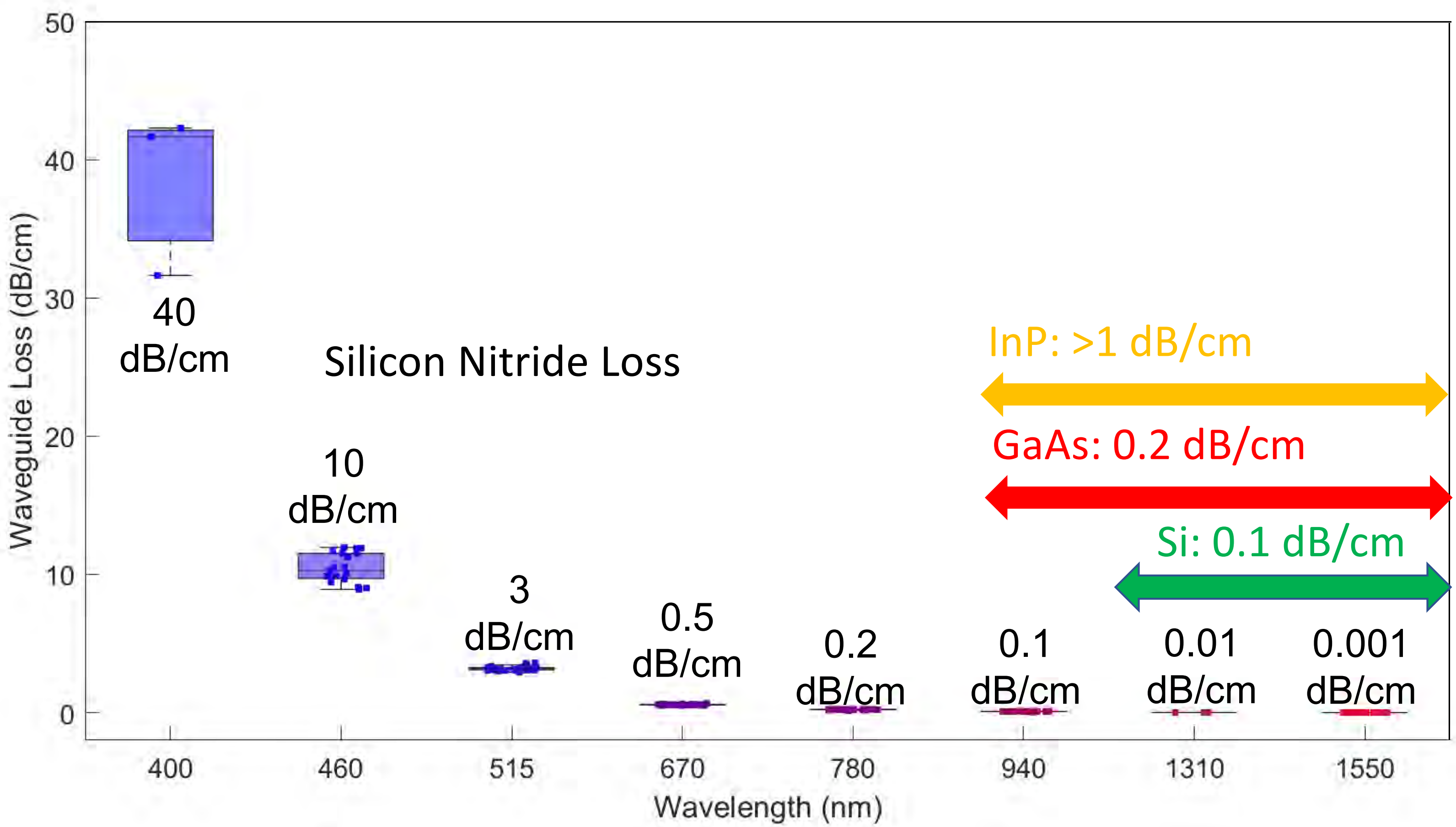


Wavelength by design across the entire low-loss fiber comm window on a single chip by bonding multiple different III-V gain material on low-loss Si waveguides

UCSB

Guo…Bowers., APL Photonics 8, 046114 (2023).

Waveguide? SOI (Si) or CSOI (GaAs) or Silicon nitride?



Courtesy: M. Tran, Nexus

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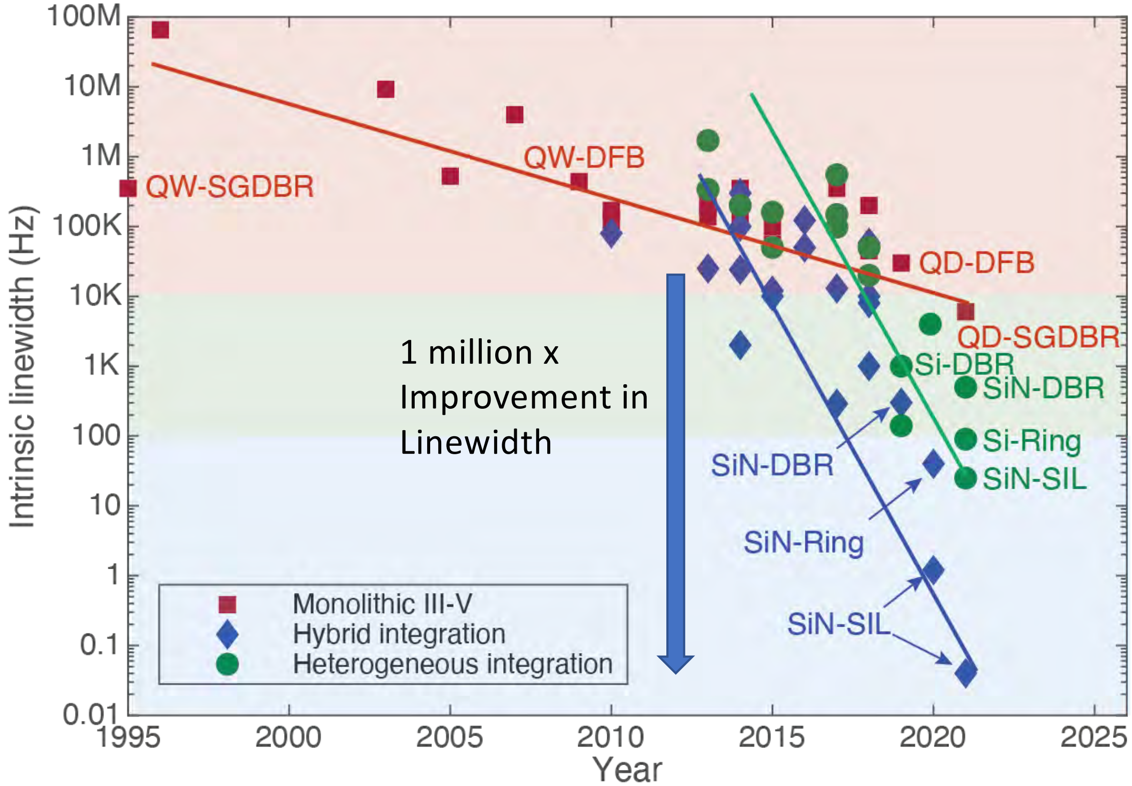
Narrow Linewidth Lasers

Spectral Linewidth of Integrated Semiconductor Lasers

We used to try to make Lasers on Si as good as native substrates
Now, they are better than native substrate lasers



$$\Delta\nu_0 = \frac{q\omega^2 n_{sp}}{2Q^2\left(I - I_{th}\right)}\left(1+\alpha^2\right)$$

Si dominates narrow linewidth lasers because the loss of Si, SiO_2 and Si_3N_4 is so much lower than InP or GaAs waveguides.

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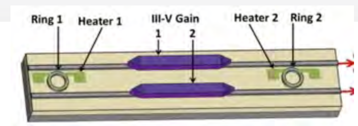
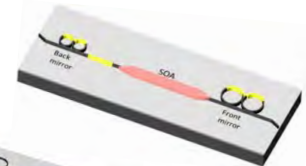
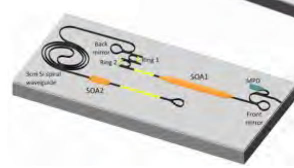
Margalit, Xiang, Bowers, Bjorlin, Blum, and Bowers, “Perspective on the Future of Silicon Photonics and Electronics”, Applied Physics Letters, (2021)

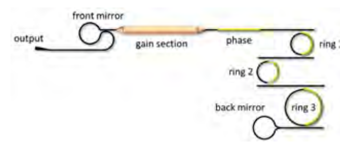
Current status of integrated narrow linewidth lasers

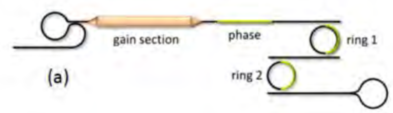
Year	Instantaneous Linewidth	Band	Si Loss
2013 J. Hulme et al.	348 kHz	C+L	6 dB/cm
2015 S. Srinivasan et al.	160 kHz	C+L	6 dB/cm
2015 Komljenovic et al.	50 kHz	O	2 dB/cm
2017 Komljenovic et al.	98 kHz	C+L	2 dB/cm
2017 L. Liang et al.	148 kHz	C+L	6 dB/cm
2018 **M. Tran et al.**	**2 kHz**	**C+L**	1 dB/cm
2019 **M. Tran et al.** **P. Morton et al.**	**120 Hz** **95 Hz**	**S+C+L** 120 nm	0.15 dB/cm

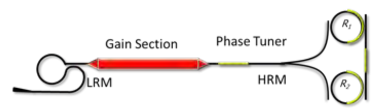


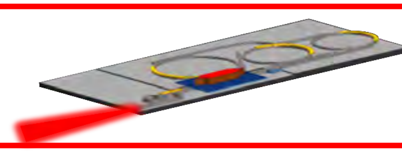












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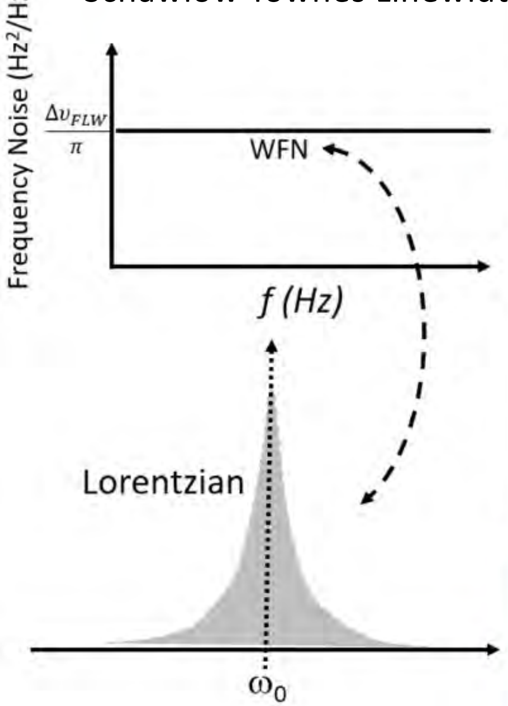
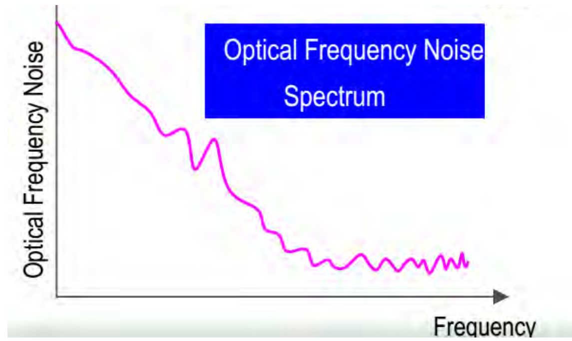
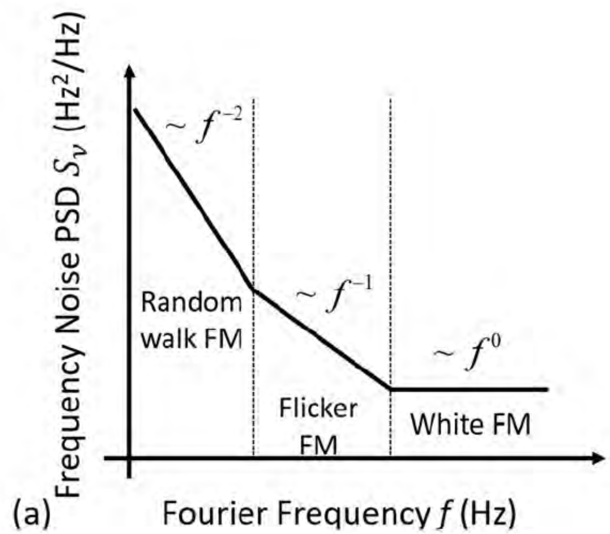
Laser Linewidth

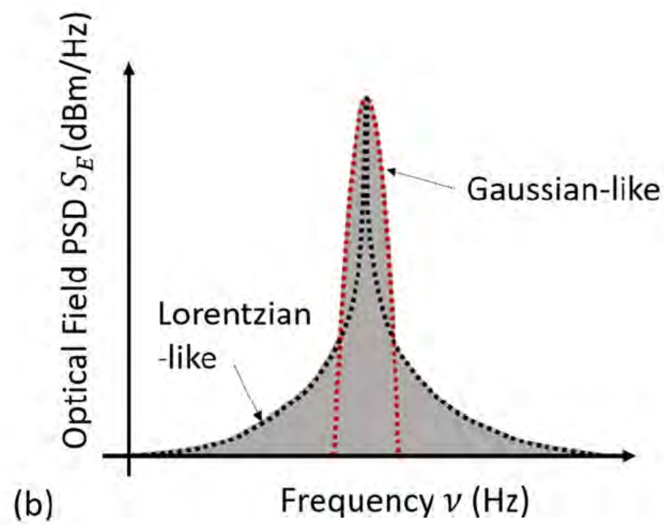
White Noise Floor:
- Lorentzian Linewidth
- Fundamental Linewidth
- Instantaneous Linewidth
- Schawlow Townes Linewidth





Low Frequency fluctuations due to
- Thermorefractive noise (TRN)
- Photothermal noise (PTN)
- Acoustic noise
- Current noise
- Temperature fluctuations





Tran, Huang, Bowers, "Tutorial: Si/III-V Heterogeneous Integration for Narrow Linewidth Semiconductor Lasers", APL Photonics 4, 111101 (2019)

Semiconductor Laser Linewidth and Reduction Strategies

Solitary Laser

Modified Schawlow Townes linewidth equation:

$$\Delta\nu_0 = \frac{q\omega^2 n_{sp}}{2Q^2\left(I - I_{th}\right)}\left(1+\alpha^2\right)$$

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

Extended Cavity Laser

$$\Delta\nu = \frac{\Delta\nu_0}{F^2}$$

$$F = 1 + A + B$$

$$A = -\frac{1}{\tau_{in}}\frac{d\varphi_{eff}(\omega)}{d\omega}$$

$$B = \frac{\alpha_H}{\tau_{in}}\frac{d}{d\omega}\left(\ln\left|r_{eff}(\omega)\right|\right)$$

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

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Vahala and Yariv, JQE, 1984 Kazarinov and Henry, JQE, 1987

Linewidth Reduction with Si/III-V Integration

Solitary Laser

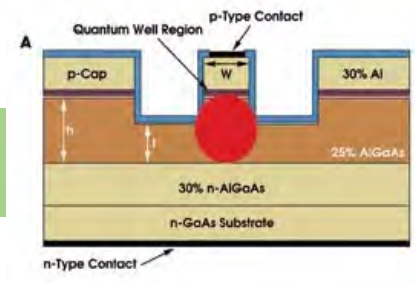
$$\Delta\nu_0 = \frac{q\omega^2 n_{sp}}{2Q^2\left(I - I_{th}\right)}\left(1+\alpha^2\right)$$

- Increase *Q*: $\frac{1}{Q} \rightarrow \frac{1}{Q_{in}}$
- Reduce I_{th}: $\left(I_{th} - I_{tr}\right) \sim \frac{1}{Q\Gamma_{qw}}$

➡ Ultimately limited by the internal loss

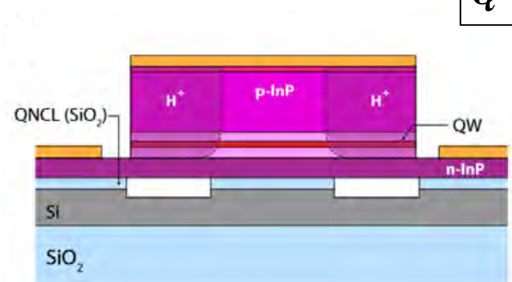
SCOWL

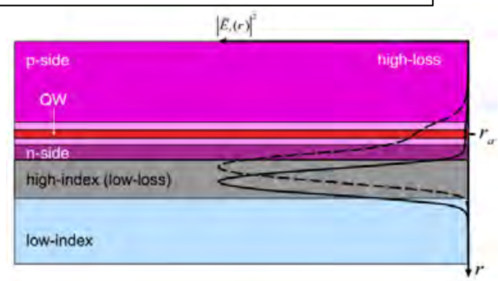
$\alpha_{\text{int}} = 0.5\ \text{cm}^{-1}$

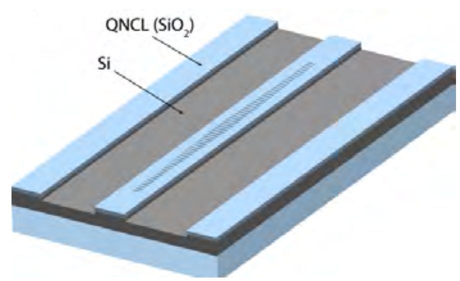


Si/III-V heterogeneous waveguide provides modal engineering capability to achieve lower loss cavity:

$$\frac{1}{Q} = \frac{1}{Q_{ext}} + \frac{1}{\Gamma_{Si} Q_{Si}} + \frac{1}{\Gamma_{III-V} Q_{III-V}}$$







✓ Undoped waveguides

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C. Santis and A. Yariv et al., PNAS (2014/2018) P.W. Juodawlkis et al, IEEE PTL (2015)

Linewidth Reduction with Si/III-V Integration

Extended Cavity Laser

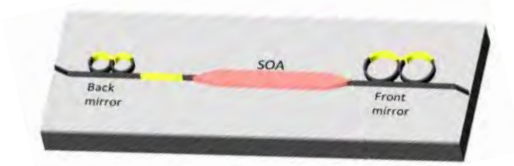
$$\Delta\nu = \frac{\Delta\nu_0}{F^2}$$

$$F = 1 + A + B$$

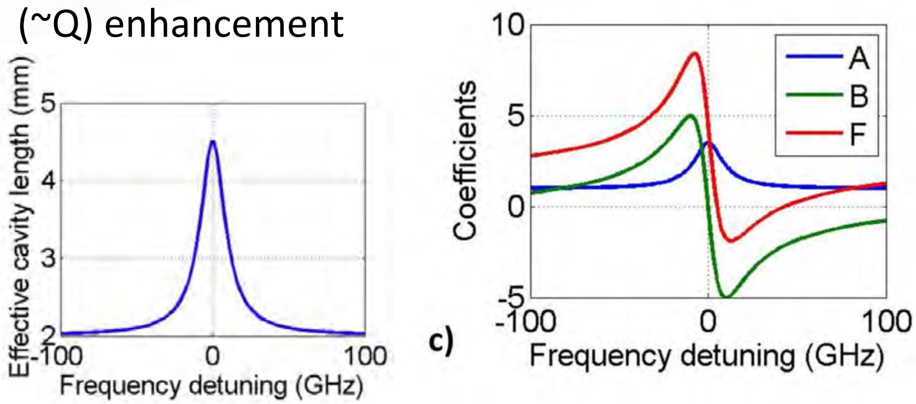
$$A = -\frac{1}{\tau_{in}}\frac{d\varphi_{eff}(\omega)}{d\omega}$$

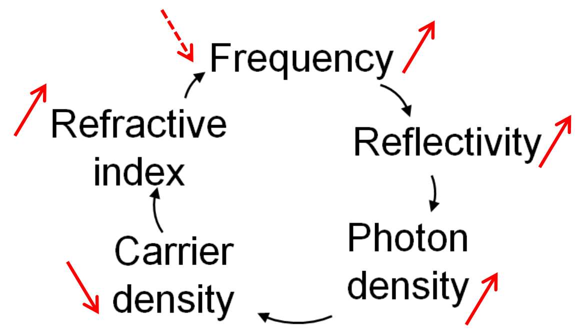
$$B = \frac{\alpha_H}{\tau_{in}}\frac{d}{d\omega}\left(\ln\left|r_{eff}(\omega)\right|\right)$$

Integrated Silicon Resonators Coupled Lasers

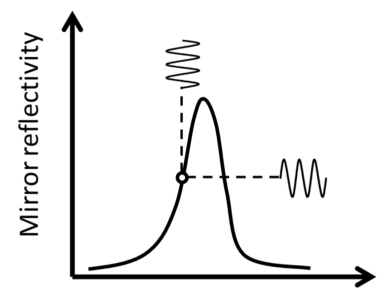


A. Resonance cavity length (~Q) enhancement





B. Negative optical feedback (detuned loading)



S. Srinivasan and J. Bowers, JLT (2015)
T. Komljenovic and J. Bowers, IEEE JQE (2015)

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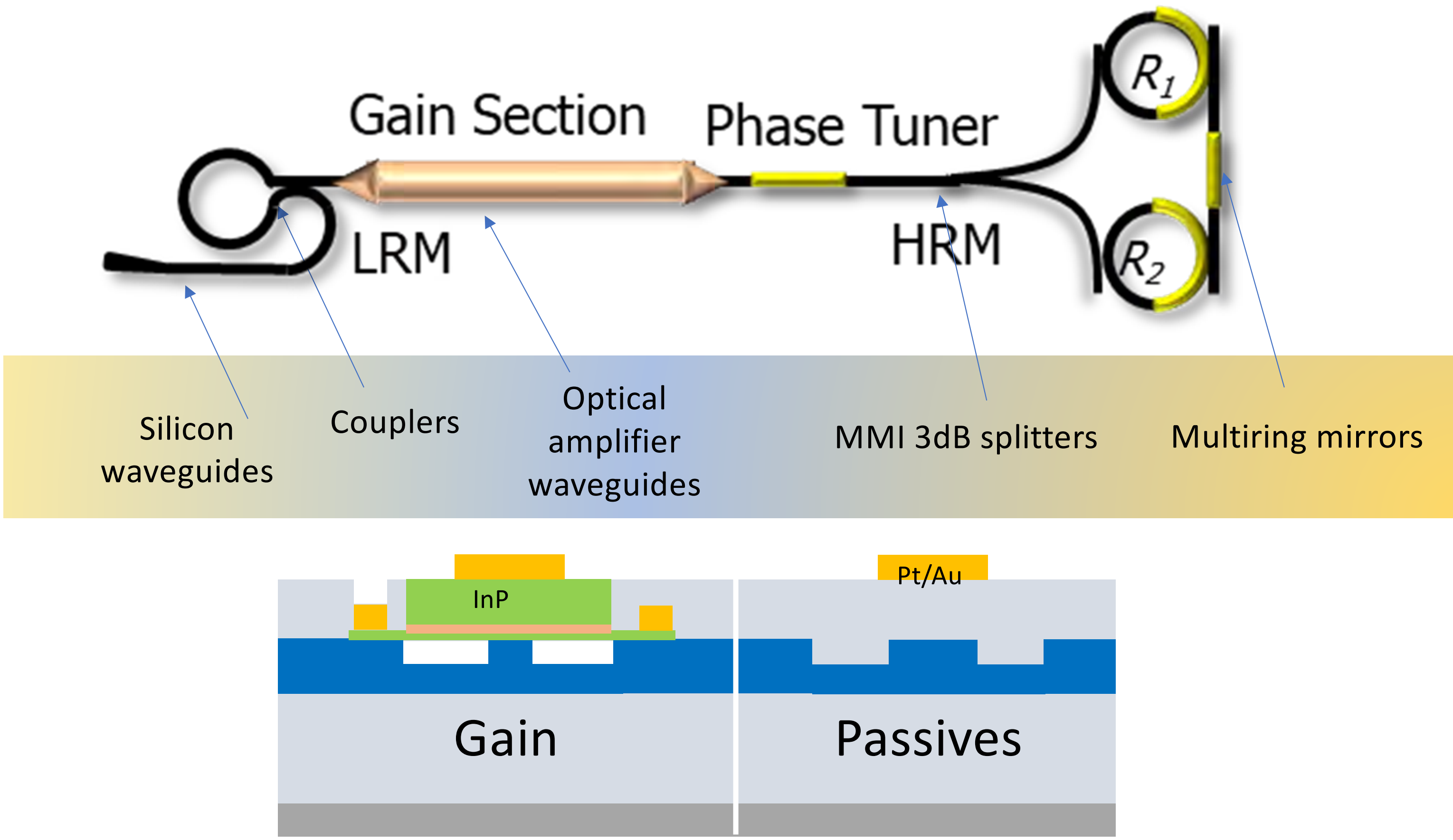
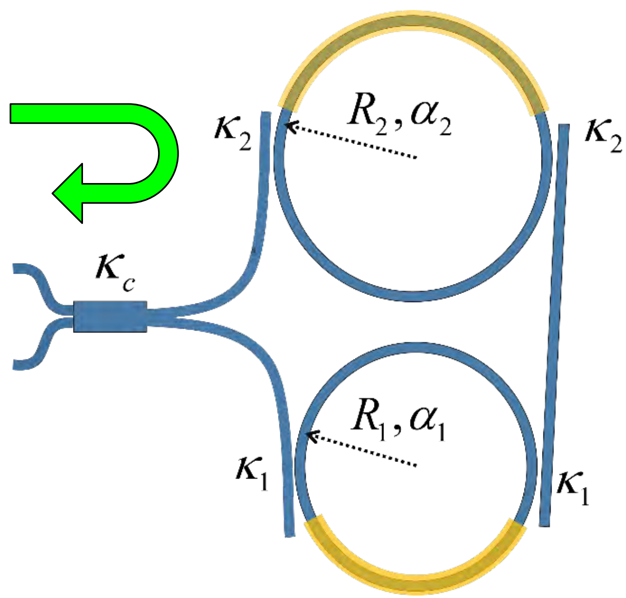
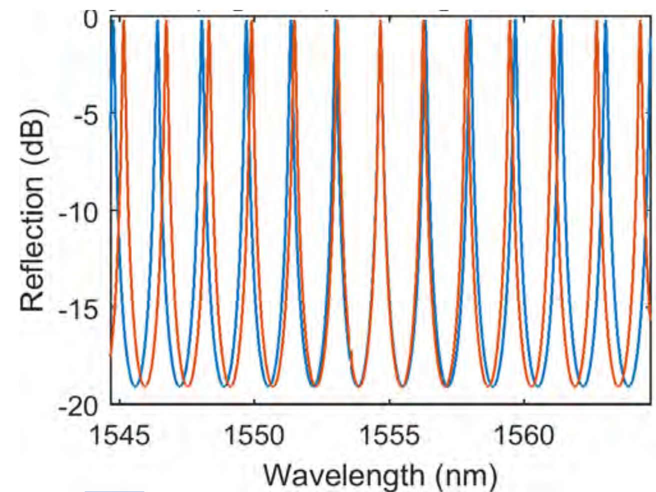
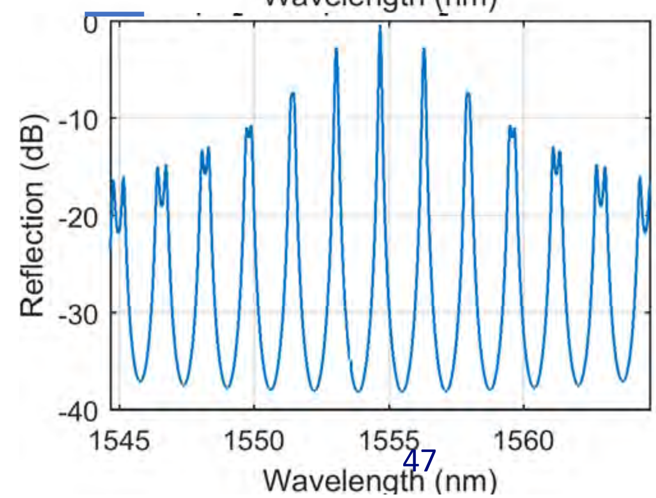
Laser Design – Double Ring Mirror Lasers



