Silicon Photonic Integrated Circuits

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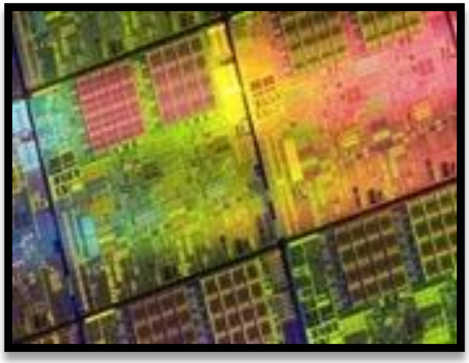
UCSB

What is Silicon Photonics?

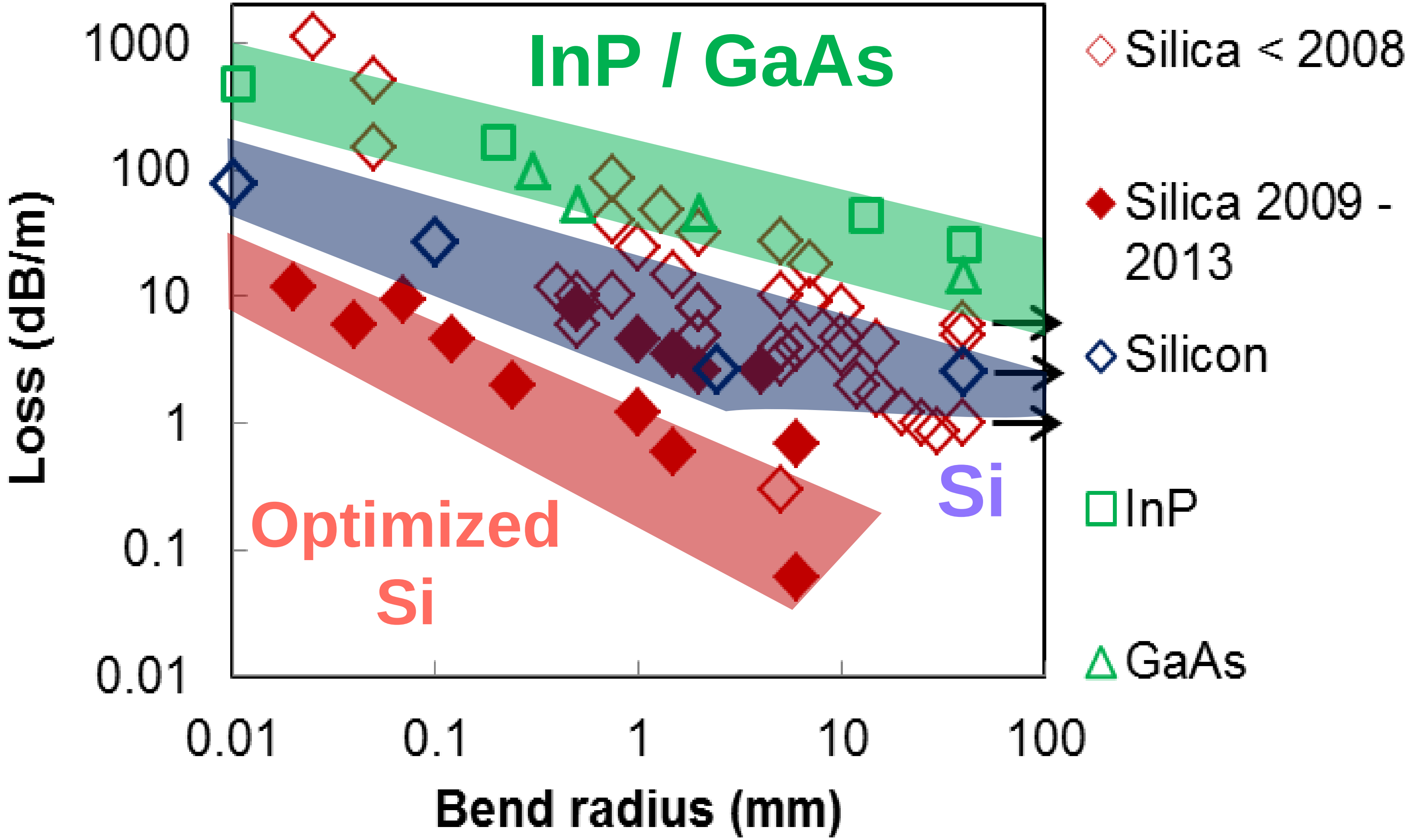
- Making photonic integrated circuits on Silicon using CMOS process technology in a CMOS fab
  - Improved performance and better process control
  - Wafer scale testing
  - Low cost packaging
  - Scaling to >1 Tb/s



High bandwidth
Long distances
Noise Immunity

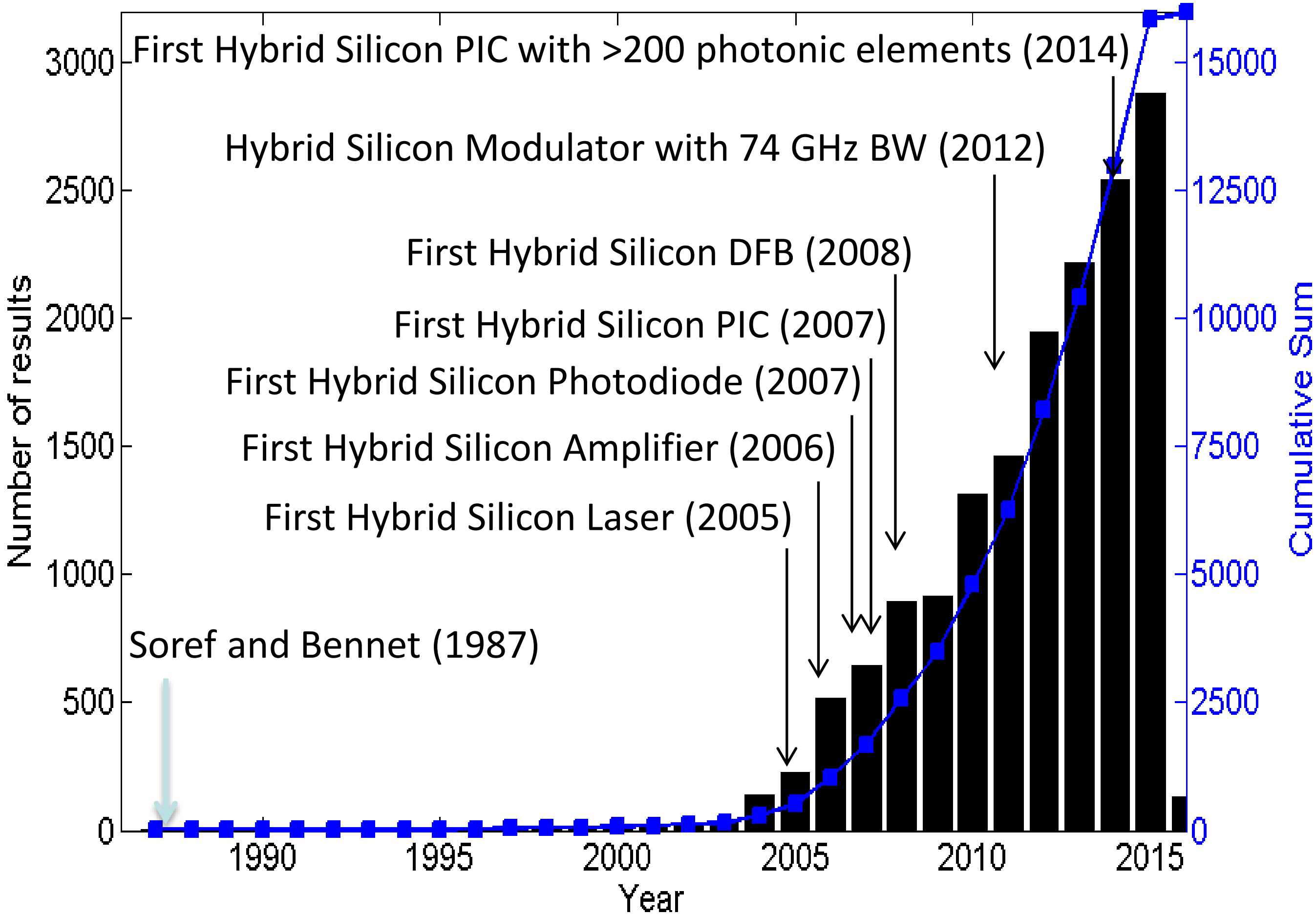
High volume
Low cost
High Scalability

Advantage - Waveguide loss



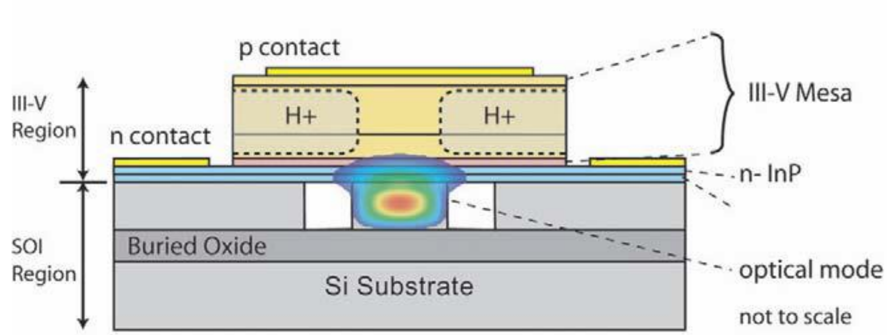
Bauters et al. Optics Express (2011)

Silicon Photonics Papers

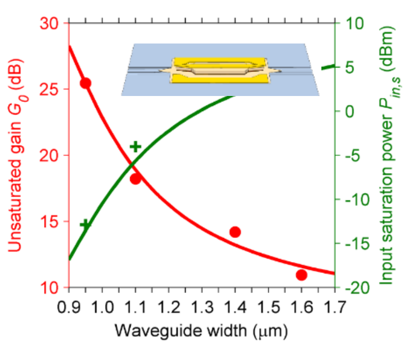


Si Photonics - Heterogeneous Integration

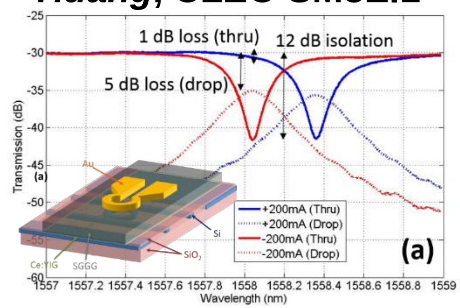
- CMOS compatible process
- Efficient light coupling with Si WG
- Component development
- PIC integration with >400 elements



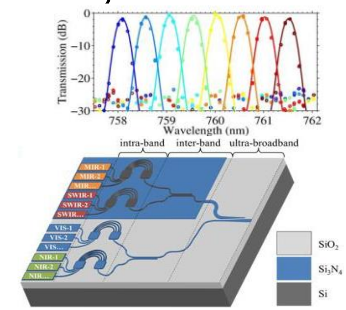
High gain SOA on Si
***Davenport*, CLEO SM4G.3**



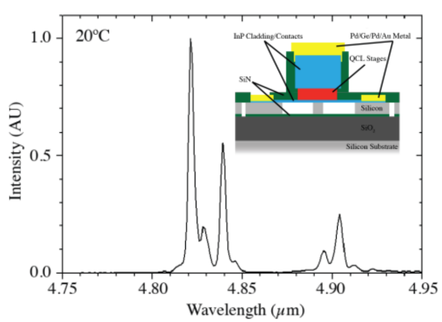
Isolators/Circulator on Si
***Huang*, CLEO SM3E.1**



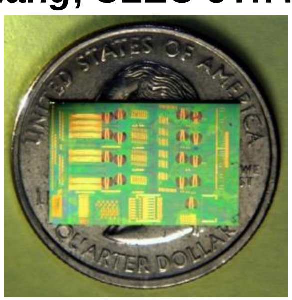
Low-Loss AWG in Vis
***Stanton*, CLEO SM1F.1**



4.8 μm QCL laser on Si
***Spott*, CLEO STh3L.4**

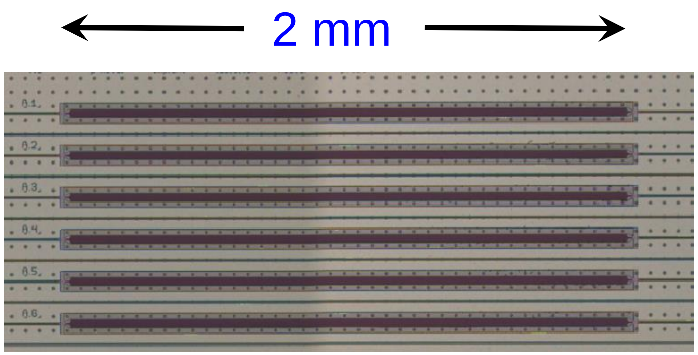


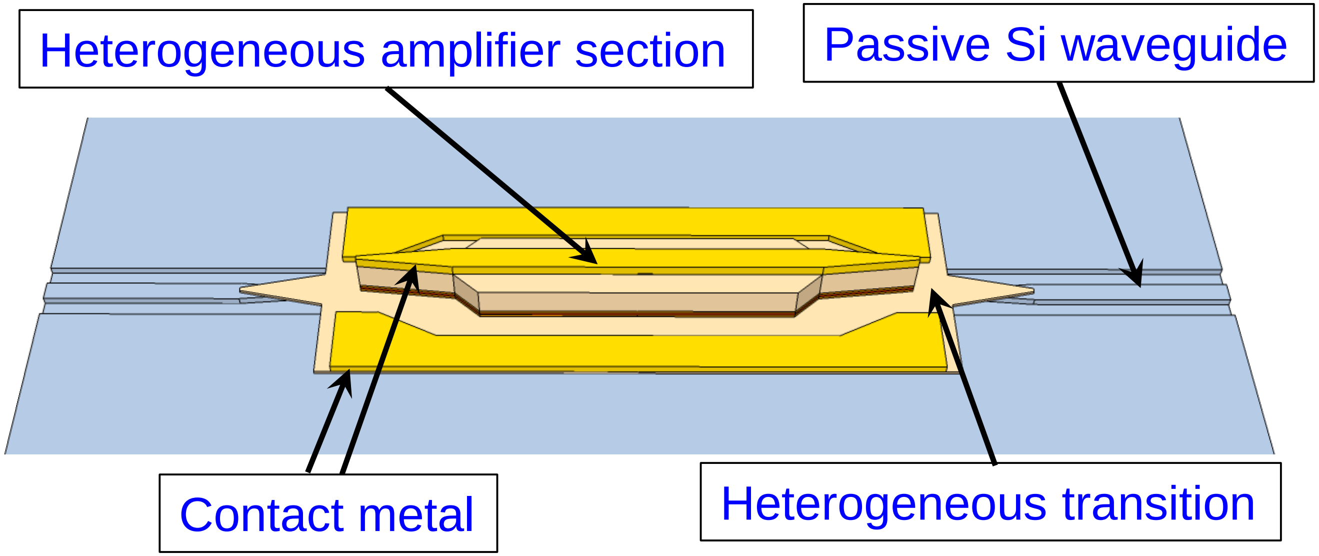
2.56 Tbps NoC
***Zhang*, CLEO JTh4C.4**



Optical Amplifier on Si

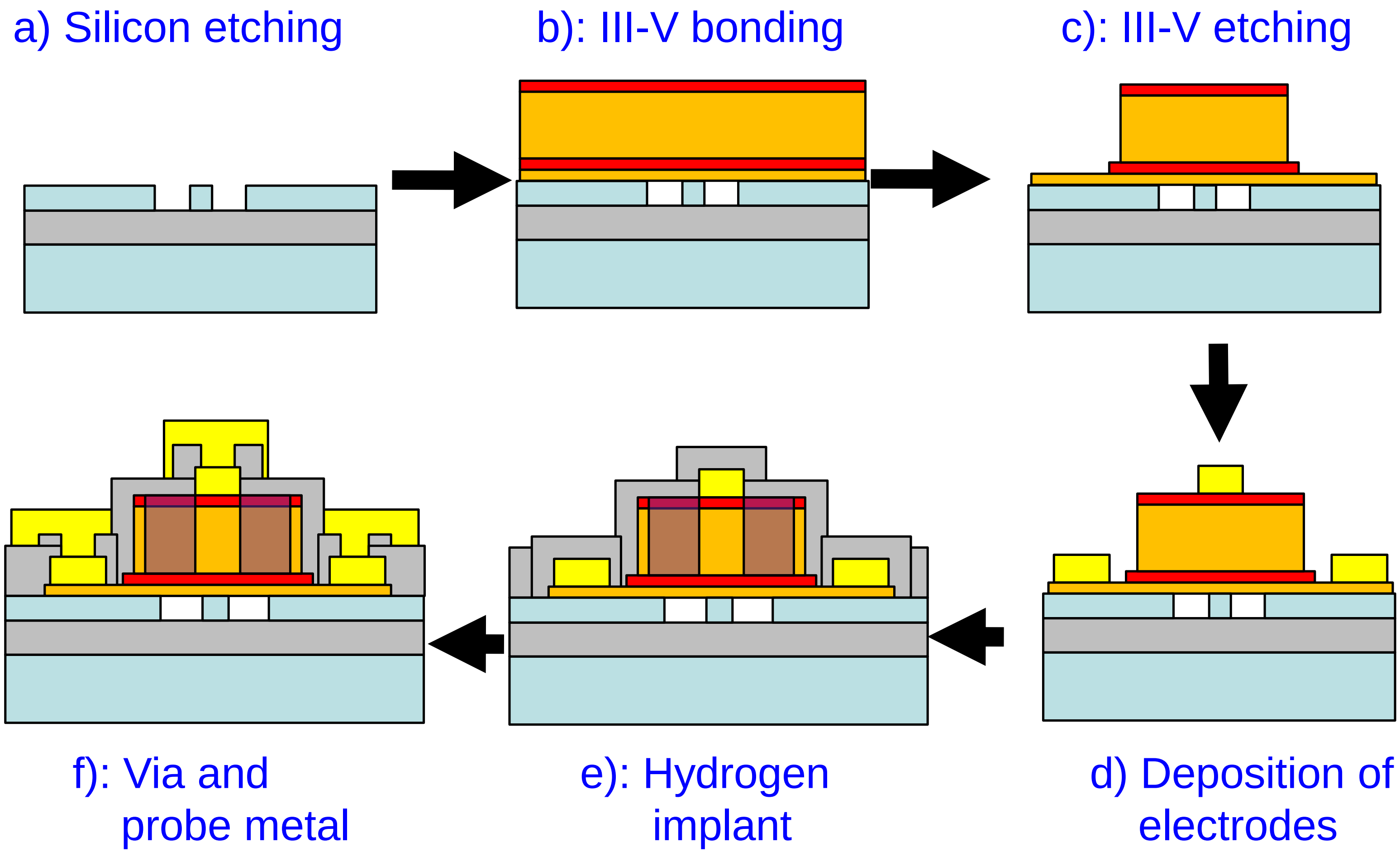
- Scale of Si PICs rapidly increasing
- Overcome insertion loss, splitter loss
- Increase power and equalize optical power in multi-channel devices
- Recover signal power before detection





