Recent developments in Heterogeneously Integrated Photonics

Enabling the transformation of photonics from boutique deployments to scale in the electronic mainstream

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CEO, Aurrion

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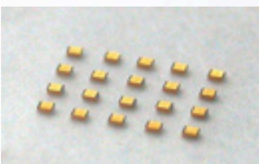
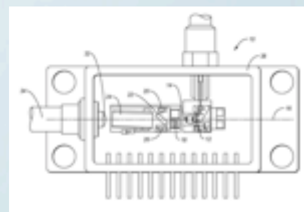
Deputy Director, American Institute for Manufacturing Integration Photonics (AIM Photonics)
Cofounder and Chairman of the Board, Aurrion

The Optics Industry Today - Boutique

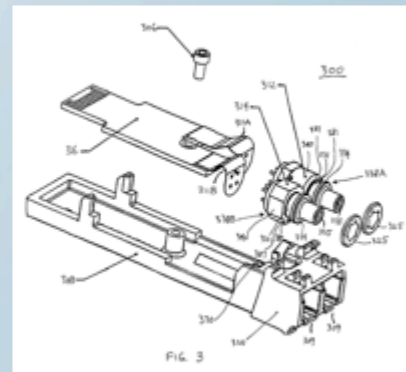
Semiconductor Chip

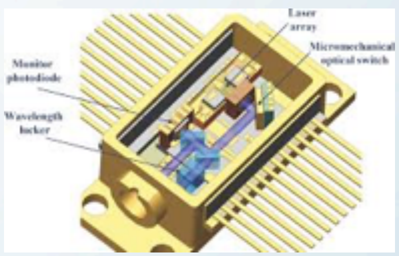


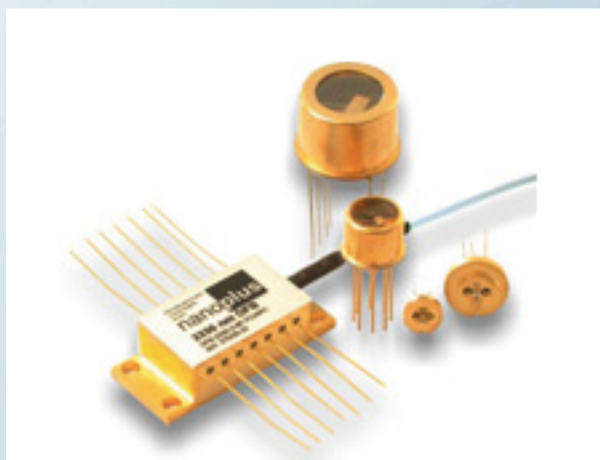
ROSA/TOSA



Pluggable







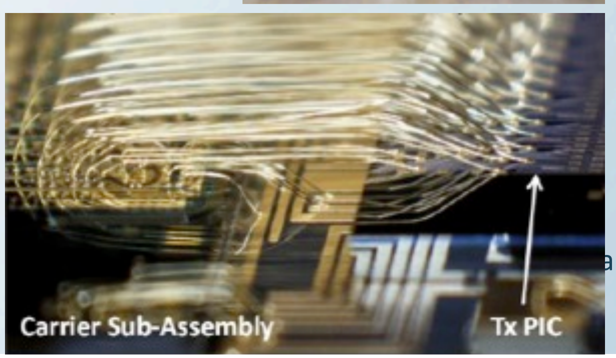
Assembly: TOSAs vs Electronics

Optics

<u>TOSA/ROSA</u>
Manual Assembly Processes

KGD at die level
Post Assembly

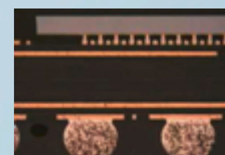
Wirebonding

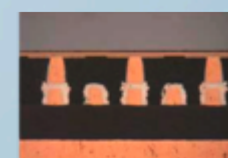


Electronics

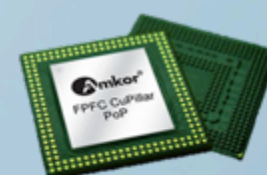
Standard Modular KGD at Wafer Scale

Standard Copper Pillar





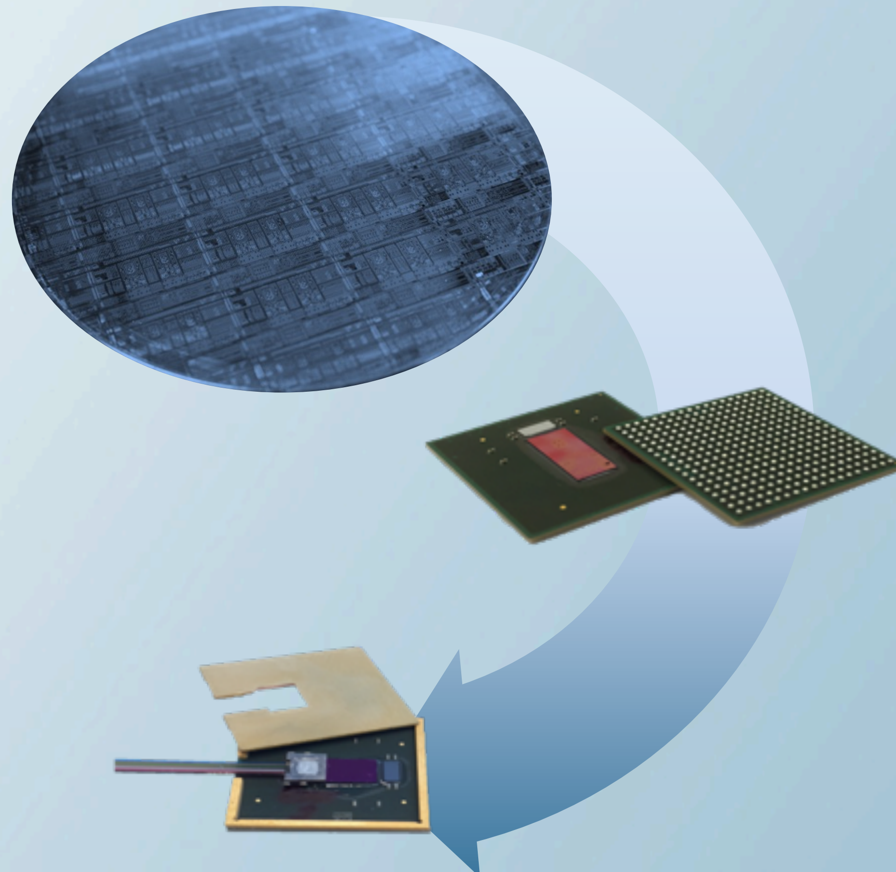
Standard Machine Assembly



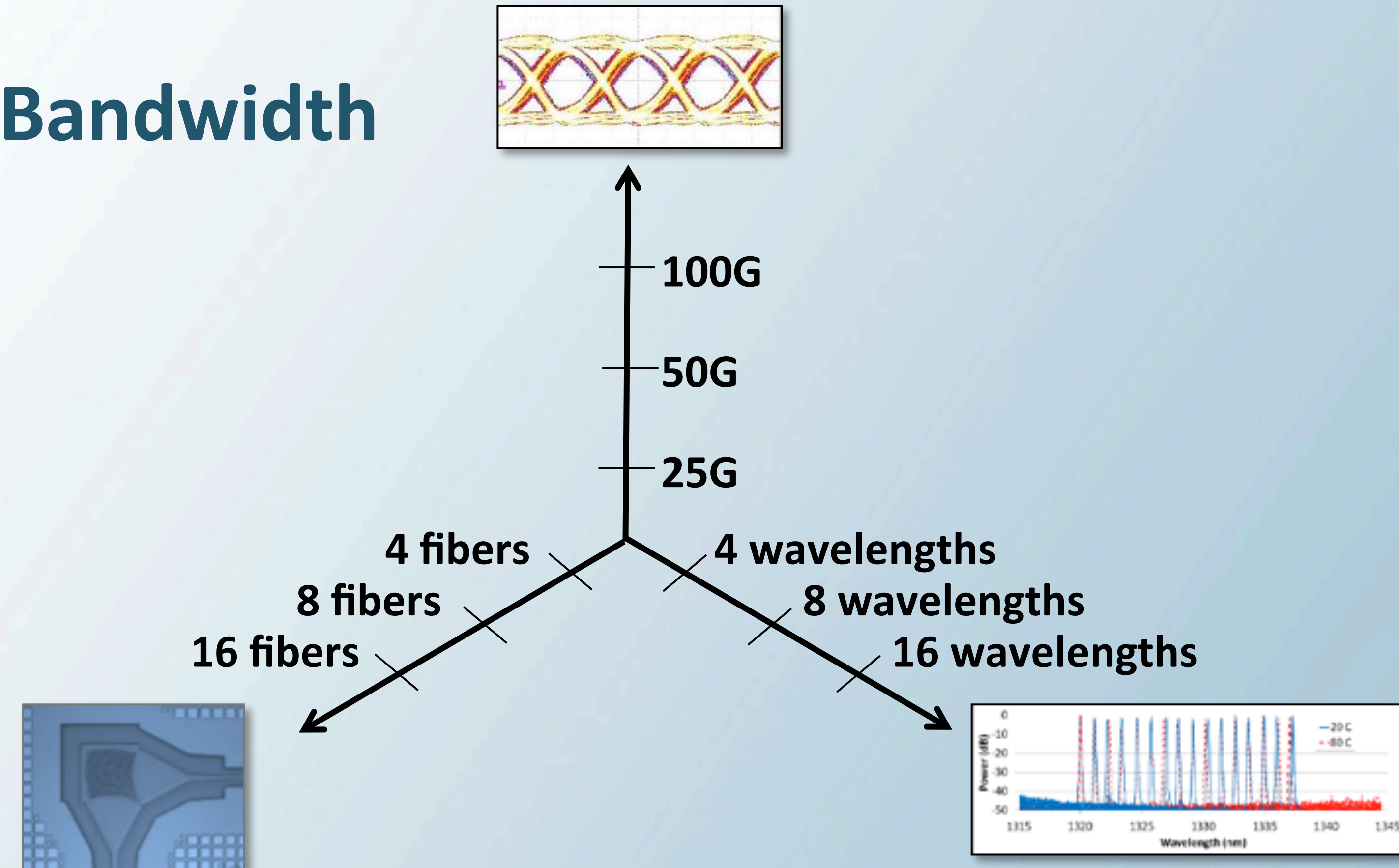
ary

Heterogeneous Photonic Circuit Manufacturing

- Silicon photonics PIC using foundries
- Assembly using silicon OSATs
- Complete BGA transceiver
- Low cost optical connector attach