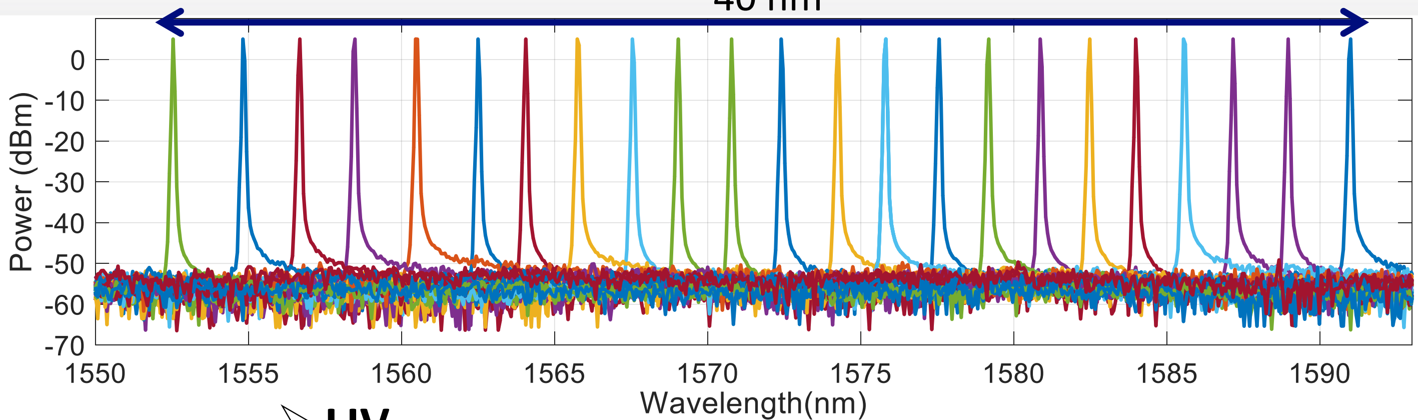
2-Ring Mirrors



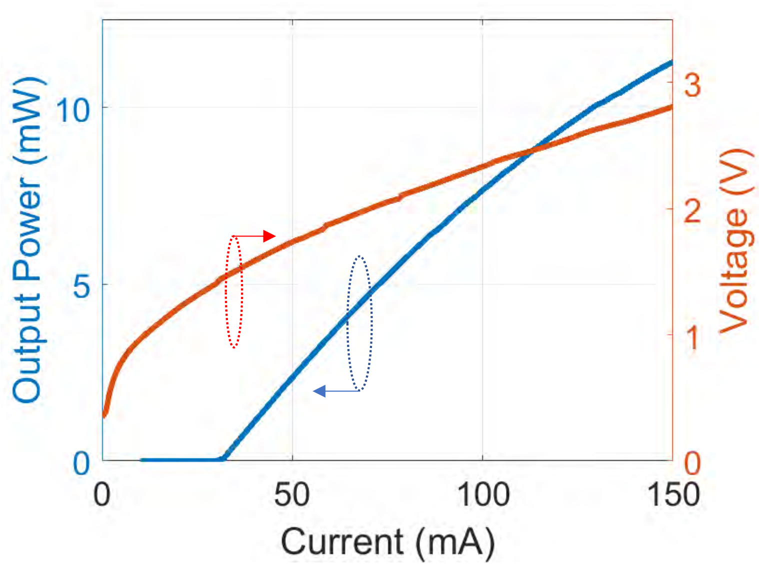




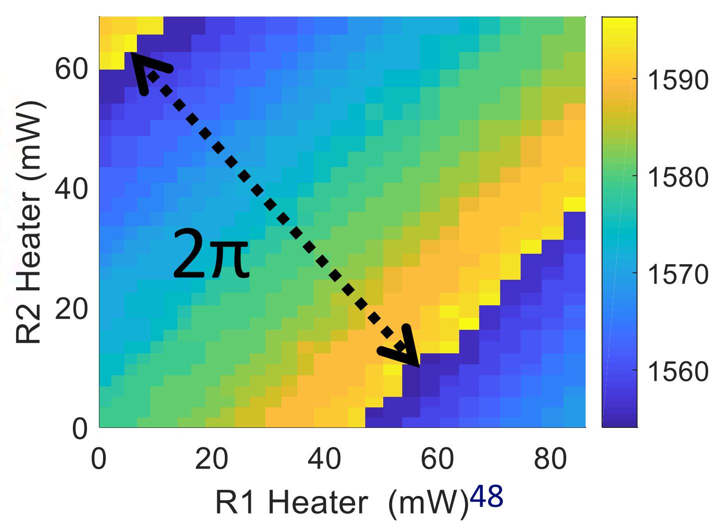
Laser Characterization



➢ **LIV**

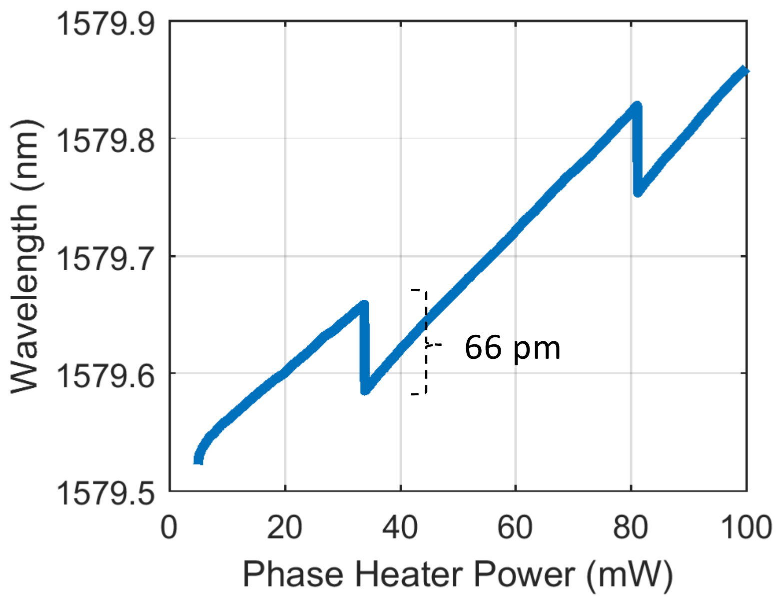


➢ **Wavelength Tuning Map**



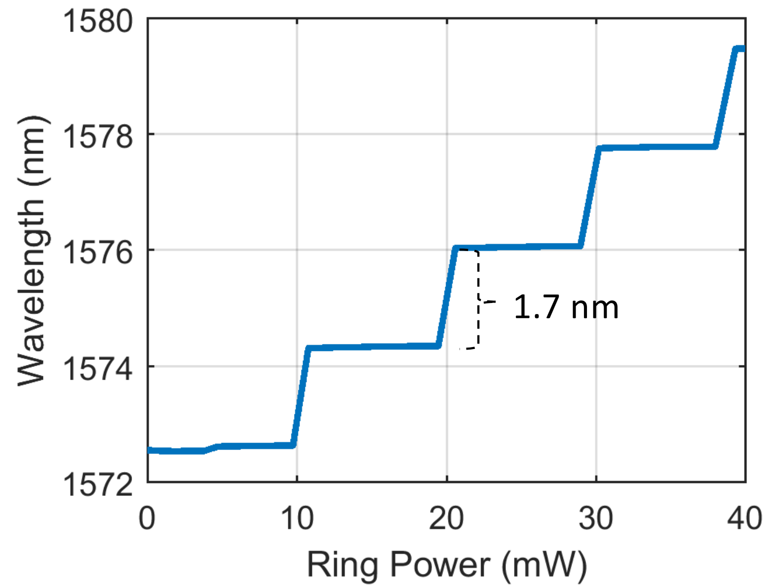
Mode Hopping

Cavity longitudinal mode hopping

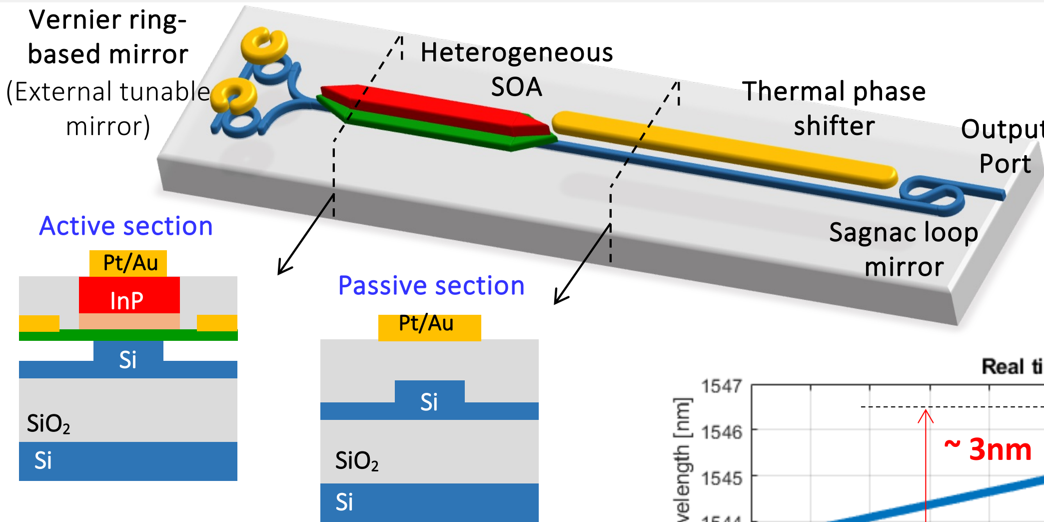


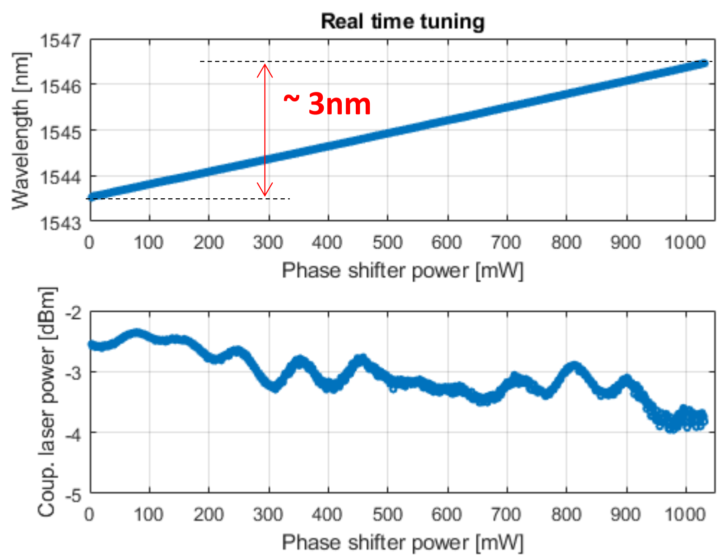
→ Cavity length ~4.7 mm

Ring mode hopping



3 nm (375 GHz) Mode-Hop-Free Tuning with a Narrow Linewidth Integrated InP/Si Laser





- Tuning over 375 GHz (3nm)
- Improving the heater efficiency will make the tuning range above 1.25 THz (10 nm)
- Resistant to vibrations and shocks
- Reduction of Size, Weight, Power, Cost (SWaP-C)
- Ideal for LiDAR and OFDR

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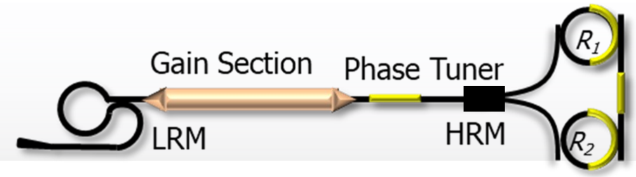
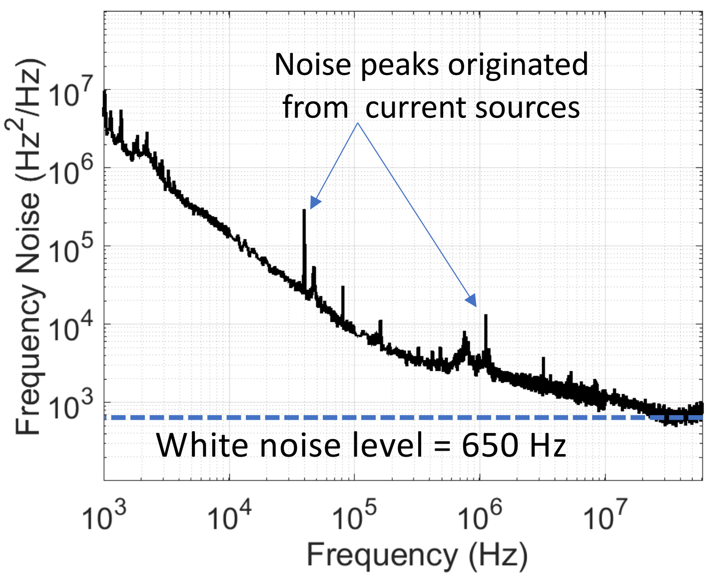
Paolo Pintus, Joel Guo, Warren Jin, Minh Tran, Jonathan Peters and John E. Bowers “Integrated mode-hop-free tunable heterogeneous laser” J. Lightwave Technology (2023) and CLEO 2022

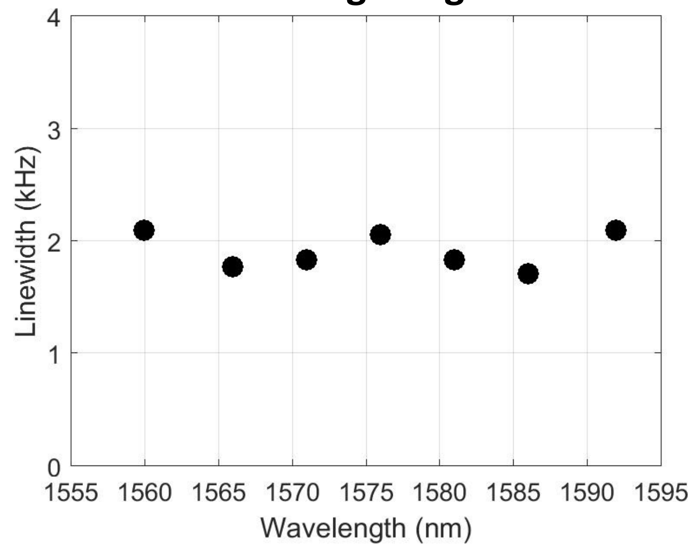
Frequency Noise and Lorentzian Linewidth



➢ **Frequency Noise Spectrum**



➢ **Lorentzian Linewidth across the Tuning Range**

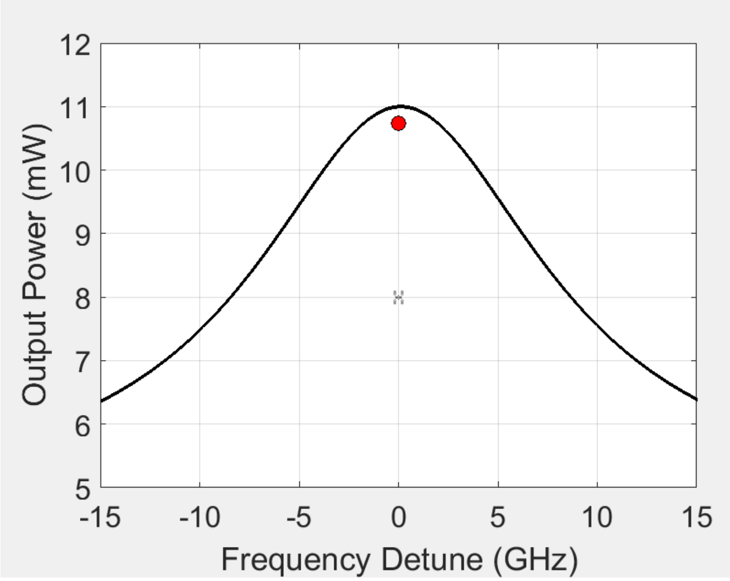


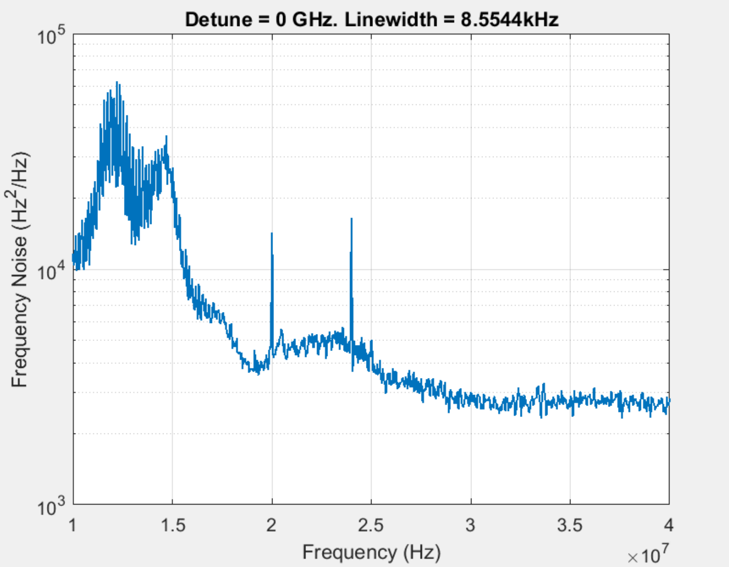
Fundamental linewidth = 2.1 kHz

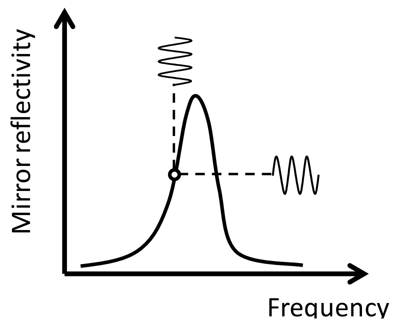
Linewidths < 2.5 kHz across the tuning range

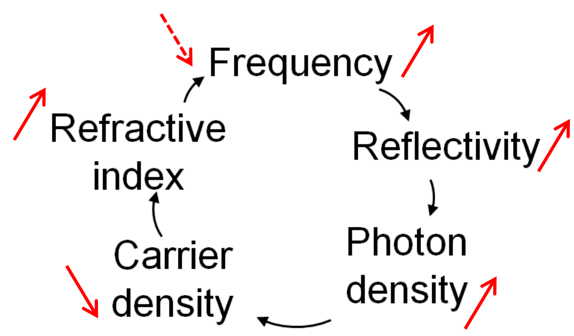
Direct Observation of Negative Optical Feedback Effect

- Narrowest linewidth is NOT at the maximum power output



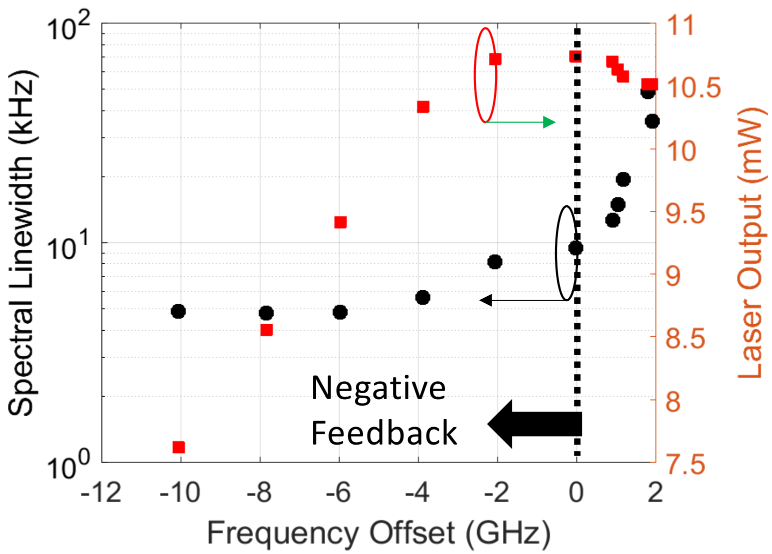






Direct Observation of Optical Negative Feedback Effect

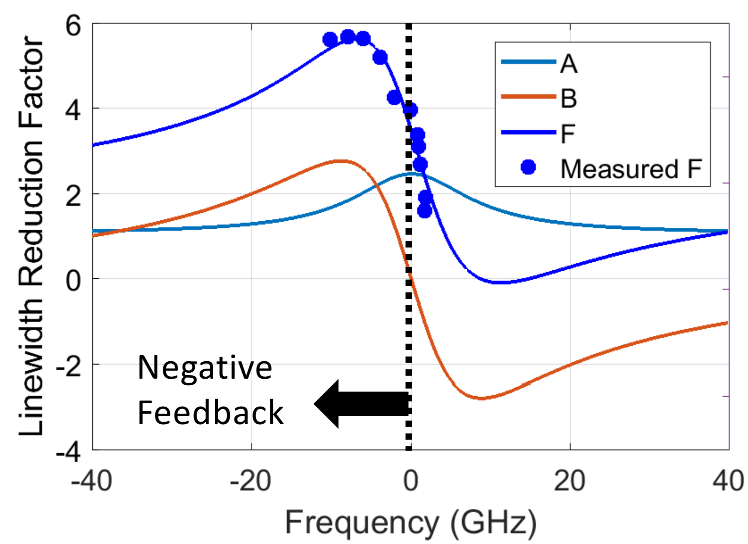
- Linewidth/power vs frequency detuning



$$\kappa_1 = \kappa_2 = 0.2;\ R_{front} = 0.5;\ P_0 = 15\ \text{mW}$$

$$\alpha = 1\ \text{dB/cm};\ \text{n}_{sp} = 1.5;\ \alpha_H = 4;\ \alpha_{\text{inermal}} = 6\ \text{cm}^{-1}$$

- Calculated/measured linewidth reduction factor



$$A = \frac{1}{\tau_{in}} \frac{d\phi(\omega)}{d\omega}$$

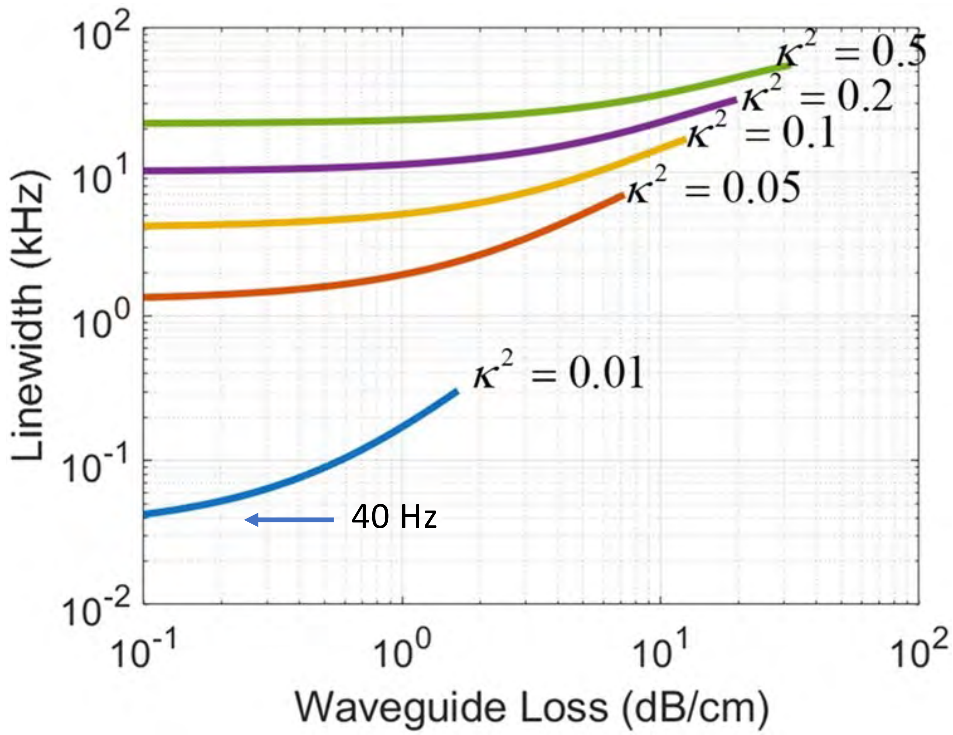
$$B = \frac{\alpha_H}{\tau_{in}} \frac{d}{d\omega} \ln\left(\left|r_{eff}(\omega)\right|\right)$$

$$F = 1 + A + B$$

$$\Delta\nu = \frac{\Delta\nu_0}{F^2}$$

Sub-kHz Linewidth Widely Tunable Lasers

Achievable Linewidths vs. Waveguide Loss

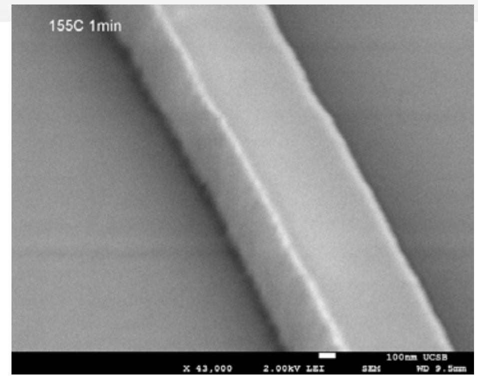


Need waveguides with lower propagation loss
→ How to achieve lower loss on Silicon?

