More then Moore with Electronic-Photonic Integration

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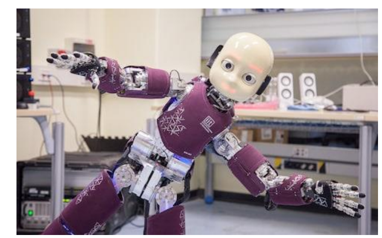
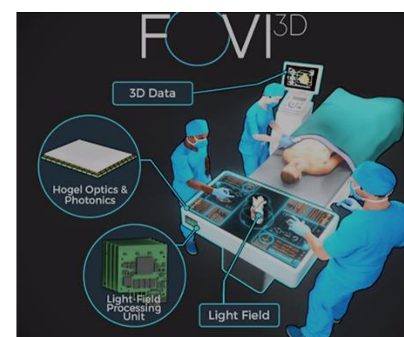
- DARPA, Micron, NSF, BWRC
- IBM Trusted Foundry, Global Foundries

Changing role of electronics





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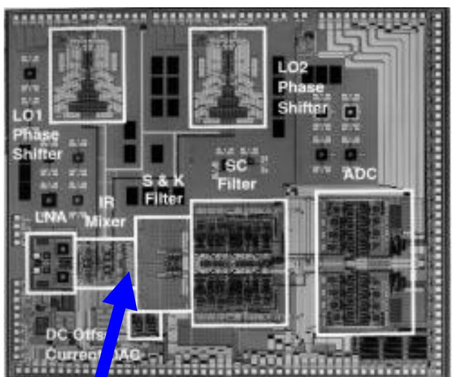
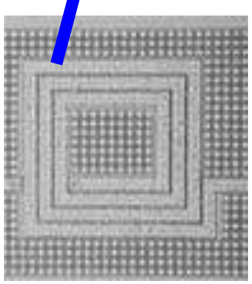
More-than-Moore perspective

Enhanced CMOS enables new applications

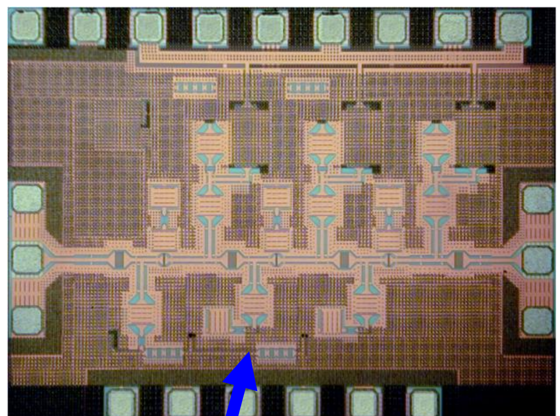
1997
One of the first CMOS radios
Rudell & Gray

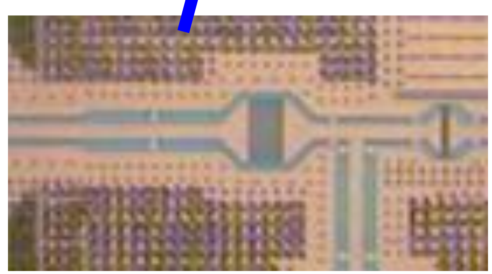




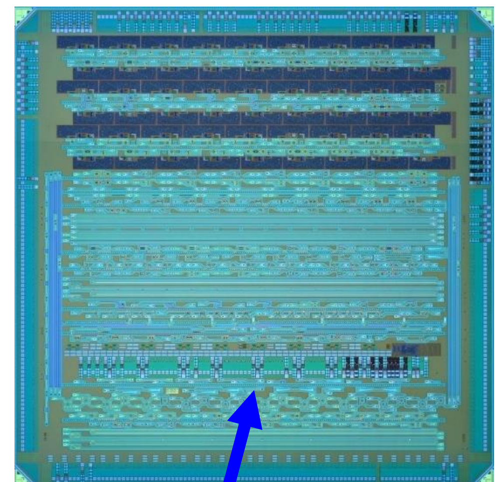
Inductors in IC process
Nguyen & Meyer
1990

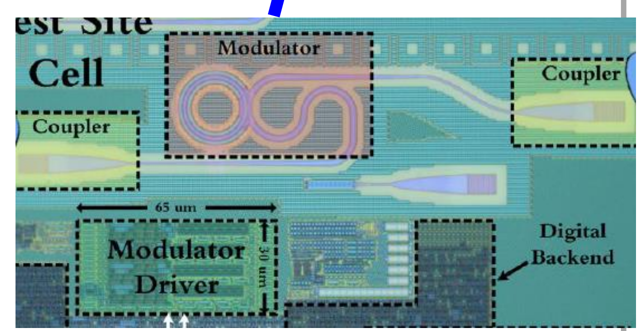
2004
World’s first 60GHz CMOS Amplifier
Niknejad & Brodersen