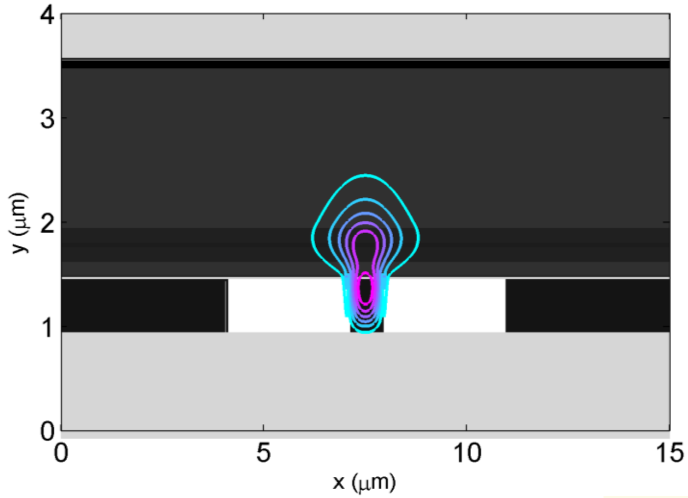
Davenport, Skendzic, Volet, Bowers CLEO 2016

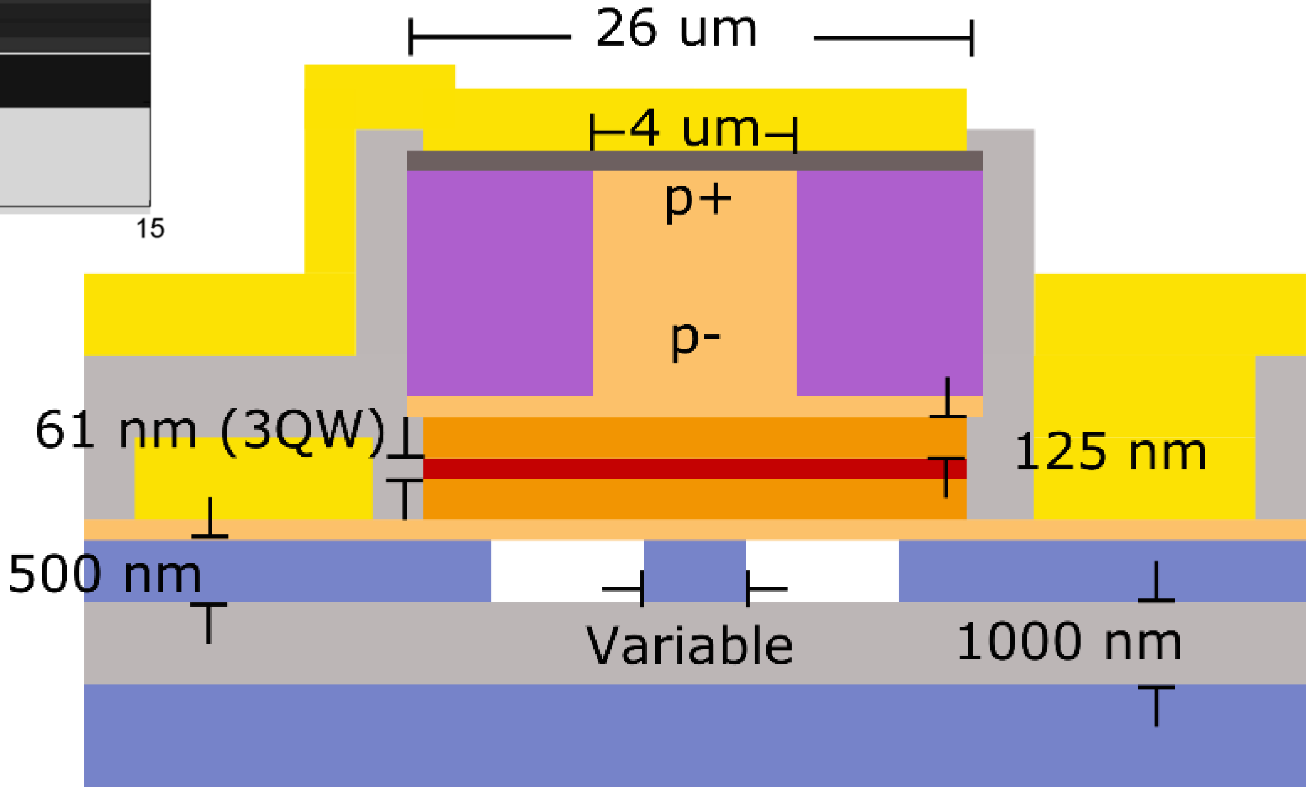
Amplifier on Si - Process flow



Davenport, Skendzic, Volet, Bowers CLEO 2016

Amplifier on Si - Dimensions





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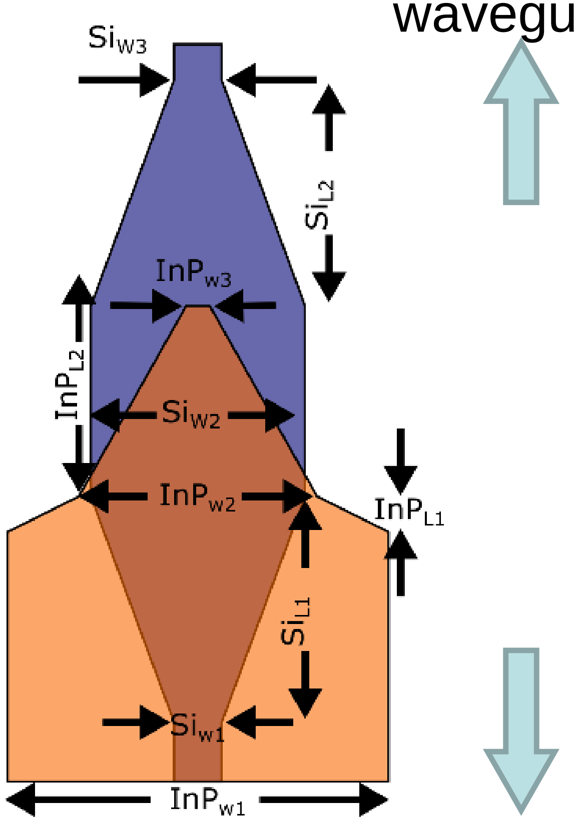
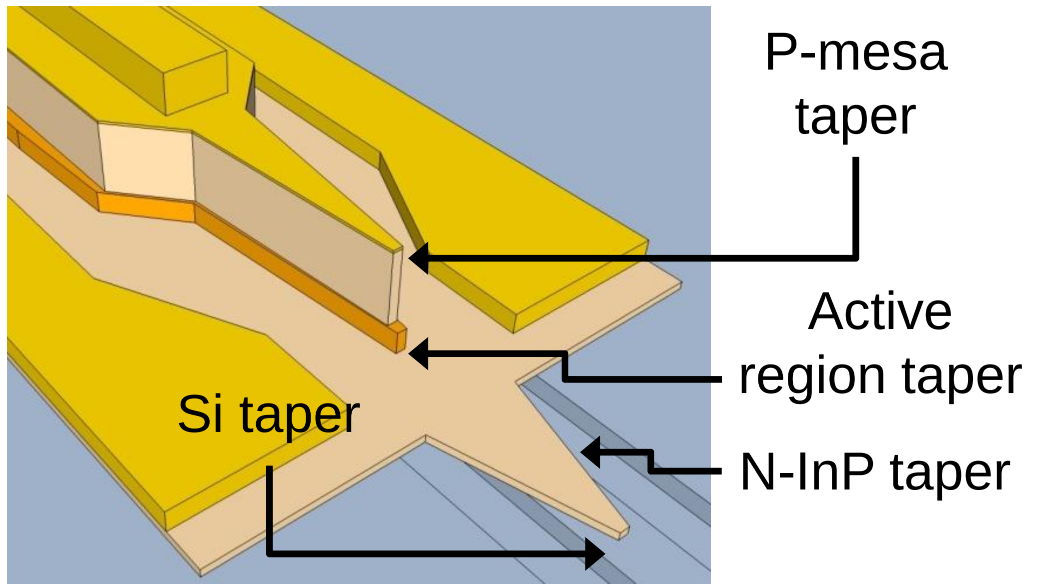
Amplifier on Si - Heterogeneous Transition

Passive Si waveguide



Active Si/InP waveguide



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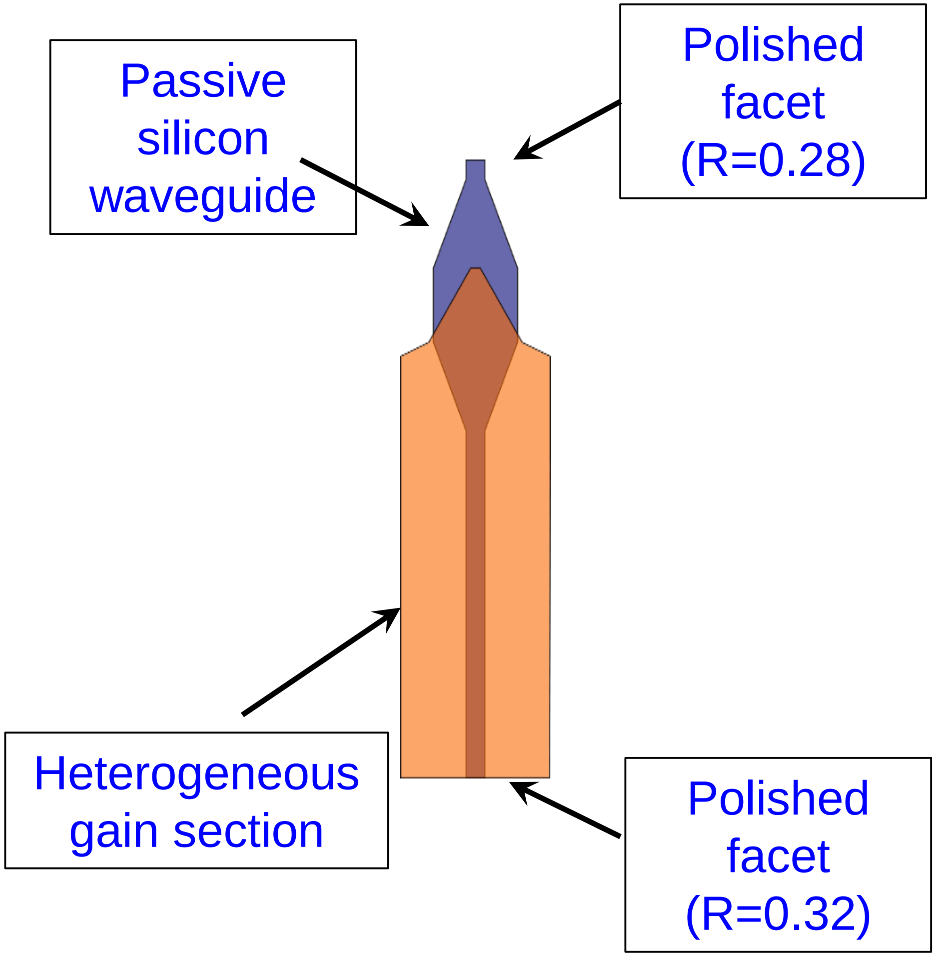
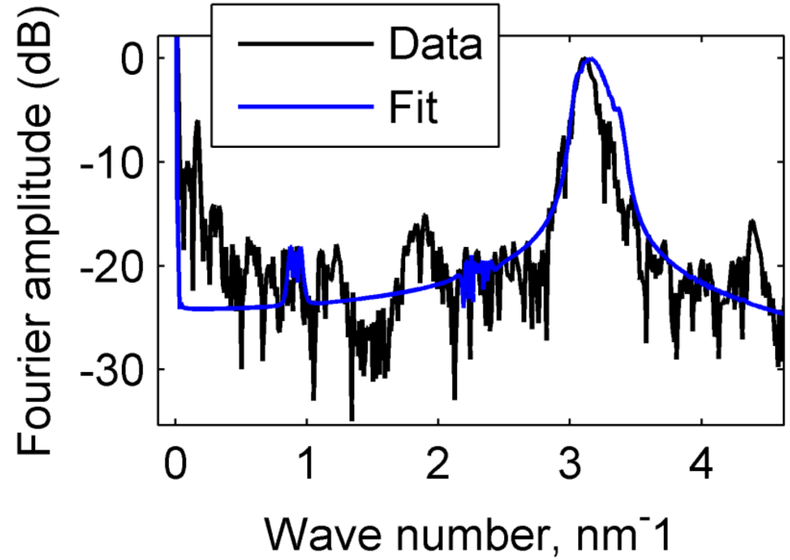
Amplifier on Si – Transition Reflection



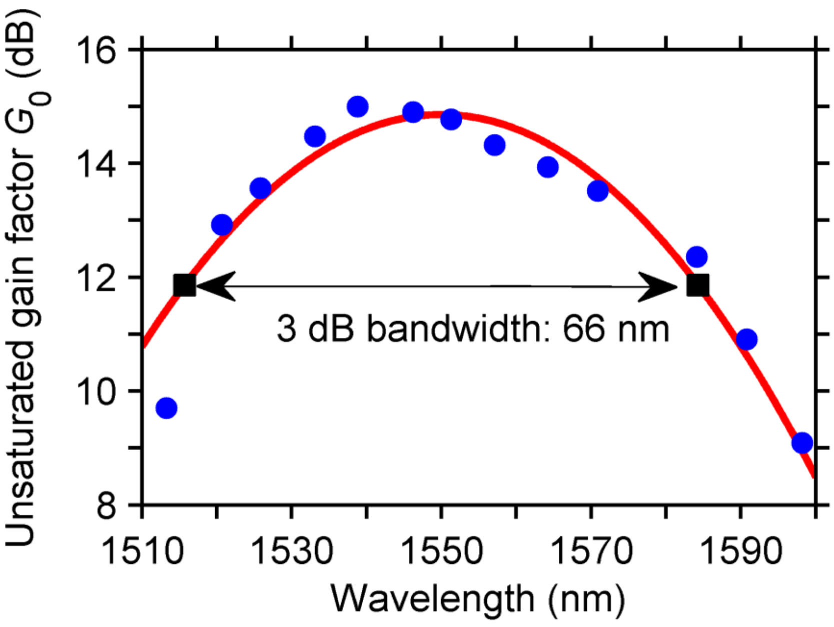


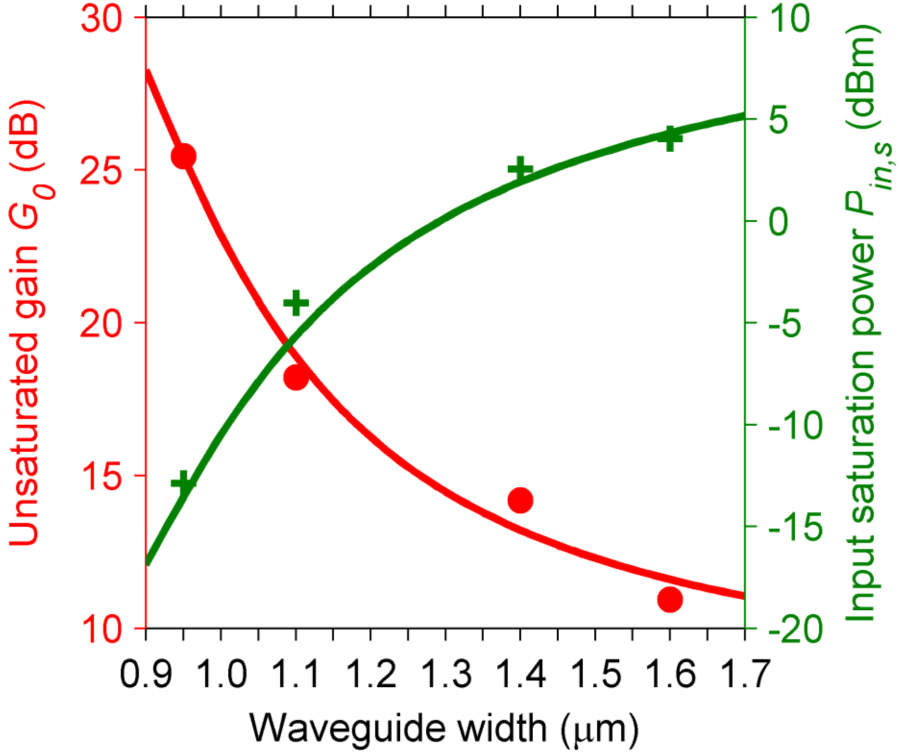
- Reflection determined by fitting model to ASE spectrum
- R_{taper} r = -46 dB