Tran, Bowers et al., "Ultra-Low-Loss Silicon Waveguides for Heterogeneously Integrated Silicon/III-V Photonics", Appl. Sci. 2018, 8, 1139.

Origins of Optical Loss in Silicon Waveguides

- **Scattering (dominant source)**
  - Line-edge/sidewall roughness introduced during lithography and etching processes

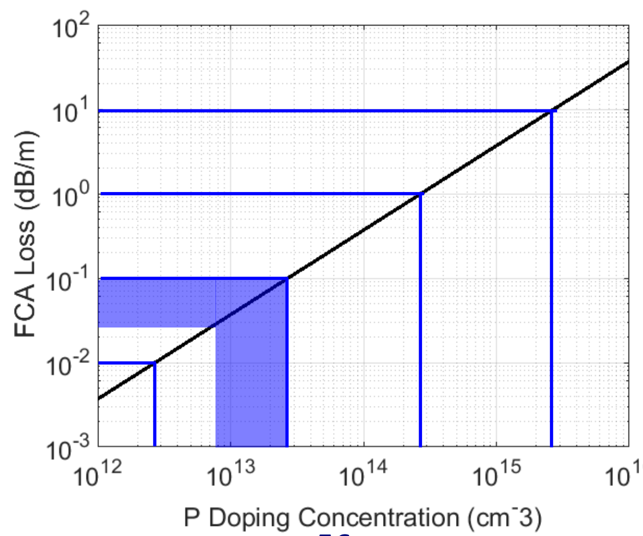


- **Bulk absorption:**
  - Free-carrier absorption

$$\Delta\alpha = 8.5\cdot 10^{-18}\,\Delta N + 6.0\cdot 10^{-18}\,\Delta P$$

- **Surface absorption:**
  - Surface defects, dangling bonds

  → Perfect in Silicon thanks to the long investment and research in the electronics industry



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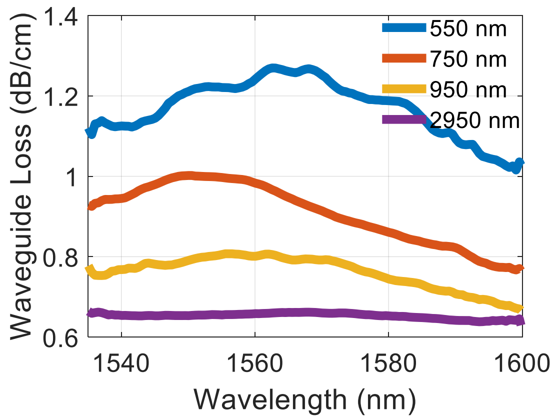
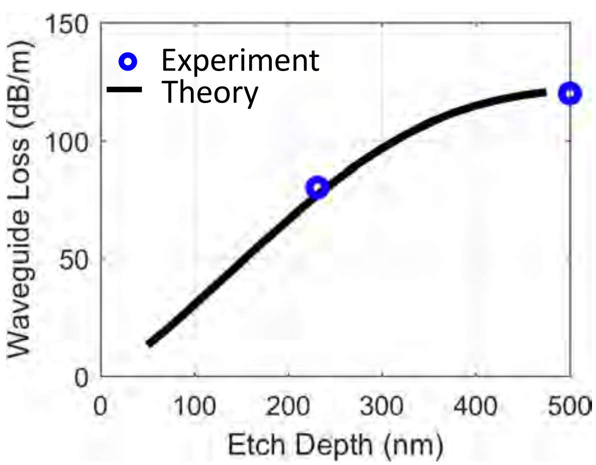
Waveguide Scattering Loss Modeling

Measured Data on 231 nm Etched WG



1 um width, two different etch depths



n_w model approximation

$$A(\sigma, L_c, n_{eff}) \cdot \left(\frac{\partial n_{eff}}{\partial w} + \frac{\partial n_{eff}}{\partial h} \right)$$

σ: sidewall roughness rms

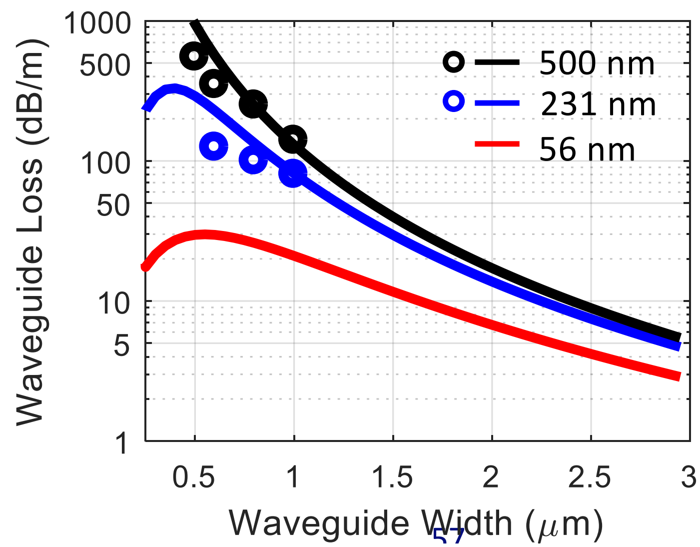
L_c: the roughness correlation length

n_{eff}: is the effective index of mode

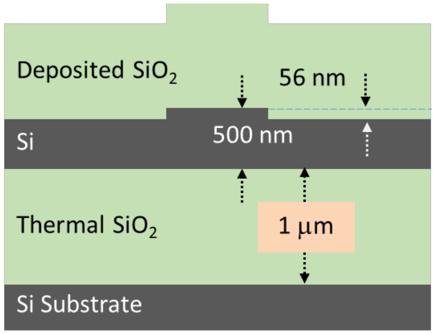
w: width of the waveguide

h: rib height of the waveguide

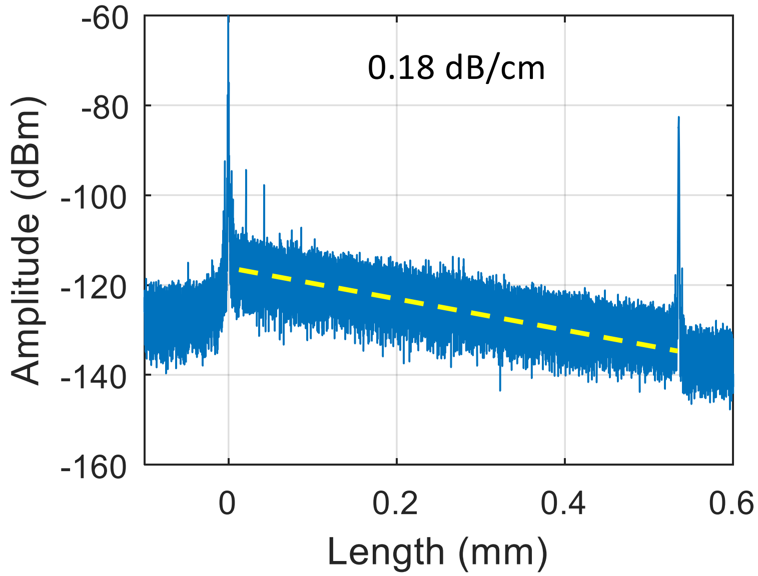
Modeled Curves and Measured Data



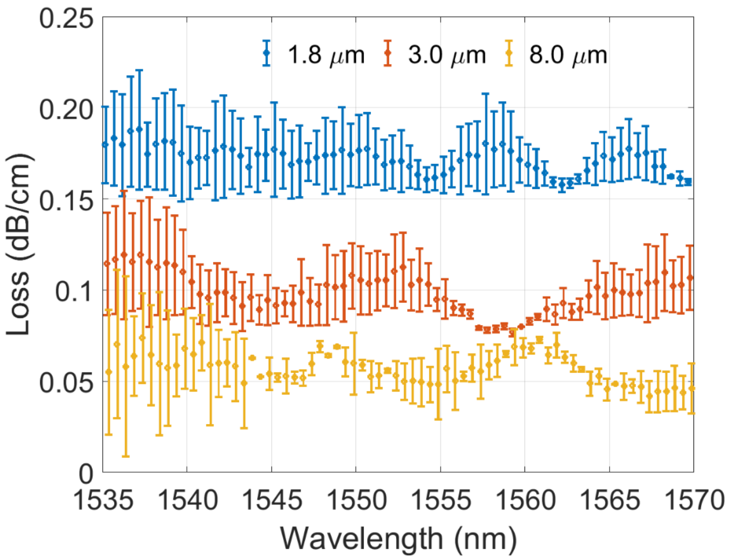
Waveguide Loss OBR Measurements



Measured OBR trace of 1.8 um waveguide

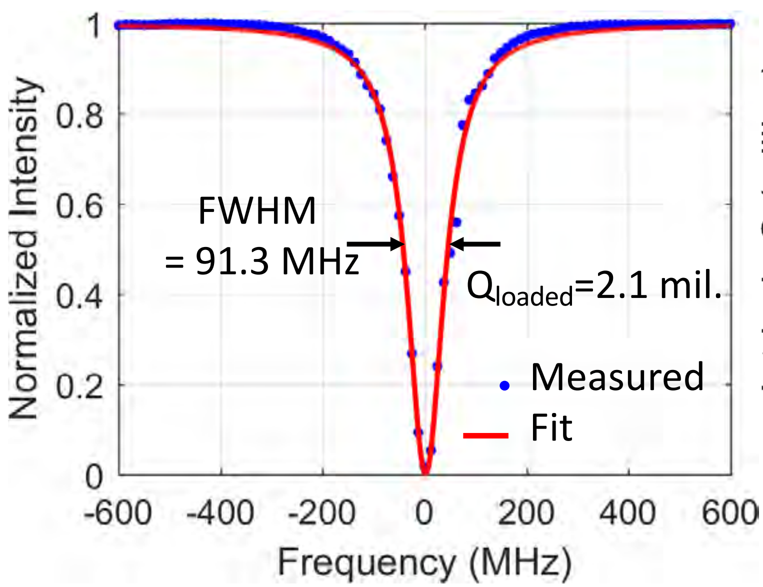


Extracted loss vs. wavelength



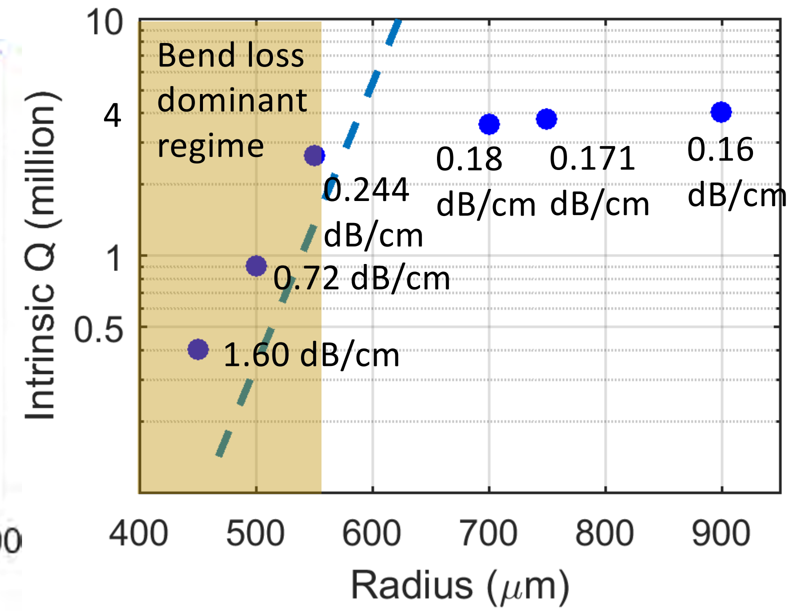
Waveguide Loss with Ring Resonators

Single mode Si ring resonator response with Lorentzian fitted Q_{int} =4.1 million



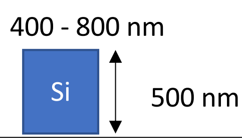
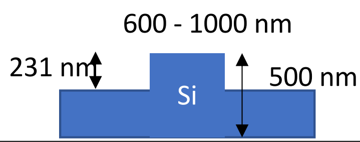
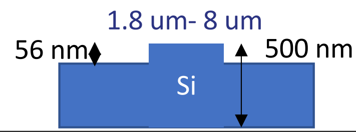
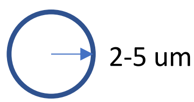
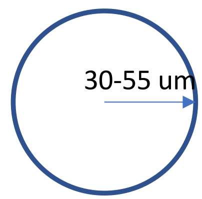
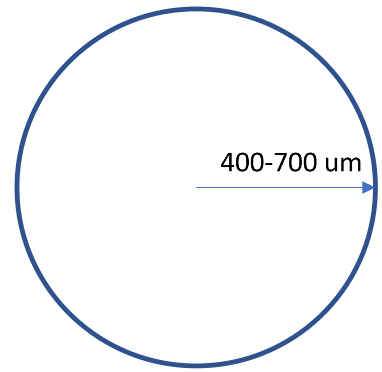
$$Q_{\text{int}} = \frac{2 \cdot Q_{loaded}}{1 \pm \sqrt{T_0}}$$

Single mode Si ring resonators with varying radii

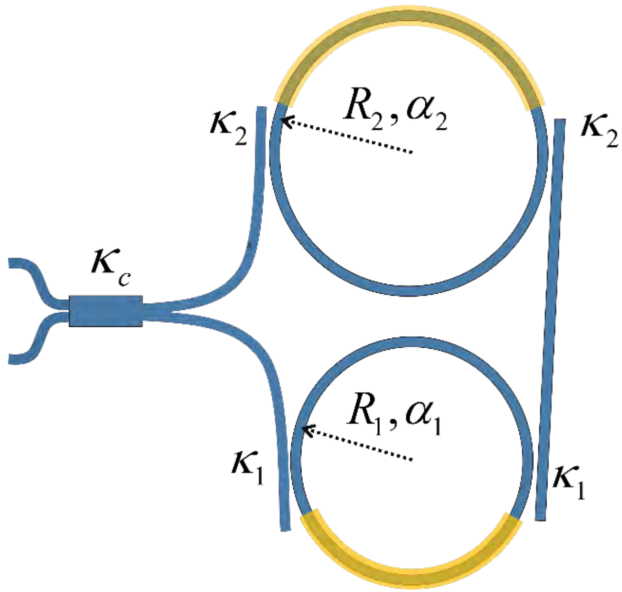


$$\alpha_{wg} = \frac{2\pi n_g}{Q_{\text{int}} \lambda_{resonance}}$$

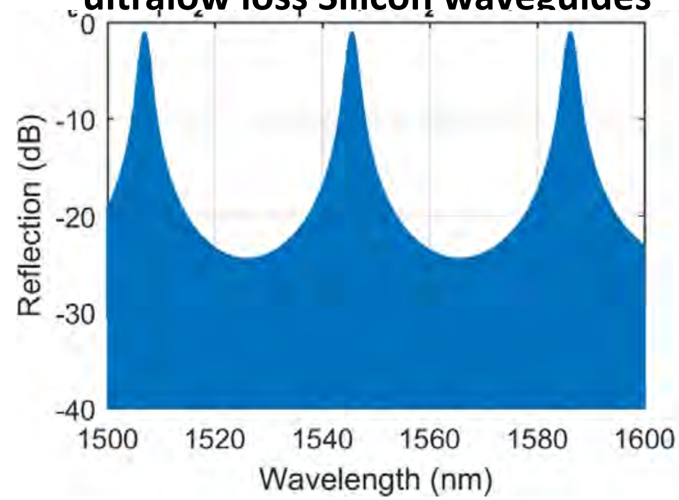
Completed Suite of Optical Waveguides

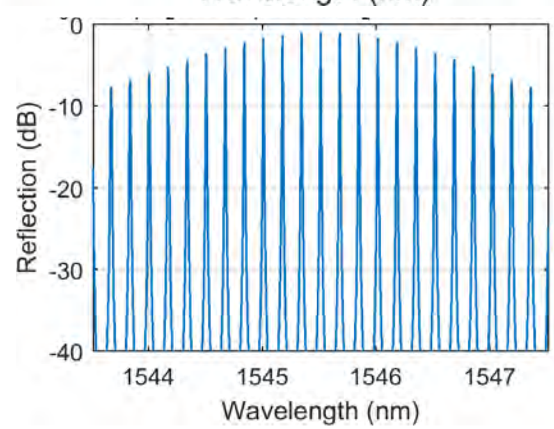
	Strip waveguide	Rib waveguide	Ultralow loss waveguide
Cross Section			
Bend Radius			
Waveguide Loss	**2.5 dB – 8 dB/cm**	**0.7 dB – 1.2dB/cm**	**0.04 dB – 0.15 dB/cm**
	▪ Polarization independent designs ▪ Very compact components	• Single mode operations • Compact functional components	• Ultralow loss, high-Q components • High power handling

Double Ring Mirror Design



With ring radii ~ 600 um of ultralow loss Silicon waveguides

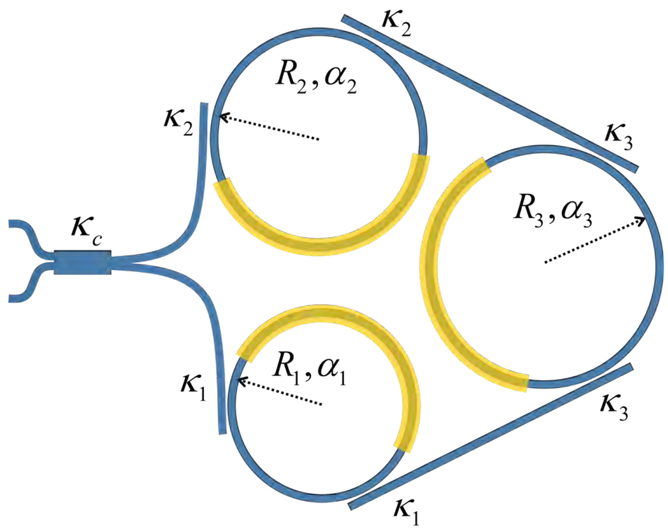


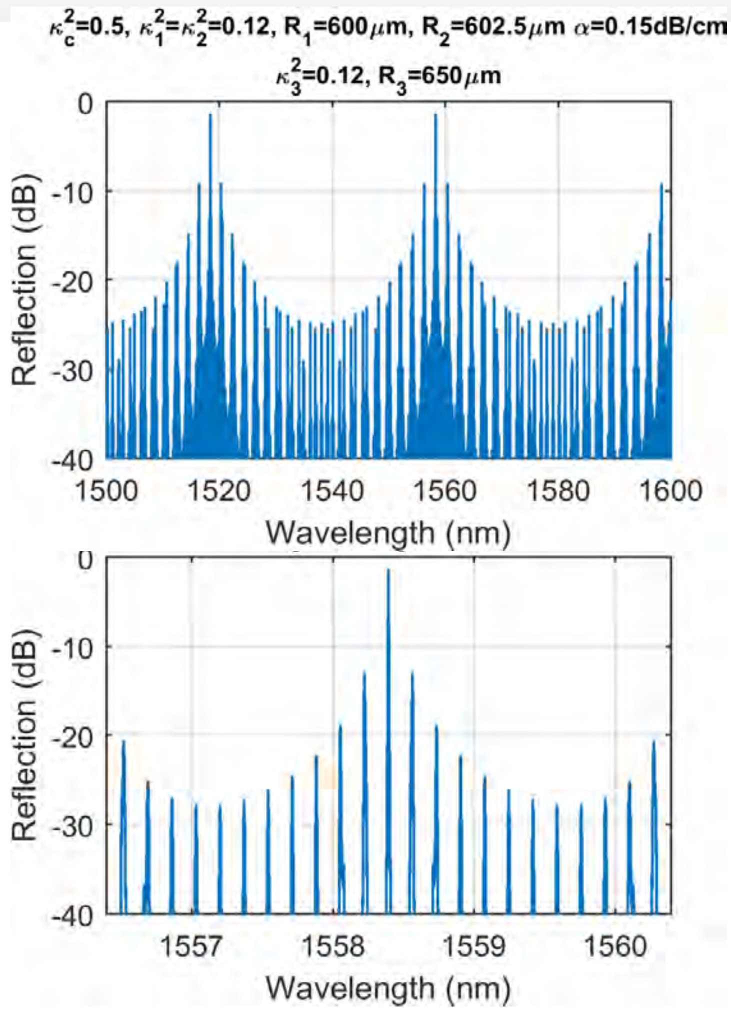


☹ Side mode suppression ratio becomes too small with 600 um bend radii

→ High Q requires extra filtering element

Three Ring Mirror Design





- ✓ The first two primary rings set the Vernier FSR
- ✓ The third ring suppresses the side modes

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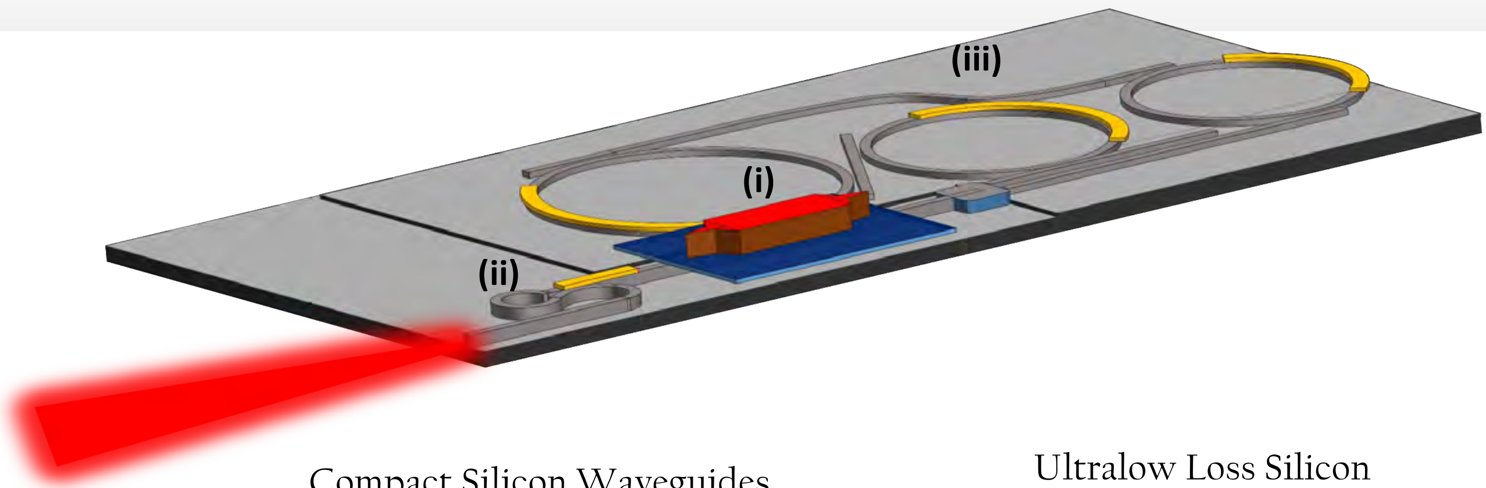
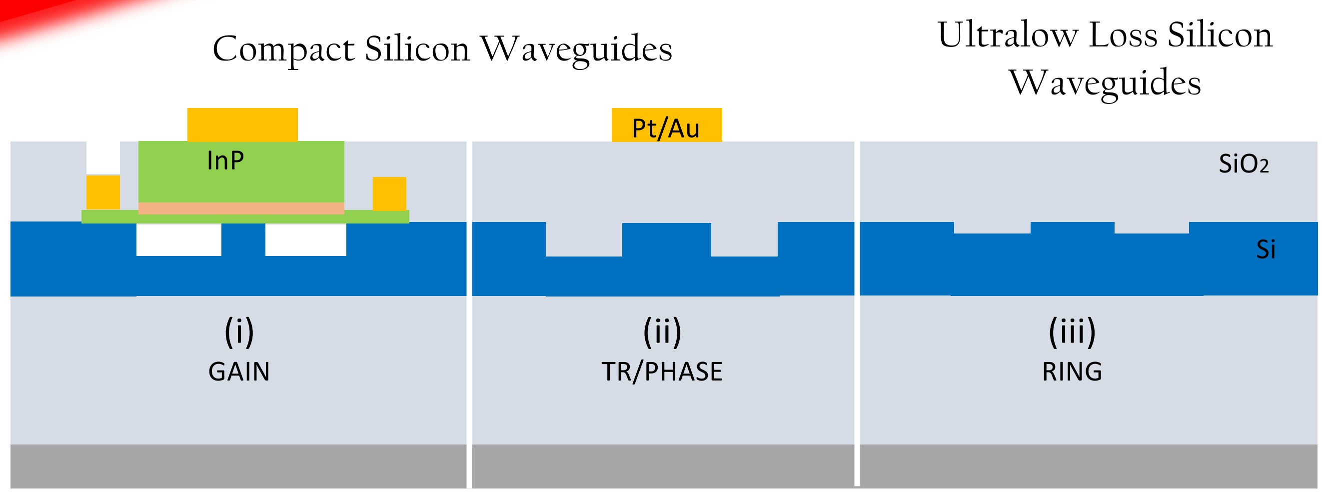
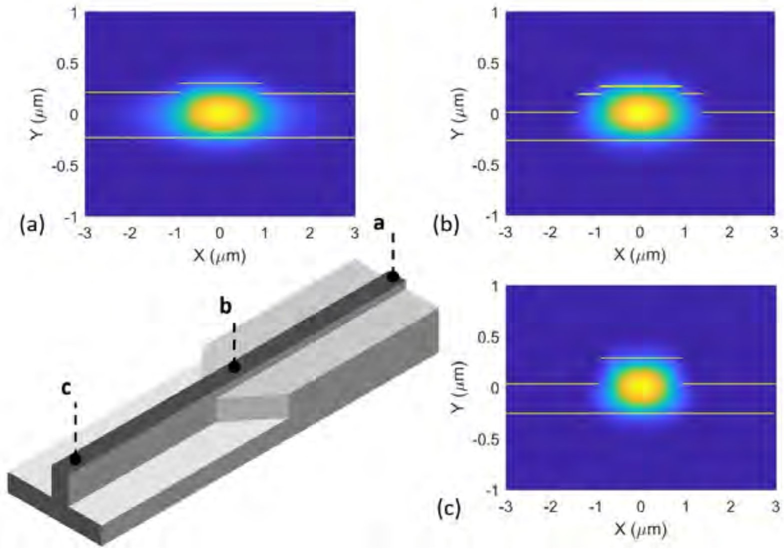
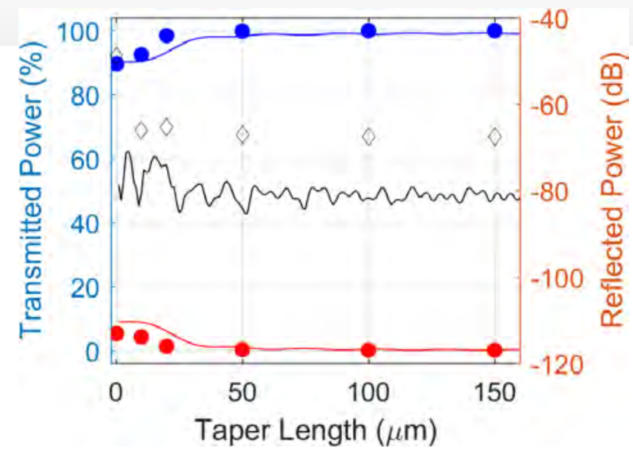
Laser Construction