Scaling Bandwidth

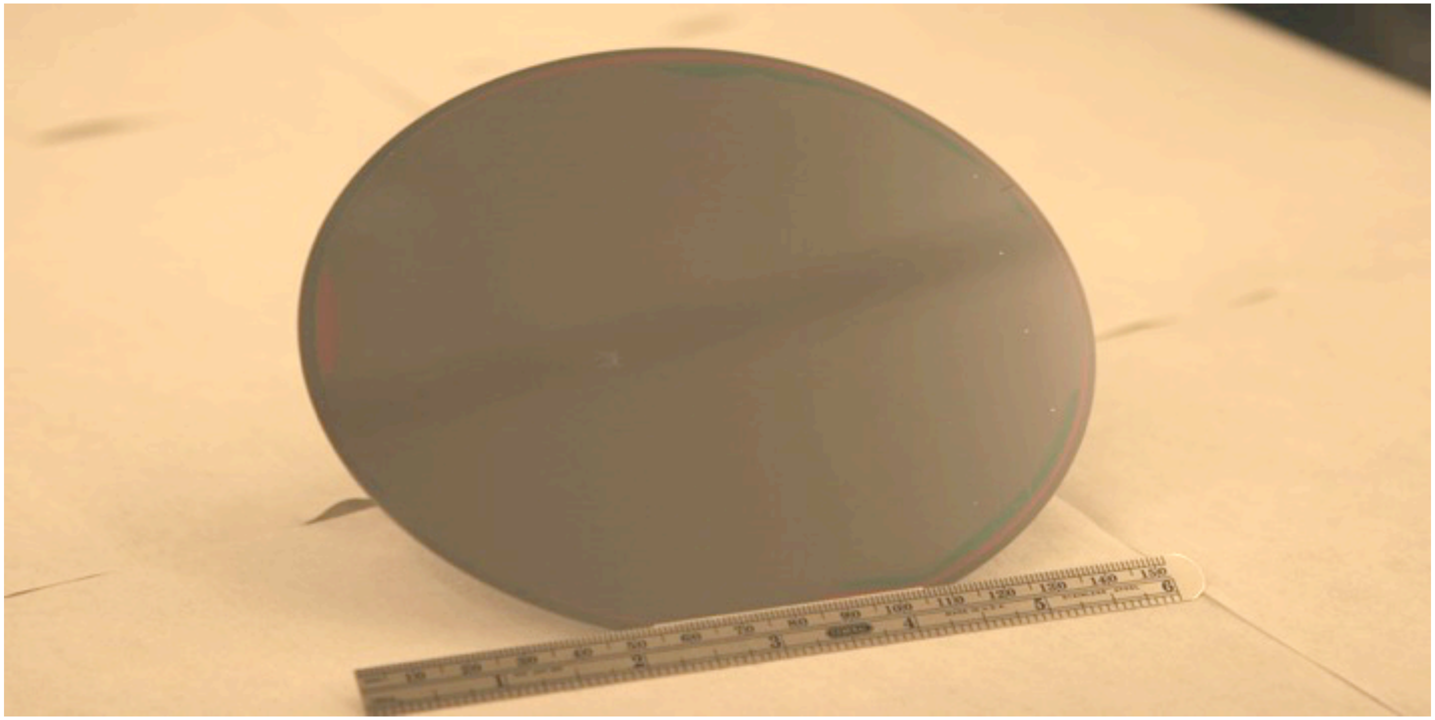


Heterogeneous Integration at UCSB

Lower loss on Silicon results in better performance: Narrower linewidth DFBs and tunable lasers-important for coherent communications and sensors.

UCSB Quantum Well Epi on 150 mm Silicon

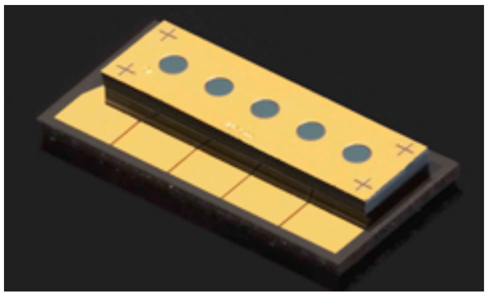
Oxygen Plasma Enhanced Molecular Bonding