Davenport, Skendzic, Volet, Bowers CLEO 2016

Amplifier on Si - Performance

- High gain: 26 dB from 0.95 µm waveguide device
- High power: 16 dBm from 1.4 µm waveguide device
- Large 3dB BW: 66 nm





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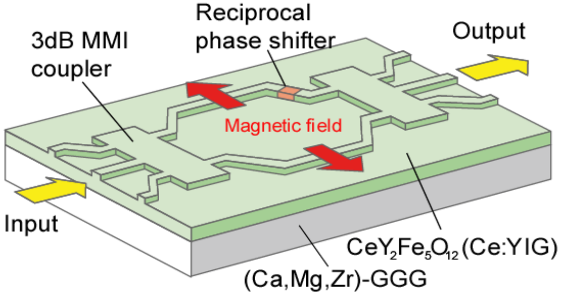
Microring Isolator - Nonreciprocity

- Optical isolators allow light transmission in only one direction
  - Necessary in many applications to block undesired feedback for lasers
- Requires nonreciprocal phenomenon to break spatial-temporal symmetry

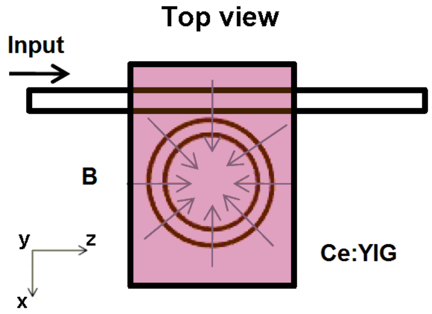
Nonreciprocal phase shift (NRPS)

- Forward and backwards propagating modes in a magneto-optic waveguide have different propagation constant (β).
- Nonreciprocal phase shift in a phase-sensitive structure can result in optical isolation for the TM mode.



Unbalanced MZI

Y. Shoji, T. Mizumoto, et al., Opt. Express (2008)



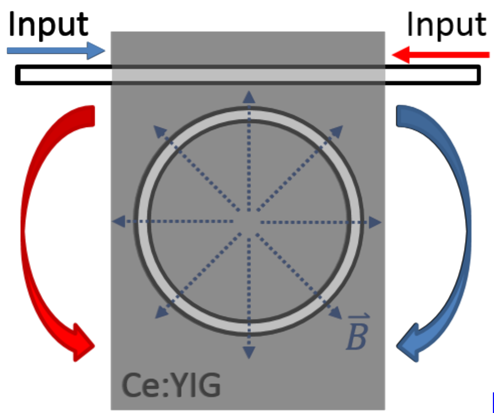
Microring

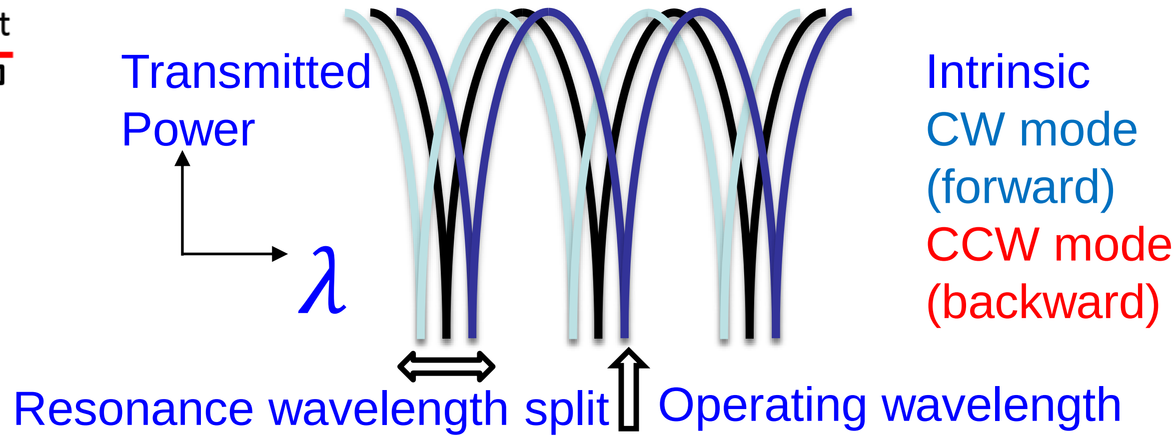
M.C. Tien, J. Bowers, et al., Opt. Express (2011)

Huang, Pintus, Zhang, Shoji, Mizumoto, Morton, Bowers OFC 2016

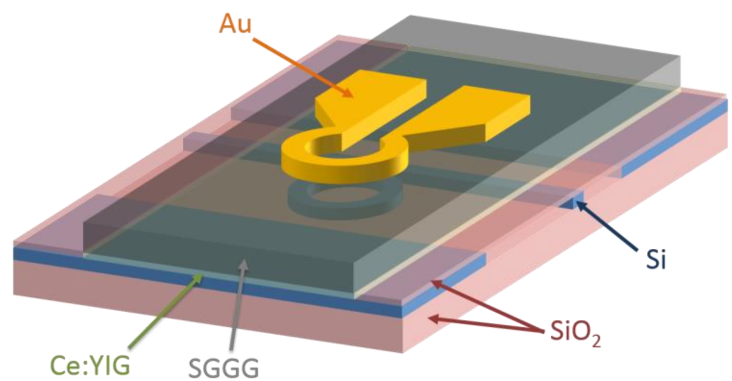
Microring Isolator - Design

- Magneto-optic material Ce:YIG wafer bonded to all-pass silicon microring
  - CW and CCW modes are different, causing a resonance split





- Resonance wavelength split dependent on waveguide geometry
- Isolation depends on extinction ratio and coupling coefficient



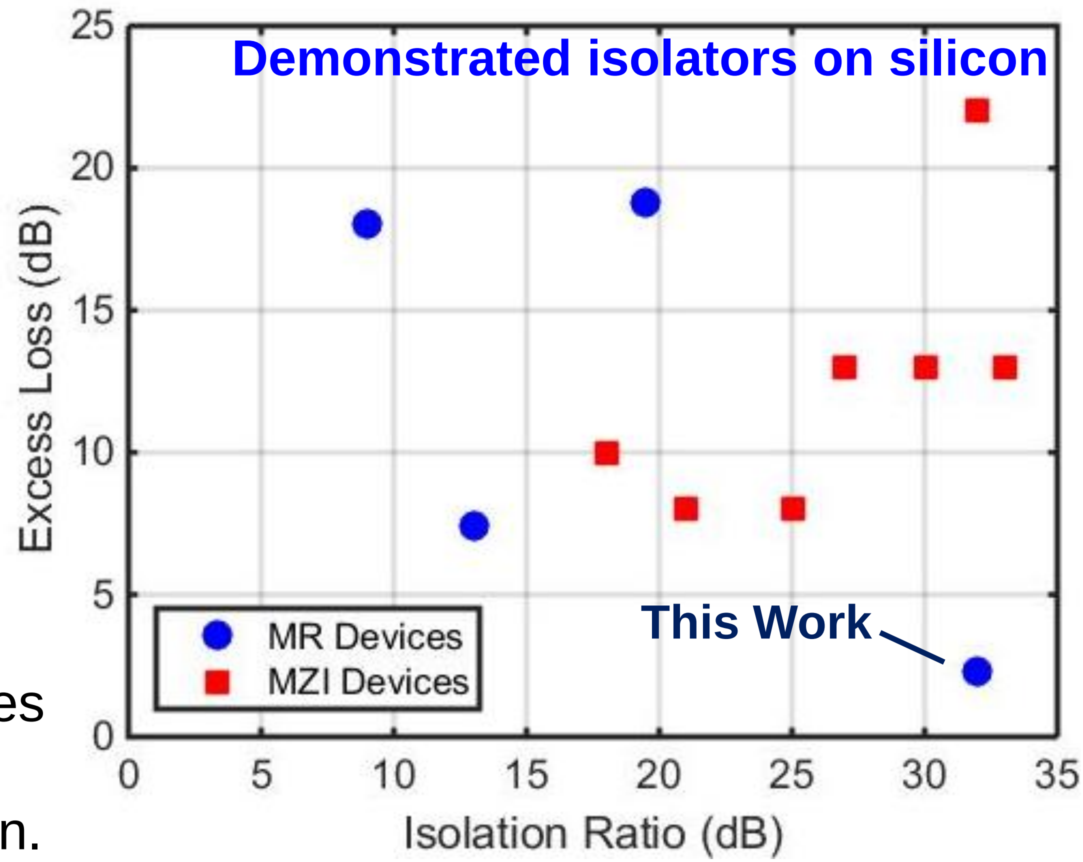
Huang, Pintus, Zhang, Shoji, Mizumoto, Morton, Bowers OFC 2016

Microring isolator - Results

- **32 dB** of isolation with record low **2.3 dB** excess loss achieved with small footprint (**35 µm** radius).

  Consumes <10 **mW** of power, and no permanent magnet is needed

- Current controlled magnetic field and Joule heating provides tuning over **0.6 nm** with >20 dB of isolation.



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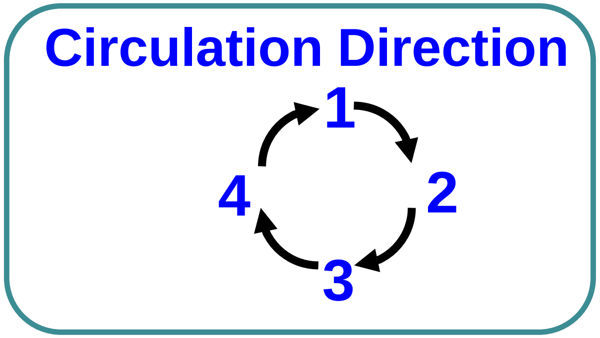
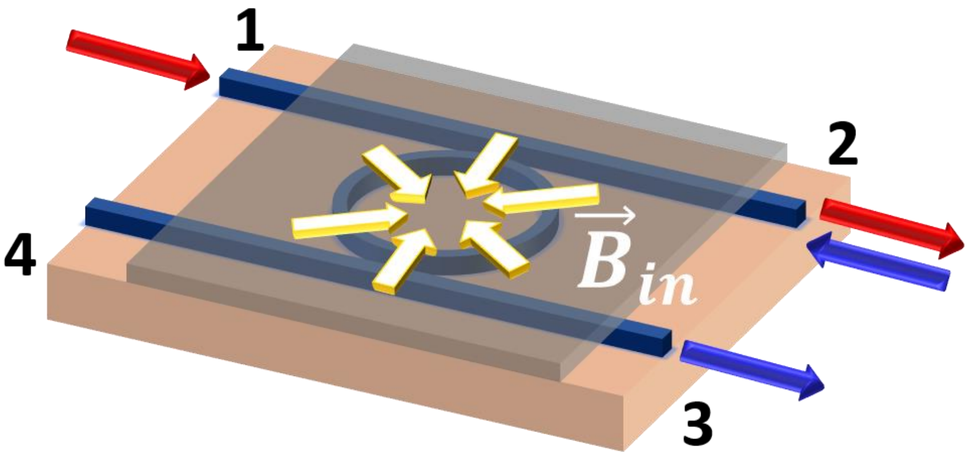
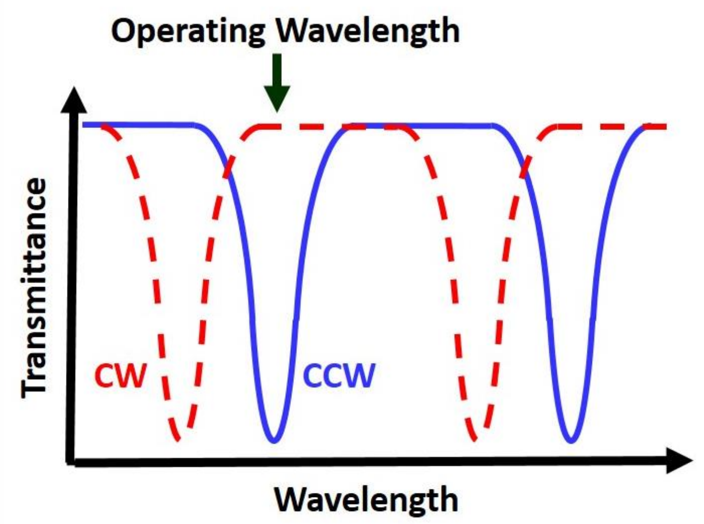
Microring Circulator

- Light circulates depending on whether it is coupled into the CW (off-resonance) or the CCW (on-resonance) mode in the ring.

1->2 2->1



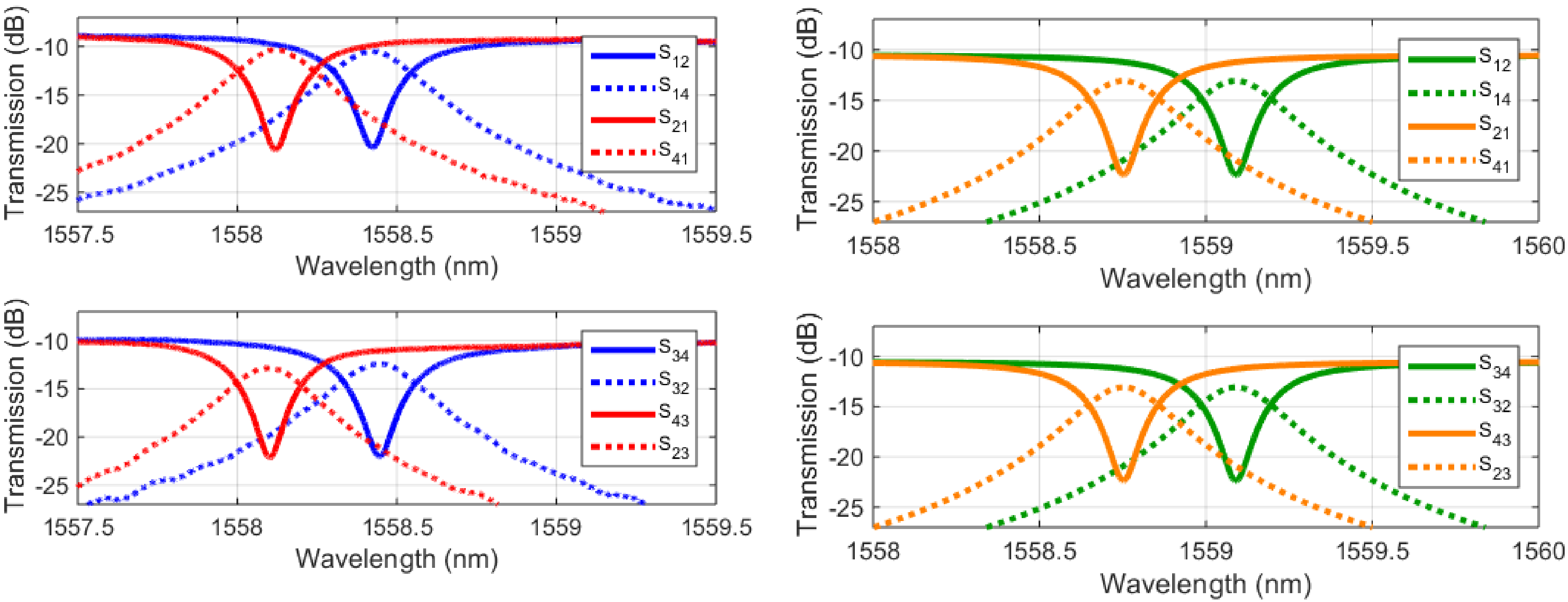




Huang, Pintus, Zhang, Shoji, Mizumoto, Morton, Bowers IPC 2016

Microring Circulator - Results

Experimental **Simulated**



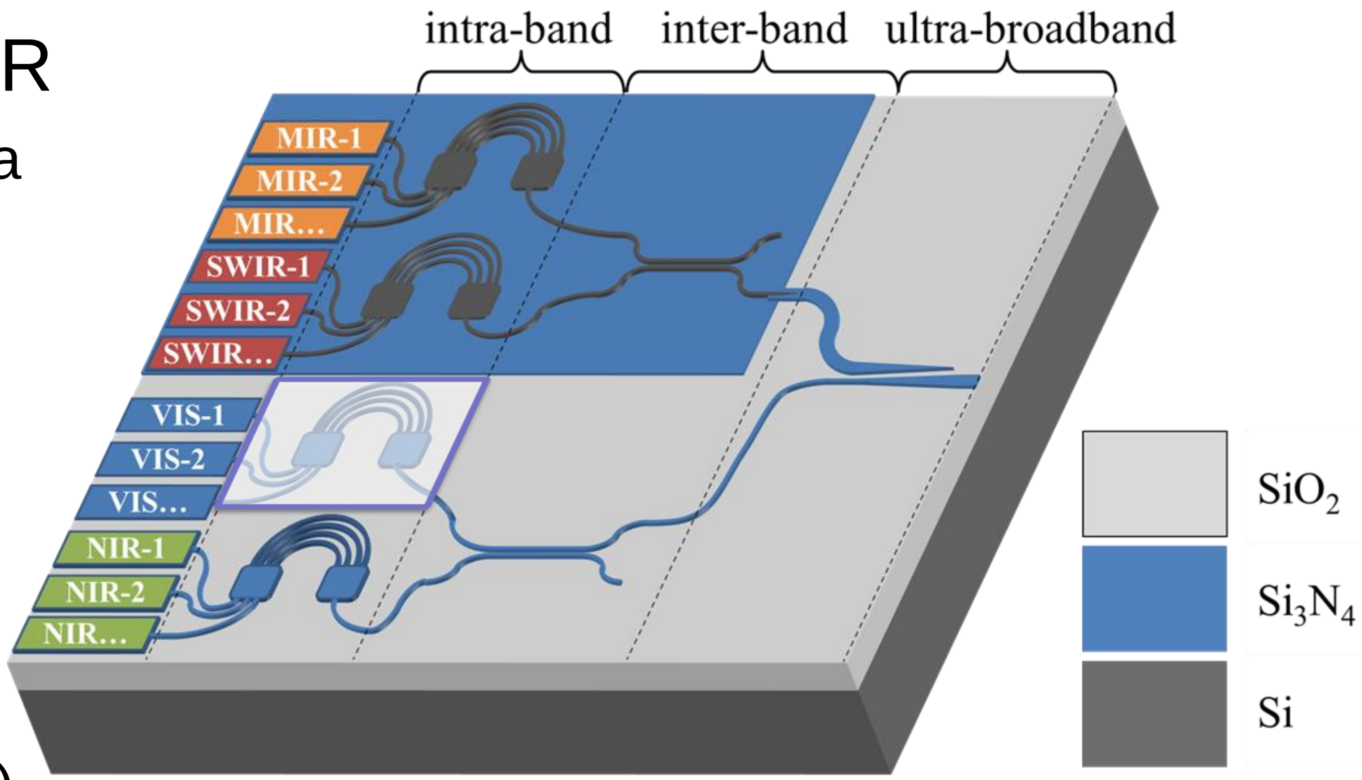
- Isolation Ratio $=|S_{21}|^2/|S_{12}|^2 = 11\text{dB}$