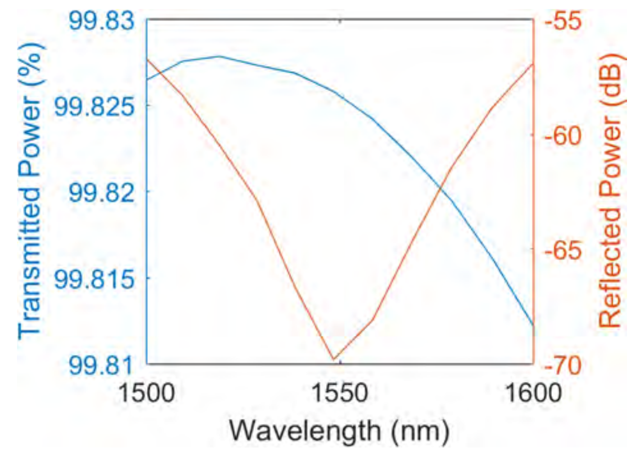




Silicon Inter-waveguide Transitions





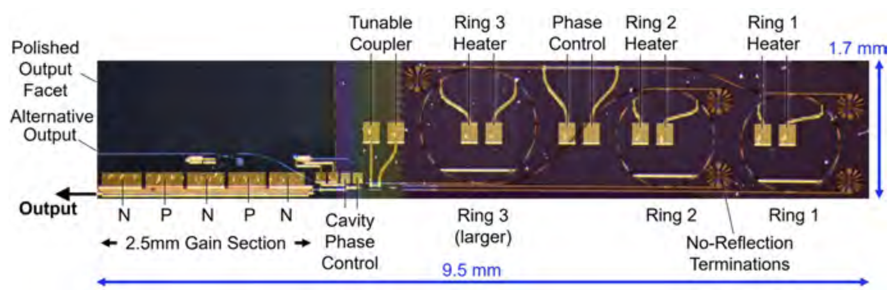


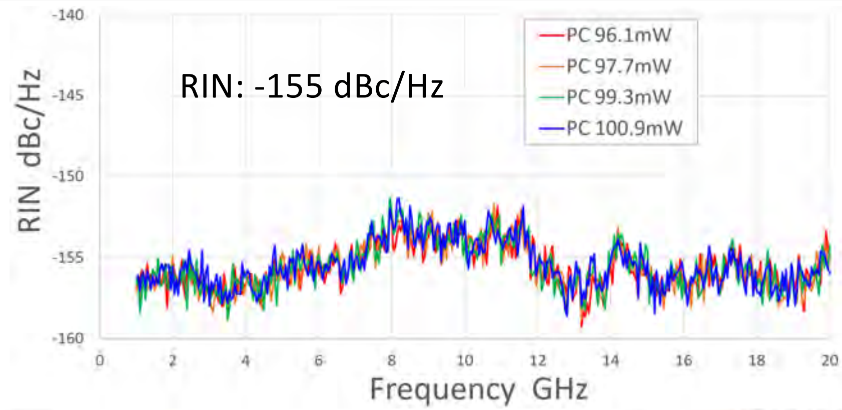
✓ Flexibility to use various types of waveguides for their optimal functionalities on the same chip

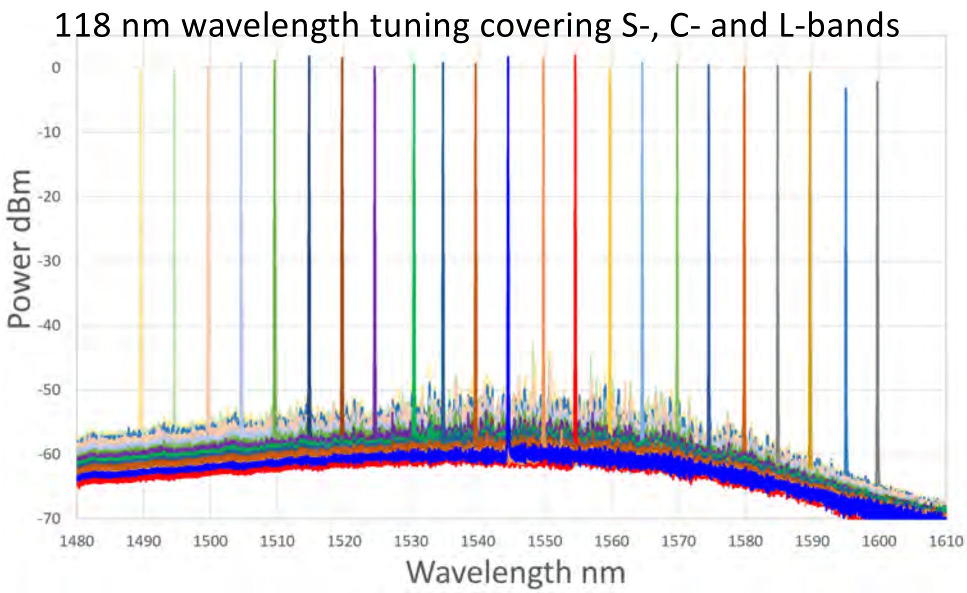
- Compact waveguides for waveguide splitters, loop mirrors
- Ultralow loss waveguide for high Q components

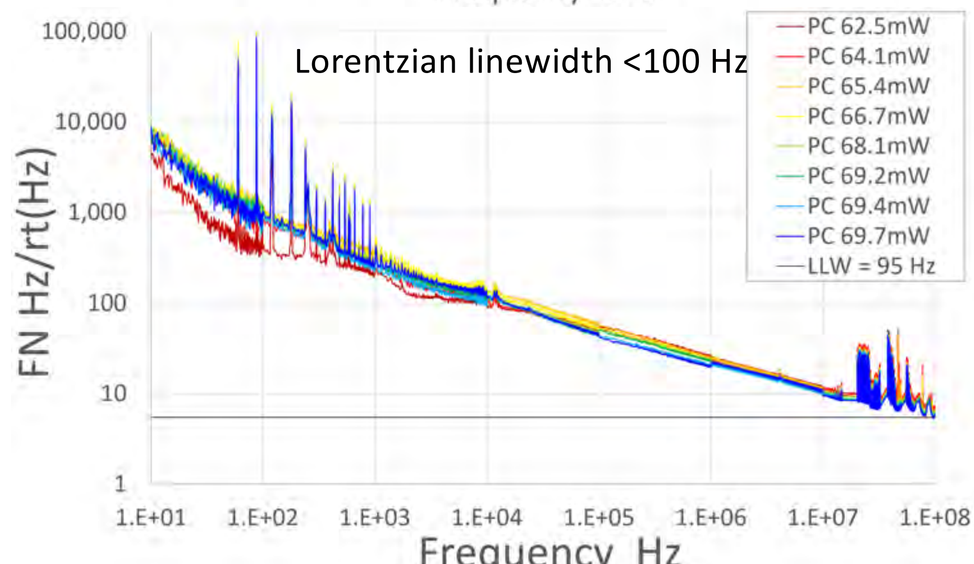
Tran, Huang, Komljenovic, Peters, Malik, Bowers, "Ultra-low-loss silicon waveguides for heterogeneously integrated silicon/III-V photonics." *Applied Sciences*, *8*(7), p.1139 2018.

3 Ring Widely Tunable Laser with 95 Hz Linewidth





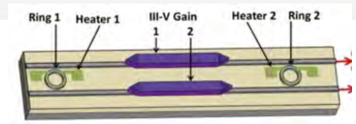


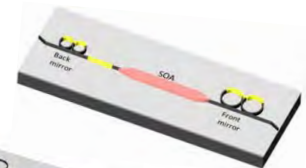


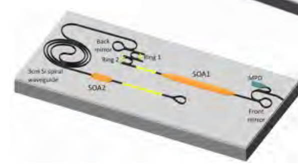
Paul A. Morton, Chao Xiang et al. "Integrated Coherent Tunable Laser (ICTL) With Ultra-Wideband Wavelength Tuning and Sub-100 Hz Lorentzian Linewidth," JLT (2022)

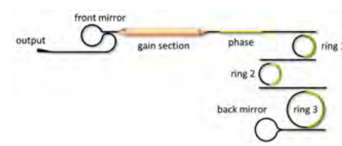
Current status of integrated narrow linewidth lasers

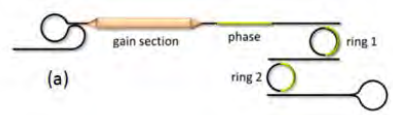
Year	Instantaneous Linewidth	Band	Si Loss
2013 J. Hulme et al.	348 kHz	C+L	6 dB/cm
2015 S. Srinivasan et al.	160 kHz	C+L	6 dB/cm
2015 Komljenovic et al.	50 kHz	O	2 dB/cm
2017 Komljenovic et al.	98 kHz	C+L	2 dB/cm
2017 L. Liang et al.	148 kHz	C+L	6 dB/cm
2018 **M. Tran et al.**	**2 kHz**	**C+L**	1 dB/cm
2019 **M. Tran et al.** **P. Morton et al.**	**120 Hz** **95 Hz**	**S+C+L** 120 nm	0.15 dB/cm

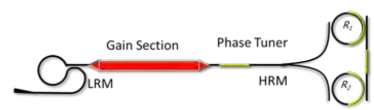


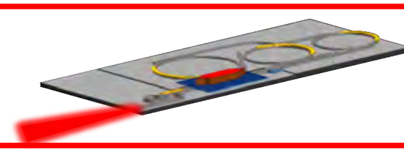




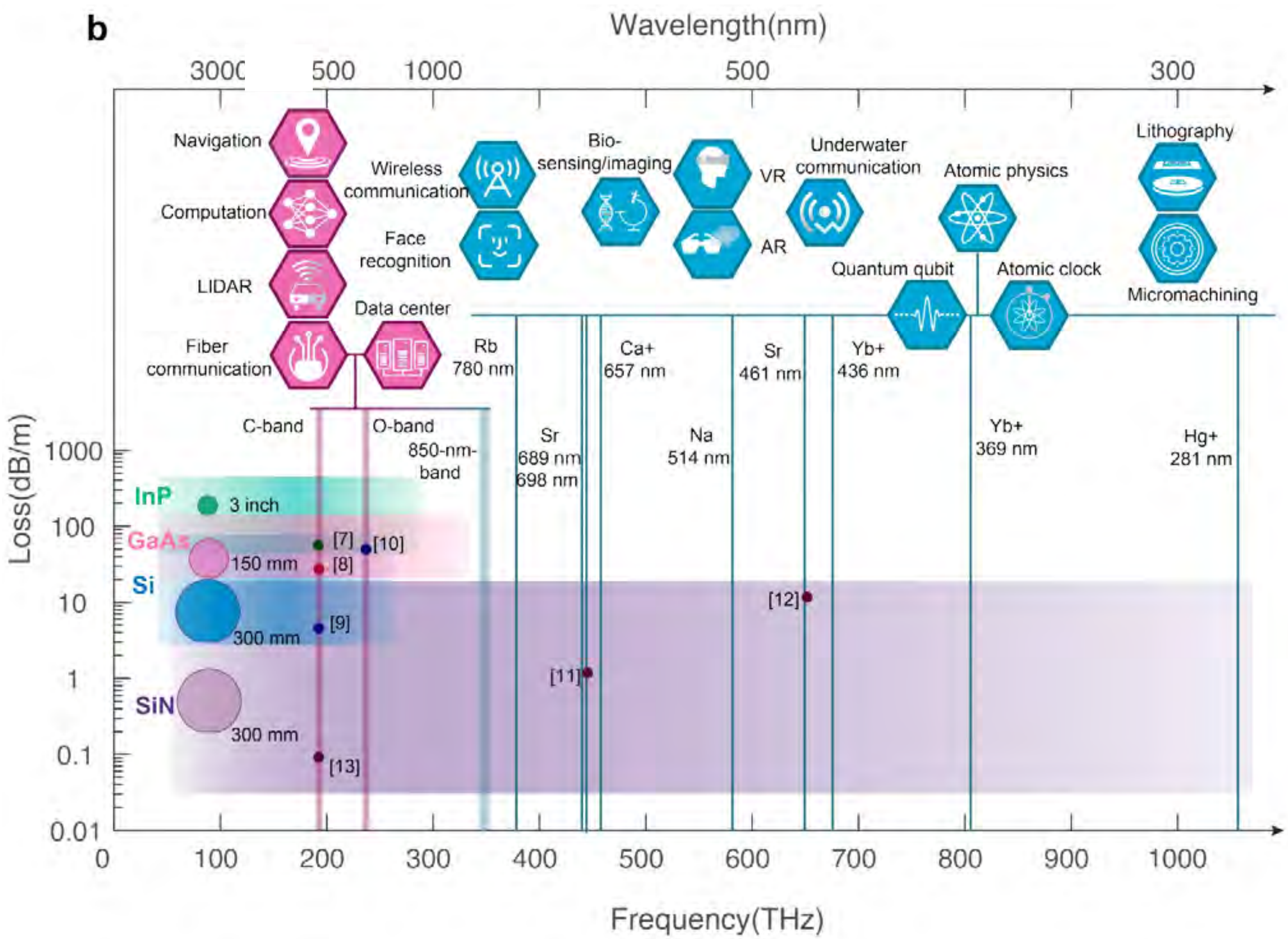


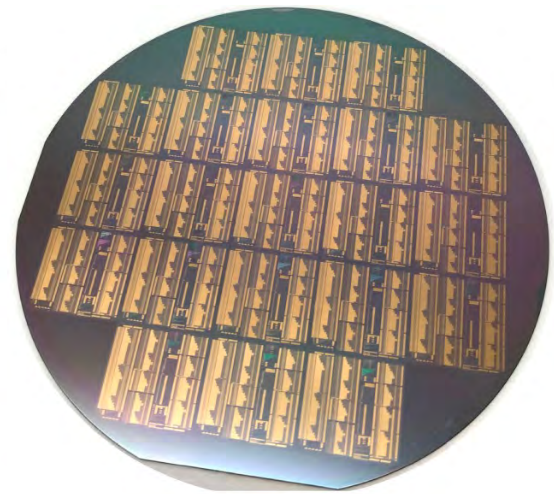






Beyond telecom: visible integrated photonics





Nexus Photonics
Heterogeneous SiN PICs

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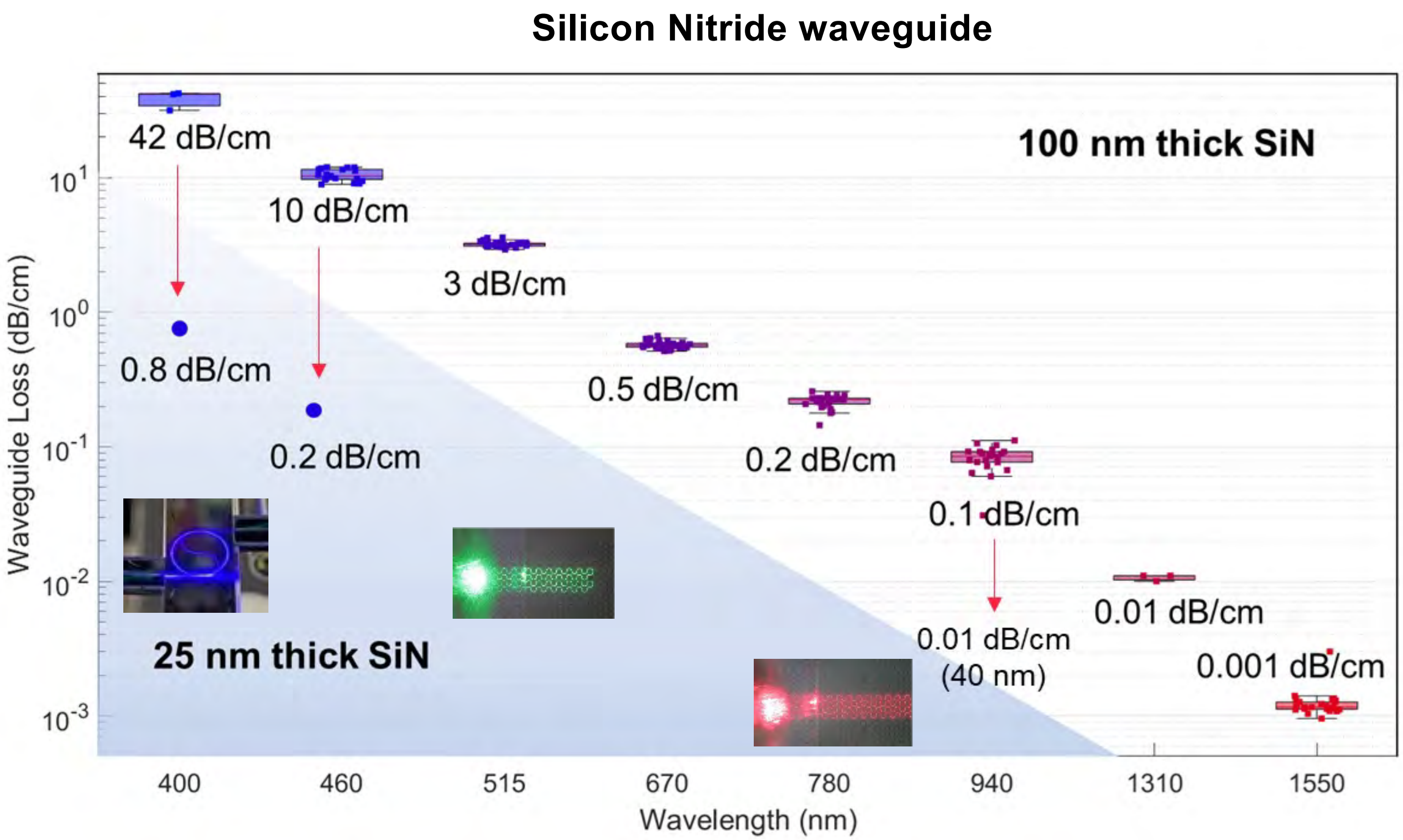
M. Tran… K. Vahala, J. Bowers, T. Komljenovic, H. Park, Nature 610, 54-60 (2022).

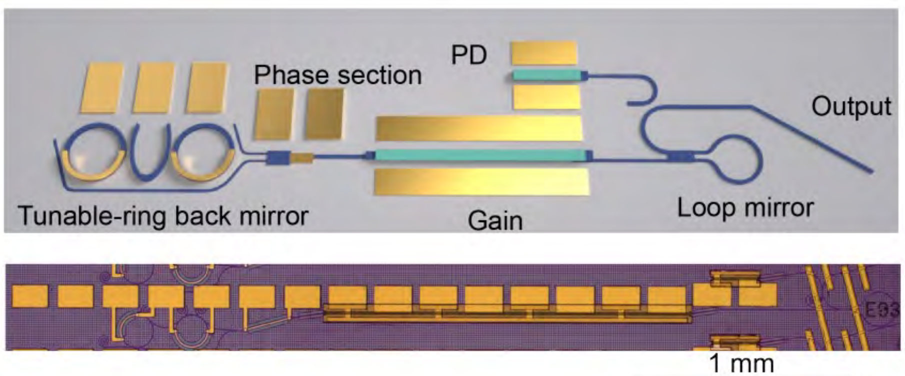
Extending the wavelength range of silicon photonics to visible

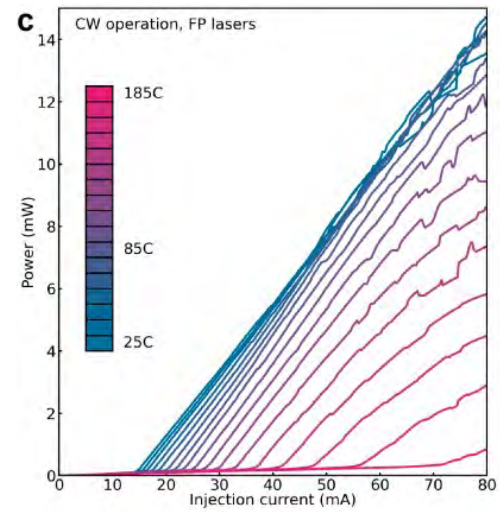


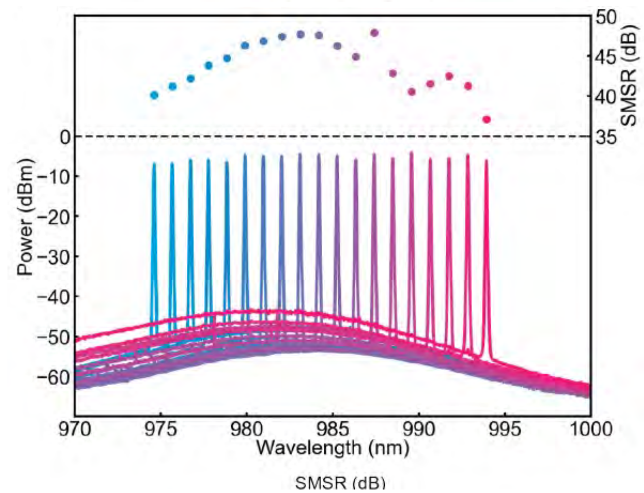
- CMOS compatible
- Ultralow waveguide loss
- Highly uniform
- High power handling
- Low thermal noise

InGaAs/Silicon nitride Narrow linewidth laser at short wavelength

- High temperature lasing (185C)
- 2 kHz fundamental linewidth
- Wide tuning range (> 20 nm)



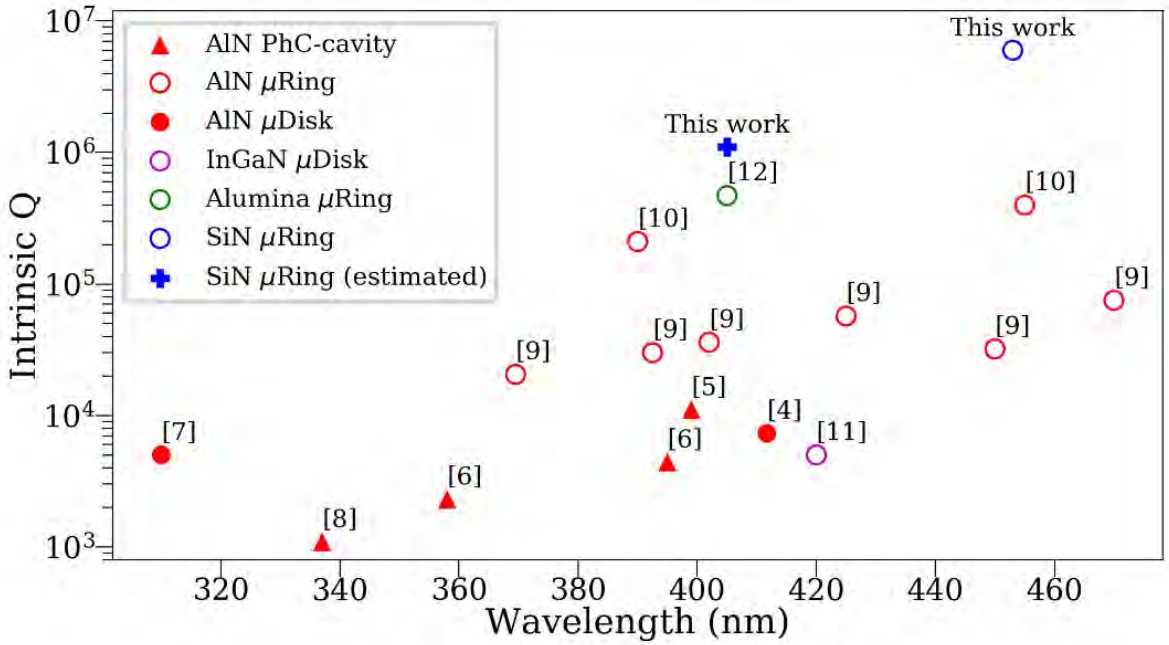


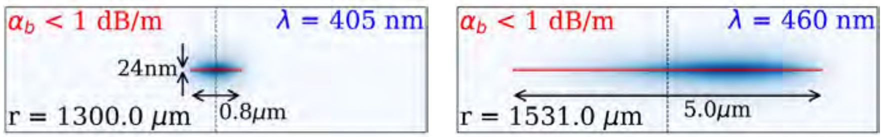


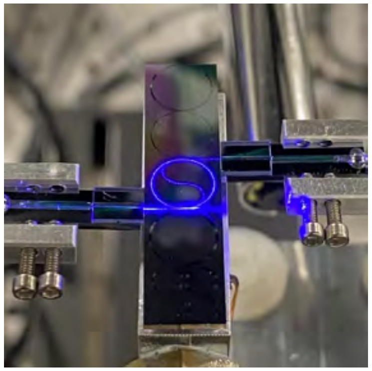
M. Tran… K. Vahala, J. Bowers, T. Komljenovic, H. Park, Nature 610, 54-60 (2022).