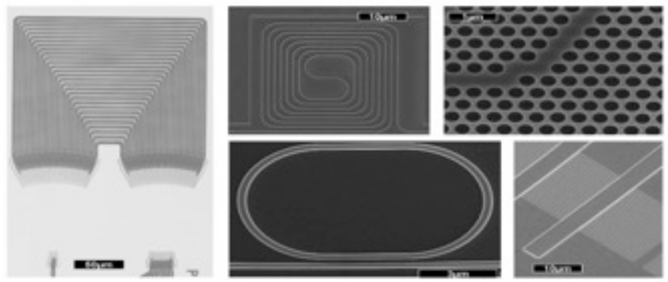
UCSB

Heterogeneous Integration of 6 Photonic Platforms

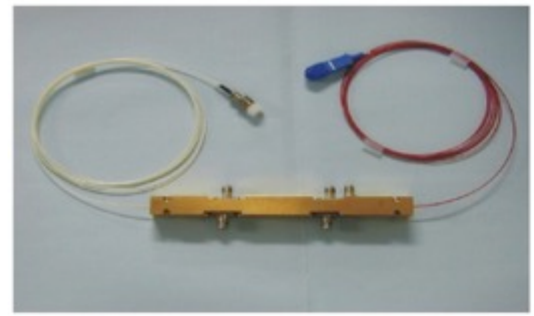
GaAs



Silicon

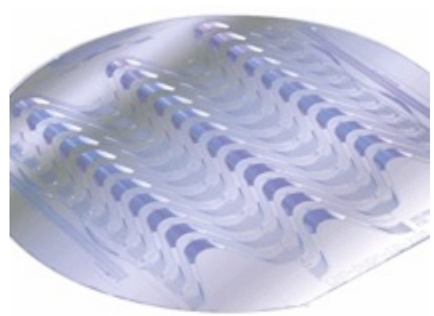


$LiNbO_3$

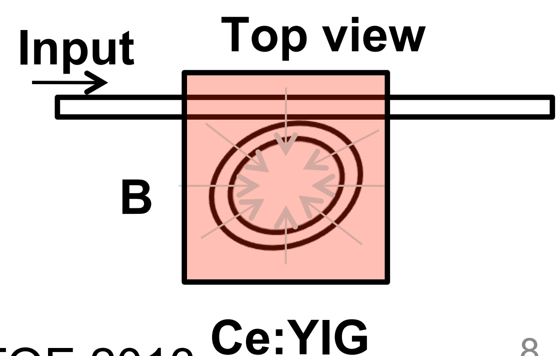


InP

SiN/SiON/SiO2

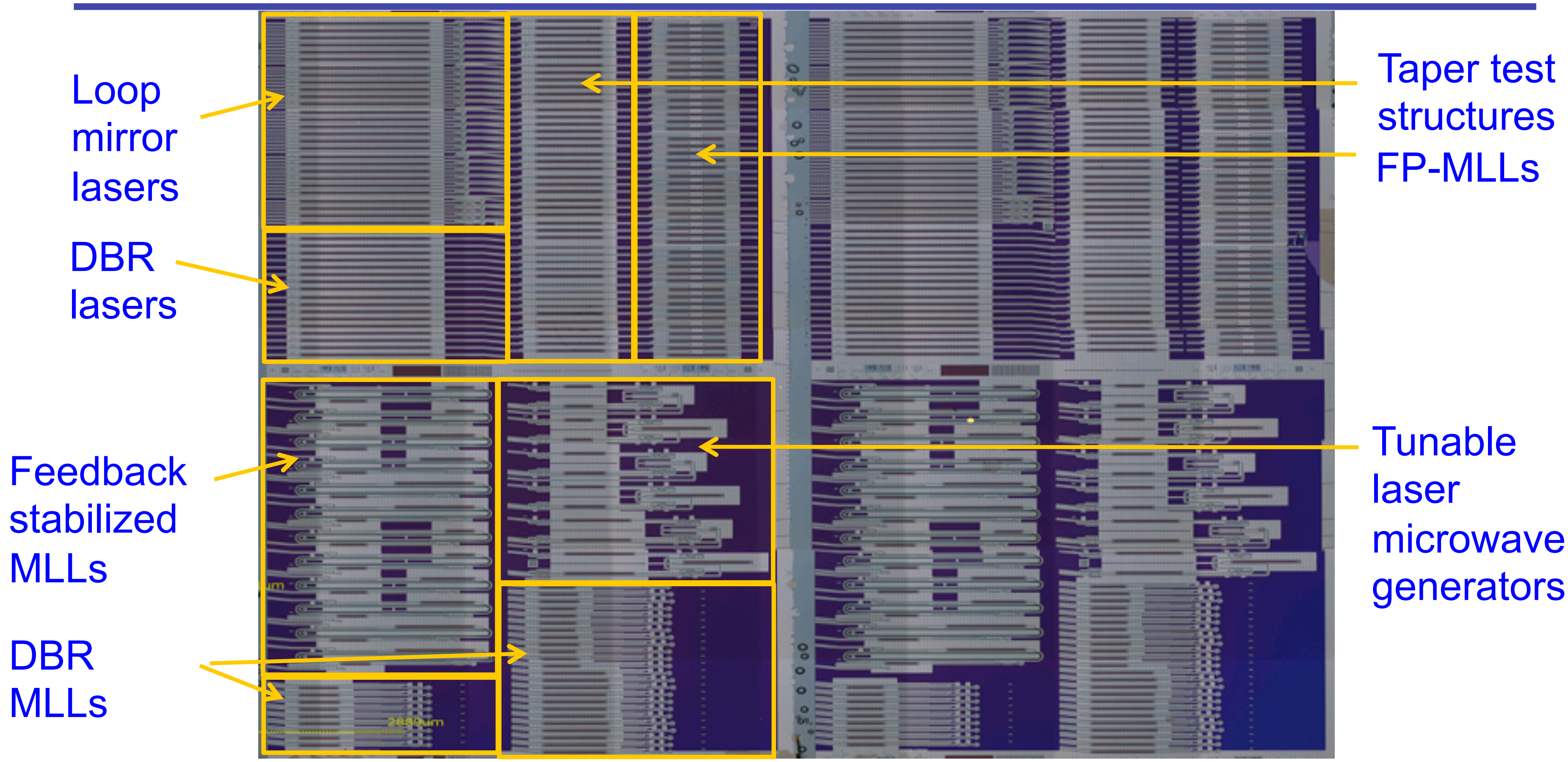


Ce:YIG Isolator



Tutorial: Komljenovic et al., JLT 2015, Heck et al. JSTQE 2013

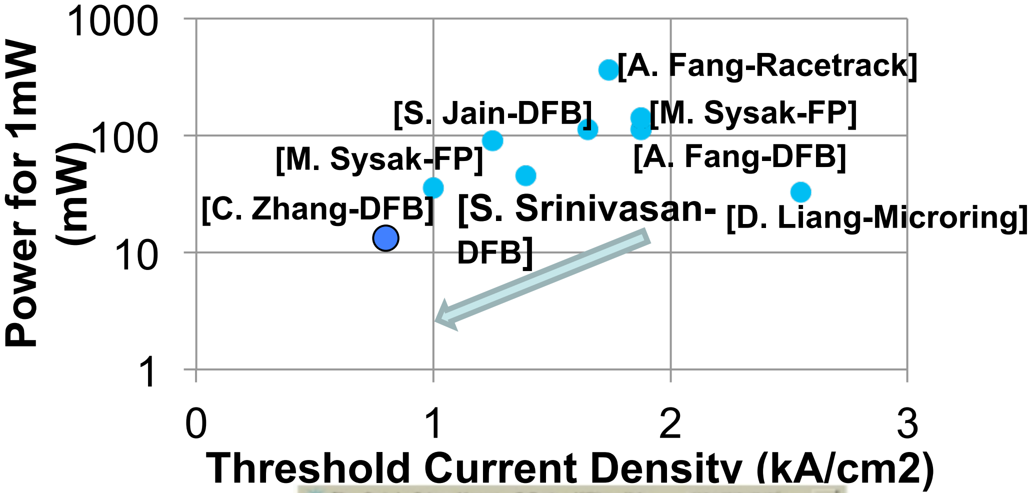
UCSB Shuttle Run

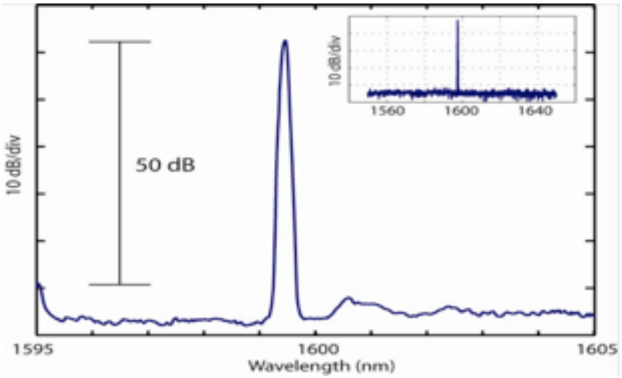


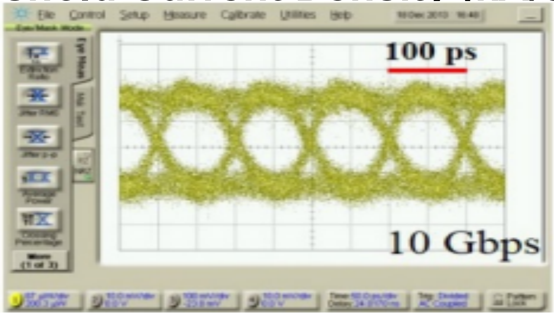
Courtesy Mike Davenport

DFB Quantum Well Hybrid Silicon Lasers

Chip showing 300 DFB lasers with yield >95%





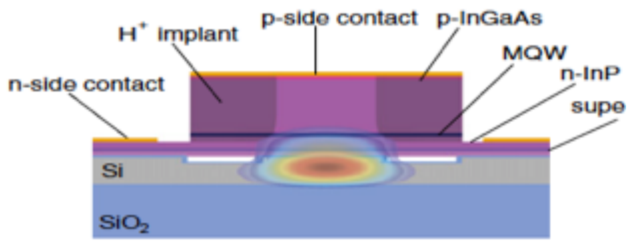


10Gbps direct modulation of a 200μm DFB laser

S. Srinivasan, et al. “Design of phase shifted hybrid silicon distributed feedback lasers”, Optics Express 2011
C. Zhang, et al. "Low threshold and high speed short cavity distributed feedback hybrid silicon lasers", Optics Express 2014

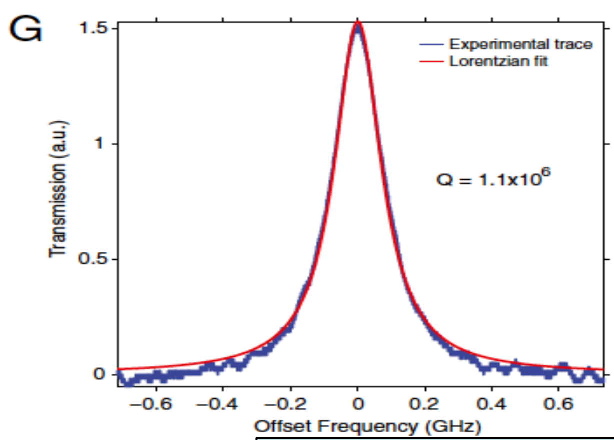
High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III-V platforms

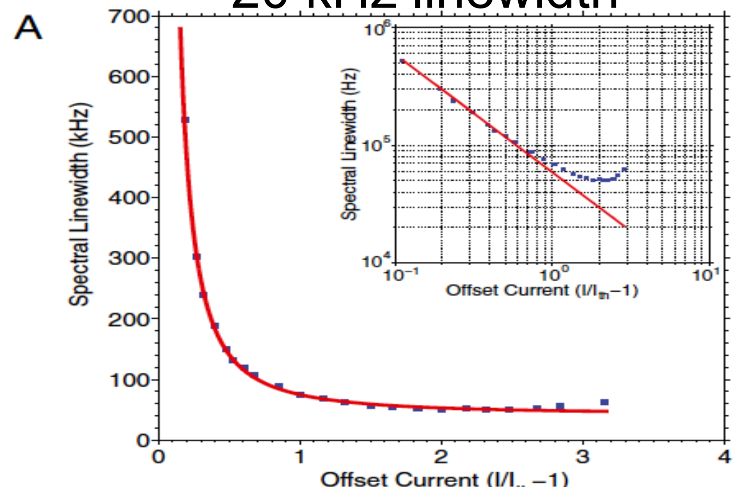
Christos Theodoros Santis[1], Scott T. Steger, Yaakov Vilenchik, Arseny Vasilyev, and Amnon Yariv[1]