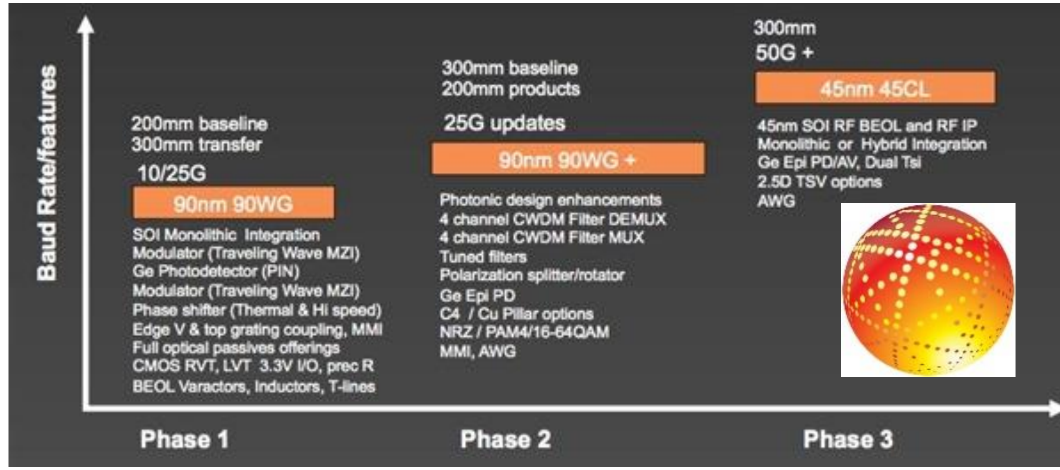


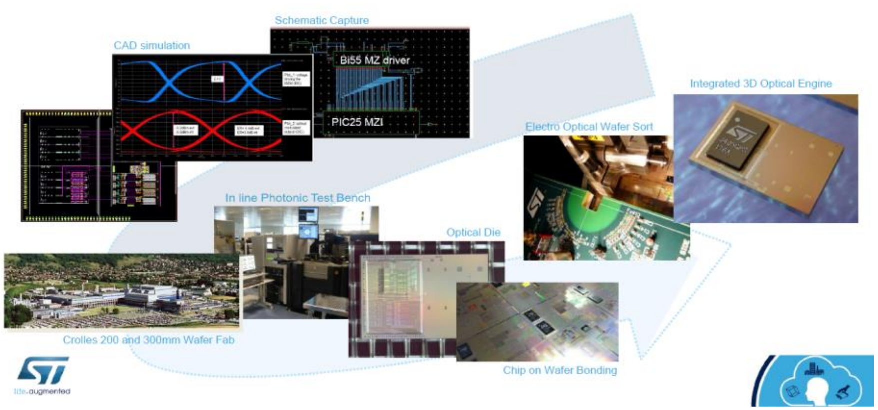
2012
World’s first siPhotonic transmitter in 45nm SOI
Stojanovic, Popovic, Ram