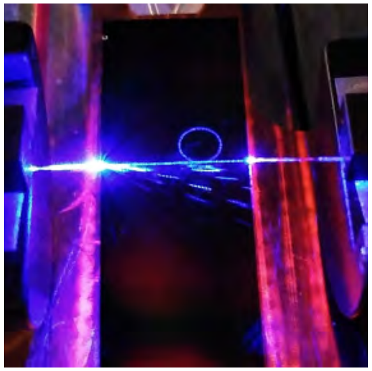
Silicon Nitride: Low loss and high Q at blue and violet

- Record-high Q (**6M, ~0.1 dB/cm**) at blue (453 nm)
- Record-low loss (**< 1 dB/cm**) at violet (405 nm)



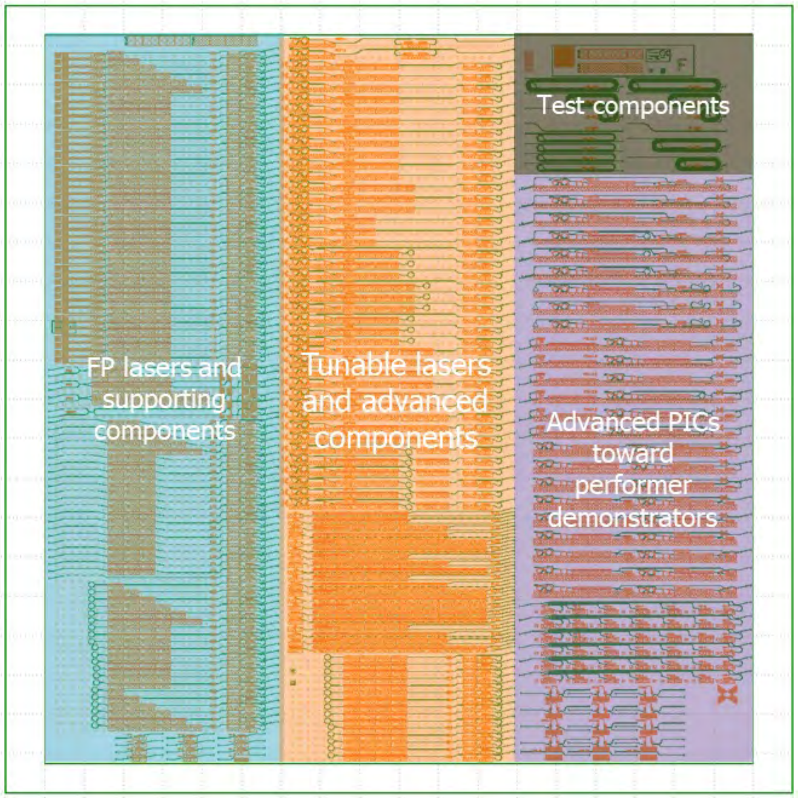


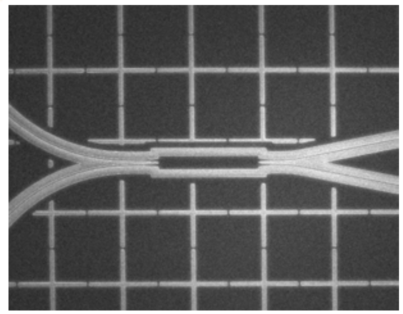


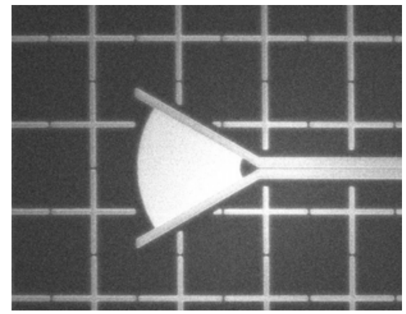


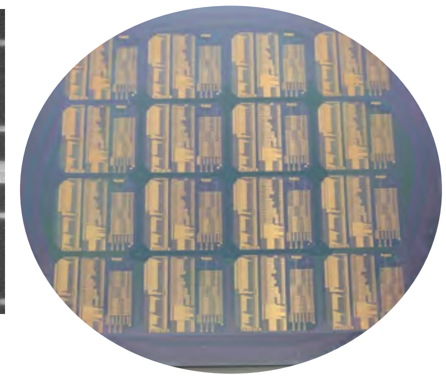
T. Morin, L. Chang... J. Bowers, Optica(2021)

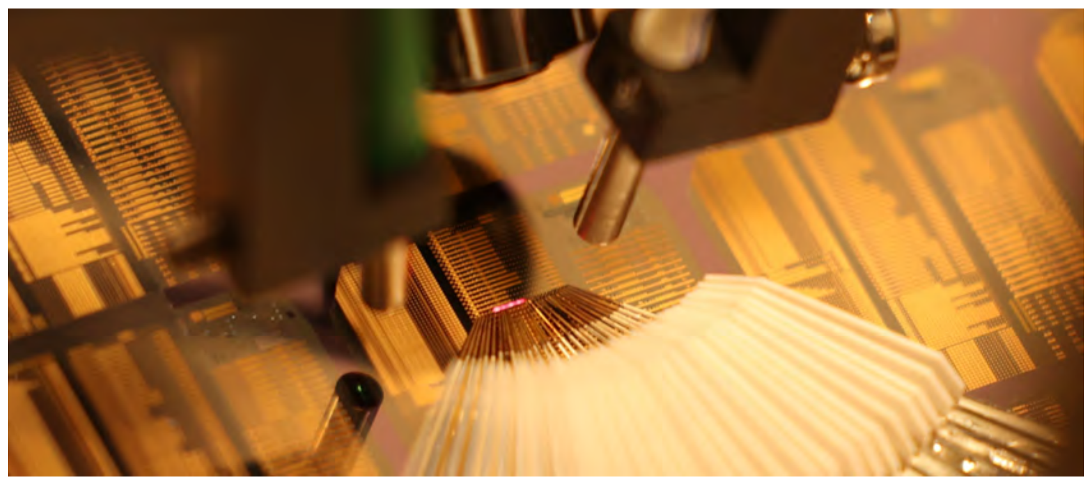
Nexus Foundry Process for Heterogeneous GaAs lasers and PICs: 780, 980 nm







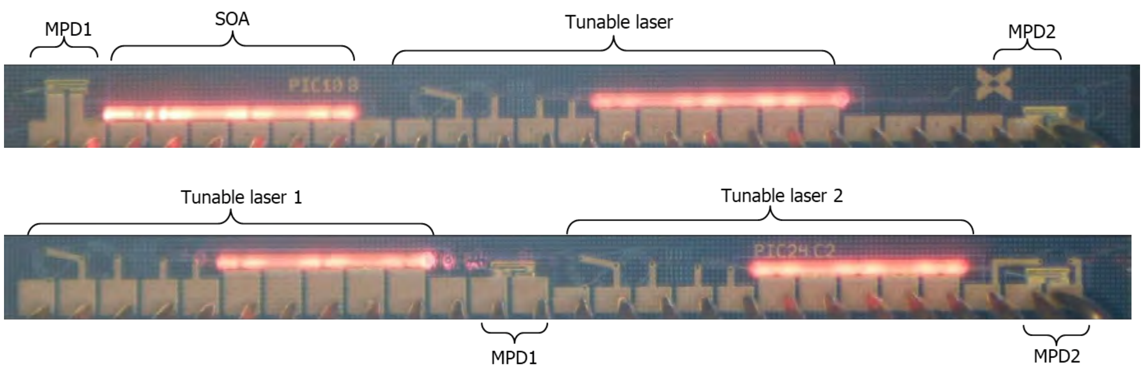




Nexus Photonics

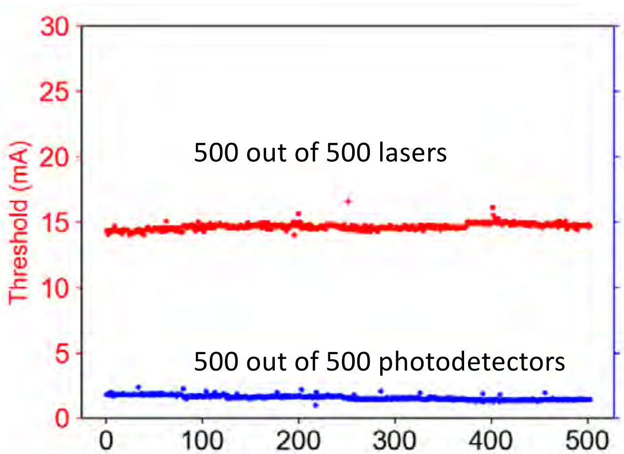
Nature 2022, Optica 2023

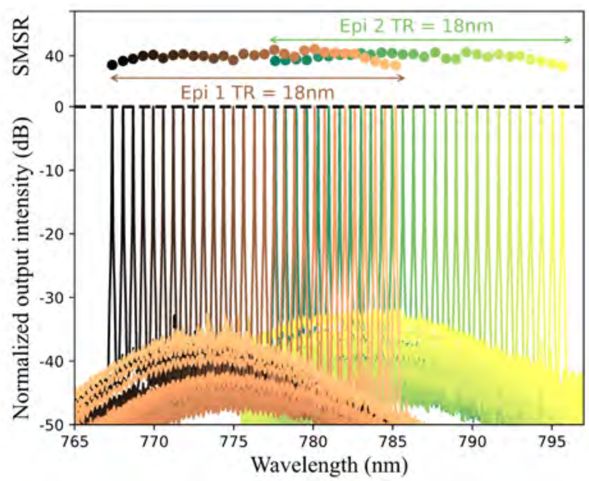
Heterogeneous GaAs lasers and PICs

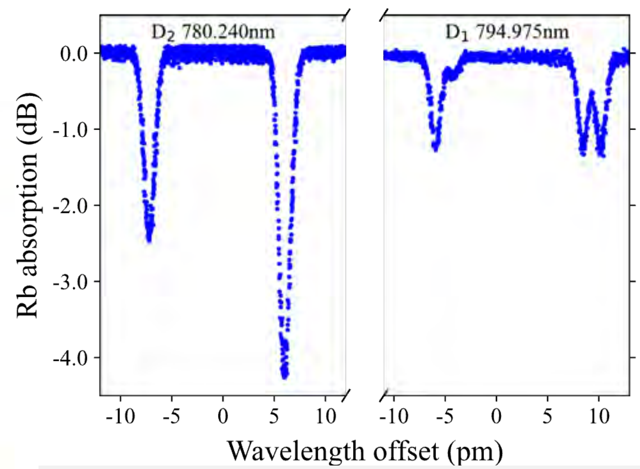


Foundry process:

- High yield (99%)
- High uniformity
- High functionality
- More than just a laser!







^{87}Rb D1 and D2 absorption spectra measured by sweeping one tunable laser across the corresponding wavelength range.

Nexus Photonics

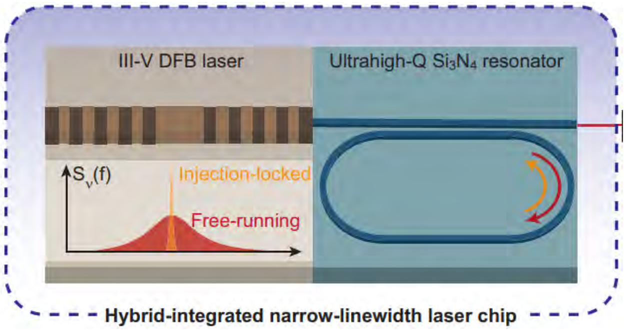
Nature 2022, Optica 2023

Self Injection Locking

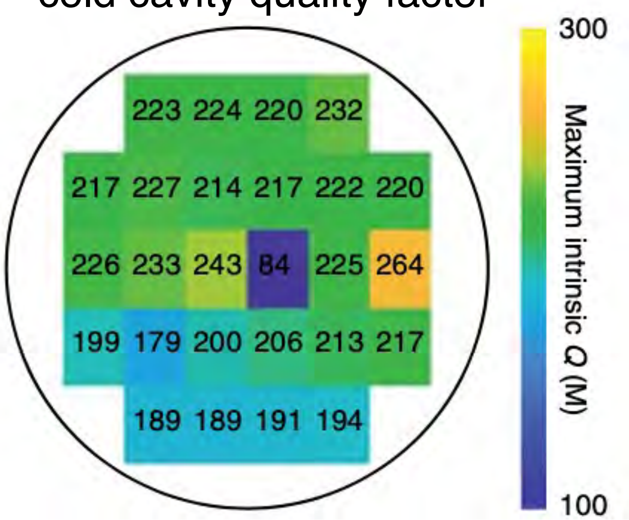
Narrow linewidth lasers

Comb Generation

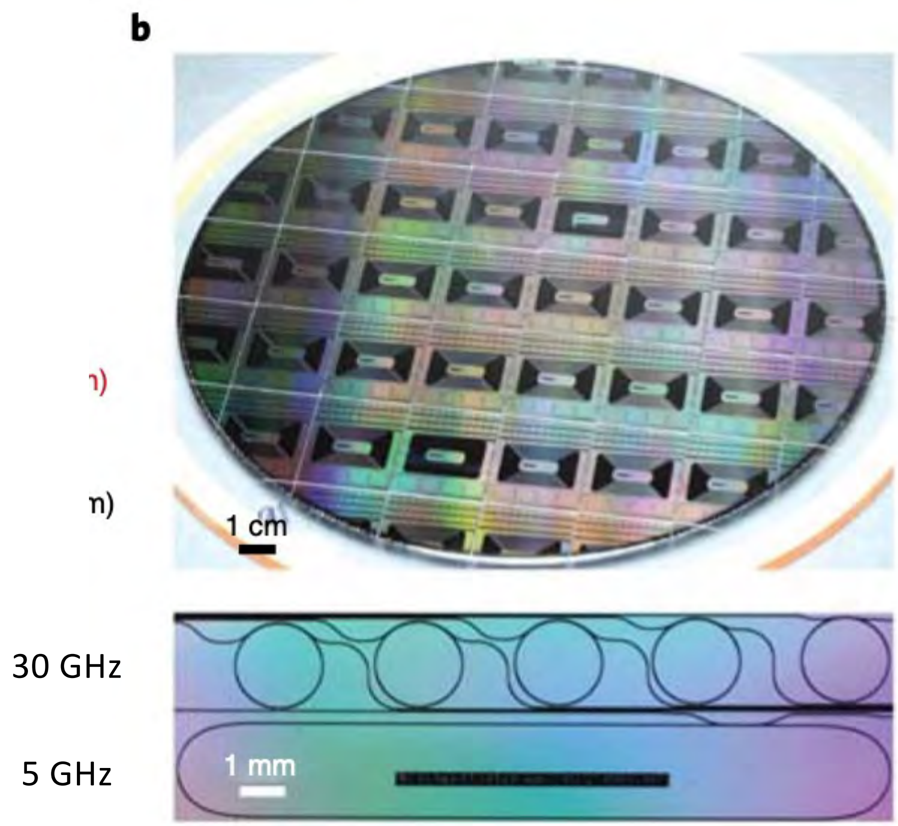
Coupling to low loss SiN Cavities



Q – cold cavity quality factor



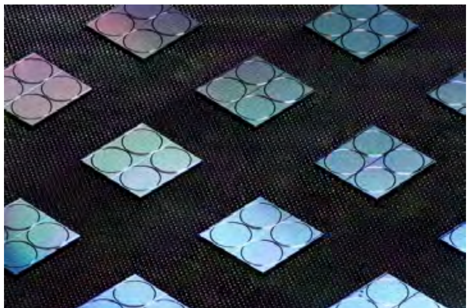
- SiN resonators with Q > 250 M
- Commercial 200 mm foundry



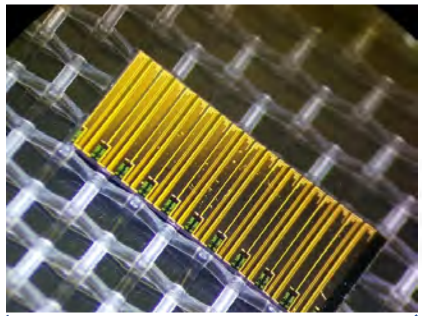
Warren Jin, … Kerry J. Vahala, and John E. Bowers "Hertz-linewidth semiconductor lasers using CMOS-ready ultra-high-Q microresonators", *Nature Photonics* (2021).

Self Injection Locking Using Si_3N_4 resonator direct pumping

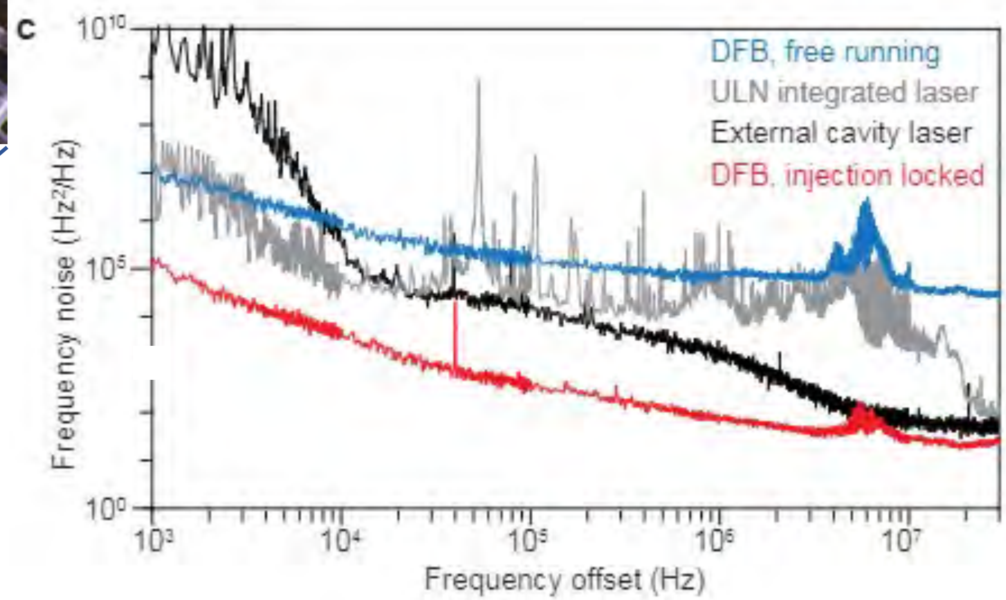
High Q SiN resonator

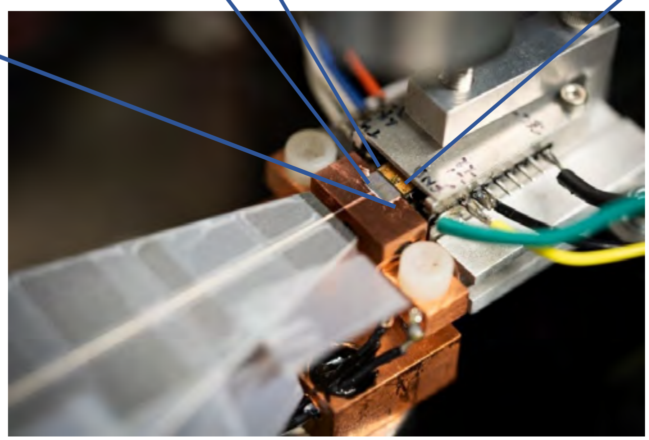


High power DFB

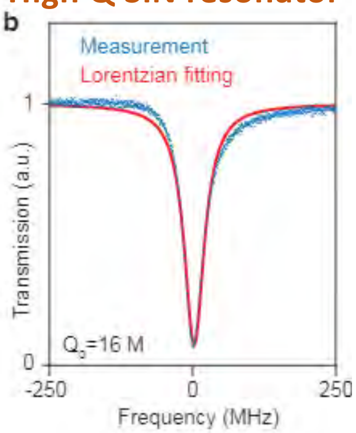


Strong noise reduction by self-injection locking





High Q SiN resonator

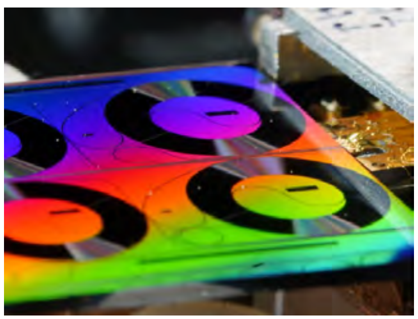


B. Shen, L. Chang J. Liu, H. Wang, Q. Yang… T. Kippenberg, K. Vahala and J. Bowers, *Nature (2020)*

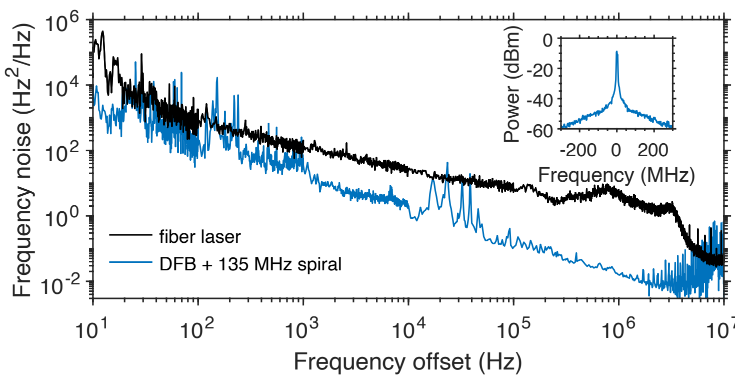
Self Injection Locked DFB Lasers

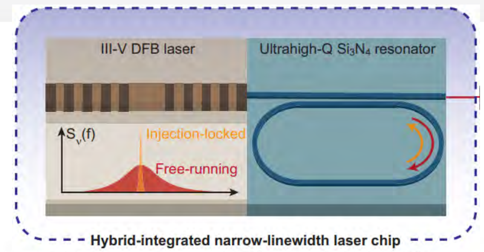
- Ultra-low-loss CMOS SiN platform: 0.1 dB/m
- High Q Resonators: **Q > 270 M**
- **> 70 dB** noise reduction (thermorefractive noise limited)
- **40 mHz fundamental** linewidth demonstrated
- Laser noise performance exceeds state-of the- art-fiber laser

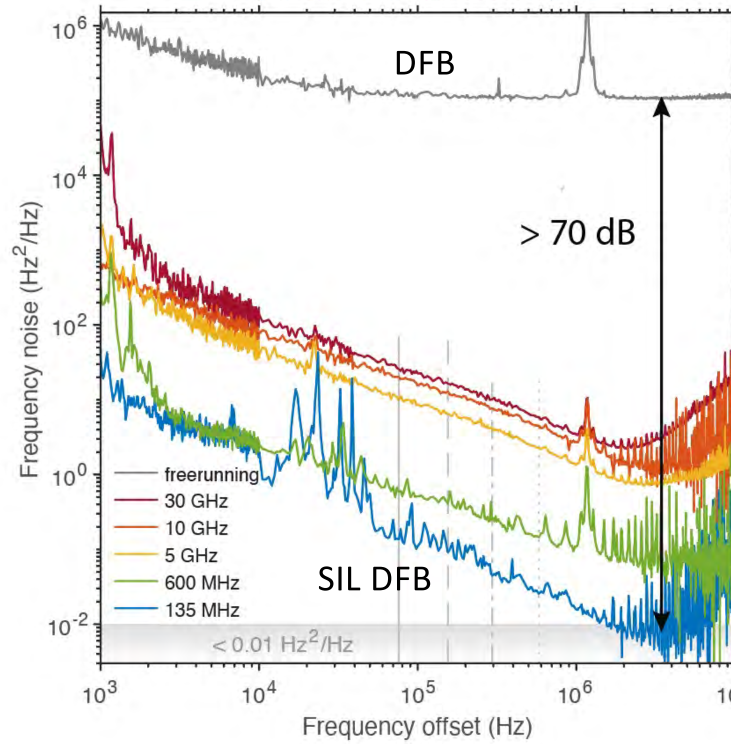
Laser-spiral ring coupling



Comparison between SIL and fiber laser

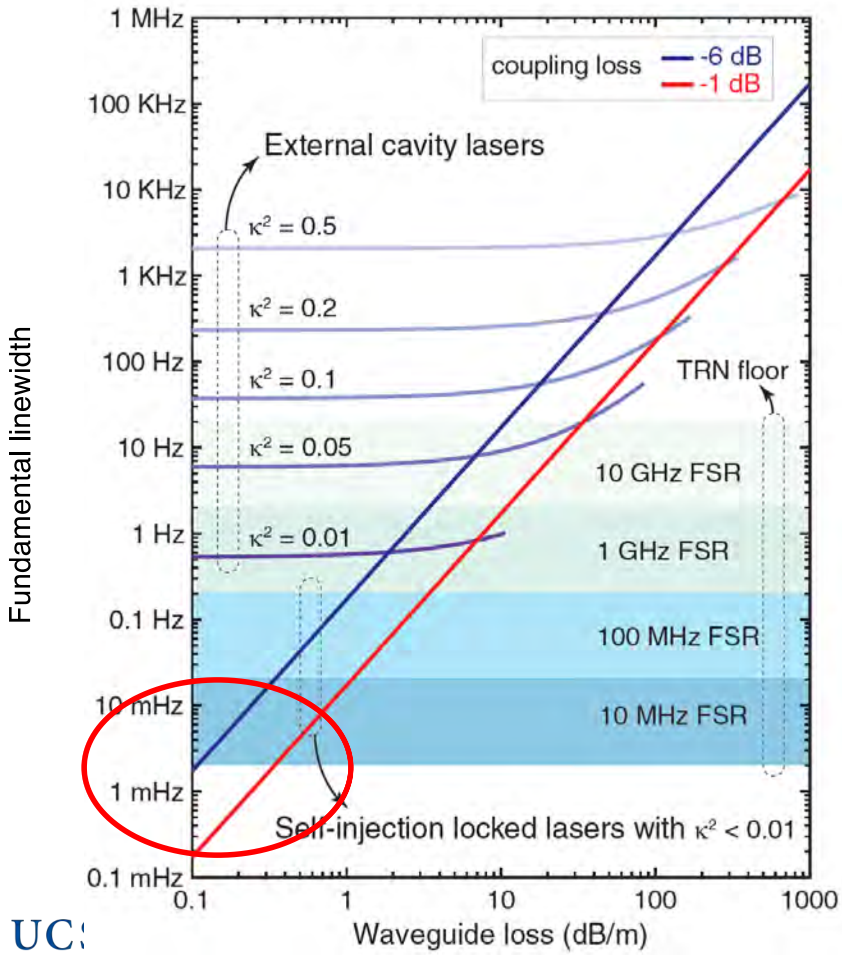


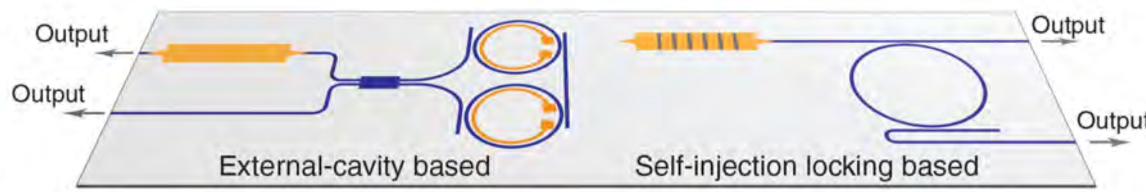




Bohan Li…Vahala, Bowers “Reaching fiber-laser coherence in integrated photonics”, *Optics Letters* **46**, 5201-5204 (2021).