$$(\Delta\nu)_{laser} = \frac{2\pi h \nu_o^3 \mu (1+\alpha^2)}{Q^2 P}$$

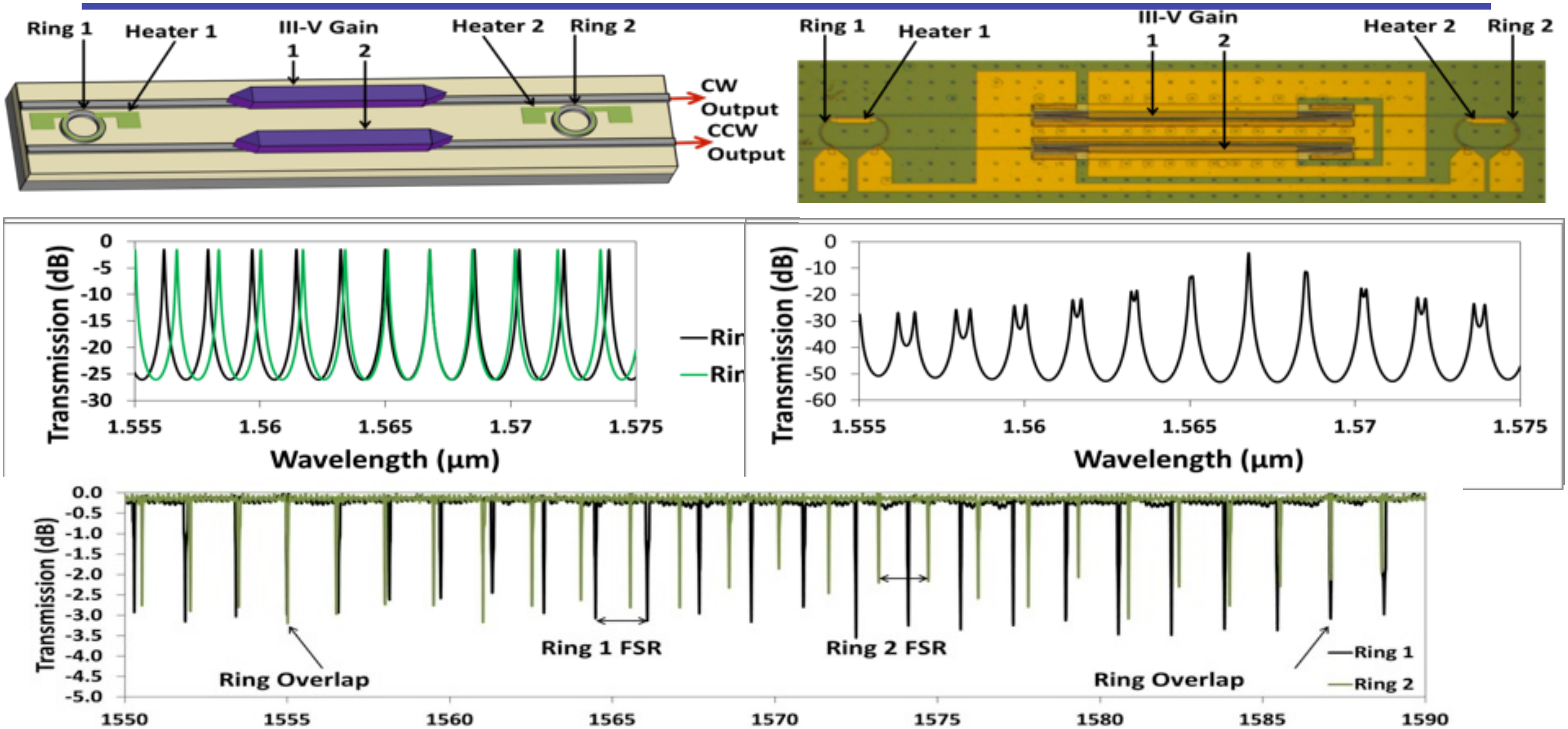
High Q (1 million)
20 kHz linewidth





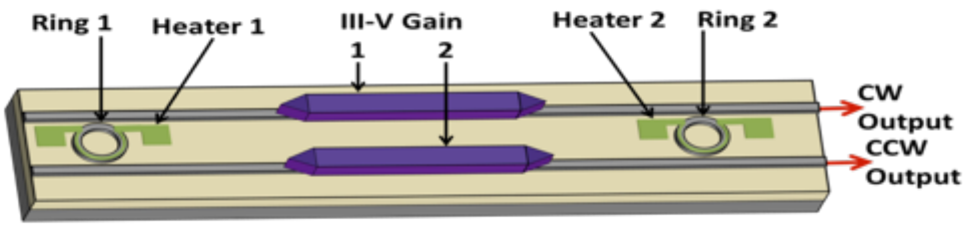
Latest: <1 kHz linewidth in a DFB laser

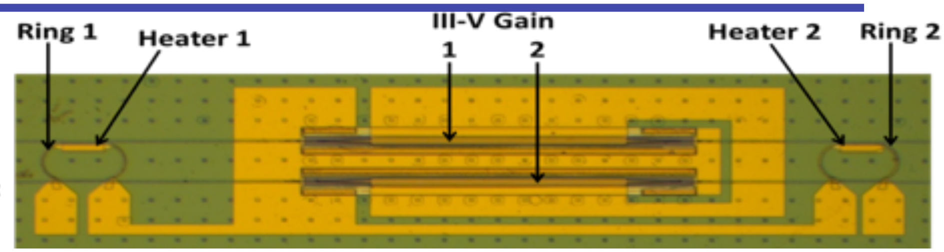
Widely Tunable Vernier Ring Laser

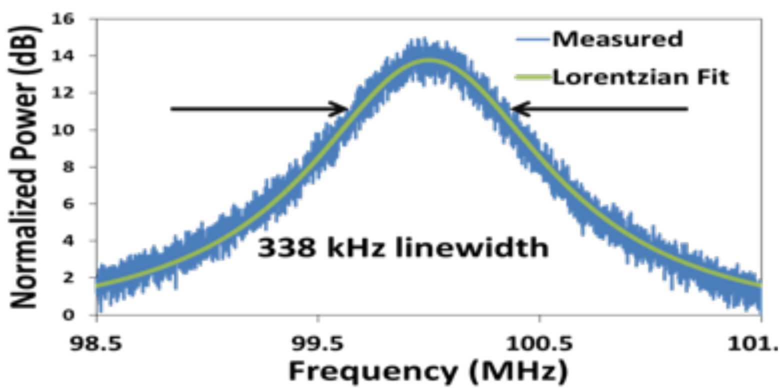


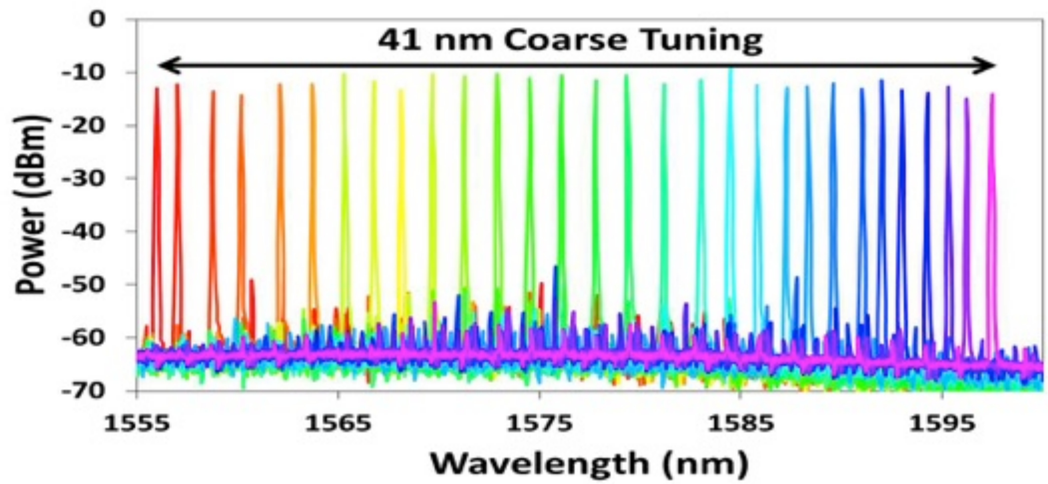
J. C. Hulme, J. K. Doylend, and J. E. Bowers, "Widely tunable Vernier ring laser on hybrid silicon," Opt. Express **21**, 19718-19722 (2013)

Widely Tunable Vernier Ring Laser







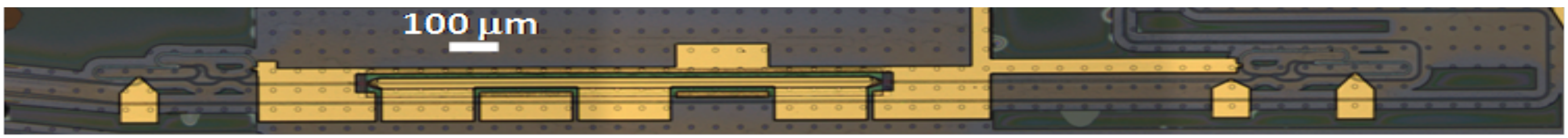


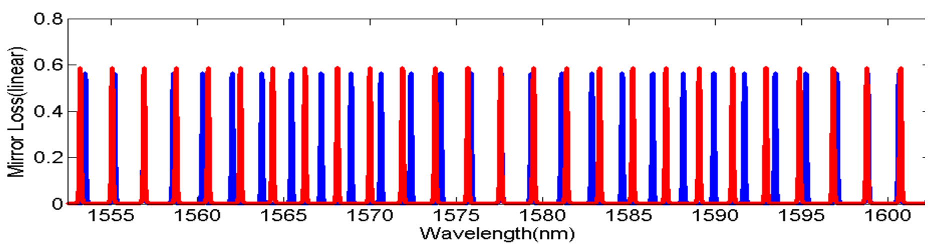
J. C. Hulme, J. K. Doylend, and J. E. Bowers, "Widely tunable Vernier ring laser on hybrid silicon," Opt. Express **21**, 19718-19722 (2013)