Huang, Pintus, Zhang, Shoji, Mizumoto, Morton, Bowers IPC 2016

AWG - Spectral Beam Combining

Visible to Mid-IR

- Multiplexing data
- Spectroscopy
- Scaling power and brightness
- Ultra low-loss arrayed waveguide gratings (AWGs) are important



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Previously demonstrated low-loss AWGs

Low-loss AWGs with < 1 dB insertion loss in near-IR:

- D. Dai *et al*., Opt. Express 19, (2011).
- J. F. Bauters et al., Appl. Phys. A 116, (2014).
- A. Sugita *et al.*, IEEE Photon. Technol. Lett. 12, (2000).

Low-loss AWGs near-visible spectrum are difficult to make

Recent demonstration of 1.2 dB insertion loss at 900 nm

- D. Martens *et al.*, IEEE Photon. Technol. Lett. 27, (2015).

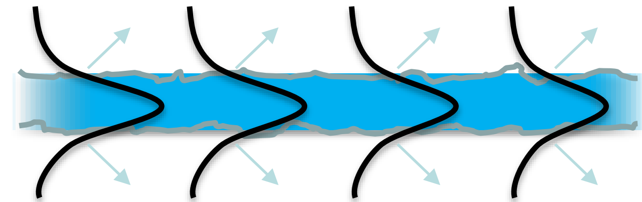
- Wavelength target 760 nm
  - Scattering loss scales by $1/\lambda^4$
  - 1.2 dB @ 900 nm -> 1.6-2 dB @ 760 nm (scattering loss contribution 1/3rd-2/3rd)

Stanton, Spott, Davenport, Volet, Bowers CLEO 2016

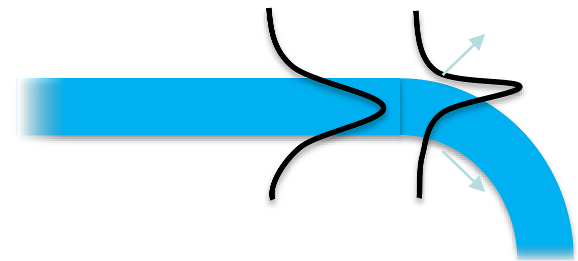
Challenges for low-loss AWGs

- Waveguide propagation loss
  - Scattering loss scales by $1/\lambda^4$
  - High aspect ratio waveguides to decrease interfacial scattering
  - Minimize material impurities

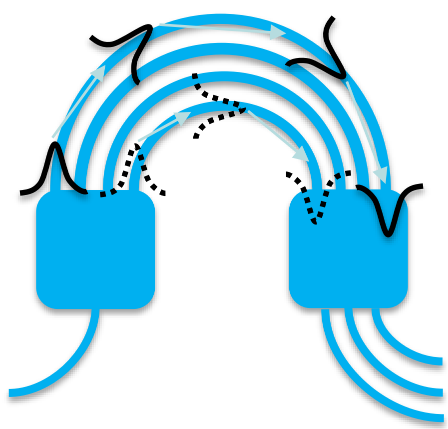
$$E(z) = E_0 e^{-\alpha z}$$



- Transition loss from straight to bends
  - Use adiabatic transitions



- Phase and amplitude errors in arrayed waveguides
  - Mask optimization - process
  - Minimize mask errors



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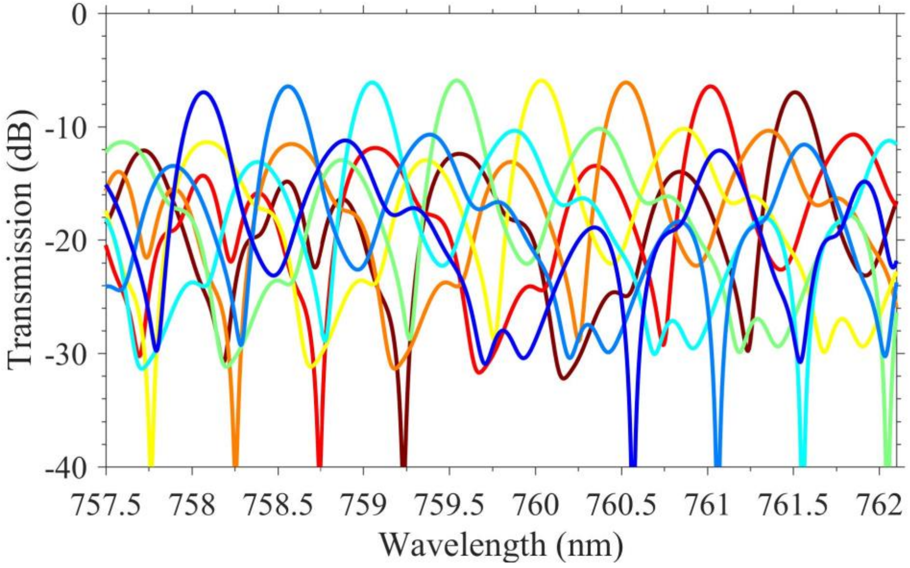
AWG - Mask Writing Address-Unit

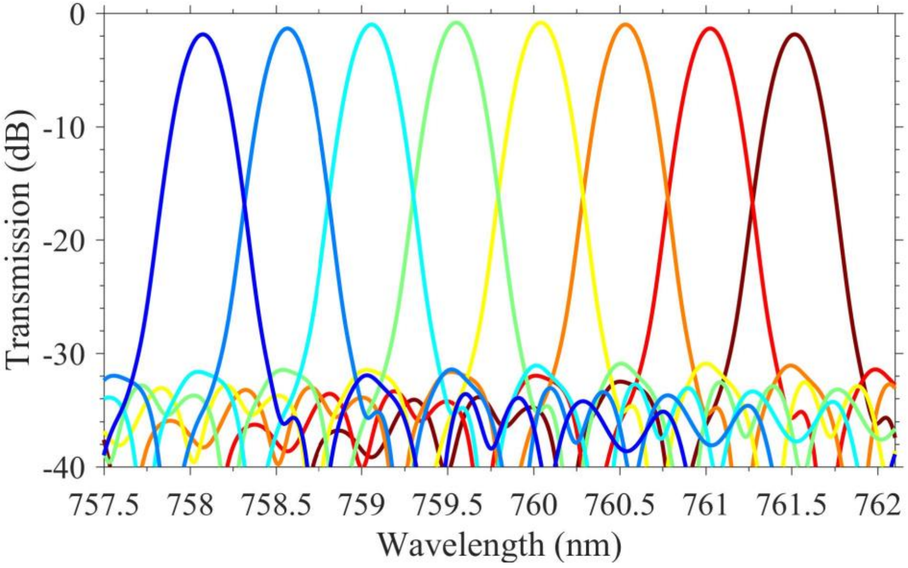
Using small address unit for the mask writing is critical in near-visible region

<u>50 nm address unit</u>



- Pseudo-random length error ± 150 nm

<u>5 nm address unit</u>



- Pseudo-random length error ± 15 nm

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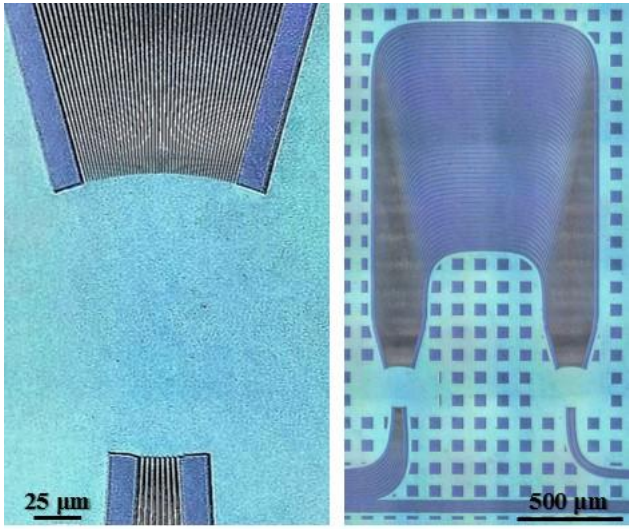
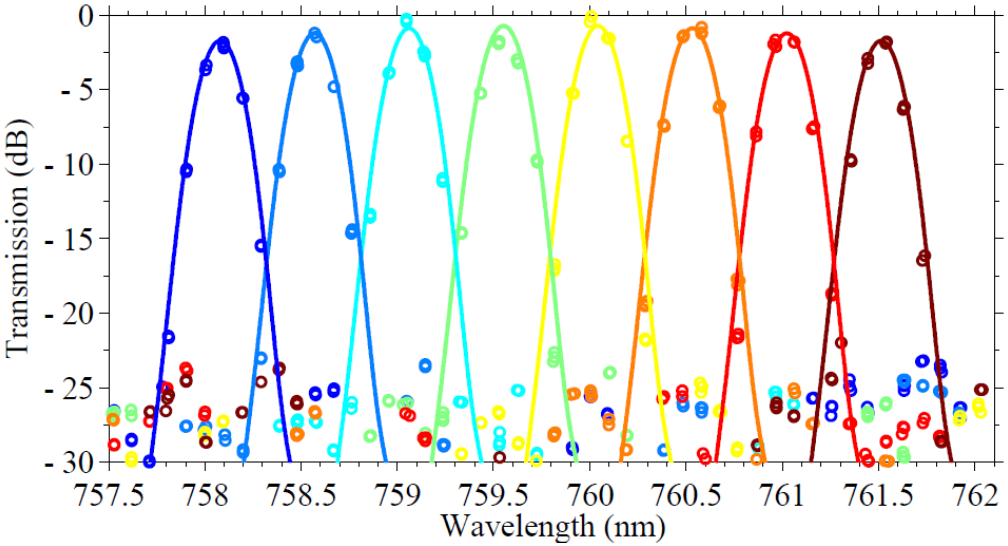
Insertion loss analysis

- Center channel insertion loss < 0.5 dB (Record – 760 nm)
- Record low crosstalk < -23 dB





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Mid-infrared Silicon Photonics

Mid-infrared (~2-20 µm) photonics

- Spectral Beam Combining
- Gas sensing
- Chemical bond spectroscopy
- Biological sensing
- Environmental analysis
- Remote sensing
- Nonlinear optics
  - Reduced two photon absorption in silicon past 1.8 µm

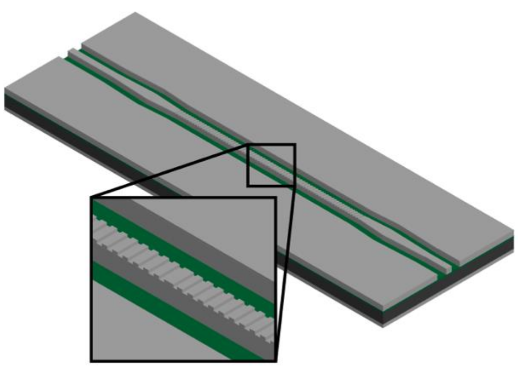
Spott, Peters, Davenport, Stanton, Merritt, Bewley, Vurgaftman, Meyer, Kirch, Mawst, Botez, Bowers CLEO 2016

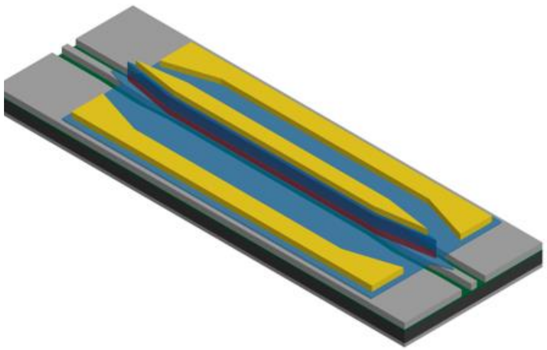
Methane trapped in ice, National Geographic

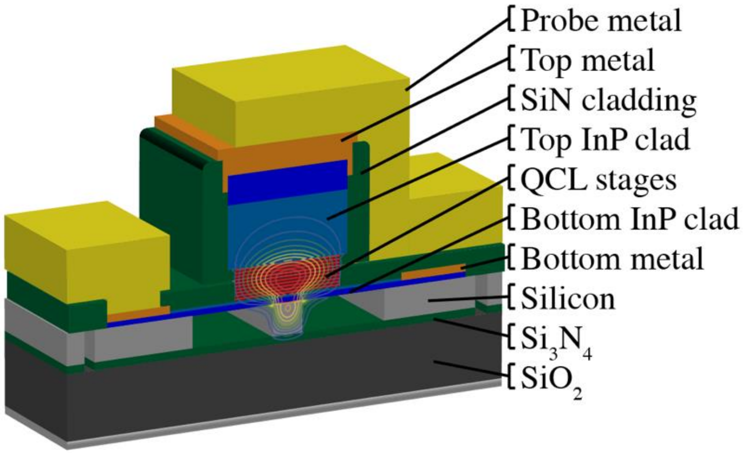
Power plant emissions, National Geographic

4.8 µm Quantum Cascade Laser

- 30-stage QCL material adapted for heterogeneous integration
- 4-8 µm-wide III-V mesas with 1.5-3.5 µm-wide Si waveguides
- 3 mm-long hybrid III-V/Si active region
- 45 µm-long III-V tapers
- λ/4-shifted 1st order distributed feedback (DFB) grating in silicon waveguide under active region