TRN limiting the linewidth from high-Q resonators

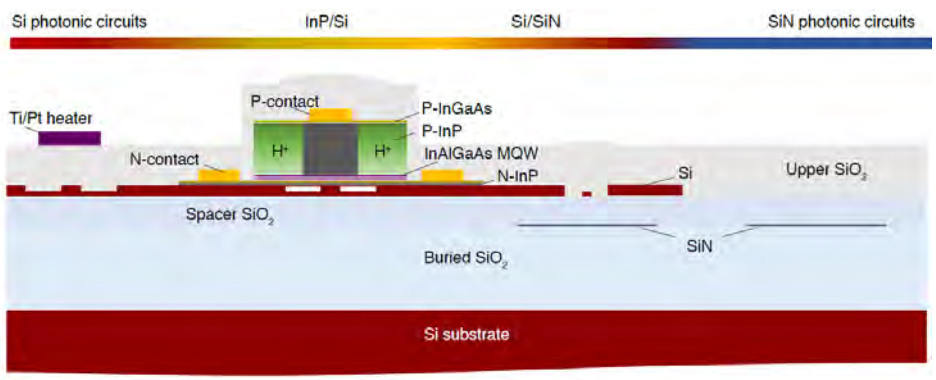


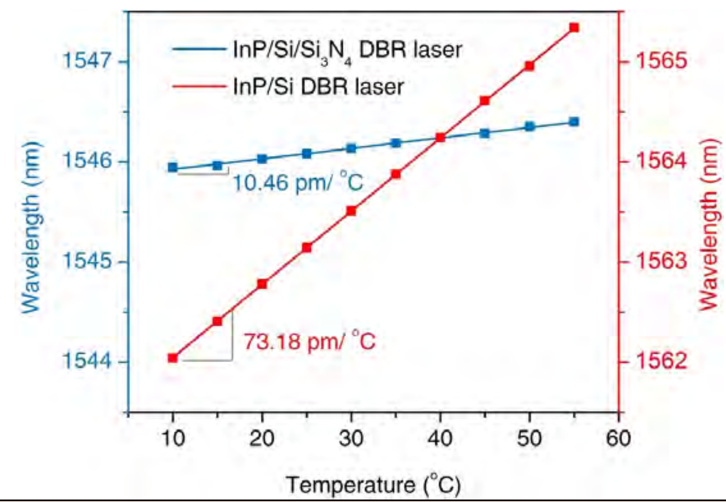


- TRN scales with mode volume
- Noise reduction factor from high-Q limited by TRN

C. Xiang, W. Jin, J. E. Bowers. 'Silicon nitride passive and active photonic integrated circuits: trends and prospects'. Photonics Research 2022

Heterogeneously-Integrated III-V/Si/Si_3N_4 laser





This eliminates the need for CWDM!
SiN AWGs and Lasers are temperature stable.

- Heterogeneously-integrated SiN laser with high-output power (> 30 mW)
- Narrow fundamental linewidth (<100 Hz, extended to Hz-level with self-injection locking to ultra-high-Q SiN)
- 10 pm/C temperature sensitivity (10-100x more stable than InP or Si)

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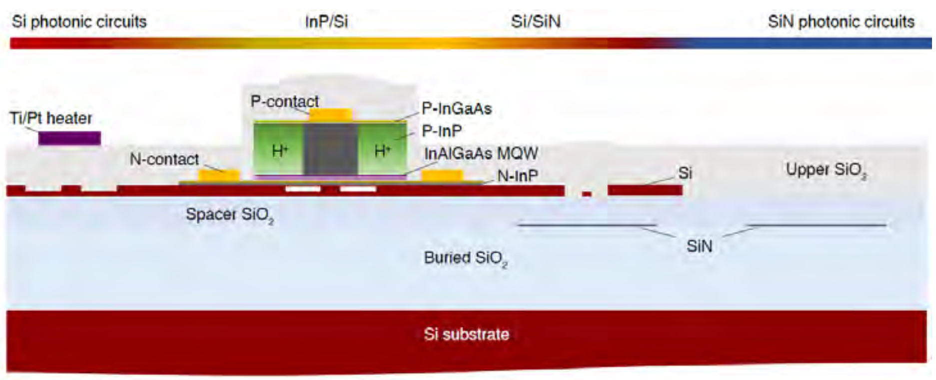
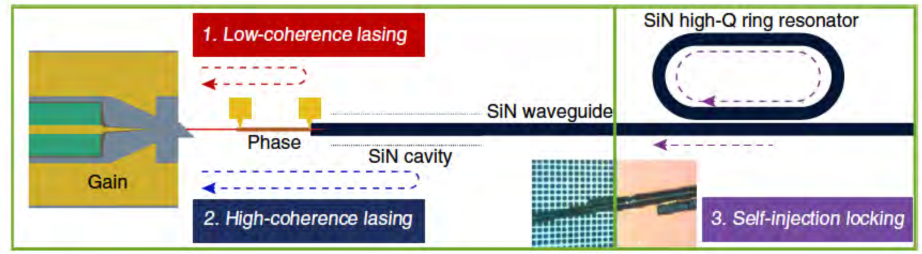
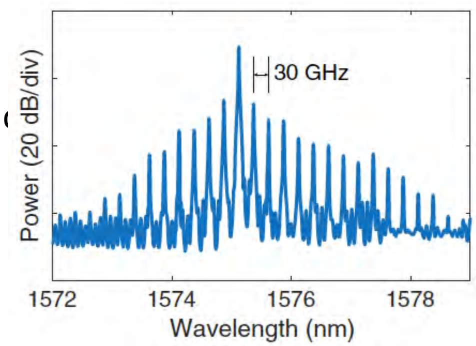
Xiang…Bowers, 'High-performance lasers for fully integrated silicon nitride photonics', Nature Communications 2021

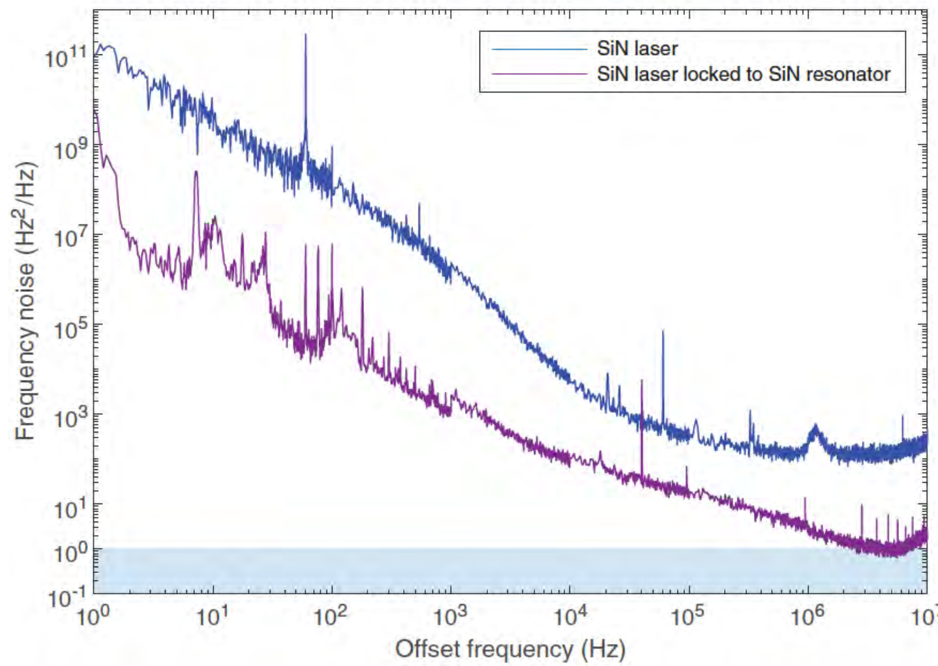
Self Injection Locked Heterogeneously-Integrated III-V/Si/Si_3N_4 laser





- 30 GHz FSR SiN resonator
- Normal dispersion
- 3 Hz Lorentzian linewidth
- Stable dark pulses observe





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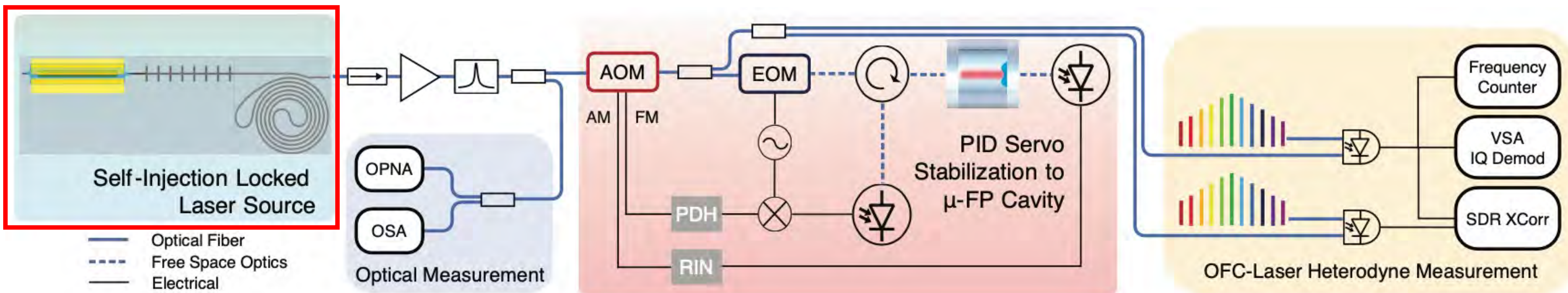
Xiang…Bowers, 'High-performance lasers for fully integrated silicon nitride photonics', Nature Communications 2021

Locking to Bulk Resonators to Achieve 1 Hz Integrated Linewidth



- PDH-lock SIL laser to vacuum-gap μ-FP cavity
- AOM provides frequency and intensity actuation for the PDH and RIN locks, respectively.
- The frequency noise, RF spectrum, and Allan deviation are measured via heterodyne with a stabilized frequency comb (for FN, two independently stabilized combs for cross correlation and greater measurement sensitivity)

UCSB, NIST, Caltech, Yale,
Guo et al., Science Advances 8, (2022).

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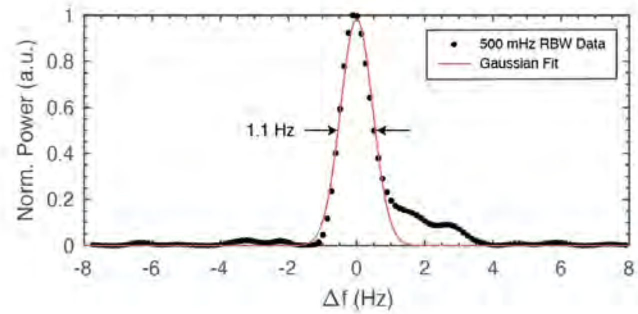
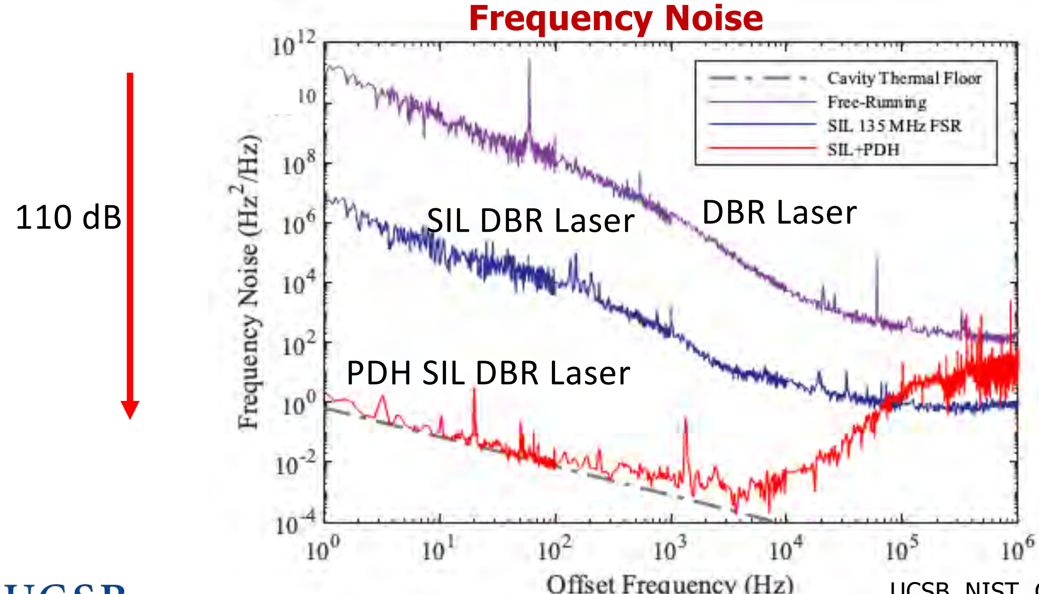
A Chip-Based, 1 Hz Integrated Linewidth Laser

- Integrated self-injection locked (SIL) laser PDH-locked to a microfabricated vacuum gap FP cavity
- 1.1 Hz FWHM measured via RF heterodyne beat
  - Hz-level integrated linewidth confirmed with FN Beta-separation line and $1/\pi$-integration estimations
- Frequency noise follows cavity thermal noise floor to 10^{-3} Hz^2/Hz at kHz offset frequencies
- Sub-10^{-14} Allan deviation out to 1 second

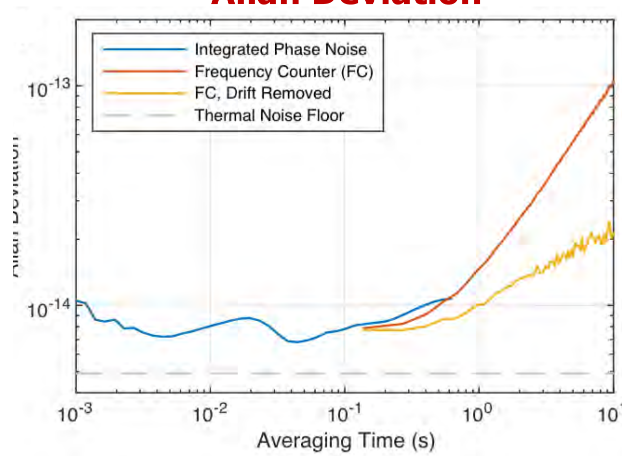
RF Heterodyne Beat



Frequency Noise



Allan Deviation



UCSB, NIST, Caltech, Yale,
Guo et al., Science Advances 8, (2022).

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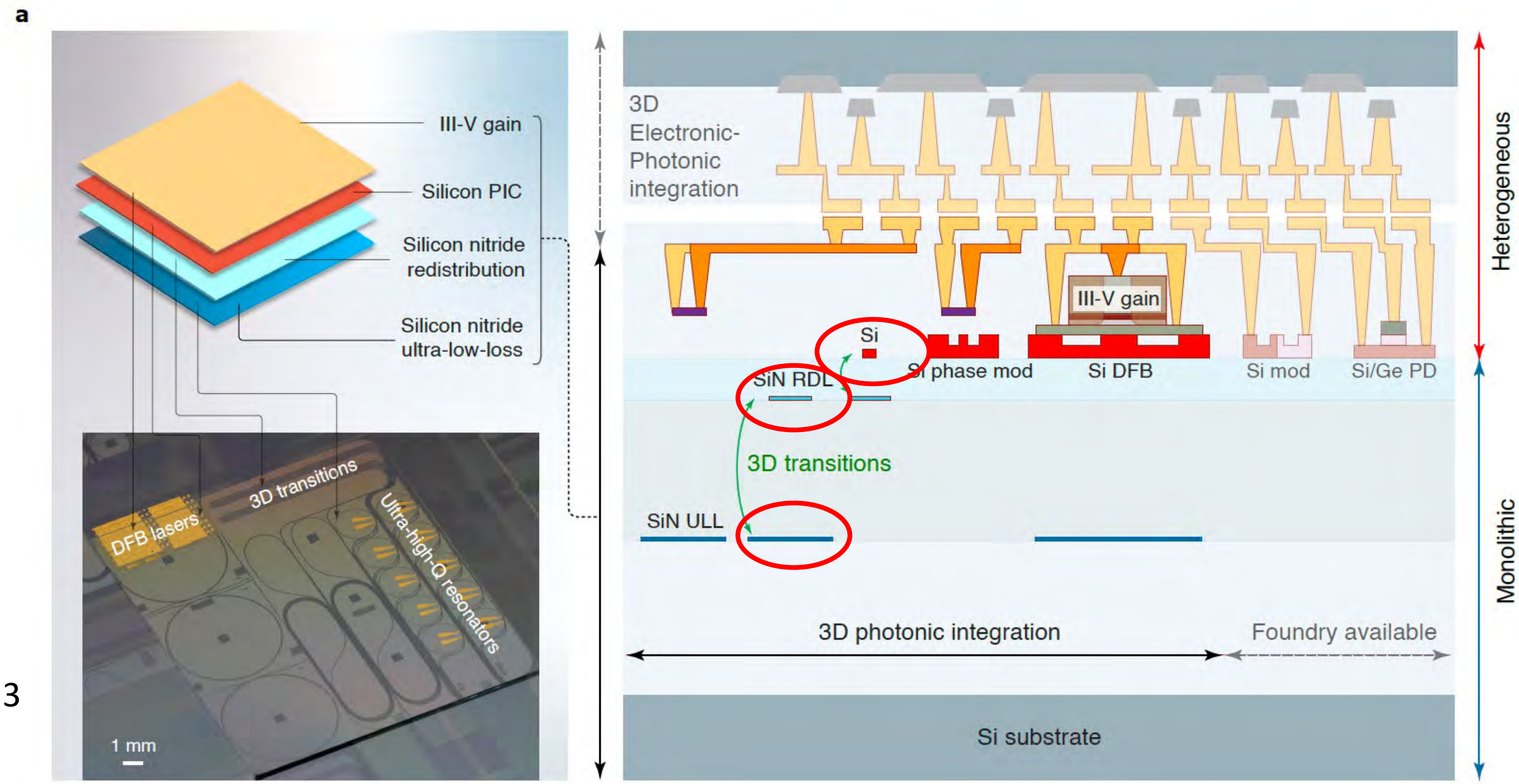
3D Optoelectronics: Towards Higher Performance PICs

- 3D Heterogeneous integration of III-V, Silicon, two SiN waveguides,
- 3D Heterogeneous integration of III-V laser, SiN resonator, modulators, PDs



Xiang…Bowers, Nature, 2023

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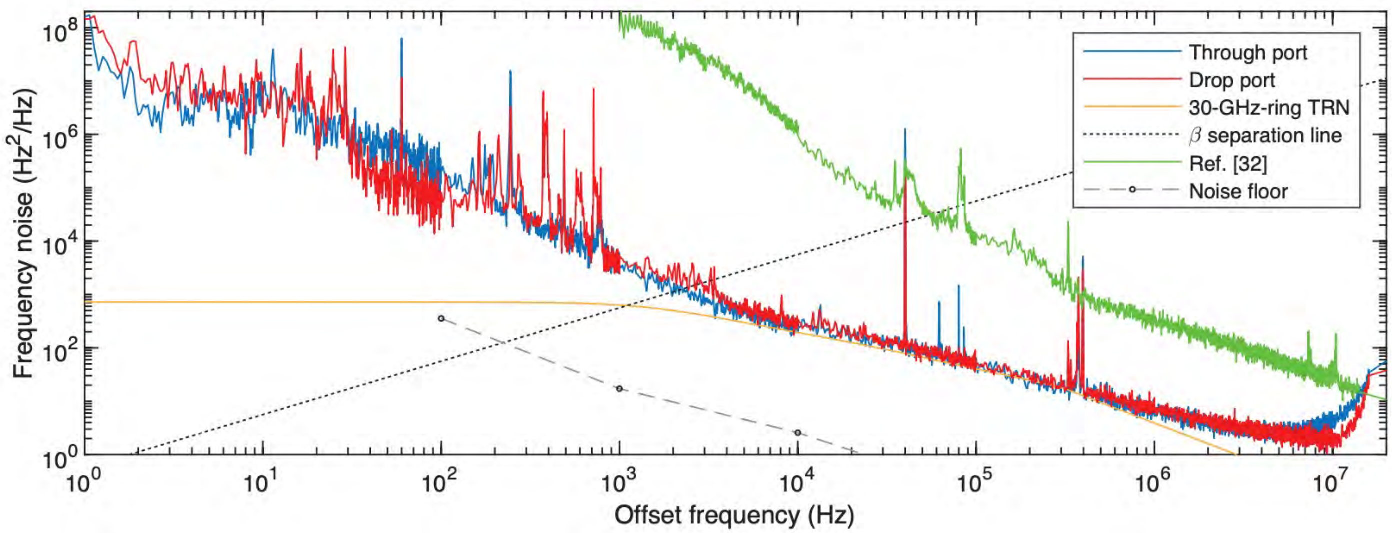
3D integration for ultra-low-noise lasers



- 5 Hz fundamental linewidth for 30 GHz ring resonator
- FN limited by thermorefractive noise
- FN=250 Hz^2/Hz @ 10 kHz offset

Xiang… Bowers. '3D integration enables ultralow-noise isolator-free lasers in silicon photonics', Nature, 620, 2023

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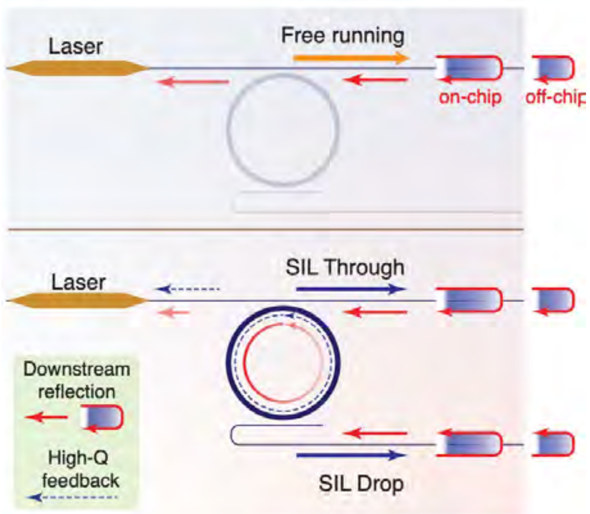
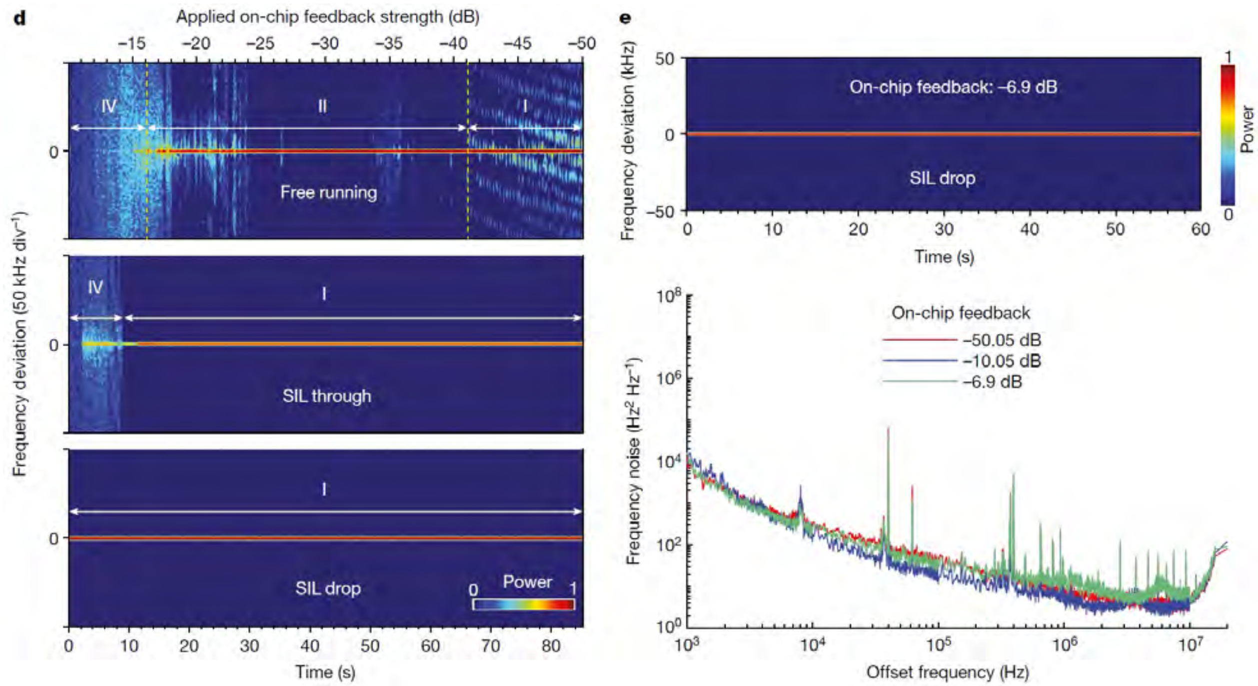
Laser isolator-free operation