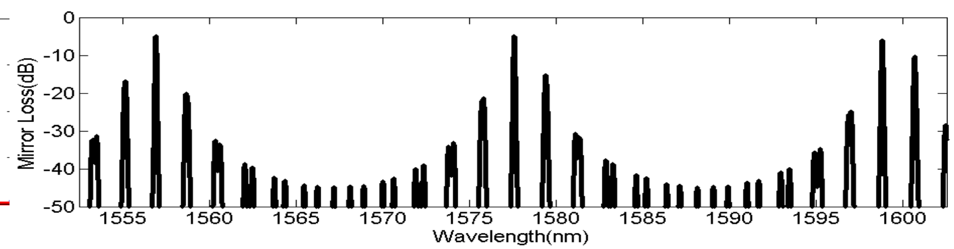
Narrow linewidth tunable laser using coupled resonator mirrors

OFC 2015

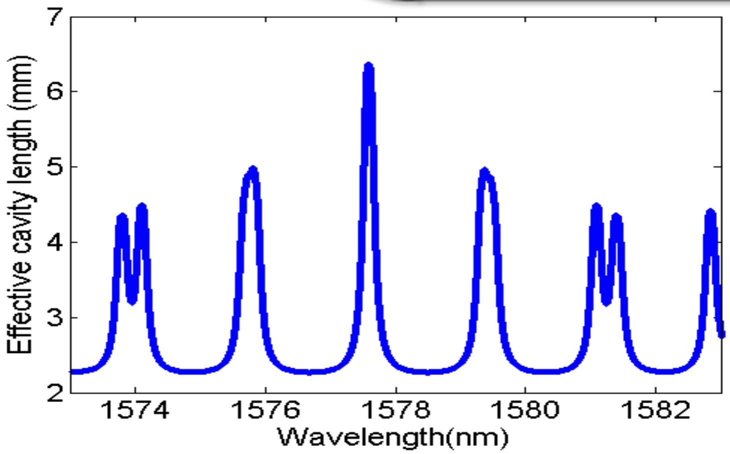
Tin Komljenovic, Michael Davenport, Sudharsanan Srinivasan, Jared Hulme, and John E. Bowers
Electrical & Computer Engineering, University of California Santa Barbara, CA 93106.
tkomljenovic@ece.ucsb.edu

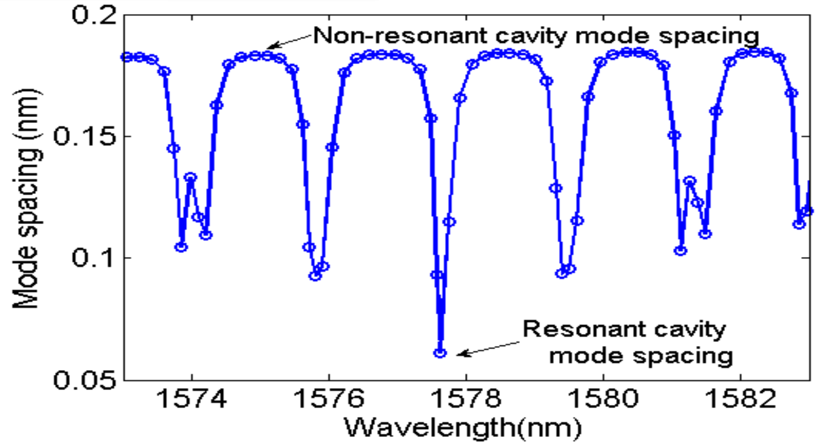






Frequency dependent cavity mode spacing

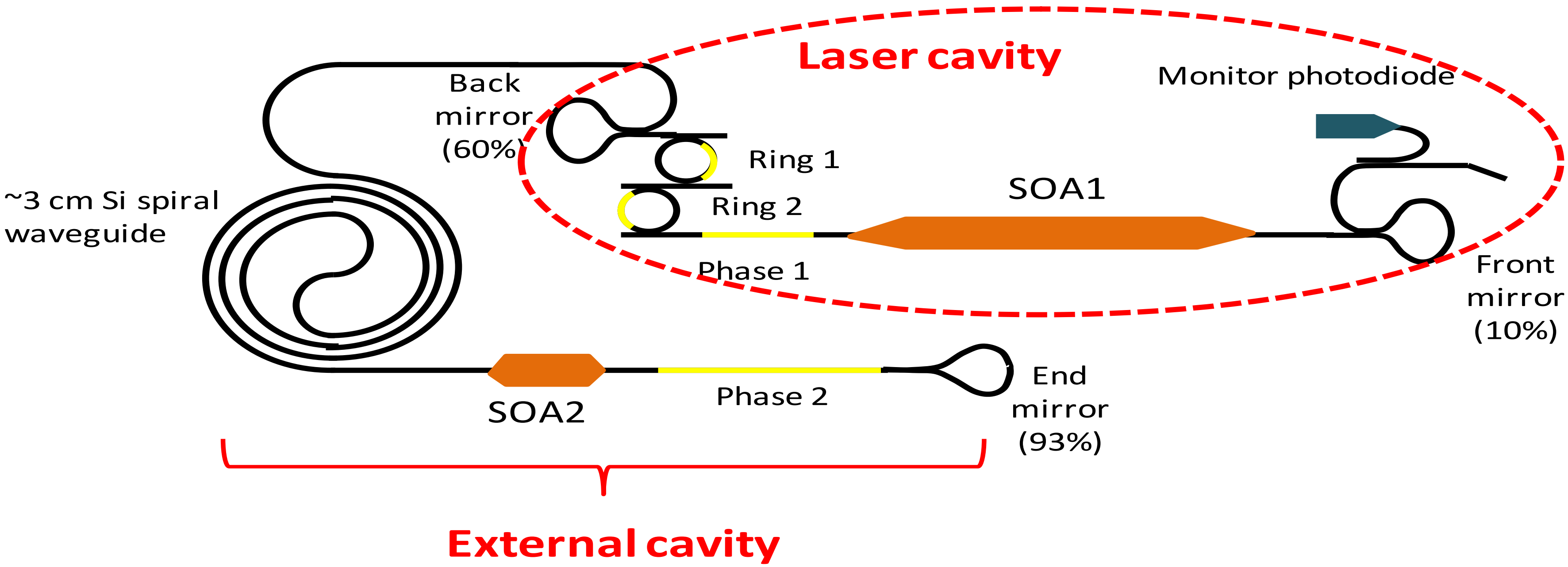




- Tuning onto resonance changes effective cavity length
- Mode spacing changing by more than a factor of two

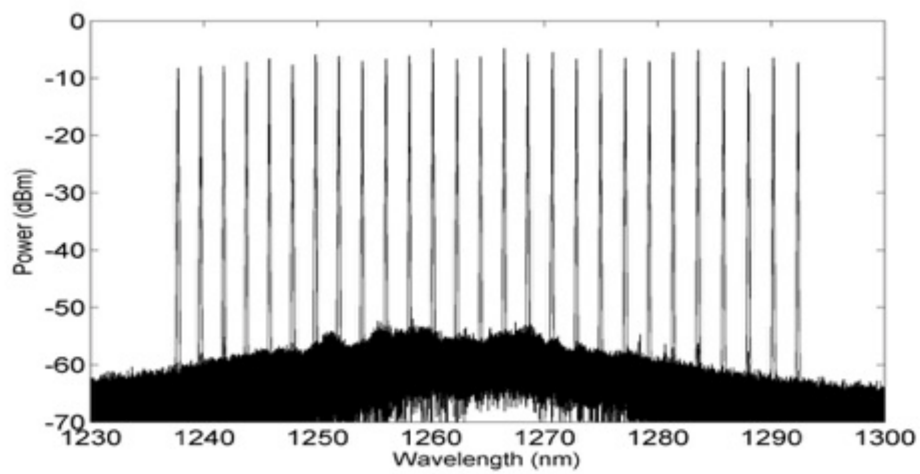
30 nm tuning 260 kHz linewidth

3d Tunable Laser Architecture



General laser performance

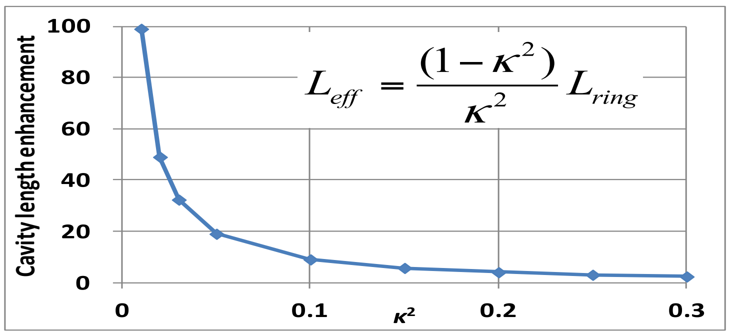
- Fabricated in an Aurrion MPW run
- 54 nm tuning range in O-band
  - 1237.7 nm to 1292.4 nm
- >45 dB SMSR
- >10 mW of output power
- 30 mA threshold

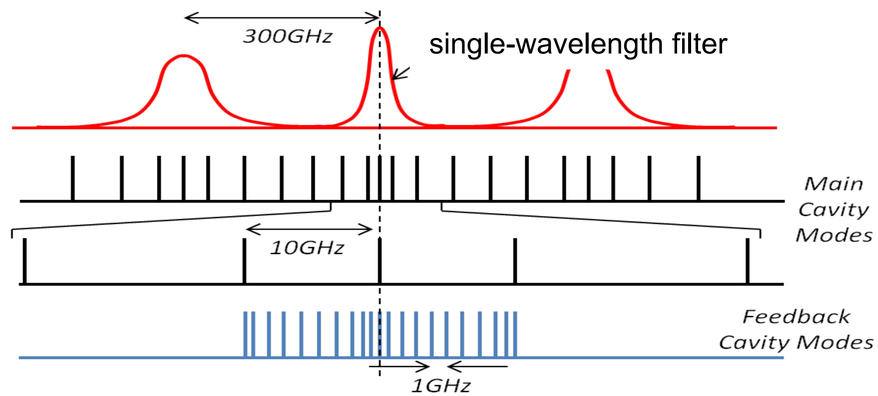


Tin Komljenovic et al., JSTQE (2015), JQE (2015), CLEO 2015

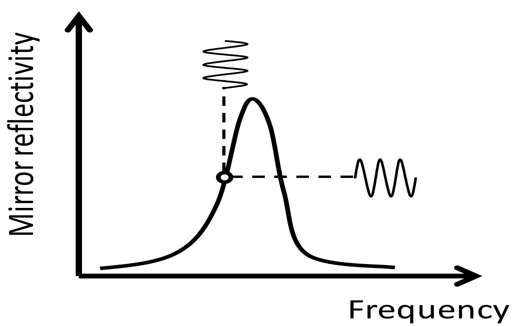
Narrow-linewidth theoretical considerations