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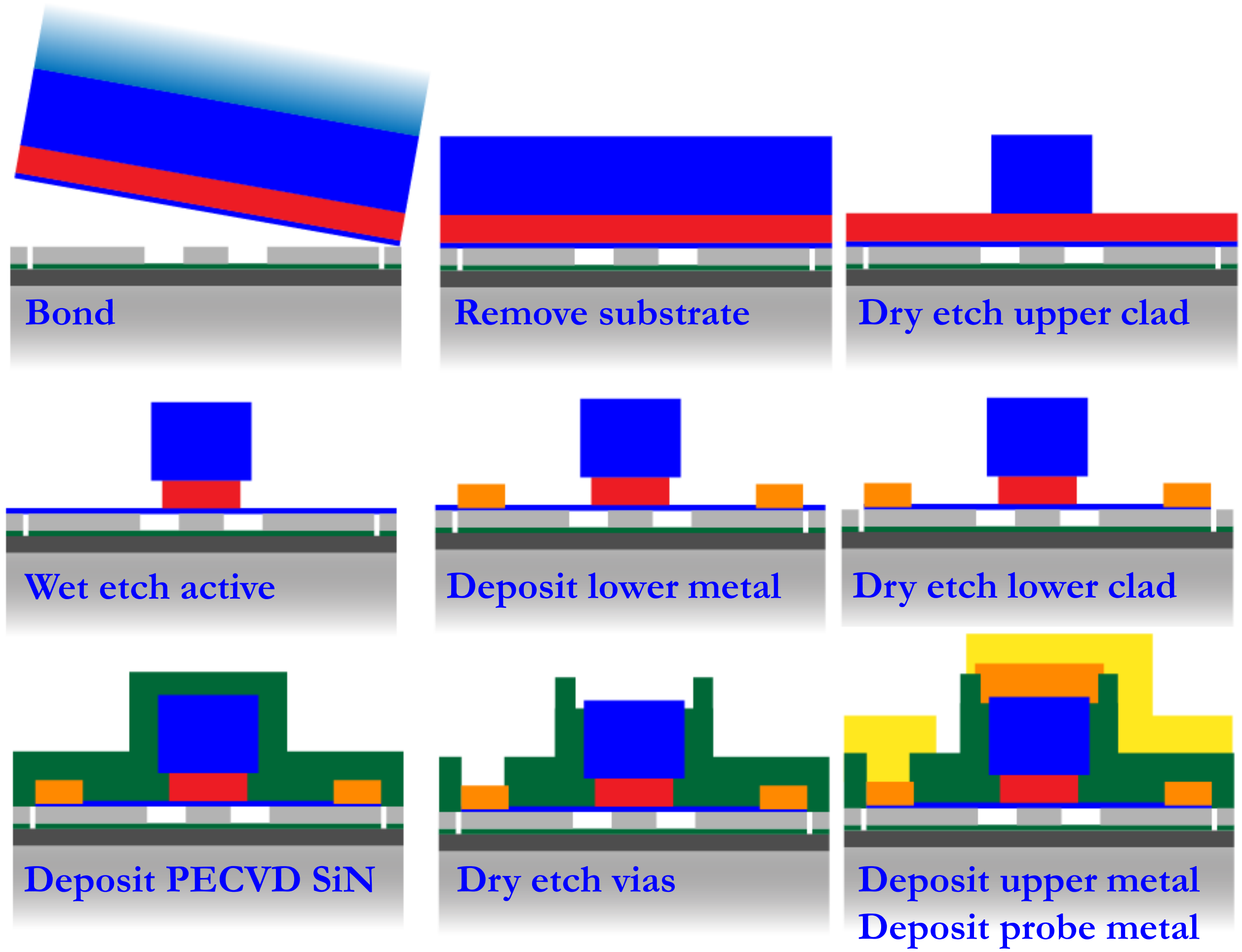
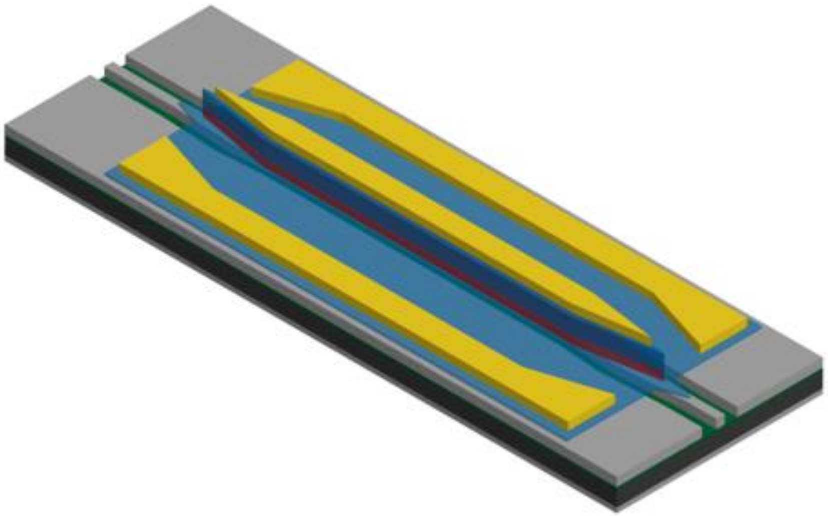
4.8 µm Laser Fabrication

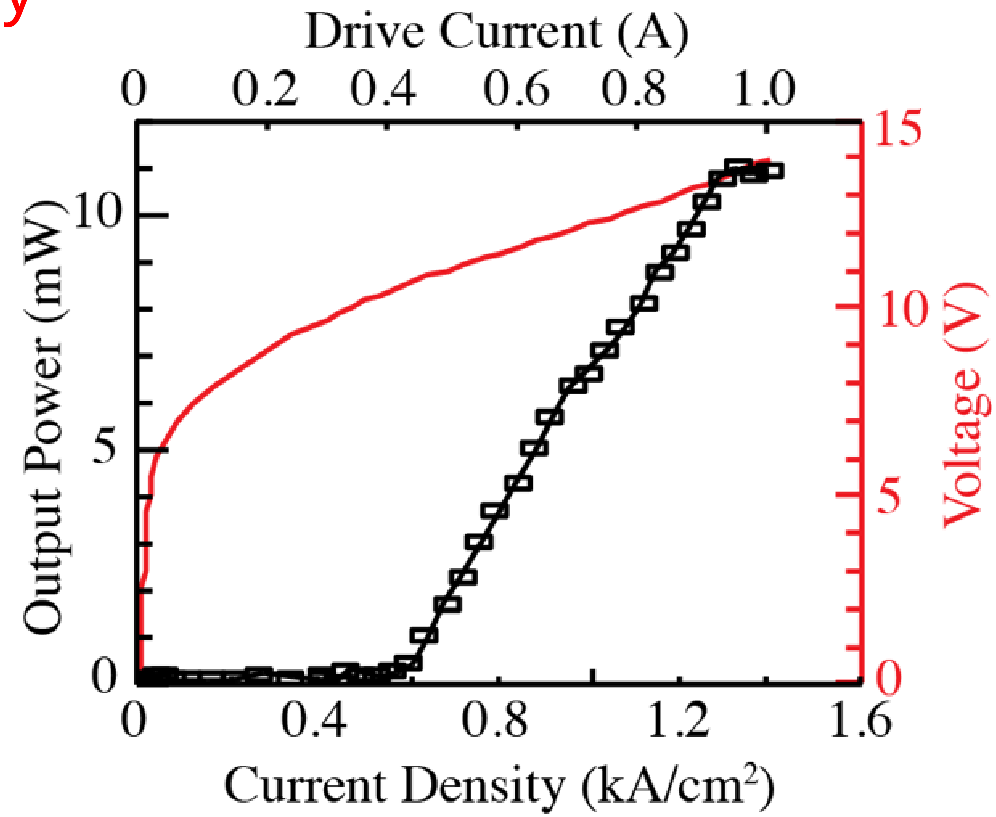


[illegible]
and selective wet etch

4.8 µm DFB (with Taper)

- Low threshold current densities
- Low differential efficiency
- Highest output power ~11 mW/facet





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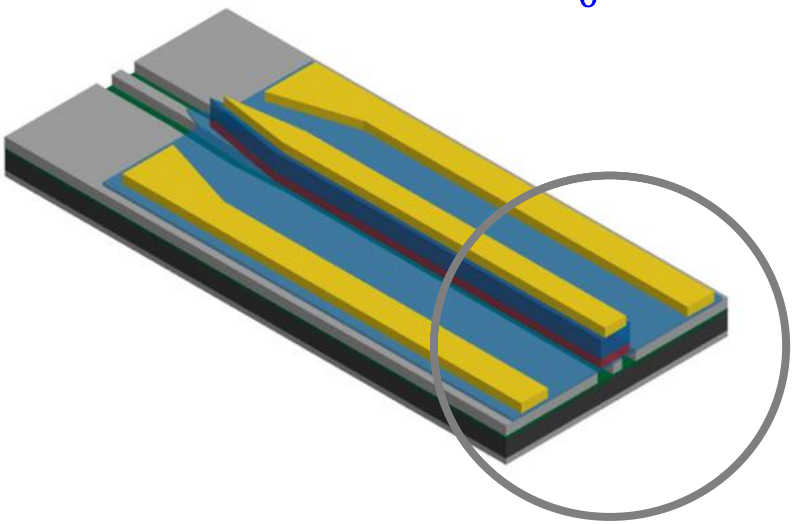
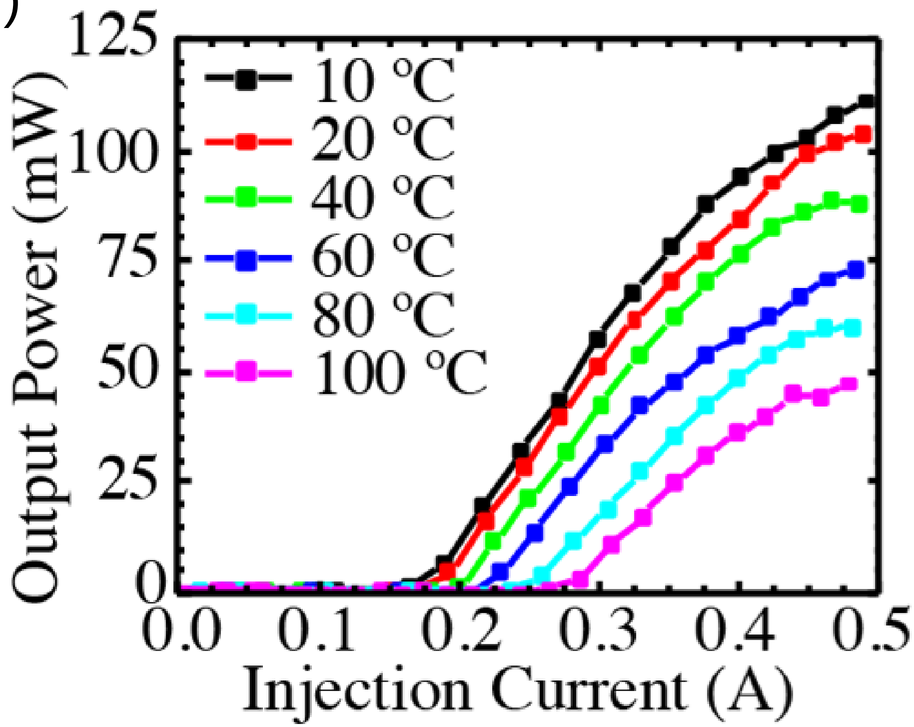
4.8 µm DFB (Taper Removed)

- Heterogeneous taper limiting performance?
  - Polished off one side for further testing
  - 211 mW output power (pulsed)
- Up to 100 ˚C pulsed operation
- Extracted T_0:
  - $J_{th} = J_0 e^{T/T_0}$ → $T_0 = 199\ K$





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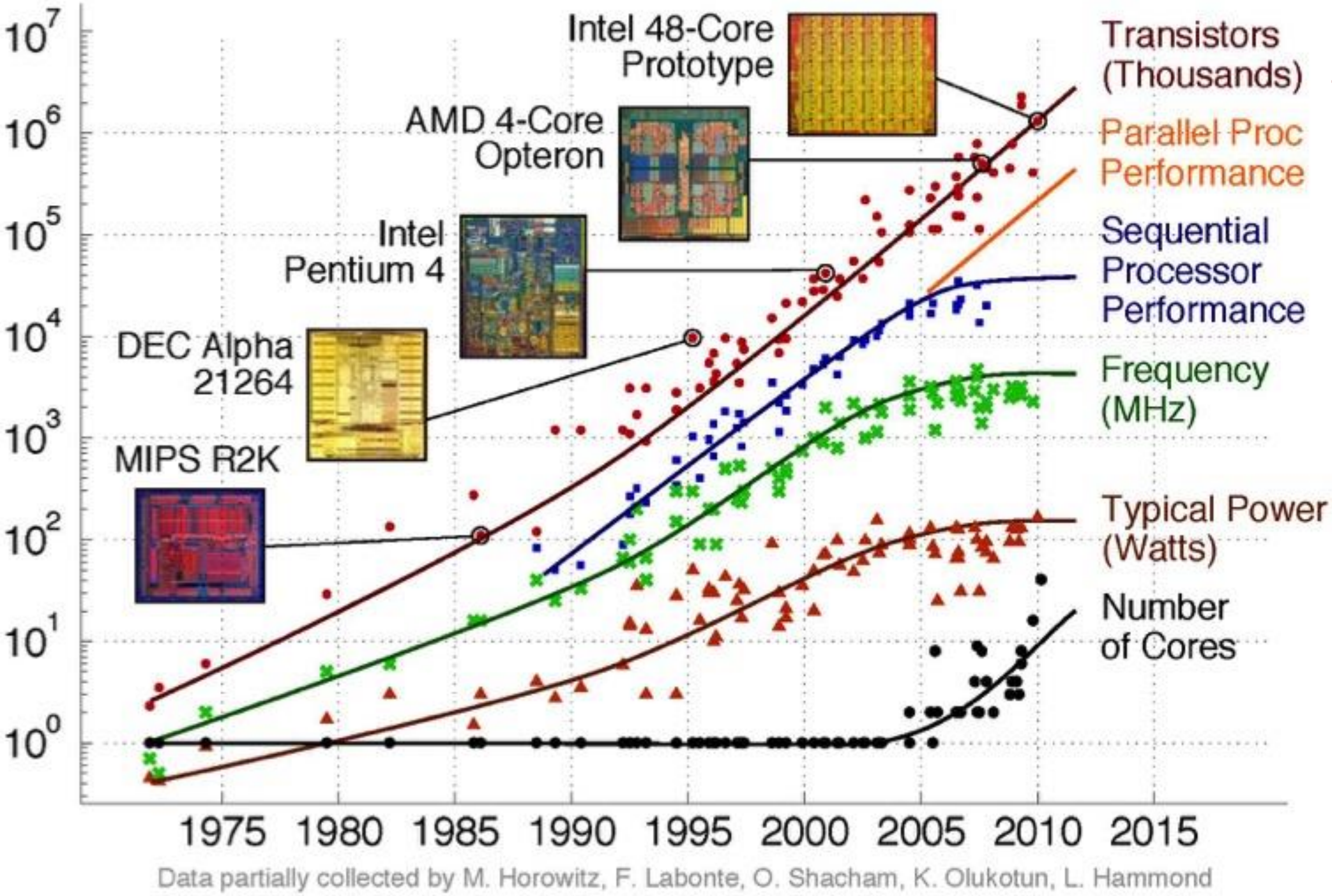
Evolution of Multicore Processors



1) Number of transistors is rapidly increasing

2) clock rates are not increasing

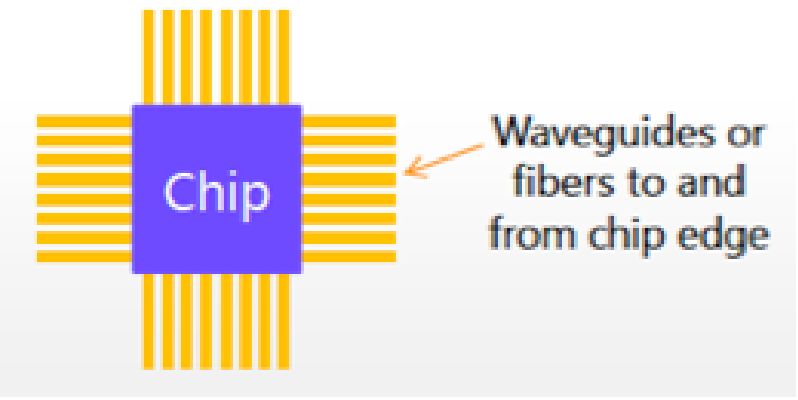
3) Power consumption is constrained

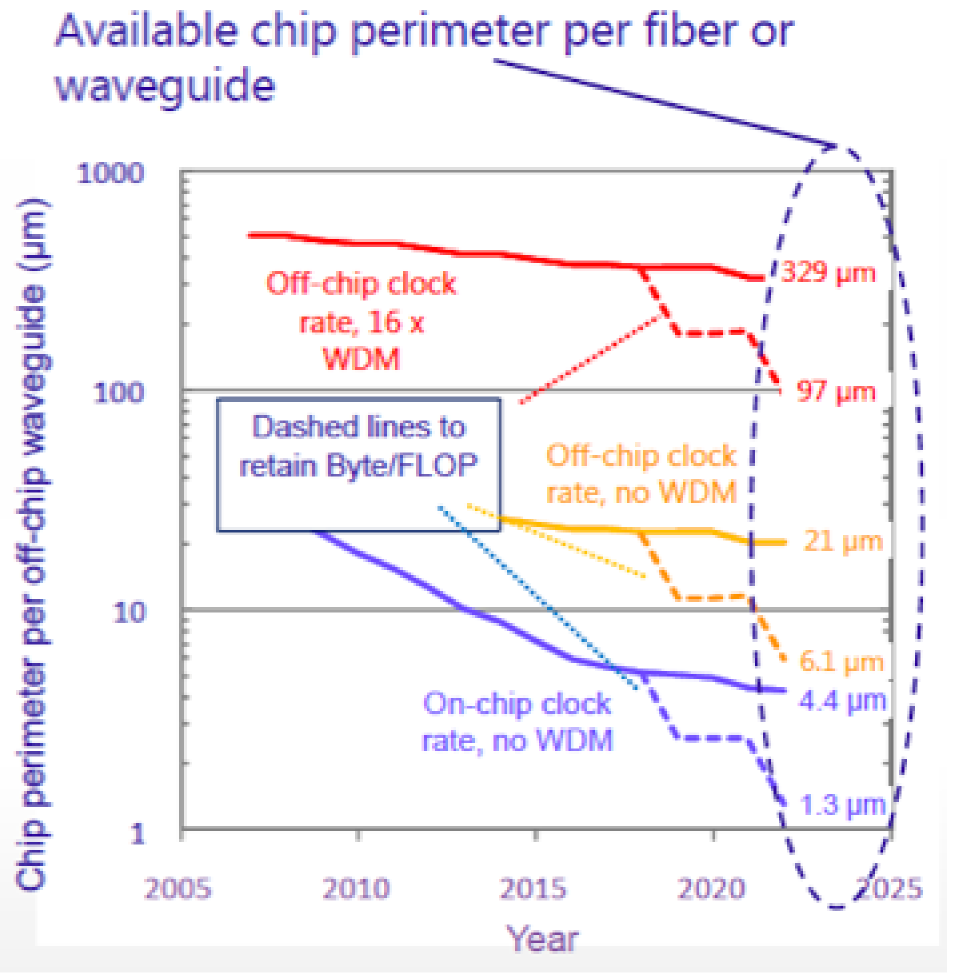
4) Rapidly increasing number of cores

Source: C. Batten

Waveguide Optics – Available Width

- Get enough optical channels off the edge of the chip?
- For waveguides around chip perimeter need:
  - Very dense waveguides, or
  - High clock speeds and WDM