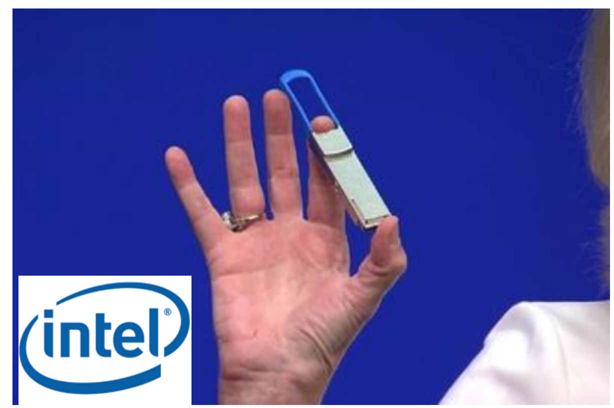




What is happening in Semiconductor Industry? – Part I

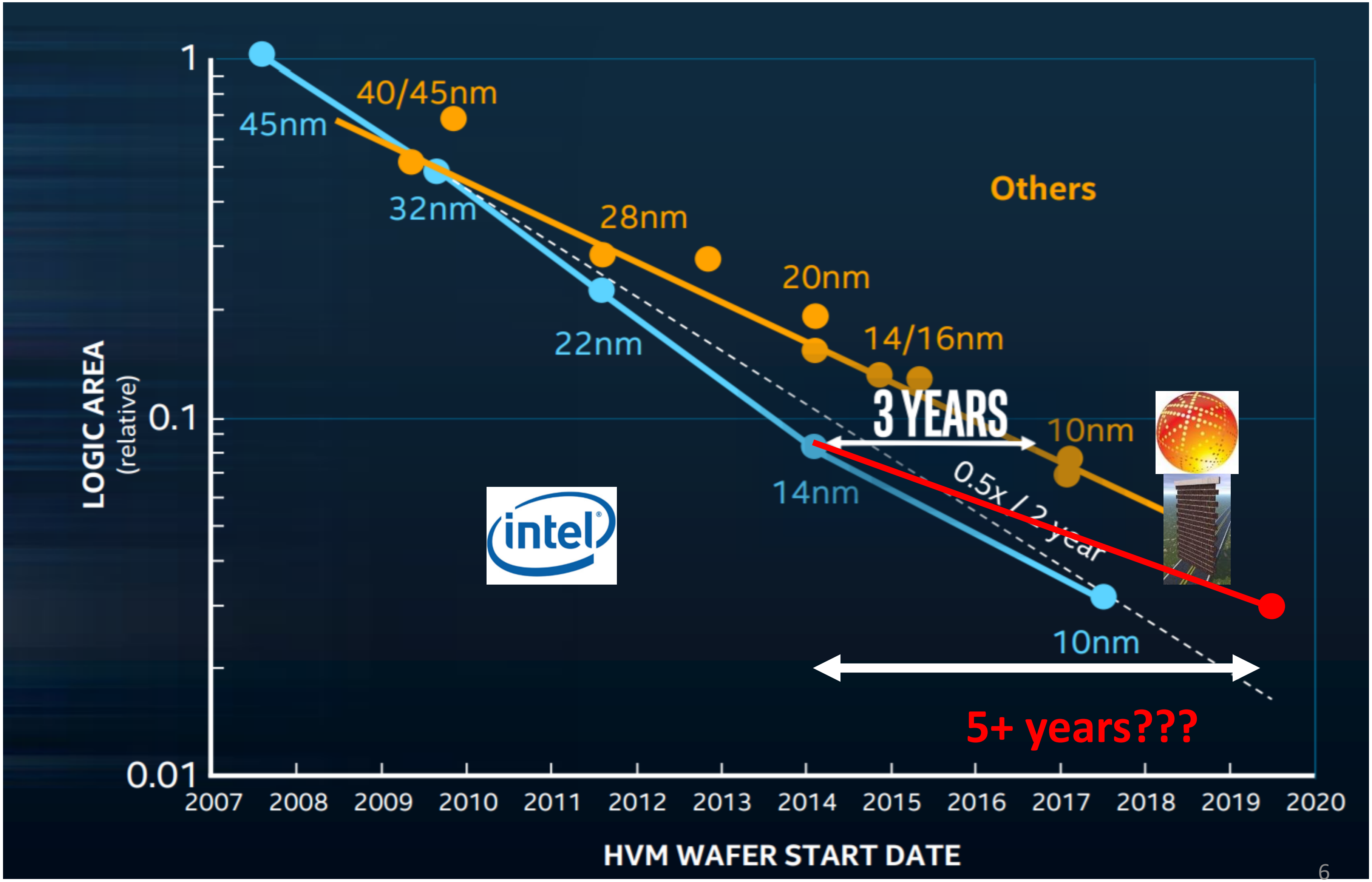






- Every major foundry has a Silicon-Photonic process

What is happening in Semiconductor Industry? – Part II



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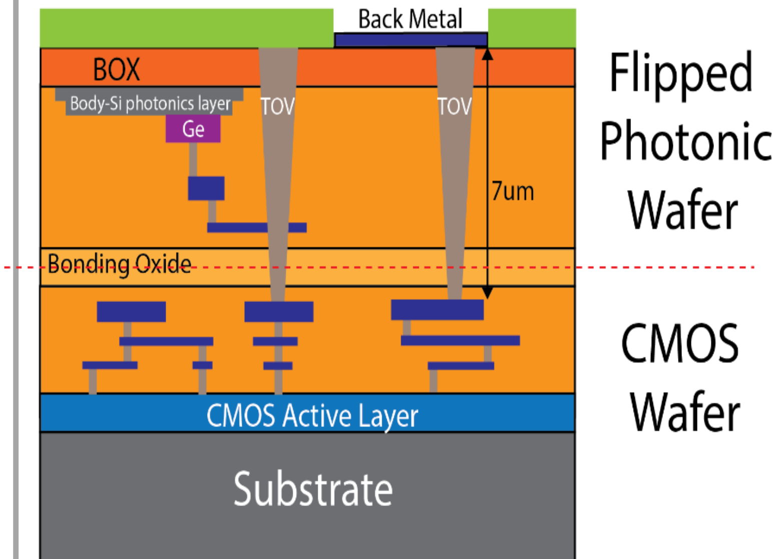
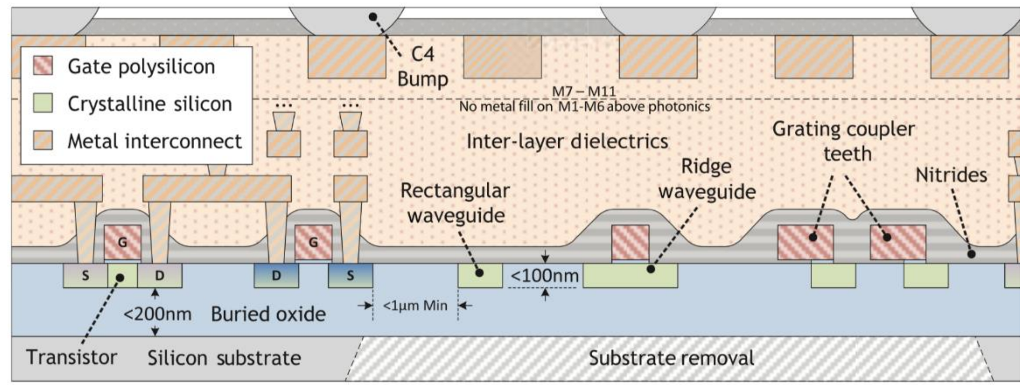
Our Process Platforms

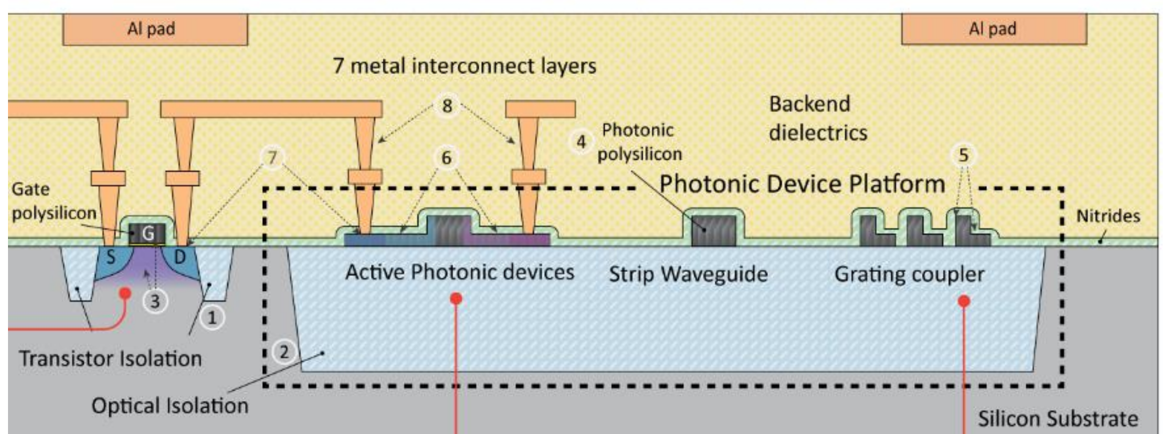


Fully-Customized SOI Photonics (CNSE)
+ any CMOS (currently 65nm bulk)