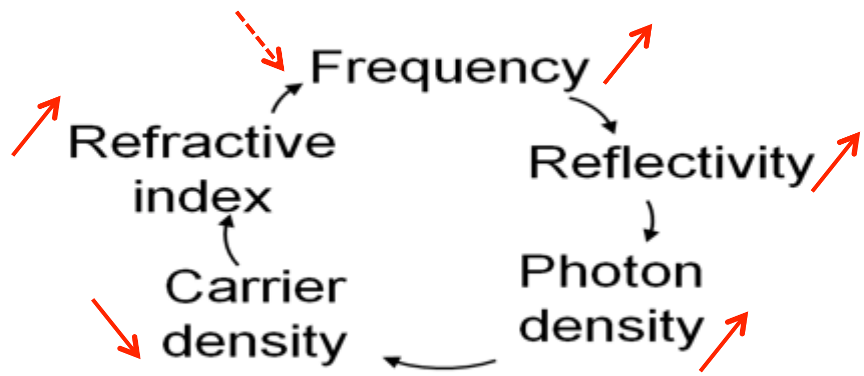
1. Resonance cavity length enhancement



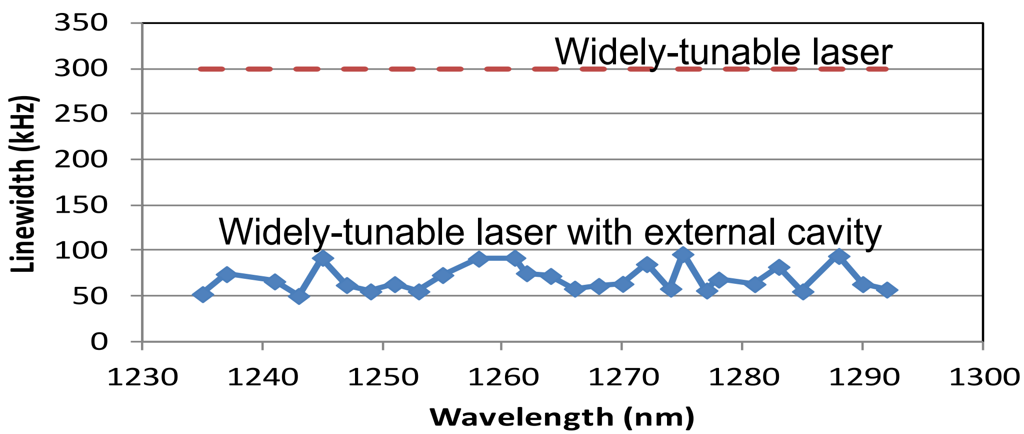


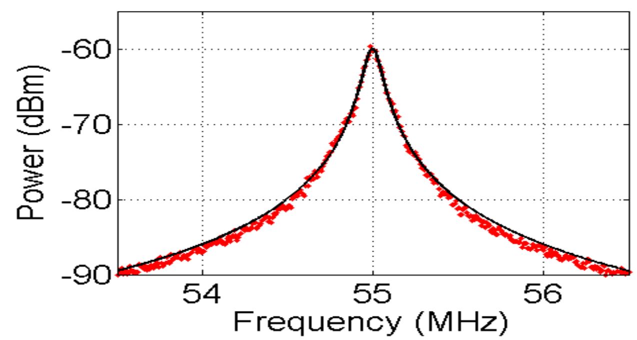
2. Negative optical feedback





Linewidth

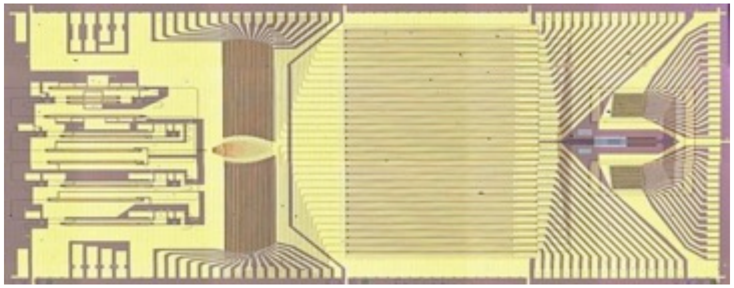




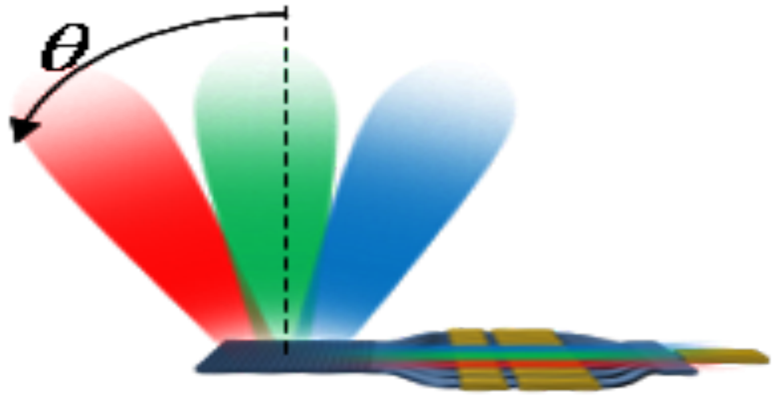
3-6x improvement due to external cavity

Fully Integrated hybrid silicon free-space beam steering source using a tunable laser phased array

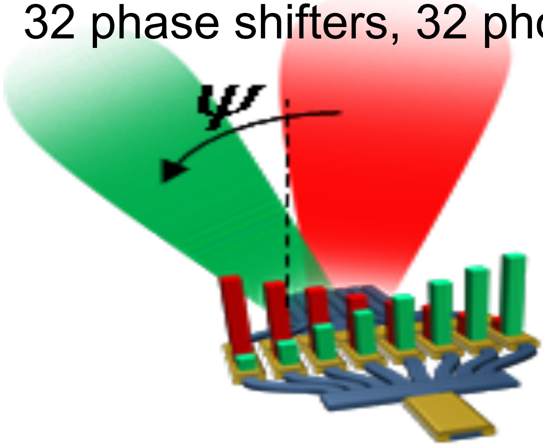
2D Scanning with
- Tunable laser and grating for θ
- Phased array emitter for ψ



4 tunable lasers, 32 amplifiers,
32 phase shifters, 32 photodetectors

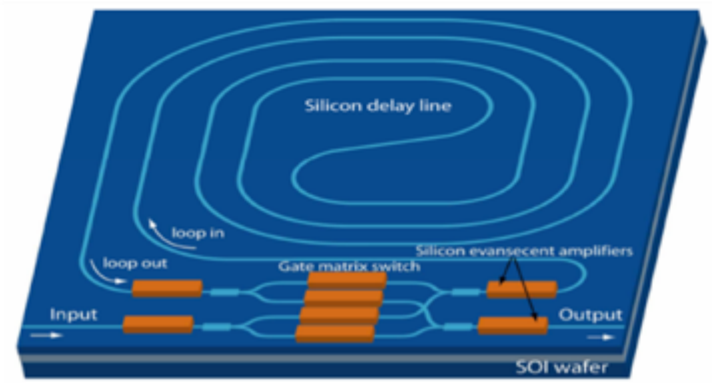


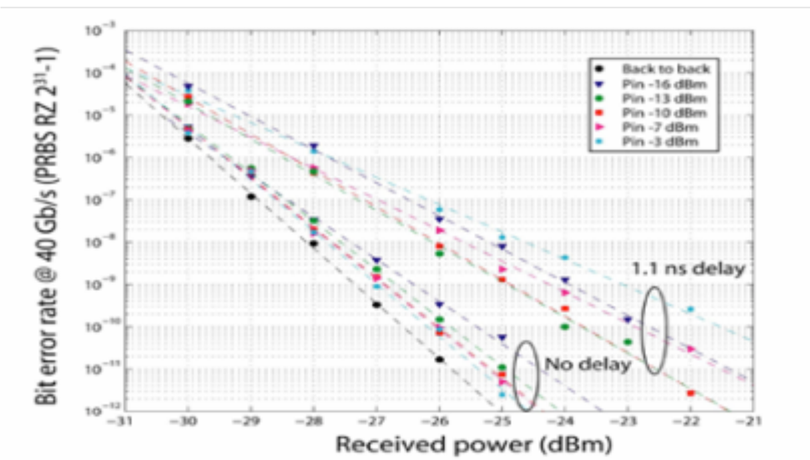
1 (wavelength)