- 26 dB and >34 dB improvement for SIL through and drop port in Regime 1 boundary
- Unaffected laser FN under on-chip feedback as high as -6.9 dB (limited by coupling loss in testing)

Xiang… Bowers. ‘3D integration enables ultralow-noise isolator-free lasers in silicon photonics’, Nature, 620, 2023

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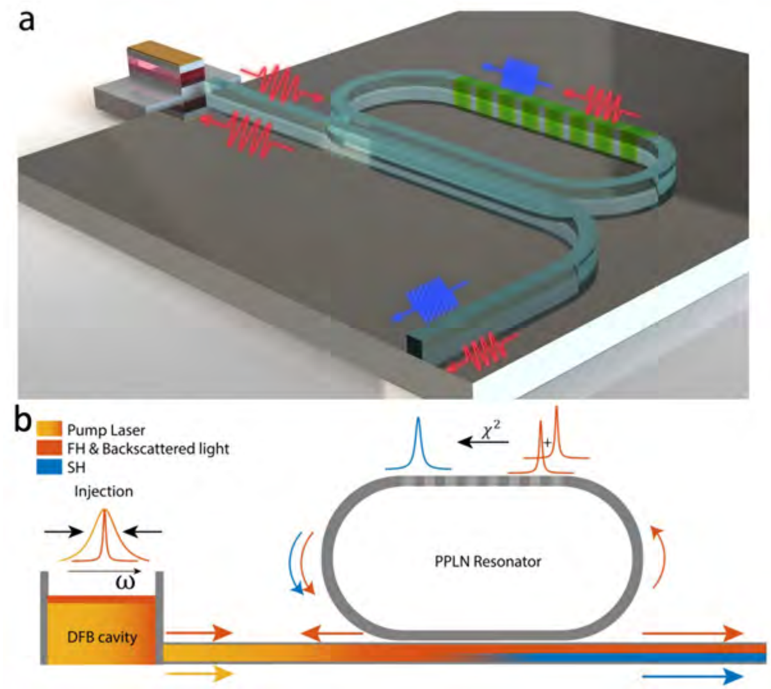
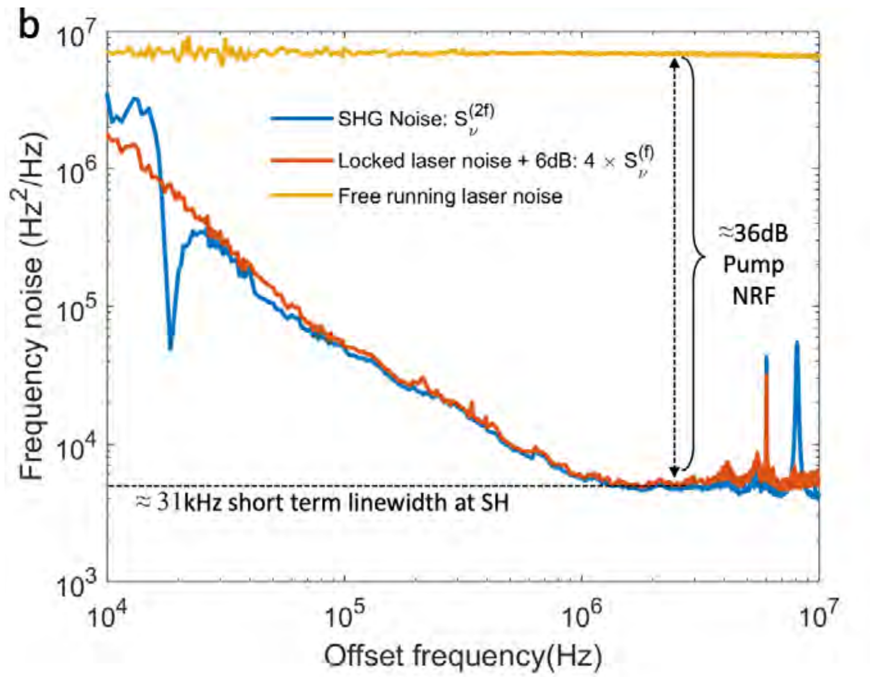
TFLN: Self injection locked to LN resonators with SHG output





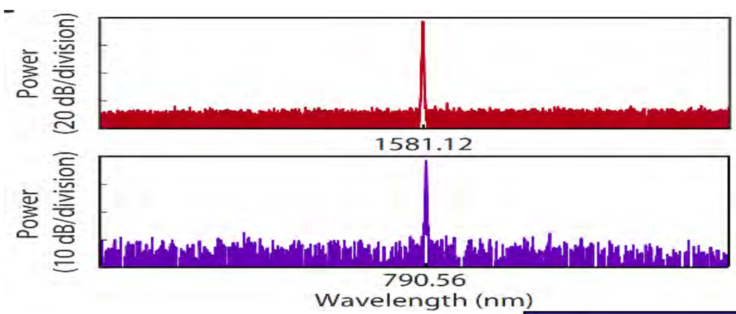
- A second-harmonic linewidth of 31kHz
- 4 x pump linewidth in SHG process

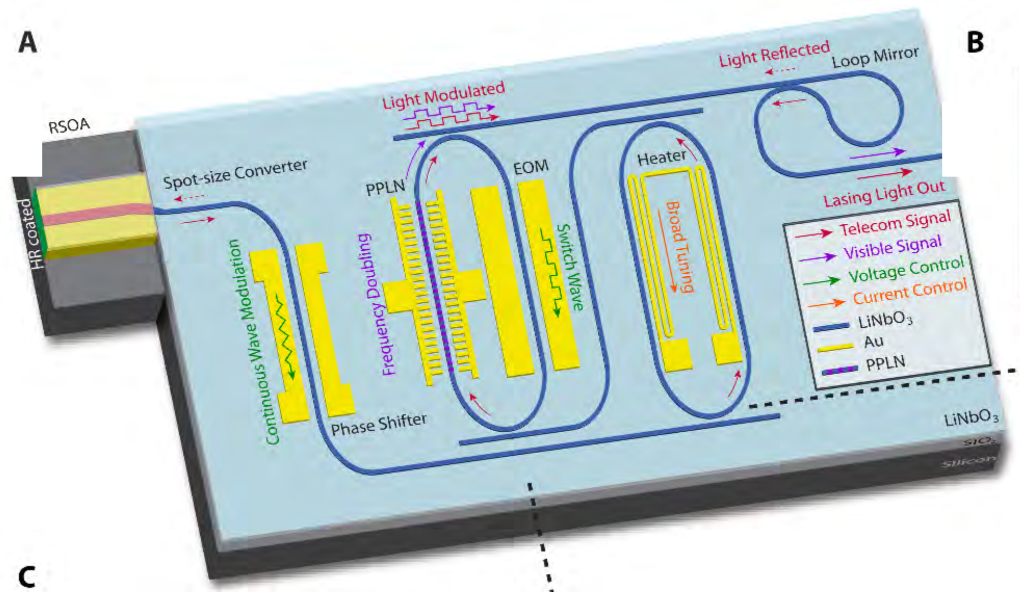
Jingwei Ling, …John E. Bowers, Kerry J. Vahala, and Qiang Lin “Self-Injection Locked Frequency Conversion Laser” *Laser and Photonics Review* 2200663 (2023).

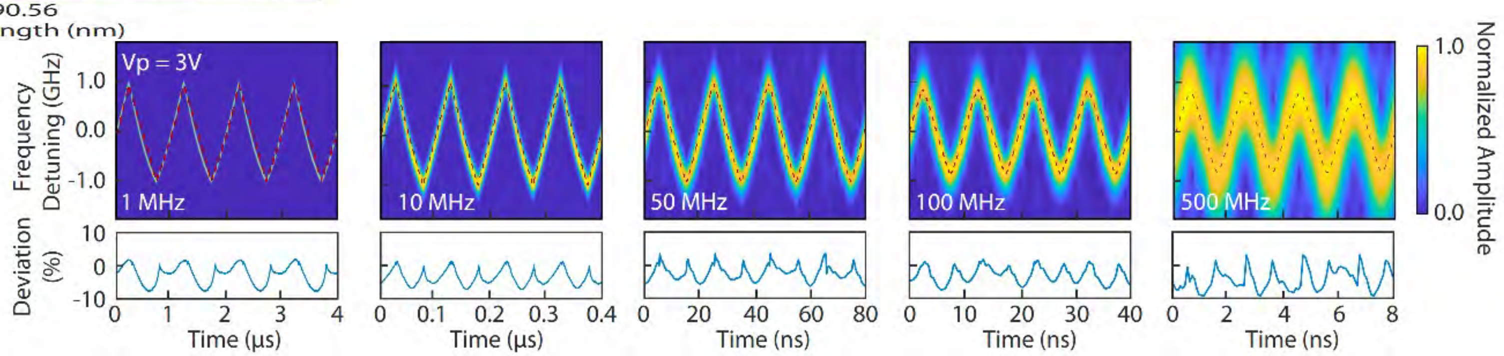
TFLN: Integrated Pockels laser: Gain plus LiNbO3

III-V gain + Lithium niobate based external cavity

- Record Fast frequency modulation (chirping), 2 × 10^{18} Hz/s
- Fast wavelength switch(50 MHz)
- Dual-wavelength lasing (telecom + visible)
- Narrow linewidth maintained (~ 10 Hz)







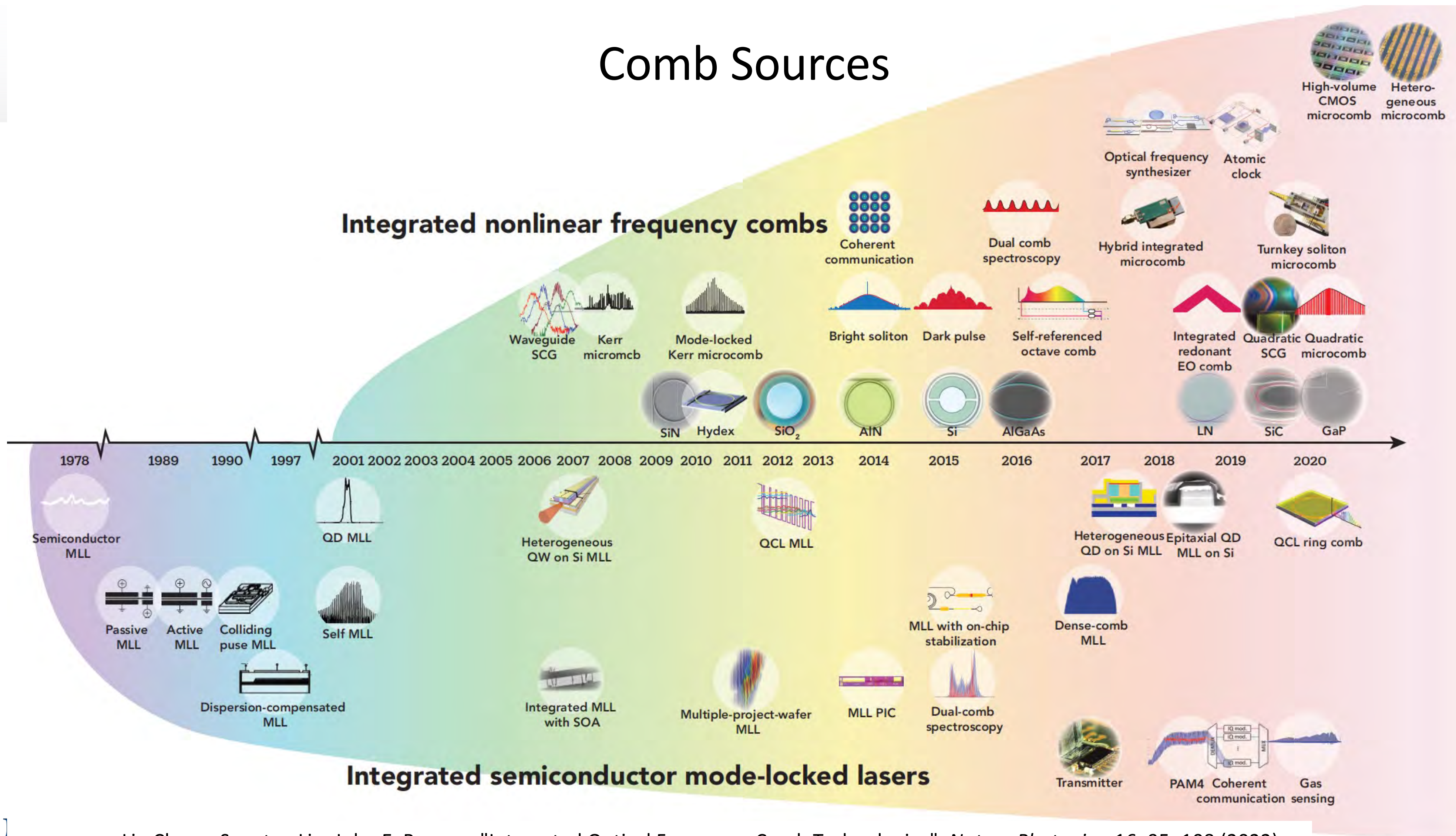
UCSB Mingxiao Li, …Kerry Vahala, John Bowers, Qiang Lin, "Integrated Pockels Laser" *Nature Communications* **13**, (2022).

Comb Generation

Mode Locked Lasers

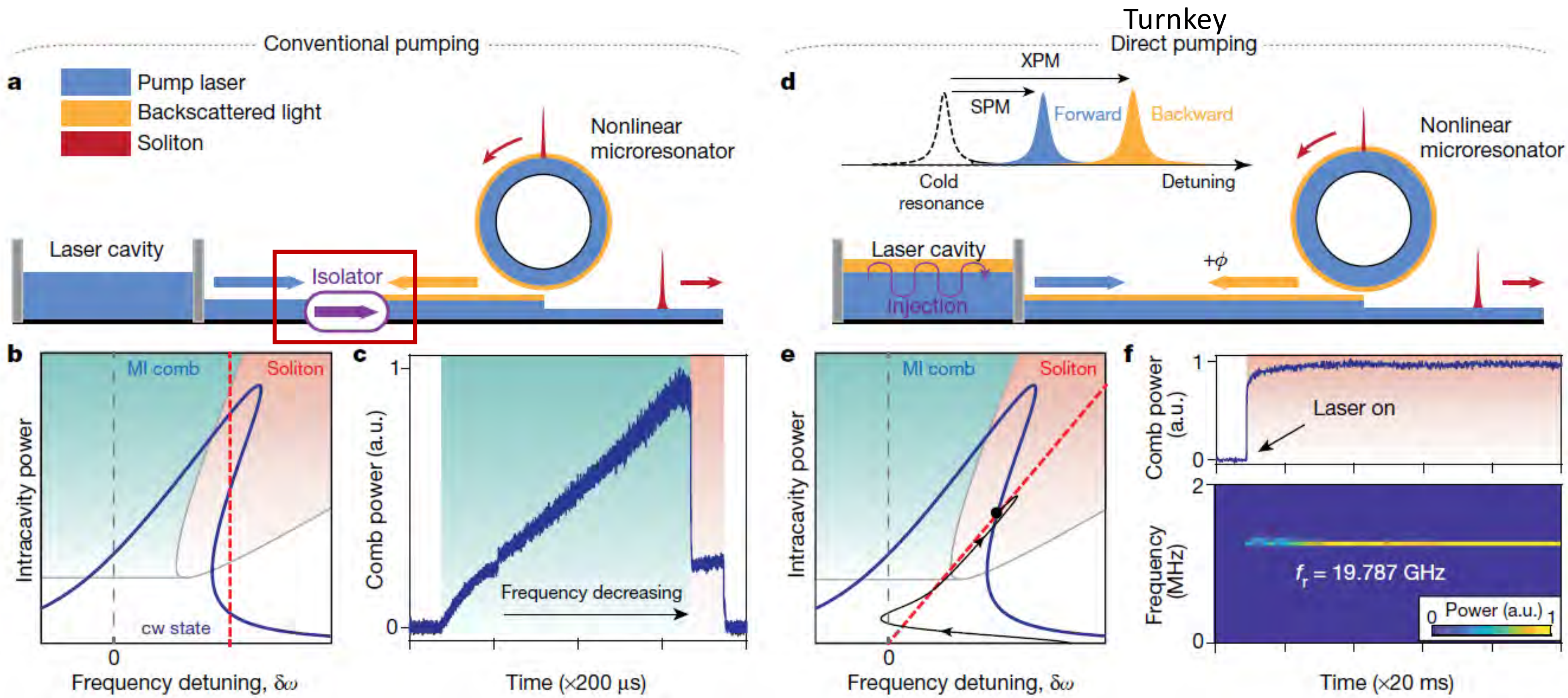
Nonlinear Combs

Comb Sources



Lin Chang, Songtao Liu, John E. Bowers, "Integrated Optical Frequency Comb Technologies", *Nature Photonics*, 16, 95–108 (2022).

Turnkey Direct pumping (self-injection locking) for microcombs



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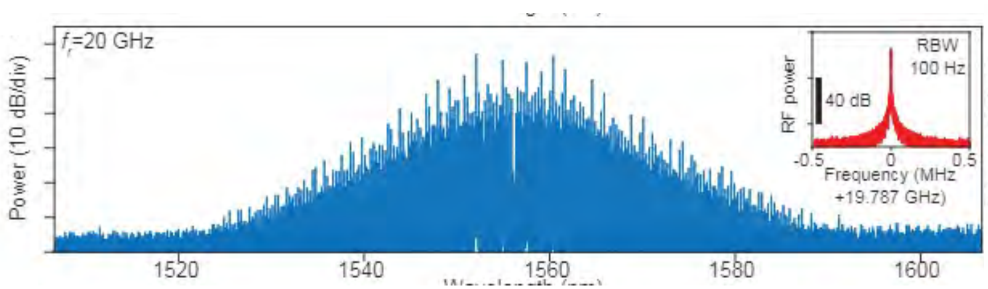
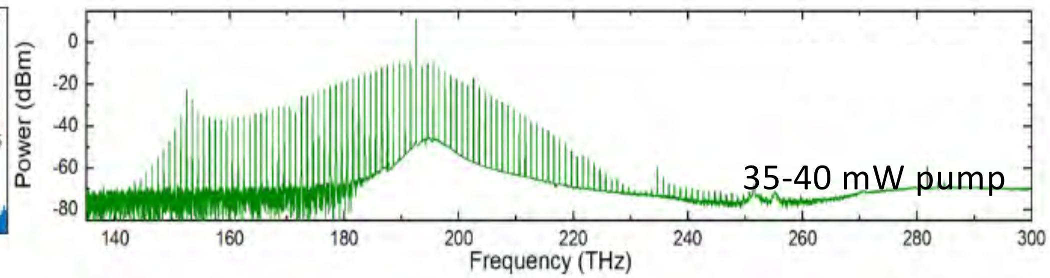
B. Shen, L. Chang J. Liu, H. Wang, Q. Yang… T. Kippenberg, K. Vahala and J. Bowers, *Nature (2020)*

Turnkey microcomb generation

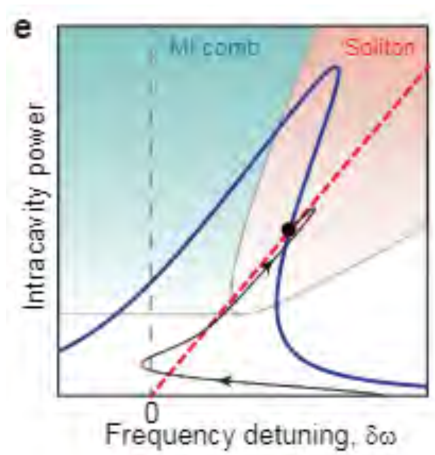
20 GHz Microwave comb

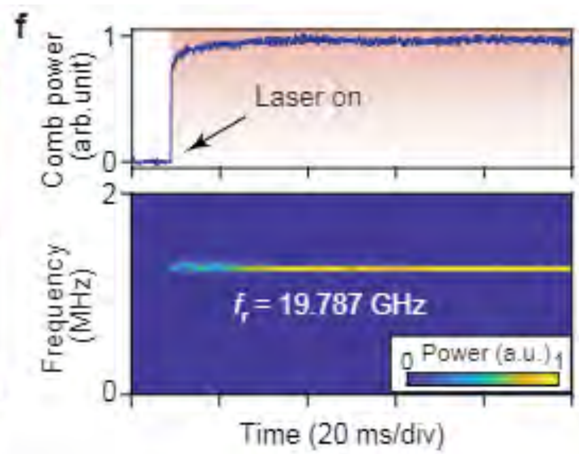


1 THz comb



Turnkey soliton generation, no tuning required





B. Shen, L. Chang J. Liu, H. Wang, Q. Yang... T. Kippenberg, K. Vahala and J. Bowers, *Nature (2020)*

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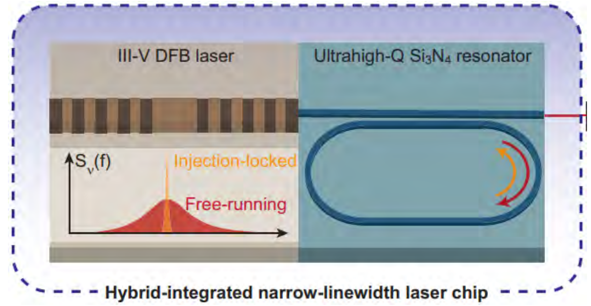
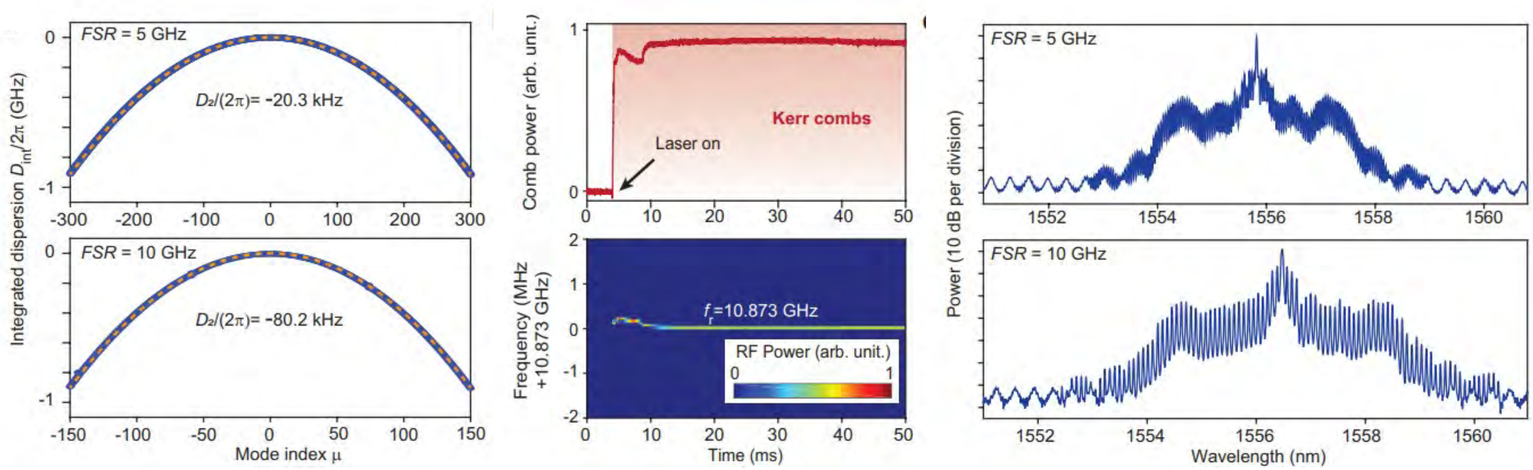
Dark pulse generation by self-injection locking

- Self-injection locking enables dark soliton generation under normal dispersion
- Get rid of the SiN thickness requirement for dispersion engineering
- Turnkey operation enabled for soliton generation



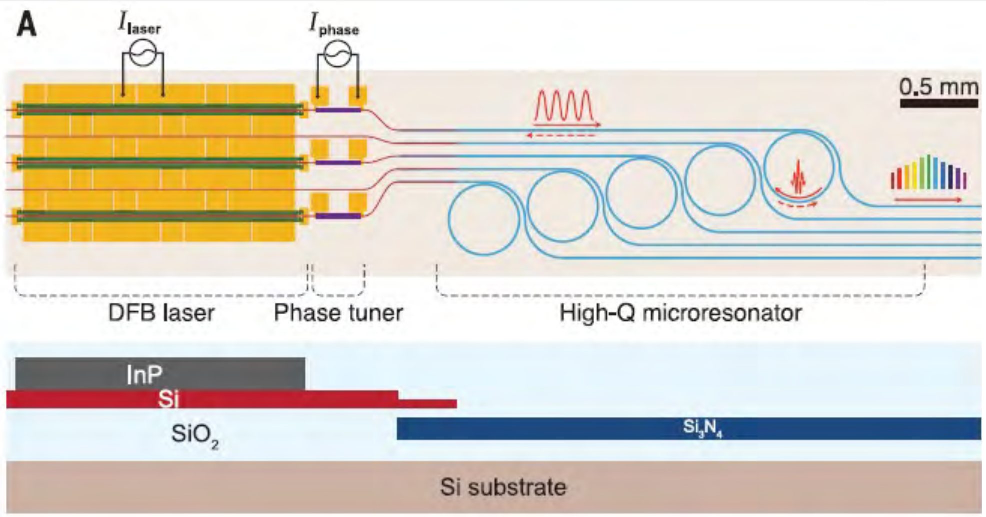
First CMOS-foundry-based microcomb production!