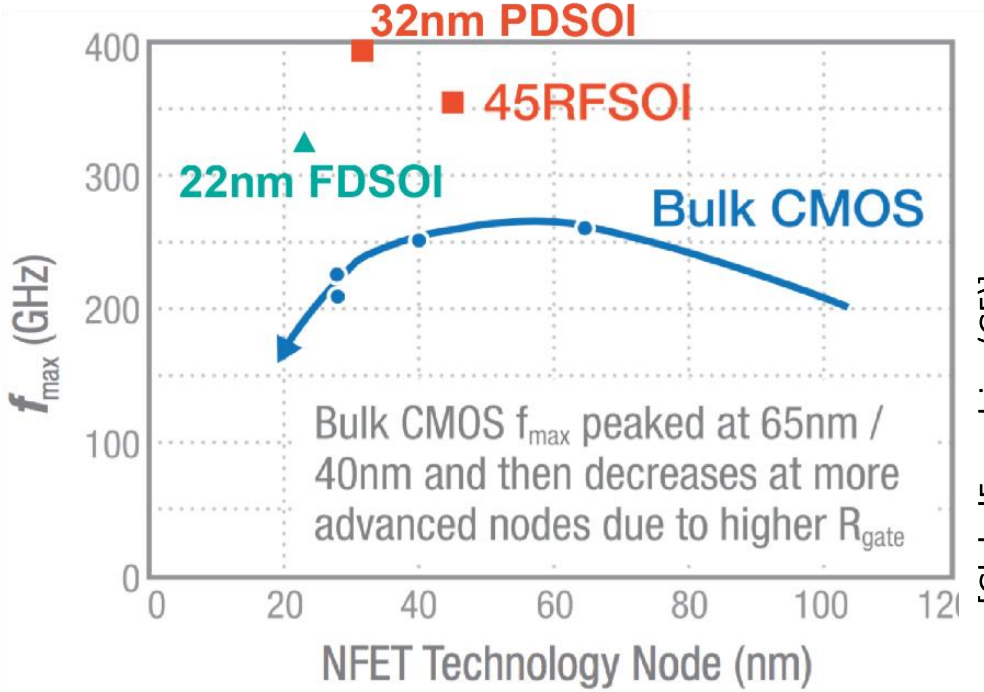
"Zero-change" (45nm and 32nm SOI)



Deposited Photonics
180nm (Micron) and 65nm (CNSE) **bulk CMOS**



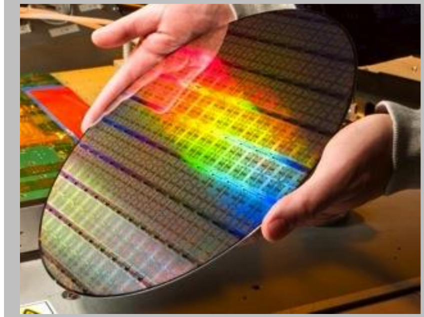
Photonics next to the fastest transistors



[GlobalFoundries (GF)]

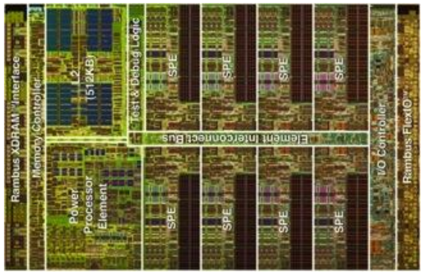
- f_T/f_{max} have not improved since 32nm node
- f_T/f_{max} affect speed, energy-efficiency, … of electronic-photonic systems
- **32/45nm: Fastest Transistors + Thick-enough Si bodies to guide the light**
  - Si body in SOI nodes below 32nm (FDSOI) cannot guide the light!

IBM/GF 12SOI (45nm) CMOS

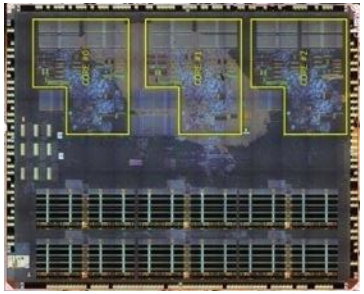


- 300mm wafer, commercial process
- MOSIS and TAPO MPW access
- Advanced process used in microprocessors
- Photonic enhancement enables VLSI photonic systems (no required process changes)