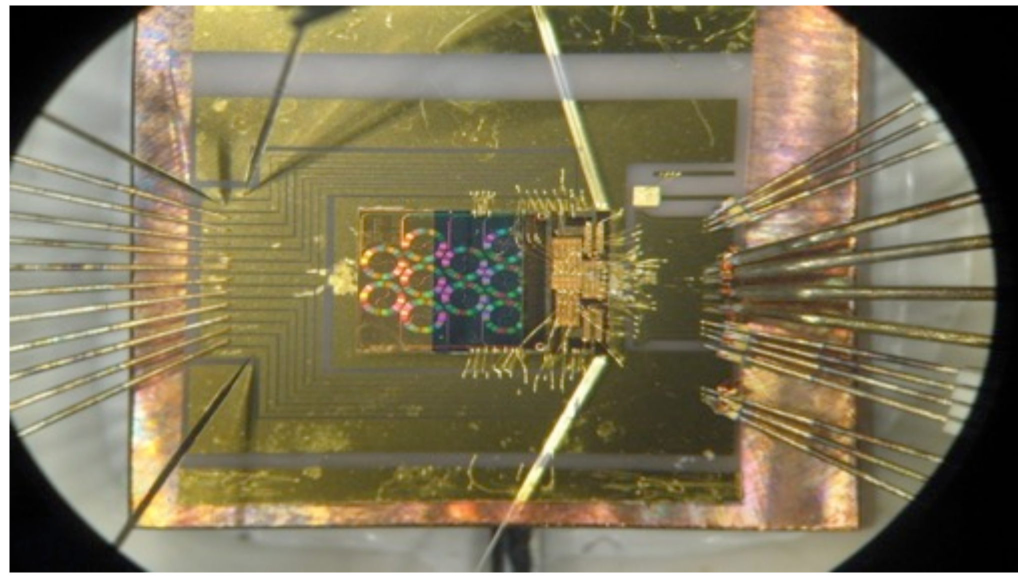


N (number of emitters)

40 Gb/s Optical Buffer Memory





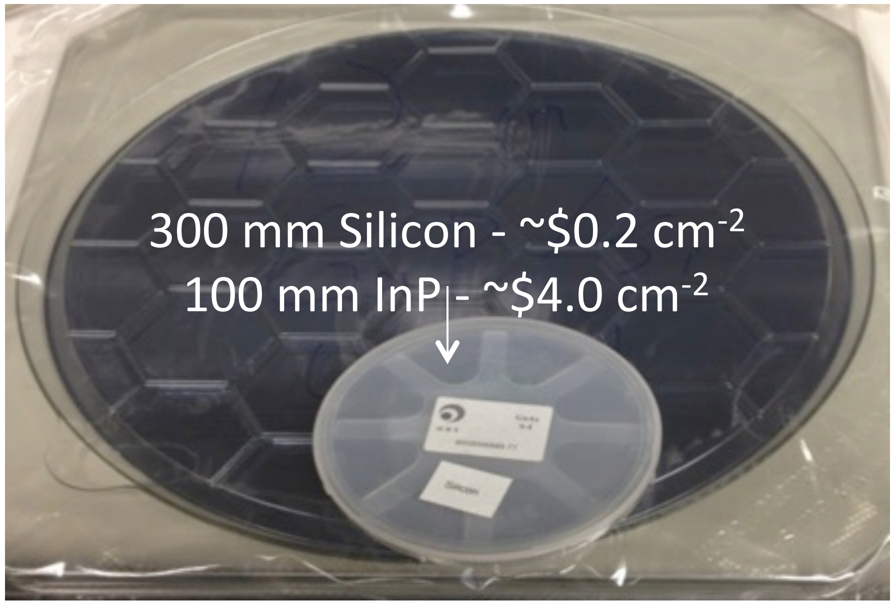


Quantum Dot Lasers

Lower threshold

Lower cost (epitaxial growth on Si)
Less sensitive to dark line defects

III-V Laser Growth on Silicon



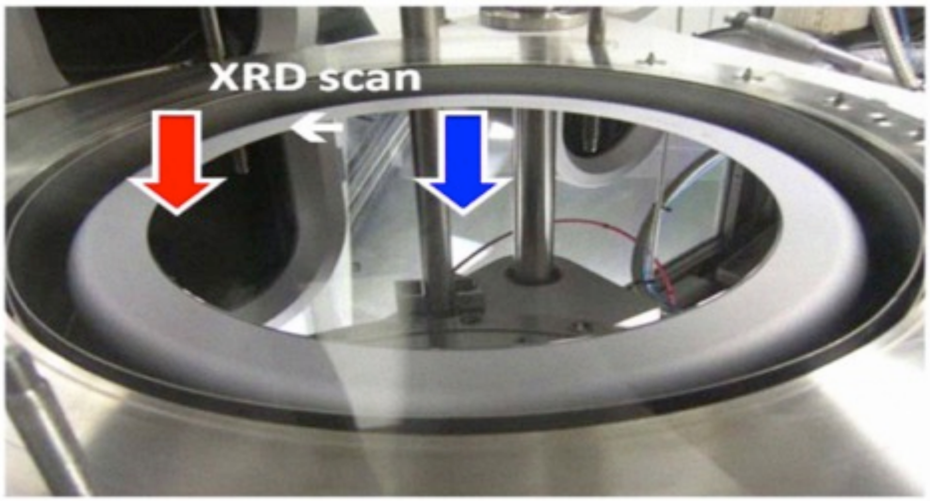
- CMOS processing of photonics is already happening, yet high cost and small size of III-V wafers remains an issue.
- **Goal:** Grow III-V lasers on larger and cheaper silicon substrates without sacrificing laser performance for lower cost and higher throughput.

[1] Bowers, John E., et al. "A Path to 300 mm Hybrid Silicon Photonic Integrated Circuits." OFC 2014

(Photo courtesy of Dr. Jordan Lang, Yale)

III-V growth on 300 mm Silicon Wafers

GaP on 300 mm Silicon using MOVPE



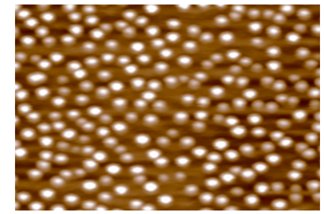
B. Kunert *et al.* *NAsP III-V GmbH*
69th Device Research Conference, Santa Barbara (2011)

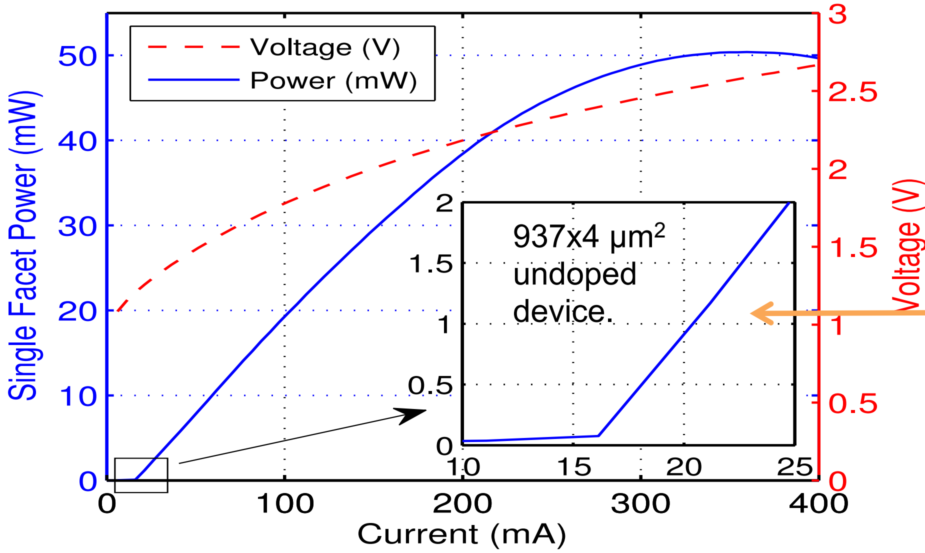
GaAs on300 mm Silicon using MBE

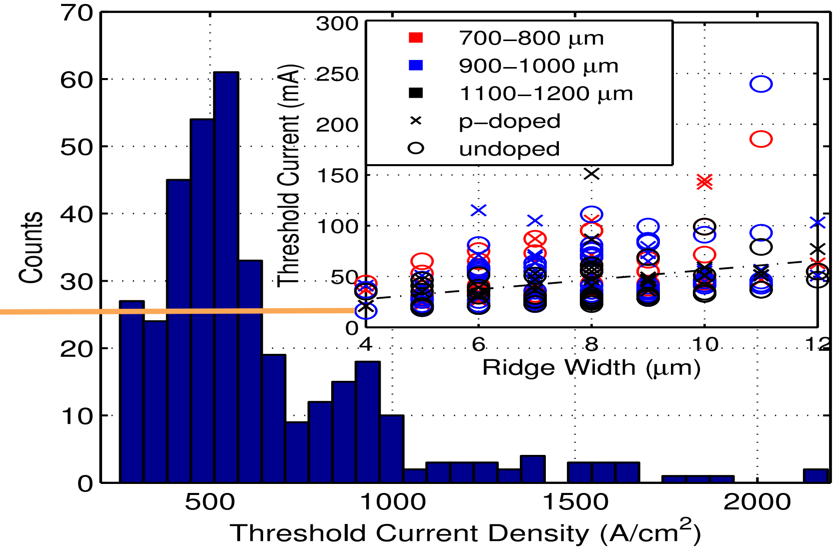
Amy Liu, IQE Inc.