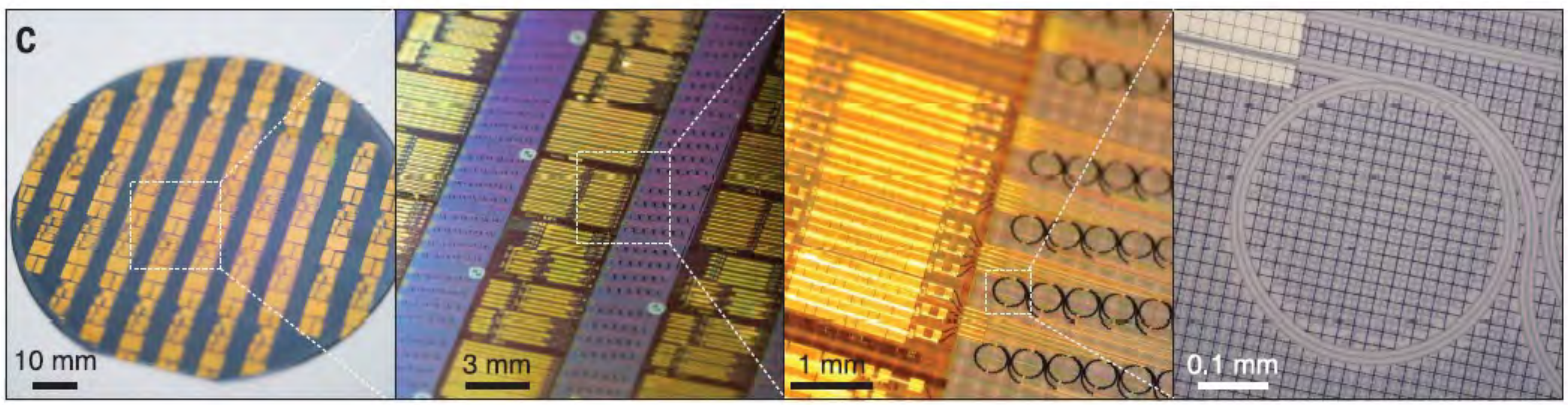


Demonstrated by Bowers group and Vahala group at 2021

Heterogeneously integrated laser soliton microcomb

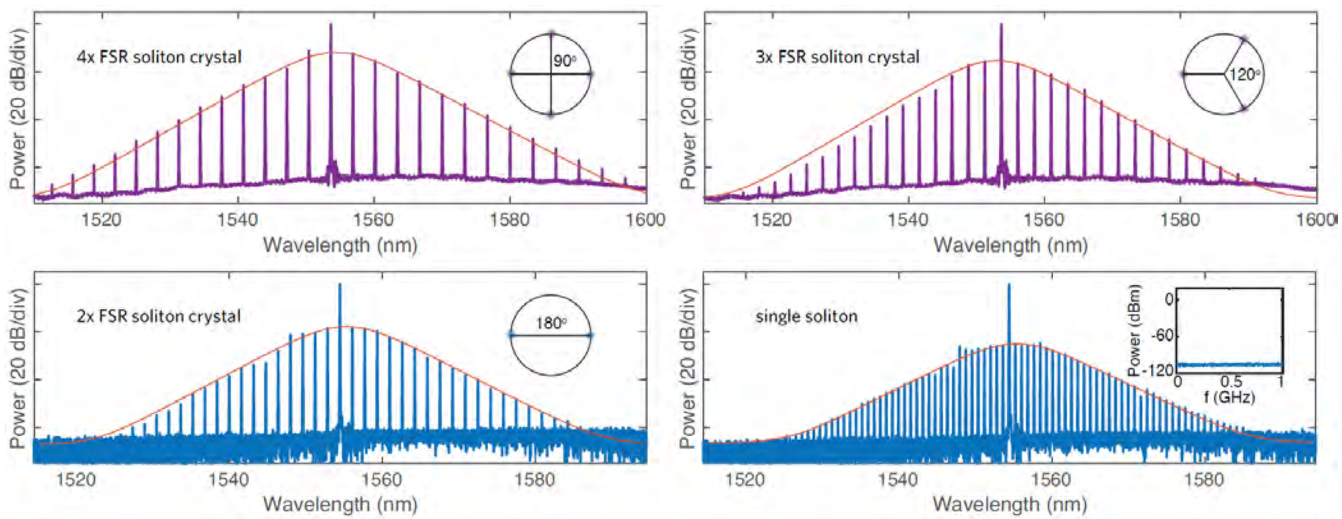
- Output single soliton (100 GHz repetition rate) and soliton crystal state
- Fully electrical current initiated and controlled
- Wafer-scale heterogeneous process





Xiang, Liu,…, Kippenberg, Bowers, 'Laser soliton microcombs heterogeneously integrated on silicon', *Science* 2021

Heterogeneously integrated laser soliton microcomb



- Current initiated and controlled soliton generation
- Soliton states dependent on the laser-resonance detuning, controlled by laser current and phase tuner current
- Manually tuned into soliton states, without feedback or sweep
- Very stable soliton without feedback, hours operation in lab environment

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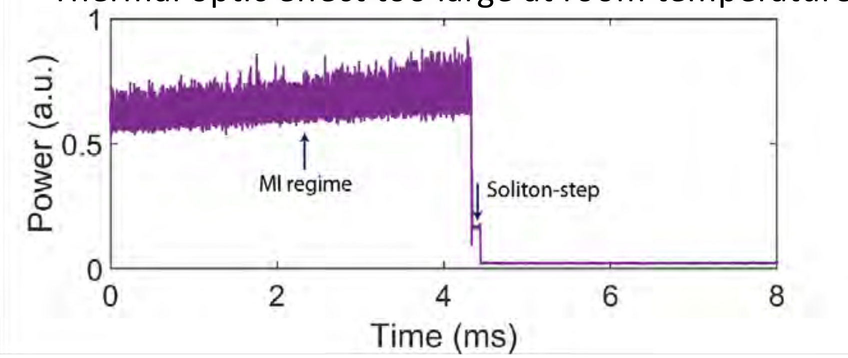
Soliton generation in AlGaAsOI resonator

Challenges:

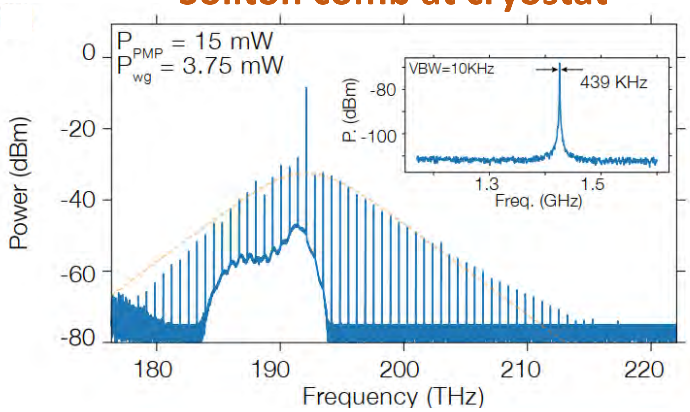
Soliton step observed

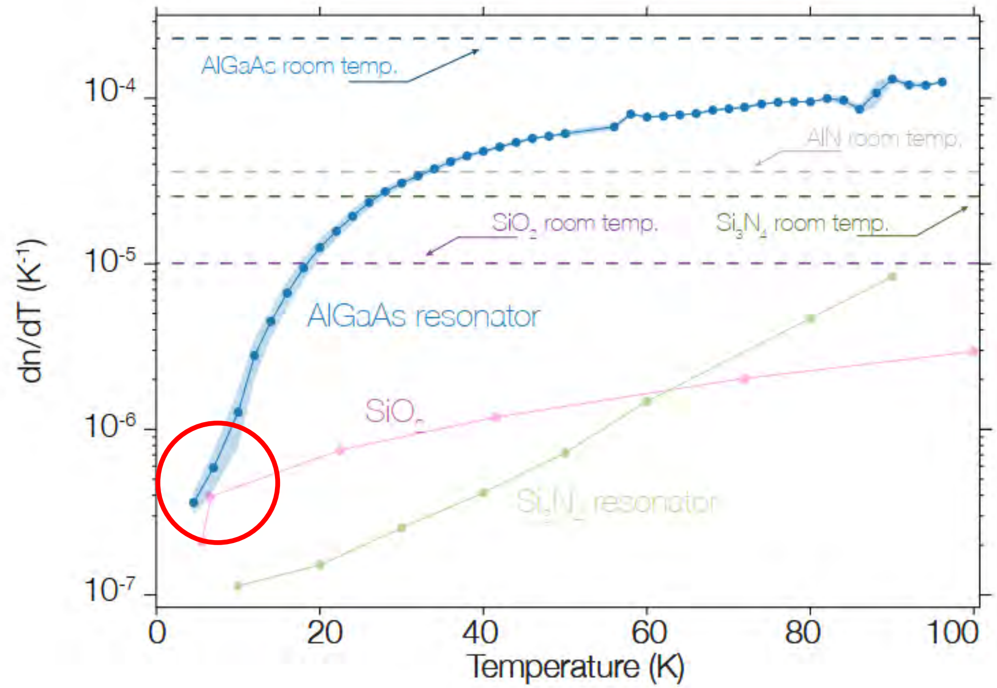
Thermal optic effect too large at room temperature



L. Chang, W. Xie, H. Shu… X. Wang, K. Vahala, J. Bowers, *Nat. Com.* (2020)

Soliton comb at cryostat





G. Moille, L. Chang… J. Bower, K. Srinivasan *Laser & Photonics Rev.* (2020)

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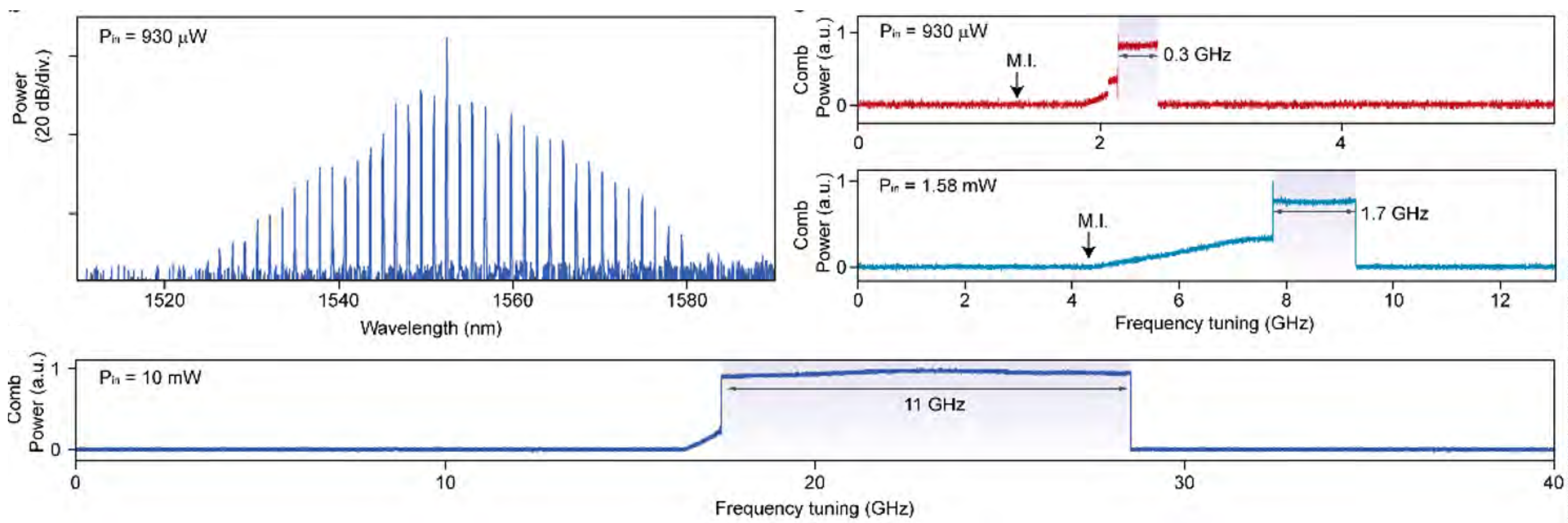
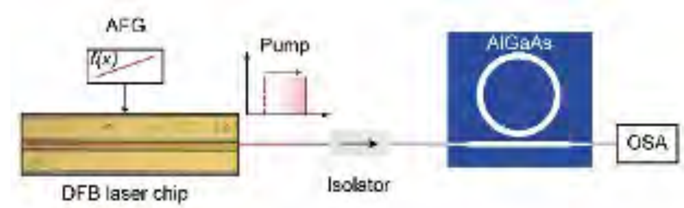
AlGaAsOI dark pulse generation



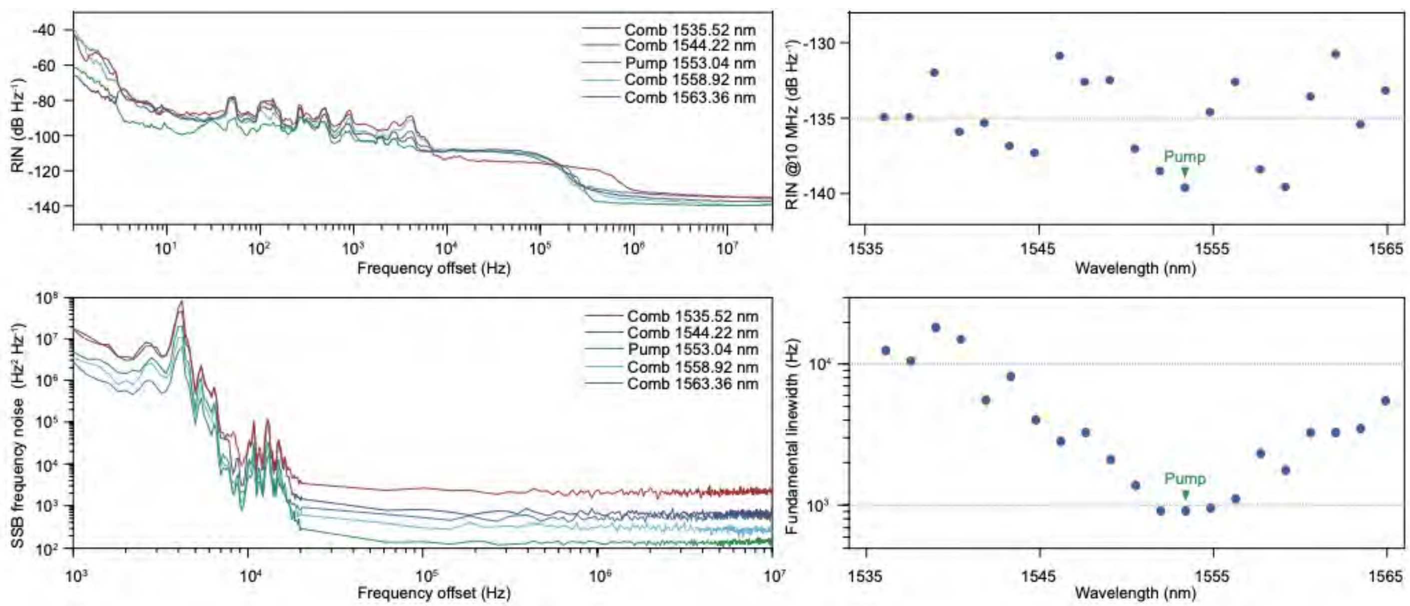
- Operating at blue detuning side of resonance (thermally stable)
- Record low threshold of coherent comb generation (< 1 mW)
- High conversion efficiency (> 15% at 10 mW)
- Wide access window (> 11 GHz at 10 mW)



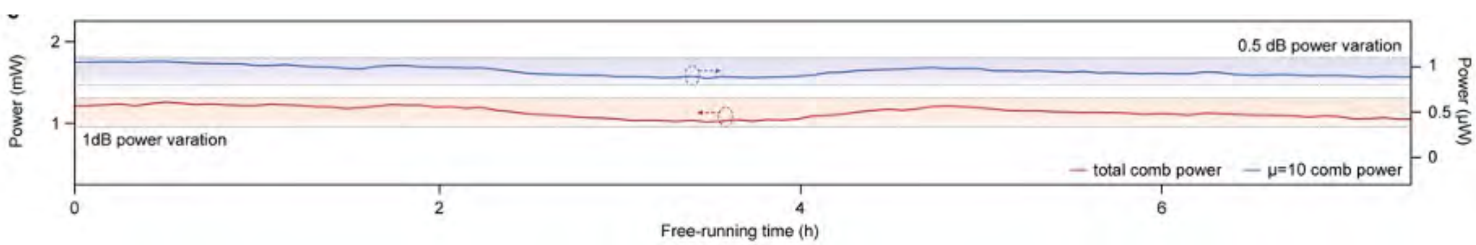
H. Shu, L. Chang… X. Wang, J. Bowers, Arxiv: 2112.08904

Noise measurement of free running comb

Coherency is good enough for many applications



Great long-term stability (> 7 hours, power variation due to the drift of lensed fiber)



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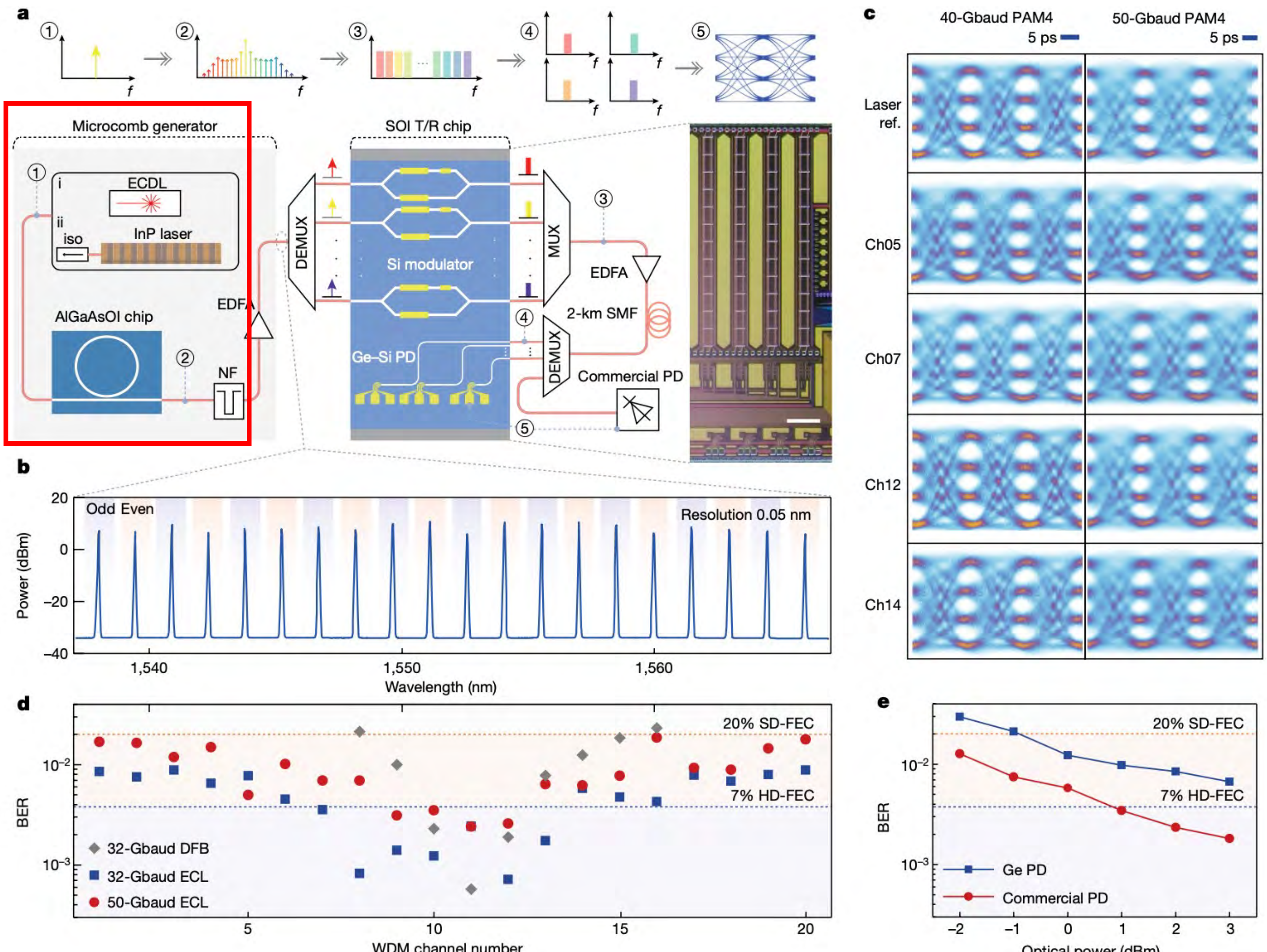
H. Shu, L. Chang… X. Wang, J. Bowers, Arxiv: 2112.08904

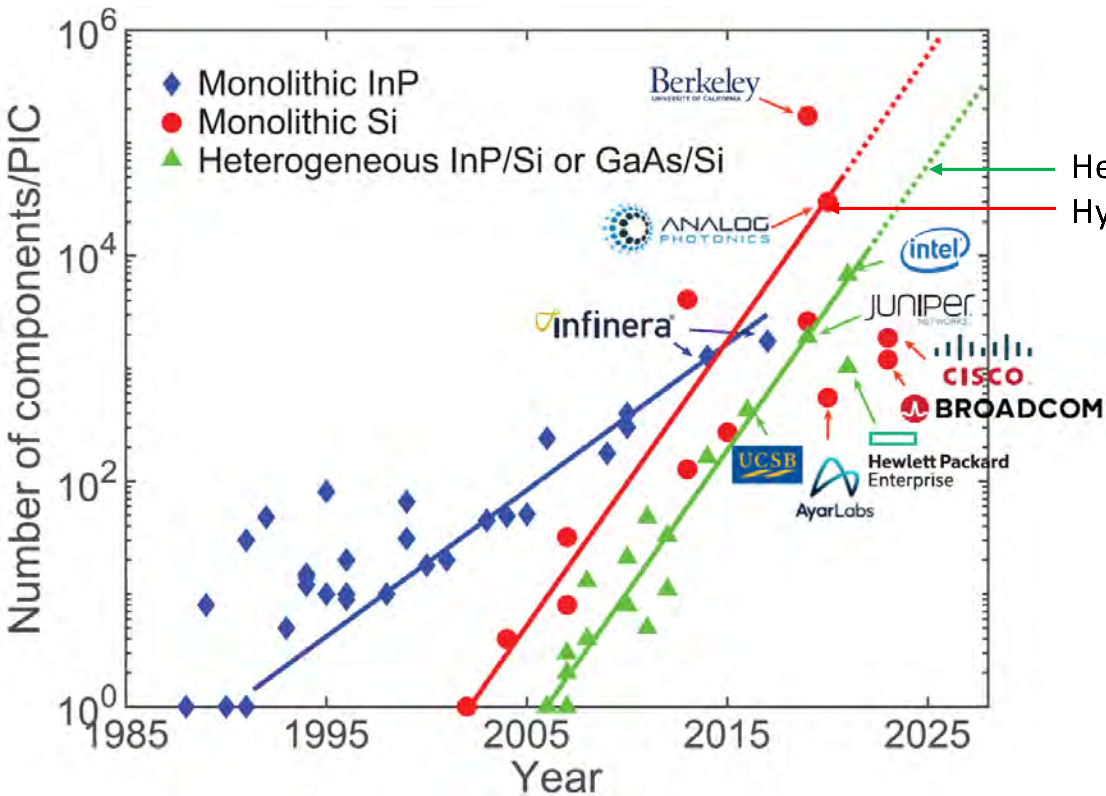
DWDM Comb Experiment

2 Tbps
20 wavelengths
PAM-4
50 Gbaud



UCSB H. Shu et al., “Microcomb-driven silicon photonic systems” Nature (2022)

There is a silicon photonics revolution happening!



Complicated, high performance PICs are being commercialized on **silicon** substrates (Intel, Cisco, Broadcom, Juniper Networks,…) in high volume.

Heterogenous lags

Hybrid by 2 years

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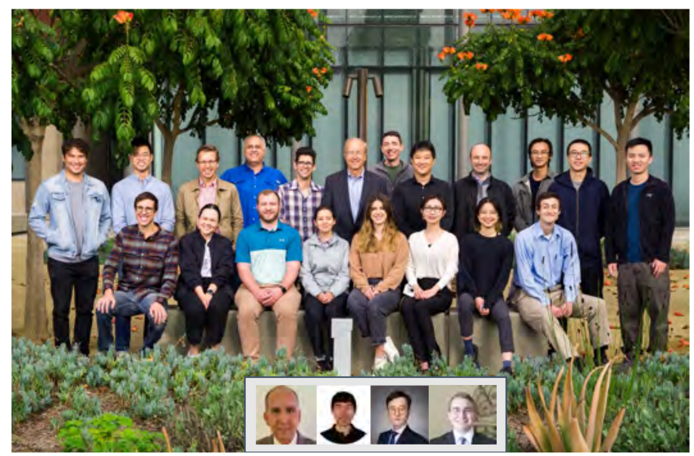

UCSB Margalit, Xiang, Bowers, Bjorlin, Blum, and Bowers, “Perspective on the Future of Silicon Photonics and Electronics”, Applied Physics Letters, (2021)