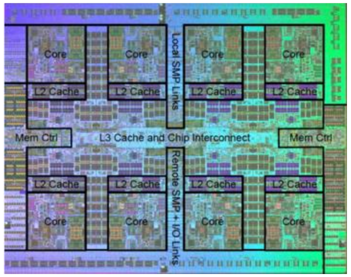
IBM Cell



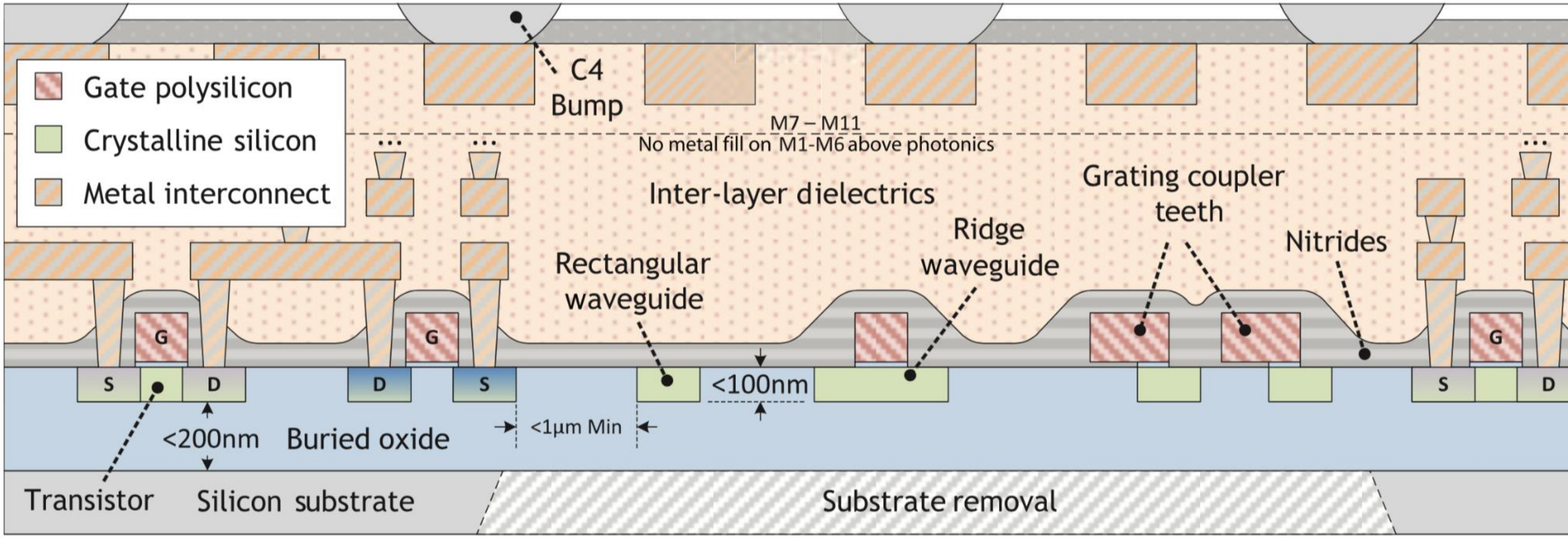
IBM Espresso



IBM Power 7



“Zero-Change” Optics in 45nm



[C. Sun, JSSC 2016]

- Photonics for free! (No modification to the process)
- Closest proximity of electronics and photonics
- Single substrate removal post-processing step

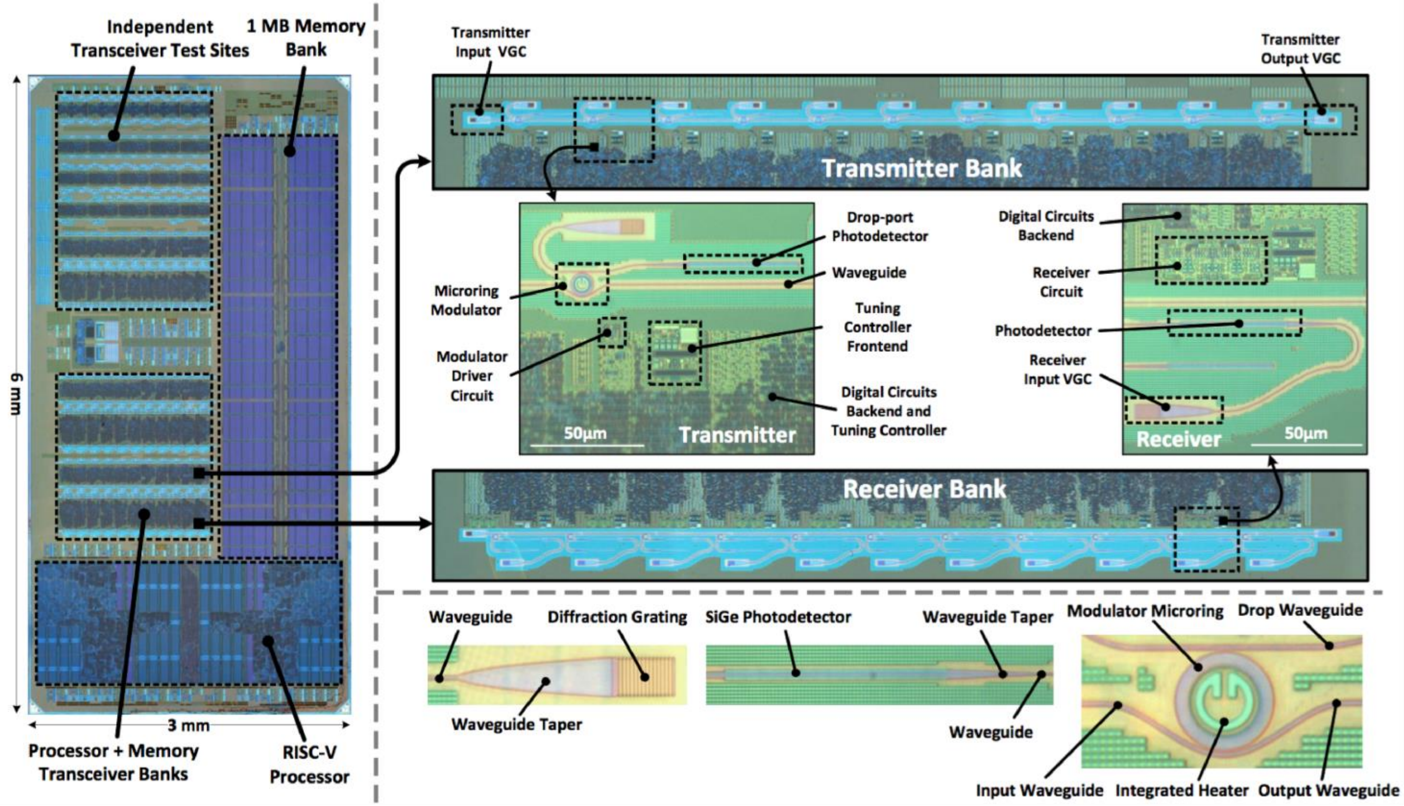
Monolithic photonics platform with the fastest transistors