Low Thresholds

- Uniform threshold current densities across die/wafers.
- Low CW threshold (150 A/cm^2)



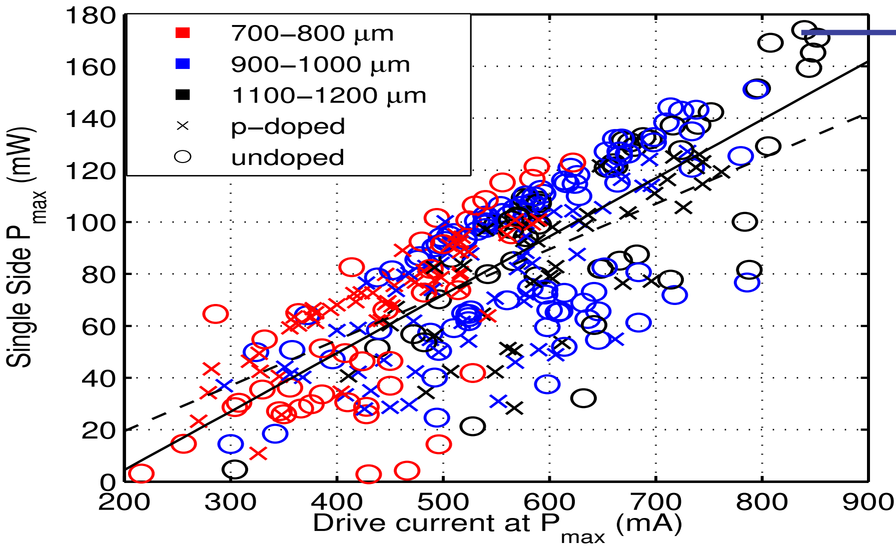


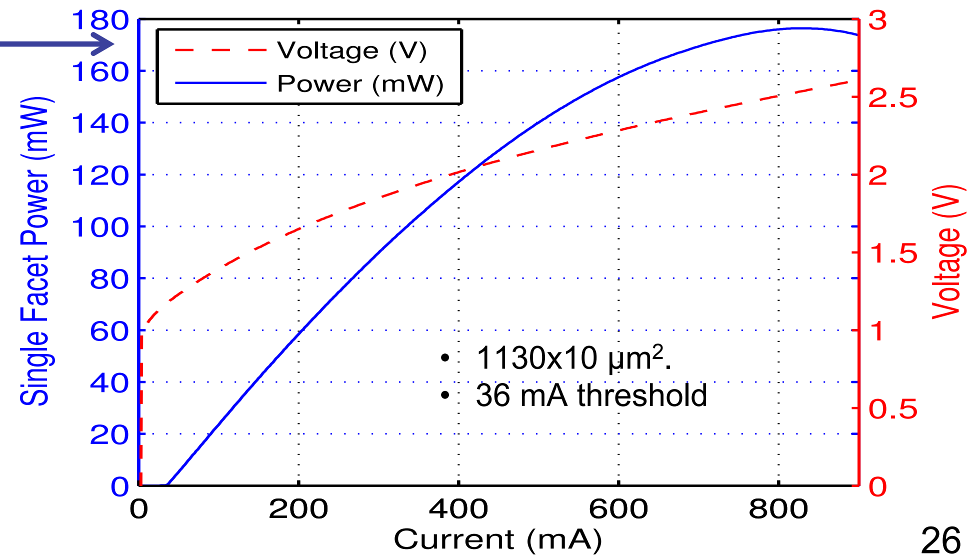


Liu, Alan Y., et al. "High performance continuous wave 1.3 μm quantum dot lasers on silicon." Applied Physics Letters 104.4 (2014): 041104.

High Output Powers

- CW powers over 100 mW routinely achieved.
- Nearly 180 mW maximum CW single side output power at 20 °C from HR coated 1130x10 μm^2 intrinsic active region (undoped) device.
  - 33% differential efficiency and 18% WPE (at 150 mA)

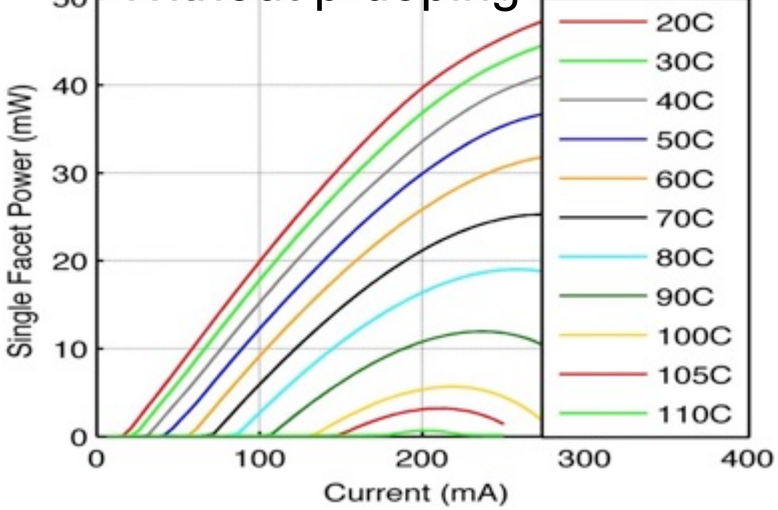




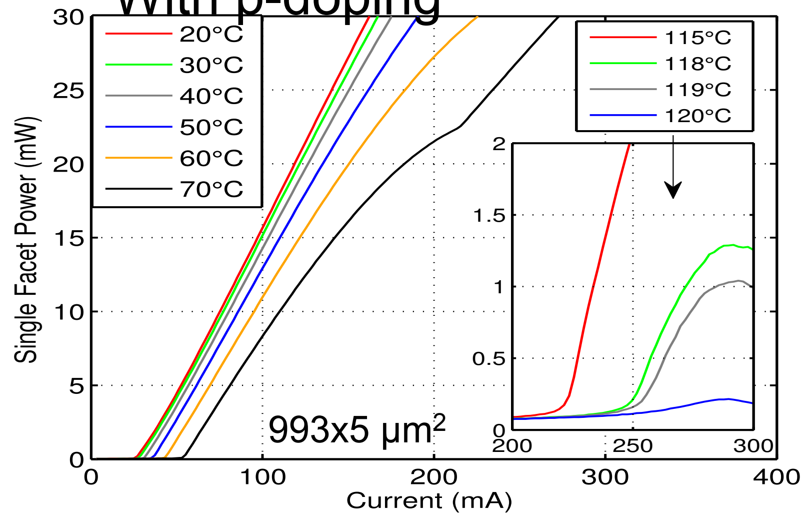
High Temperature Performance

- P-doping the active region improves thermal performance
- Continuous wave lasing up to 119^{o}C
  - (dual state lasing at high currents/temperatures).

Without p-doping



With p-doping



Alan Liu et al., Photonics Research (2015)

Hybrid Silicon Record Performance

- 2011 Lowest waveguide loss on silicon: **0.04 dB/m** Jared Bauters et al.
- 2012 Best reliability: >**40,000 hours at 70C** Srinivasan et al.
- 2012 Highest laser yield: **99%** Srinivasan et al.
- 2012 Fastest Si modulator: **74 GHz** Tang et al.
- 2013 Highest receiver capacity: **400 Gbit/s** Piels et al.
- 2013 Largest laser array bandwidth**: > 200 nm** Jain et al.
- 2012 Highest level of integration with lasers: **164 devices** Jared Hulme et al.
- 2014 Largest LED bandwidth: **>200 nm** DeGroote et al.(Ghent and UCSB)
- 2014 Highest temperature**: 119C** Alan Liu et al.
- 2014 Highest power: **180 mW** Alan Liu et al.
- 2014 Lowest threshold: **2 mA** Liang et al. (HP)
- 2014 Narrowest linewidth: **9 kHz** (NEC)

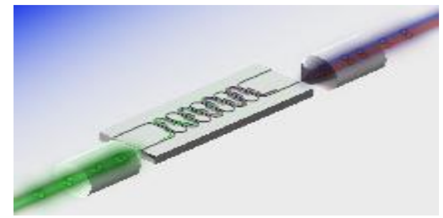
American Institute for Manufacturing Integrated Photonics
("AIM Photonics")

Lead: RF SUNY (Mike Liehr)

Hub location: Albany and Rochester, NY

West Coast Hub: UCSB (John Bowers)

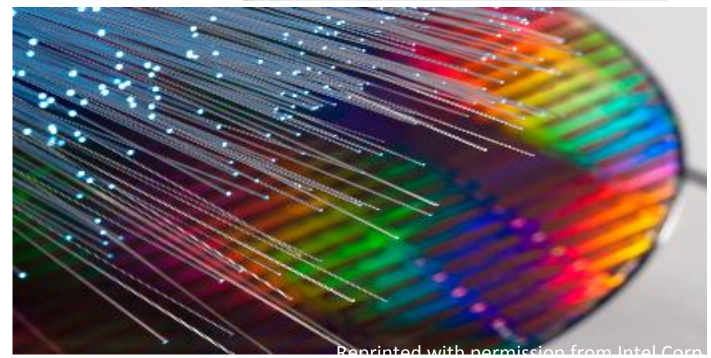
Federal Funding: $110 M



Objective

Develop and demonstrate innovative manufacturing technologies for:

- **Ultra high-speed transmission of signals for the internet and telecommunications**
- **New high-performance information-processing systems and computing**
- **Sensors and imaging enabling dramatic medical advances in diagnostics, treatment, and gene sequencing**



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This Institute will focus on developing an end-to-end photonics 'ecosystem' in the U.S., including domestic foundry access, integrated design tools, automated packaging, assembly and test, and workforce development.

All these developments will require cross-cutting disciplines of design, manufacturing, packaging, reliability and testing.