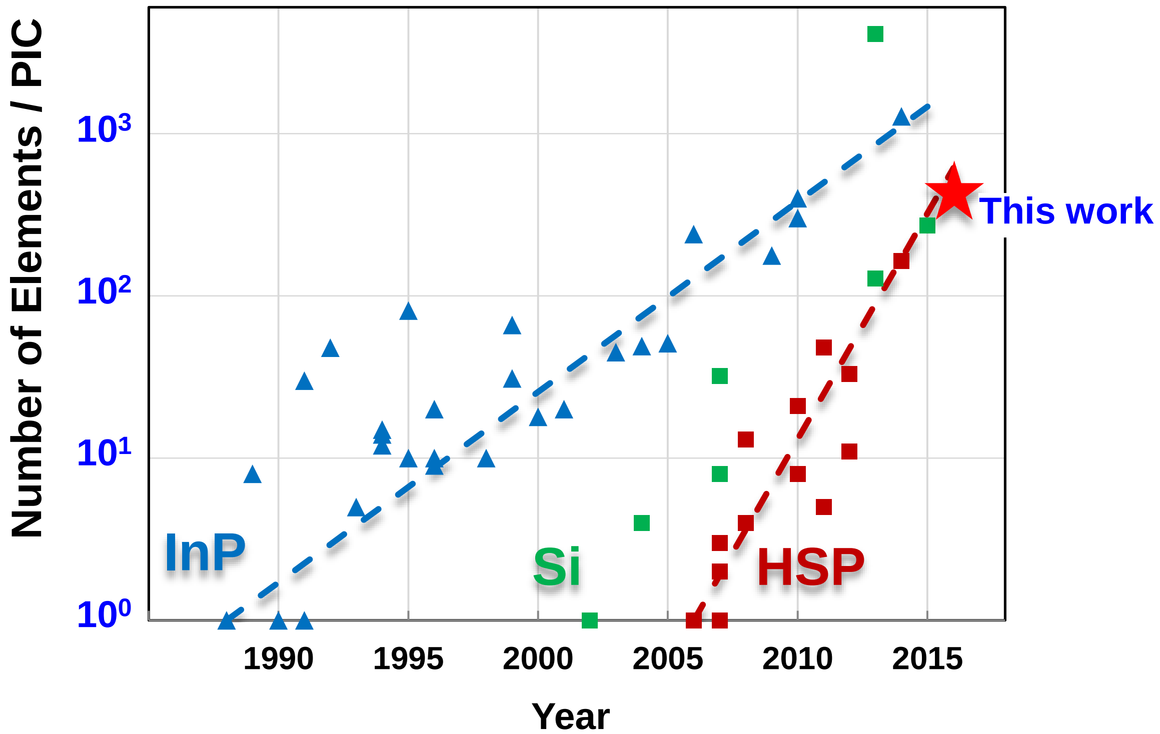




David Miller IEEE Photonics Conf 2013

Photonic Moore's Law

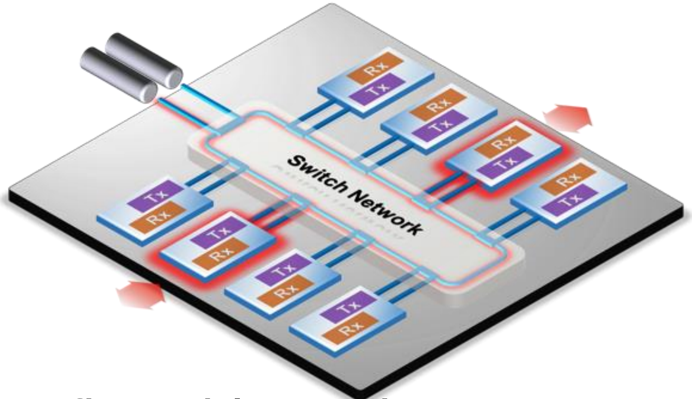
- Integrated reconfigurable transceiver network for chip-level interconnection
  - Over 400 elements on chip
  - Total 2.56 Tbps data capacity

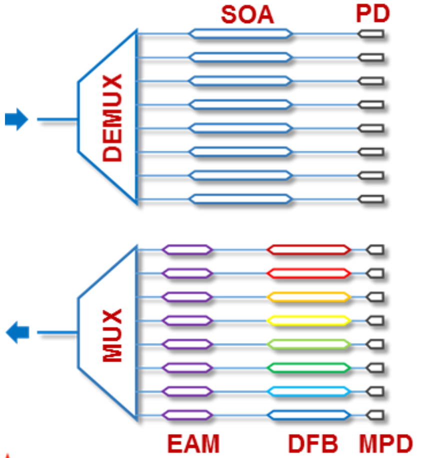


Chong Zhang, S. Zhang, J. Peters, J. E. Bowers CLEO 2016

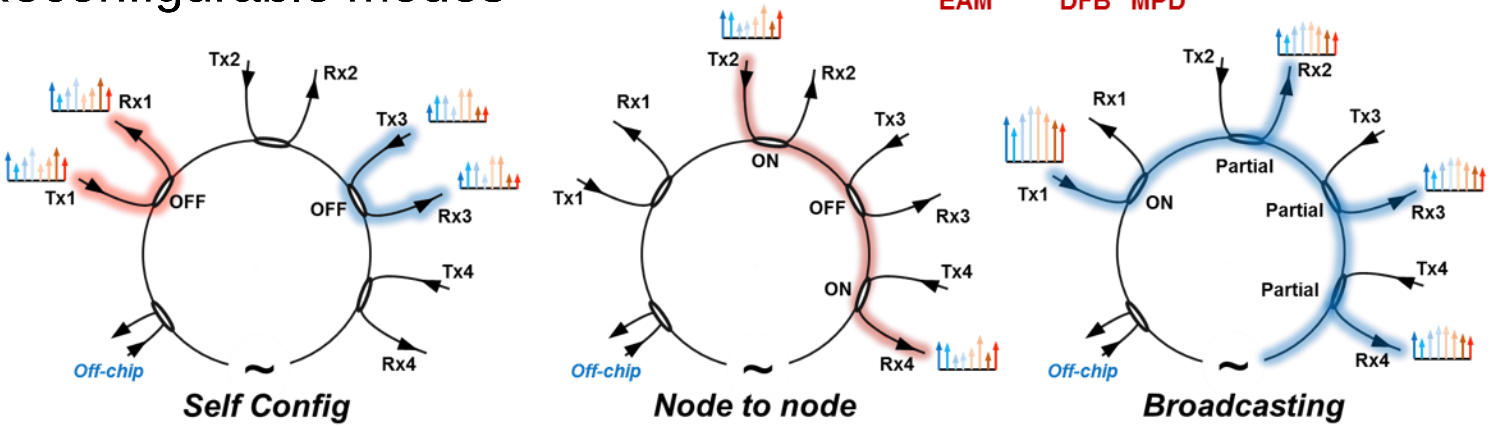
Reconfigurable NoC (Network-on-Chip)

- BUS-ring network on chip with flexible configuration
- WDM signal routing enabled by broadband switch fabric





- Reconfigurable modes



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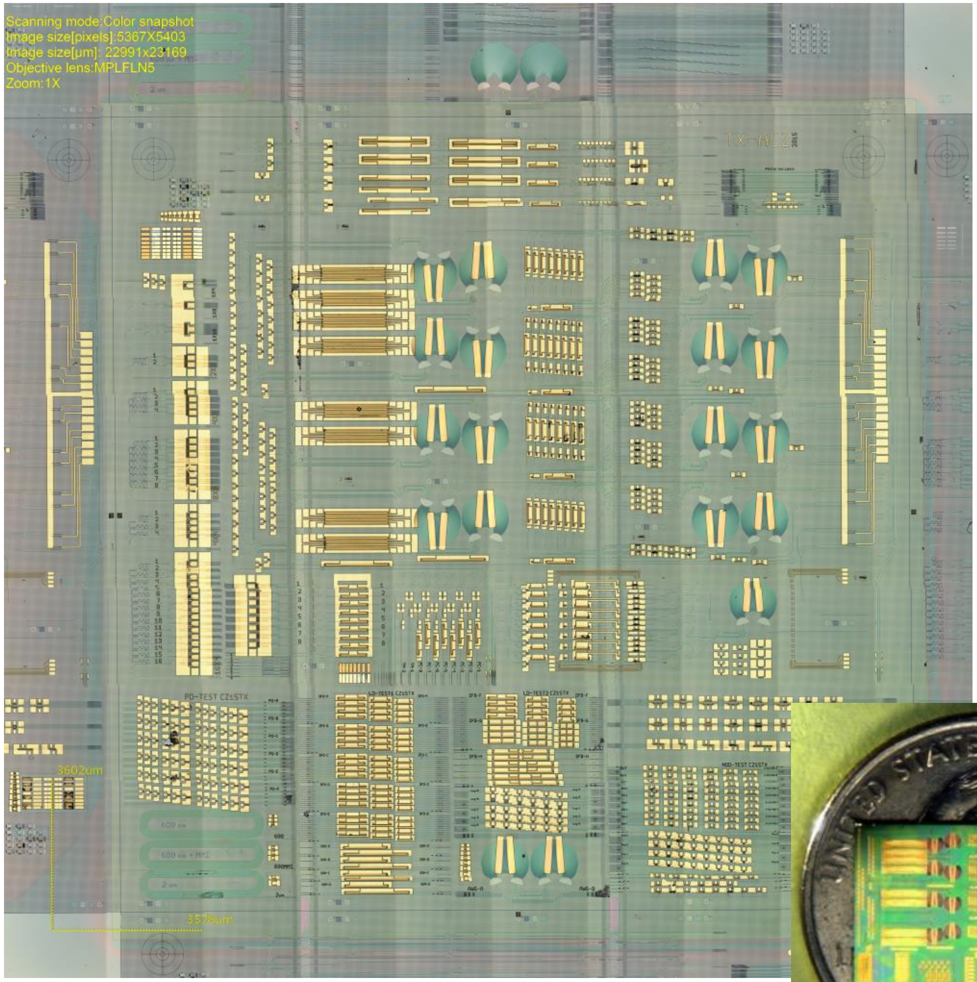
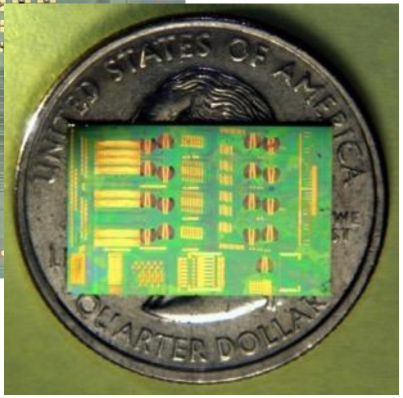
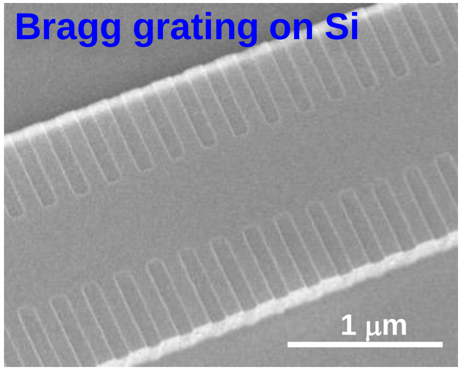
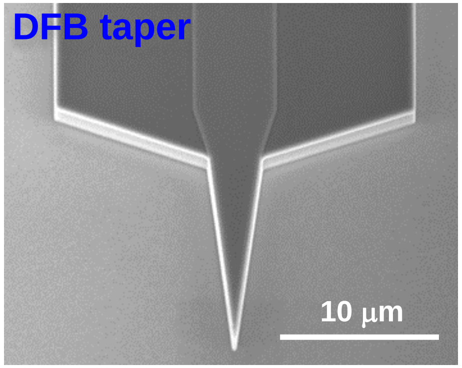
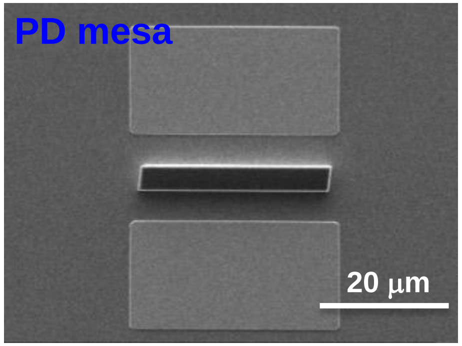
Reconfigurable NOC - Layout and Fabrication











48 DFB, 93 EAM, 67 PD, 17 AWG…

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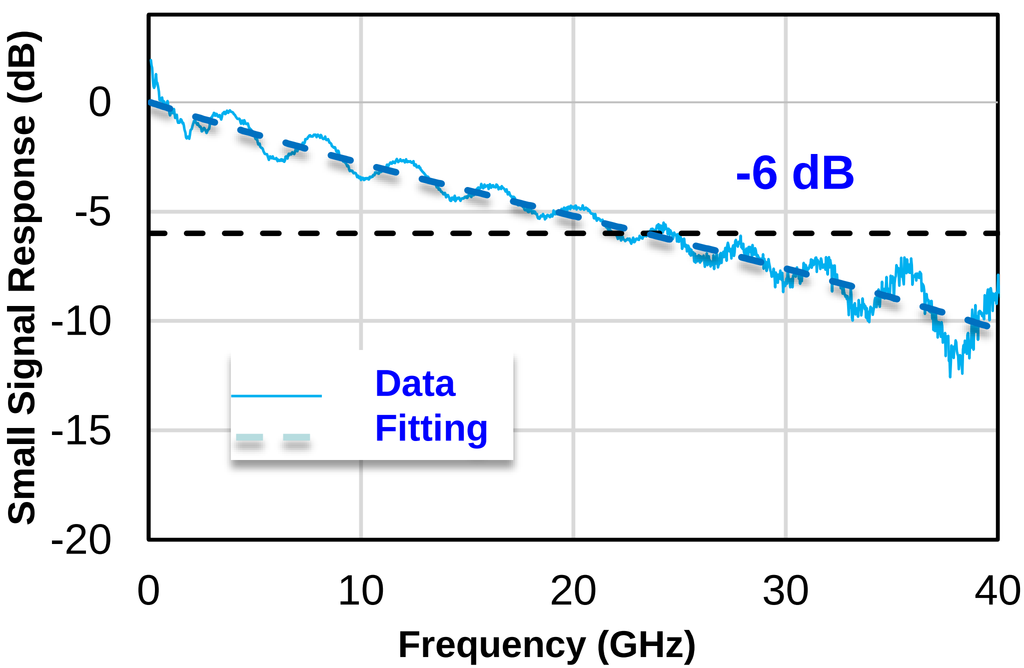
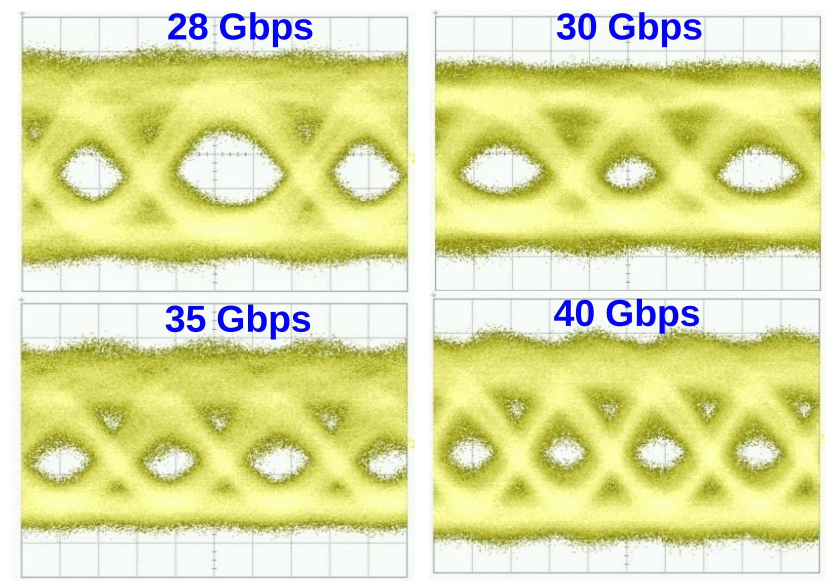
Reconfigurable NOC - Link Performance

- A 6-dB bandwidth of 24 GHz was measured for the EAM-PD link.
- Data rate of 40 Gbps per channel, showing a potential large capacity of the transceiver array, with 320 (8×40) Gbps per transceiver node, and 2.56 Tbps (8×320 Gbps) for the whole photonic circuit.