World’s first processor to communicate with light

Silicon-Photonic components integrated directly in the chip

Zero-change DARPA POEM & PERFECT – Stojanović, Ram, Popović, Asanović

45nm SOI **70+M transistors, thousands of photonic devices**

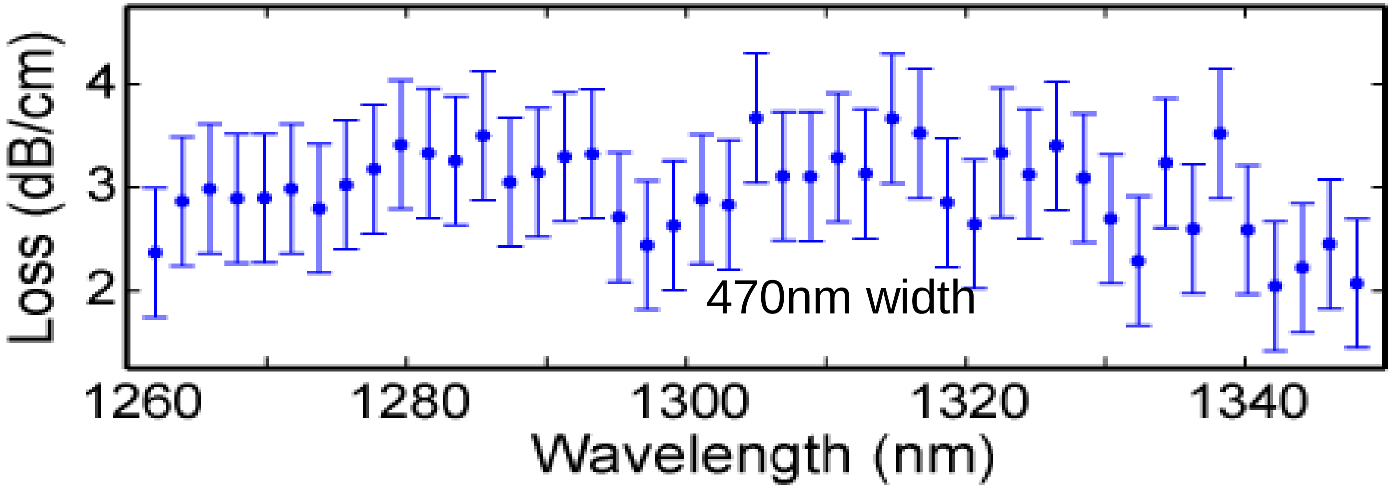


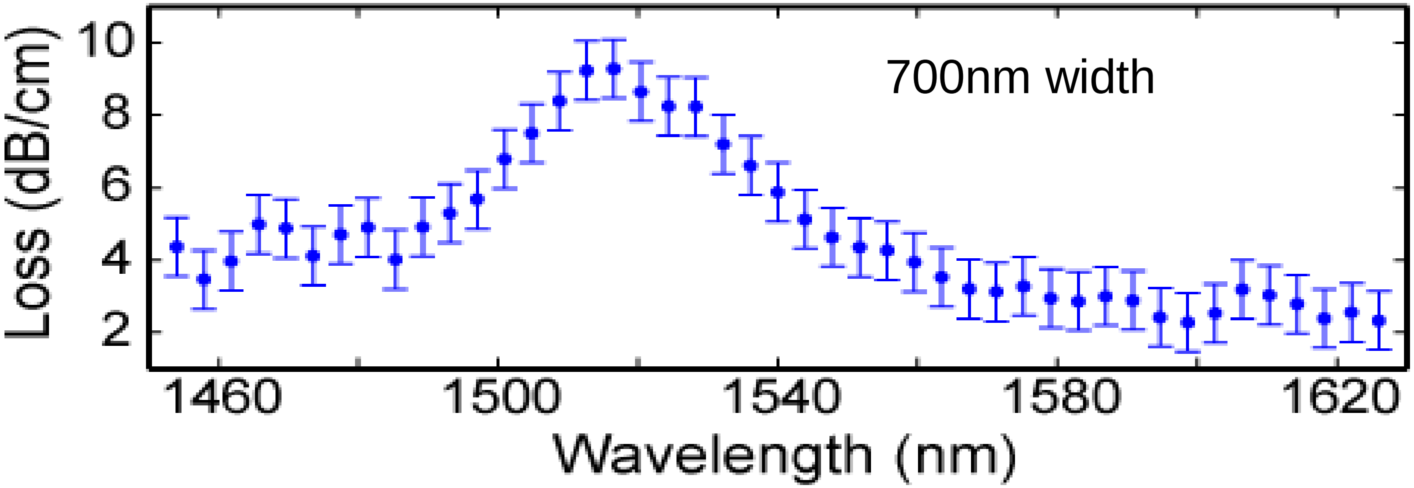
C. Sun *et al. Nature, Dec. 15.*

SiFive

Ayar Labs

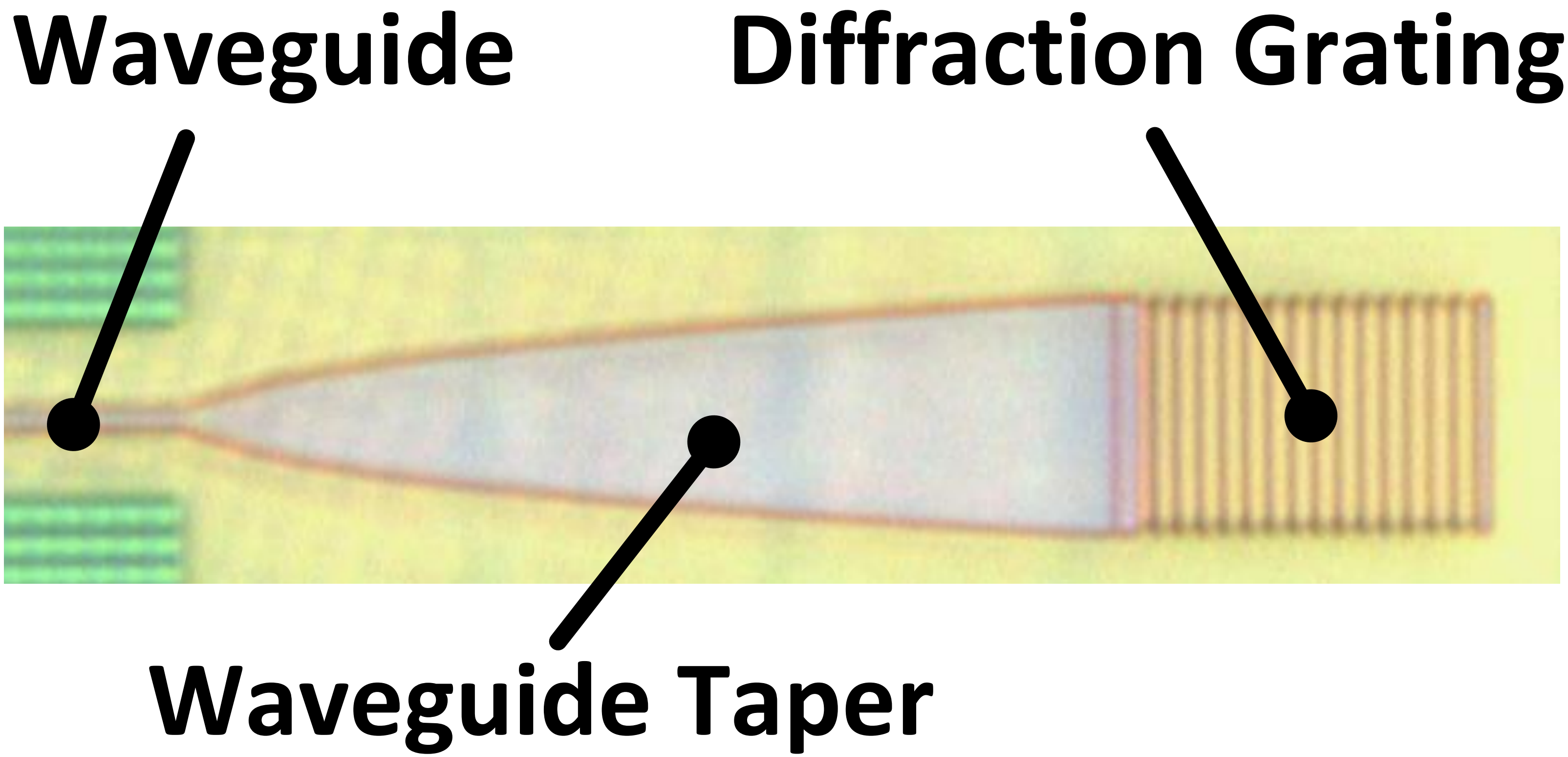
Si Waveguides





Key Device Components

Vertical couplers

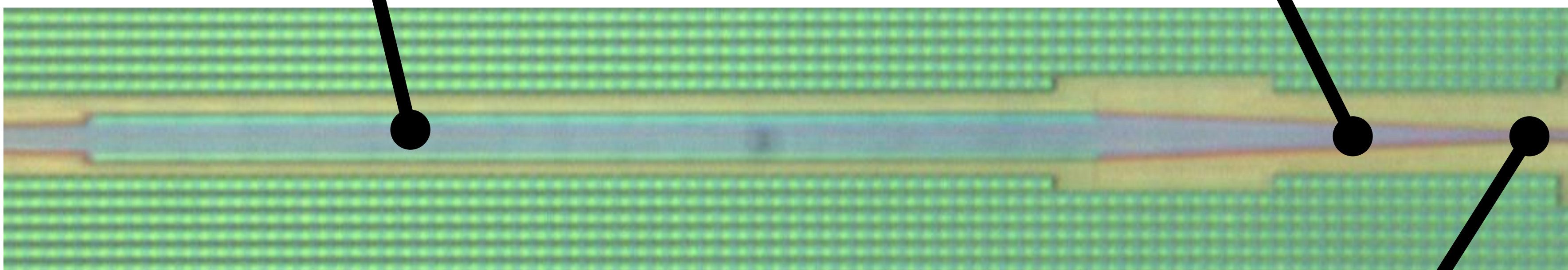