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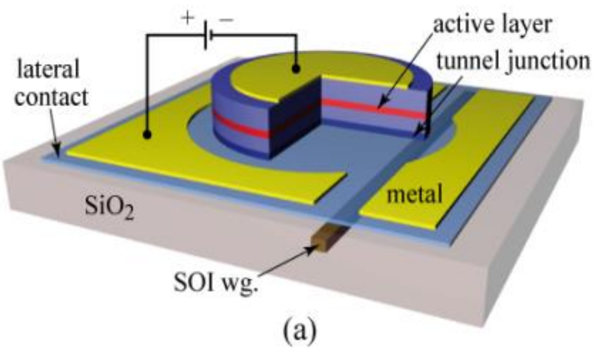
Low-Cost Lasers - Missing Piece

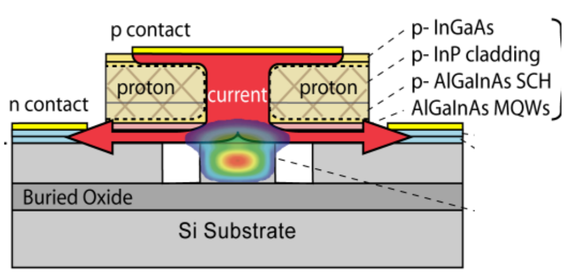
Si : Indirect bandgap, low internal quantum efficiency (10^{-6})

❑ Hybrid integration

- Size and cost limitation



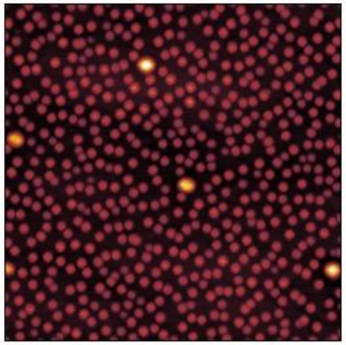
Ghent Univ. 2007



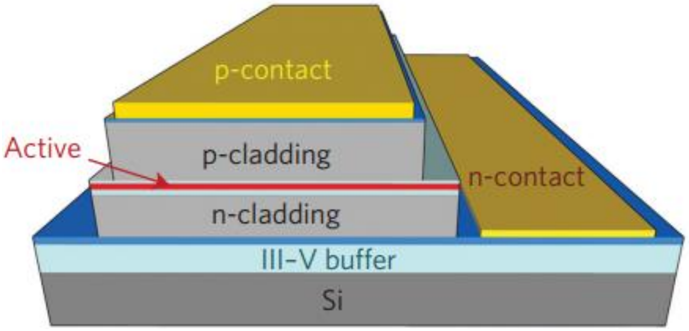
UCSB, 2006

❑ Monolithic integration

- Low cost and high yield



UCSB 2016

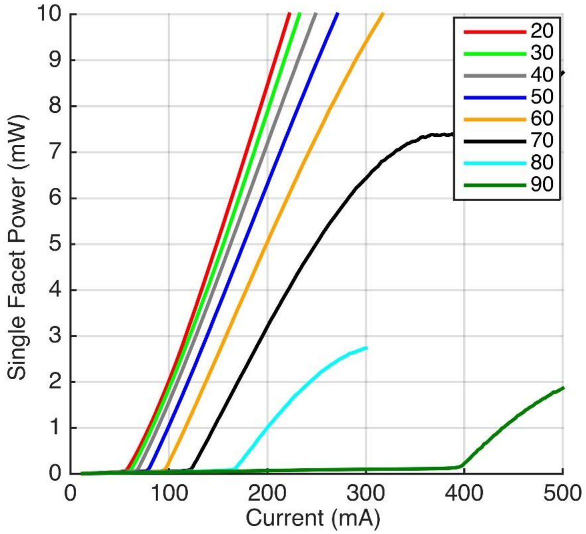


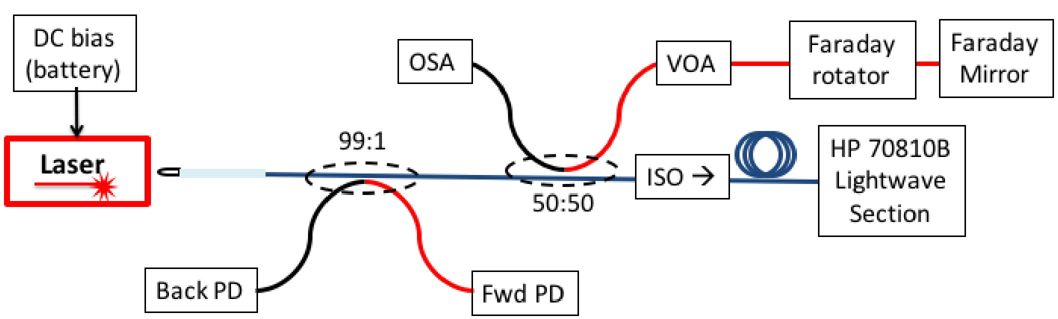
University College London. 2016

Issues with Epitaxial Lasers on Si

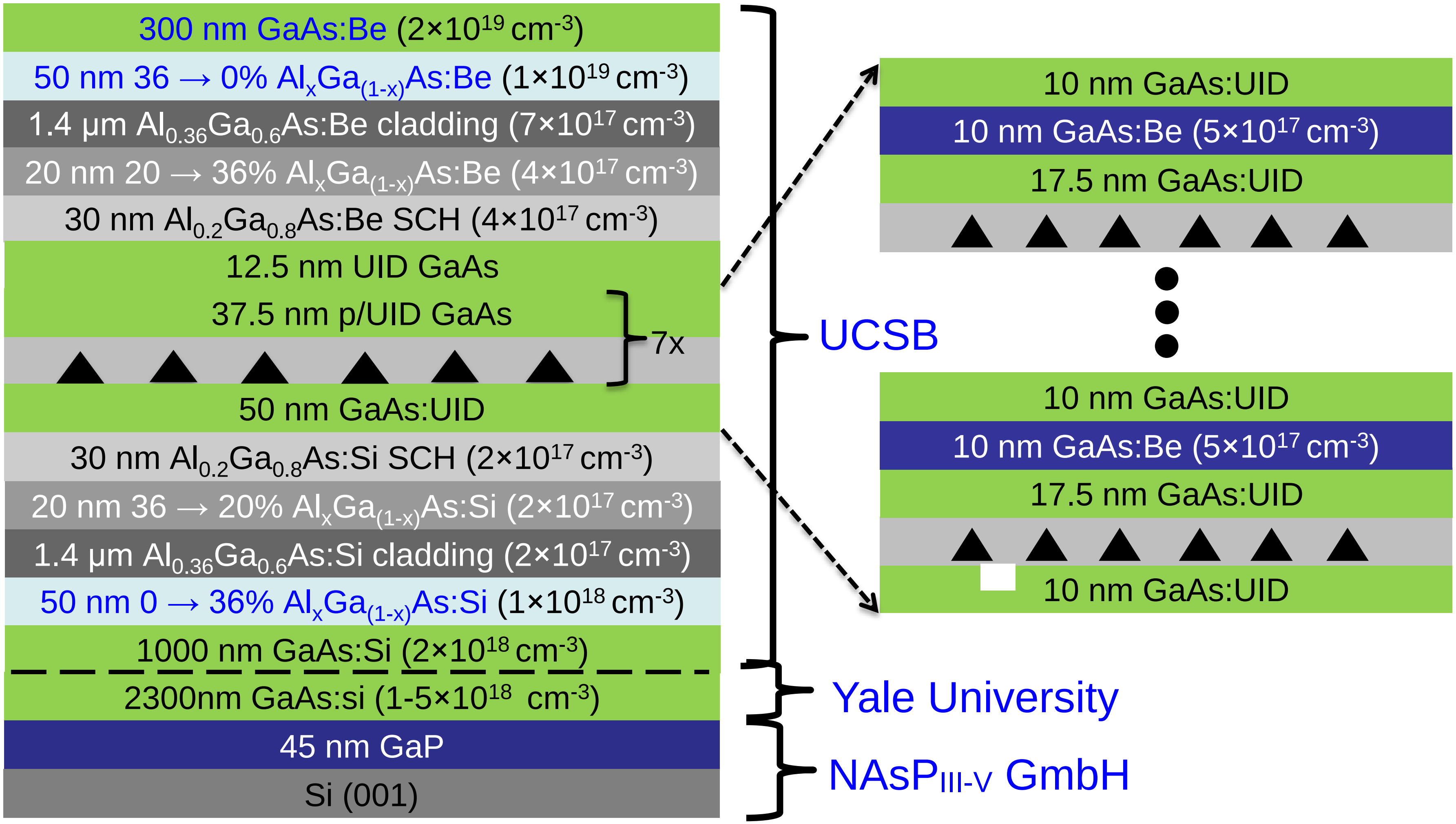
- Offcut Si substrates: Not compatible with standard CMOS foundry process
- Ge buffer layers: Absorptive and relatively thick, preclude potential incorporation in the SOI technology
- Low energy consumption: Required for high integration density

- 1.3 µm Qdot lasers grown on GaP/GaAs buffer lasers
- Reduced back-reflection sensitivity of Quantum-Dot lasers
  - Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016





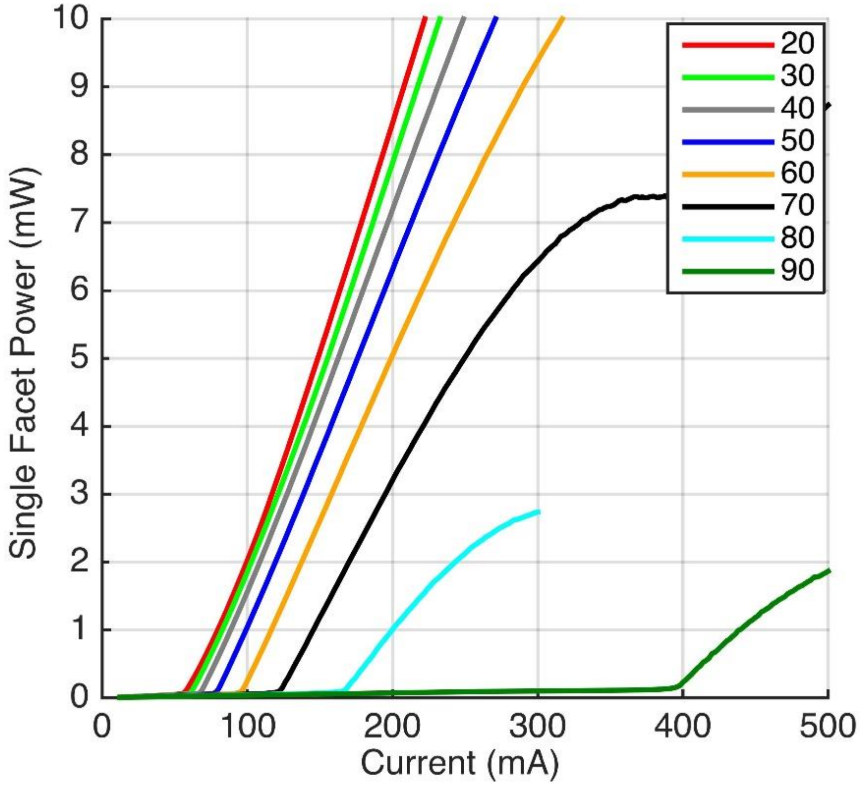
Lasers on GaP Buffer - Epi Design

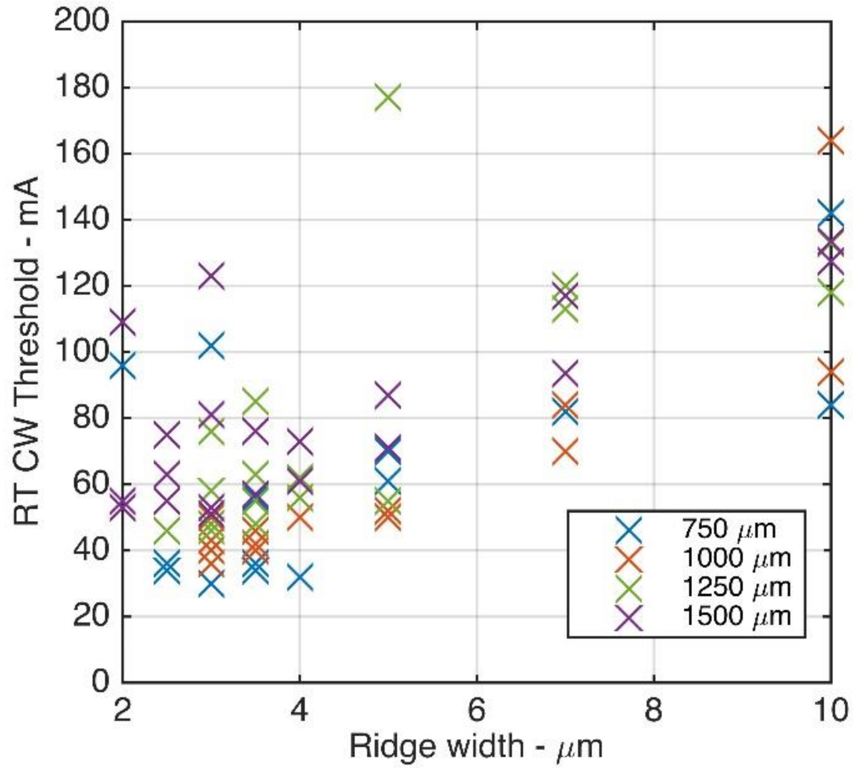


Liu, Peters, Norman, Huang, Jung, Lee, Gossard, Bowers ICMBE 2016

QD Laser - High Temp Lasing

- CW lasing to 90°C
- Characteristic temperature, T_0
  - 42K 40-90°C
- I_{th} 30 mA (3-4 µm ridge laser)

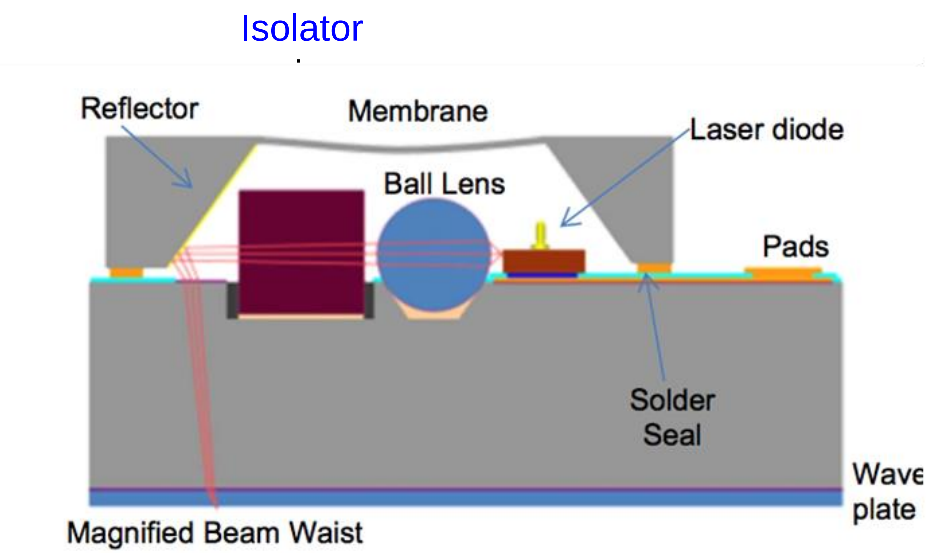


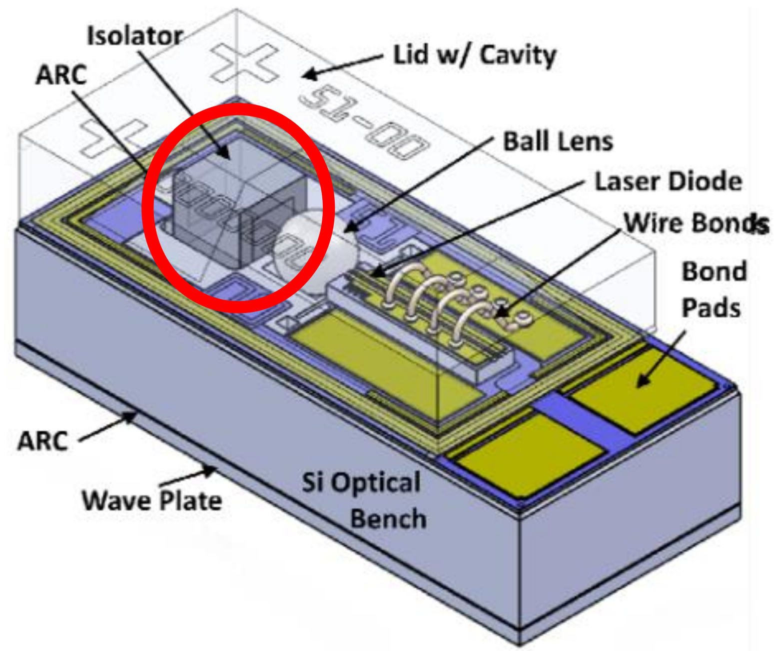


Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016

Sensitivity to reflections

- Unintentional reflections can disturb lasing stability (increased linewidth and intensity noise)
- Isolators typically used to prevent this, but adds $$$ and footprint, on-chip isolators would potentially add loss
- Desirable to avoid isolators altogether





Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016

Sensitivity to reflections - Theory

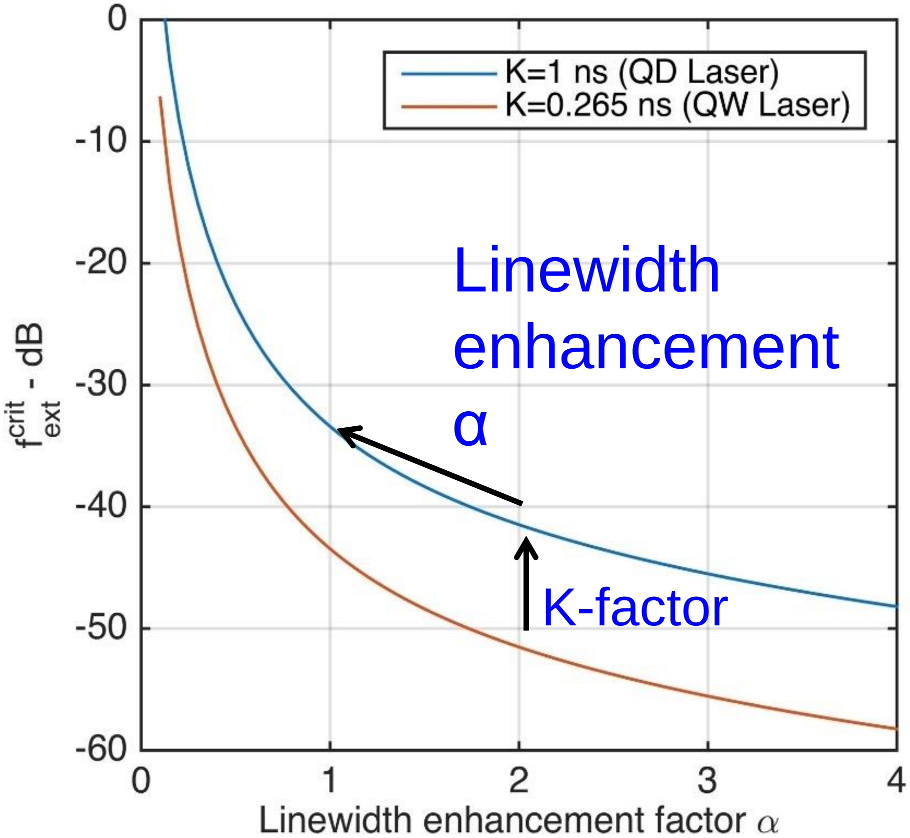
- Laser stability with feedback depends on [1]:
  - Damping of relaxation oscillation (higher in QD lasers)
  - ~1/α² (α may be lower in QD lasers)

[1] J. Helms and K. Petermann, IEEE J. Quant. Electron. 833 (1990)

damping factor improvement >10 dB

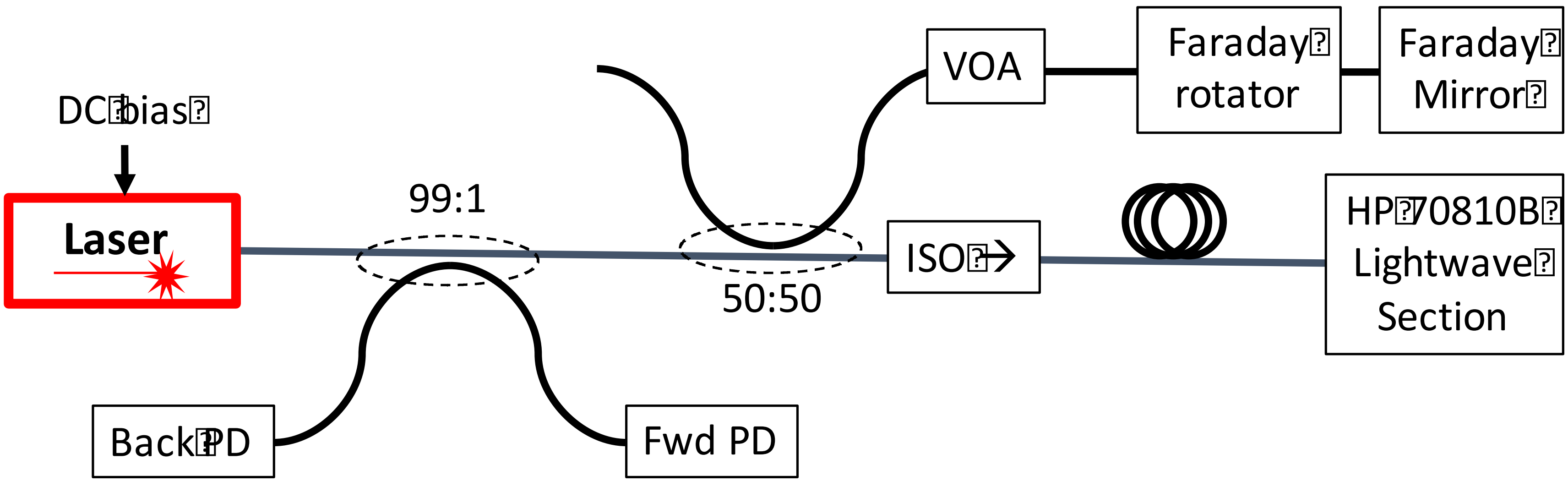
$$f_{ext}^{crit} = \frac{\tau_L^2 (K f_r^2 + \gamma_0)^2}{16|C_e|^2} \left(\frac{1+\alpha^2}{\alpha^4}\right)$$

some improvement



Sensitivity to reflections - Measurement

- Characterization of sensitivity to optical reflections
  - Laser output split with a 50:50 coupler with half going to spectrum analyzer for RIN measurement, other half reflected back to laser
  - Polarization control with in-line Faraday rotator plus Faraday mirror
    - External cavity length: ~15 meters
  - Feedback level is defined as ratio of power levels in forward and back monitor PDs



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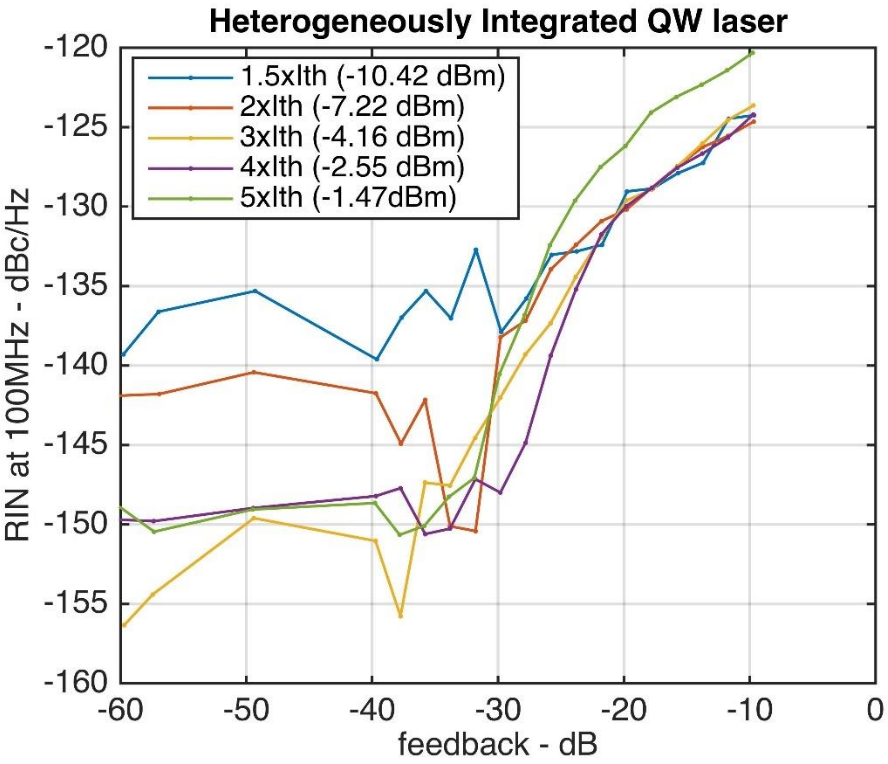
Sensitivity to reflections: QW vs QDot

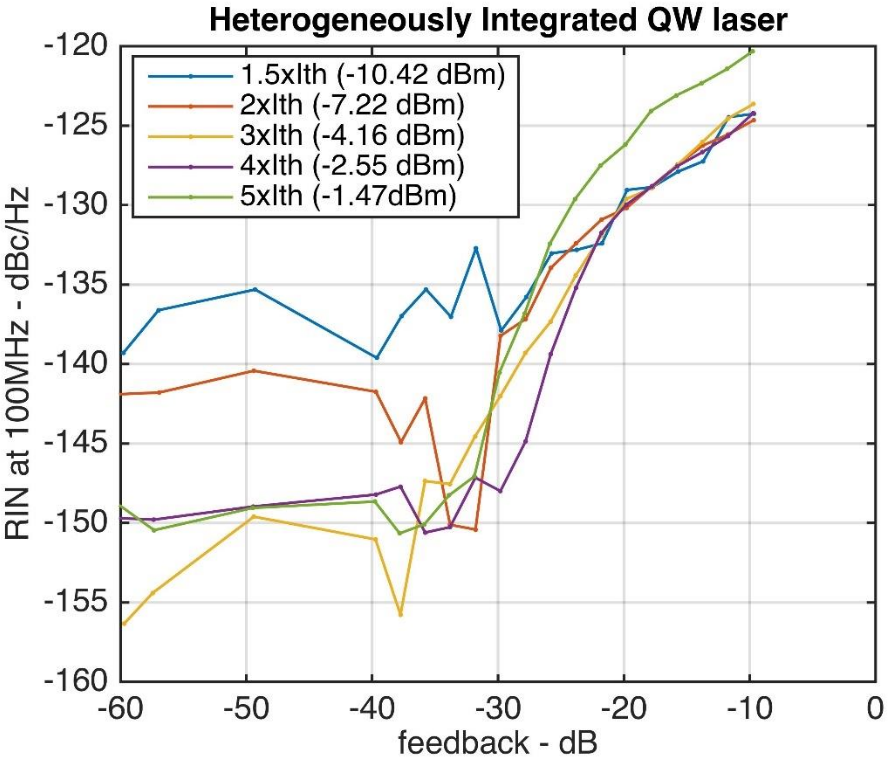
- For QW laser, low frequency RIN increases by up to 30 dB vs feedback

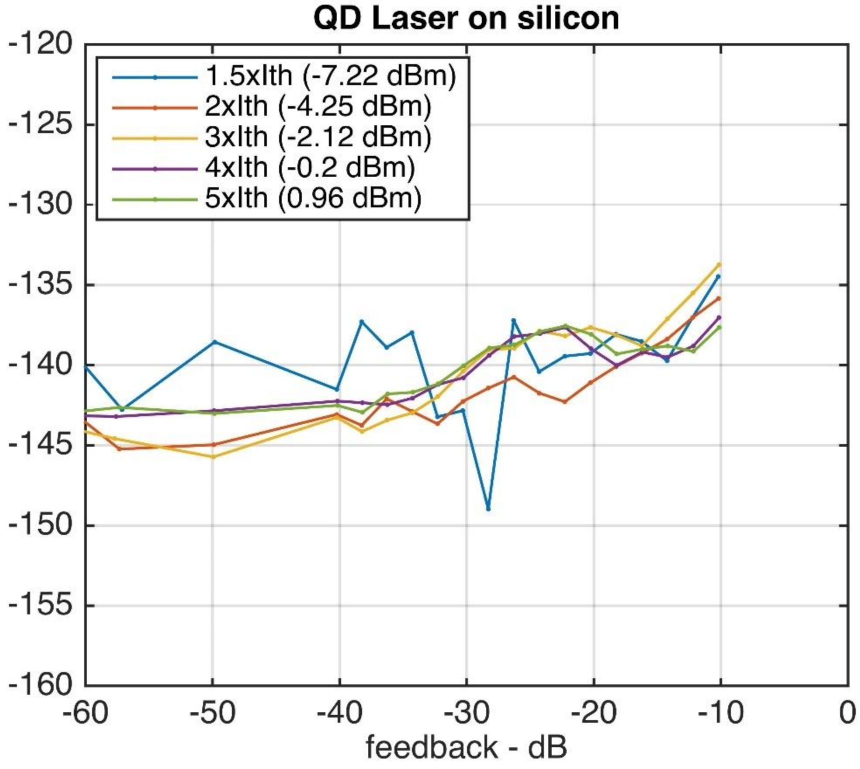


Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016

Sensitivity to reflections: QW vs QDot

- For QW laser, low frequency RIN increases by up to 30 dB vs feedback
- For QD laser, increase in RIN is only ~10 dB

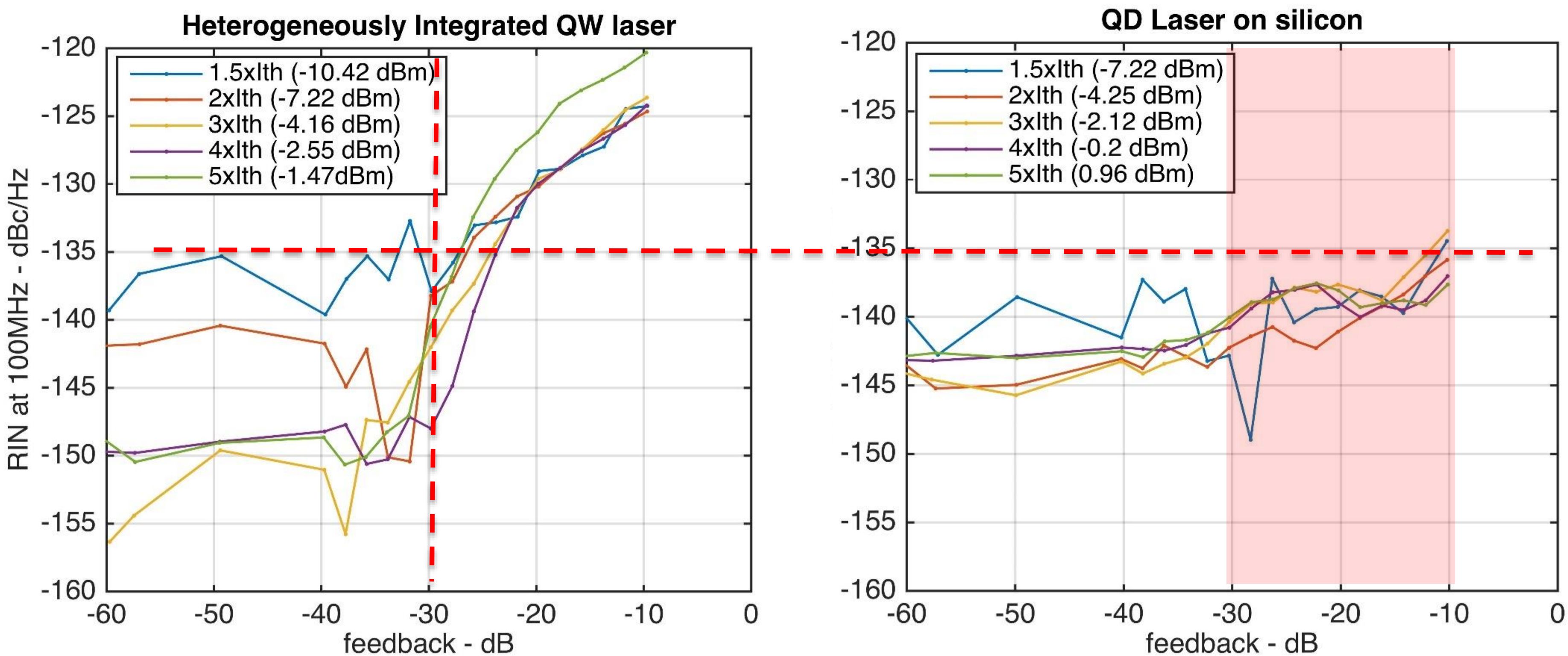




Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016

Sensitivity to reflections: QW vs QDot

- For QW laser, low frequency RIN increases by up to 30 dB vs feedback
- For QD laser, increase in RIN is only ~10 dB
- 20 dB higher feedback for RIN increase to -135 dBc/Hz in QDs vs QWs



Liu, Peters, Huang, Jung, Komljenovic, Davenport, Norman, Lee, Gossard, Bowers ISLC 2016

Summary I

- Optical amplifiers on Si (1550 nm)
  - High gain: 26 dB (0.95 μm waveguide device)
  - High power: 16 dBm (1.4 μm waveguide device)
  - Large optical 3dB bandwidth: 66 nm
- Isolator / Circulators on Si
  - 32 dB of isolation with record low 2.3 dB excess loss
  - No permanent magnet needed
  - <10 mW of electrical power
- Arrayed Waveguide Grating (AWG)
  - Centered near-visible (760 nm)
  - Record center channel insertion loss < 0.5 dB (760 nm)
  - Record low crosstalk < -23 dB (760 nm)

Summary II

- 4.8 µm Quantum-Cascade Lasers on Si
  - >200 mW power (pulsed) from DFB laser
  - Pulsed operation up to 100 ºC
  - Threshold current densities below 1 kA/cm^2
- Network-On-Chip circuit on Si
  - Reconfigurable transceiver network for chip-level interconnect
  - Over 400 elements on chip, including 48 low threshold lasers
  - 2.56 Tbps total capacity

Summary III

- First electrically-pumped CW laser monolithically grown; Si foundry compatible (001), without Ge layer
  - Thresholds down to 30 mA
  - Output power up to 110 mW
  - CW lasing up to 90 C

- Reflection sensitivity reduction QDot vs QWell 20 dB
  - Potential for isolator-free integration of QDot lasers