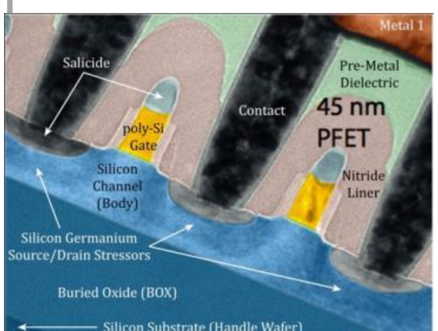
[Wade OIC 2015]

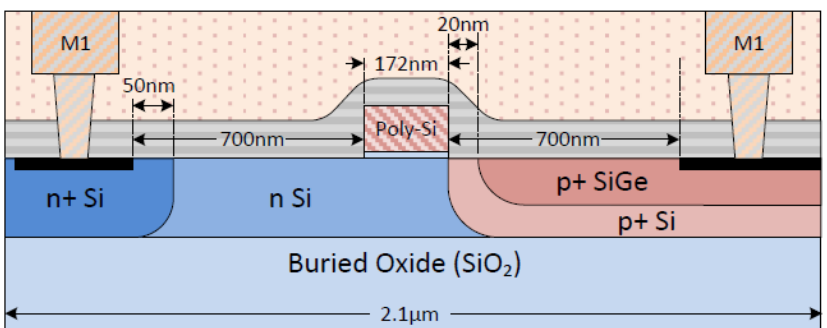
Key Device Components

SiGe from PMOS strain engineering used in Photodetectors

SiGe Photodetector **Waveguide Taper**



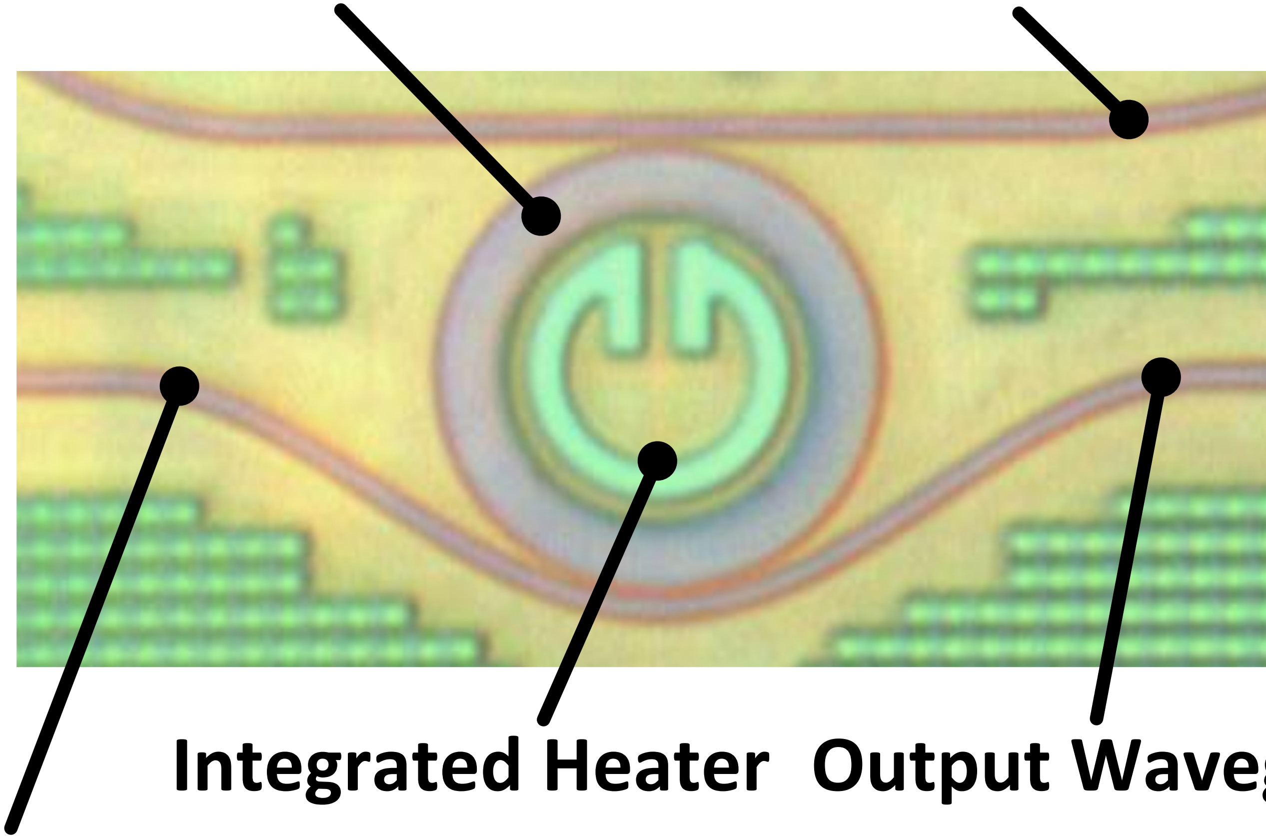




Waveguide

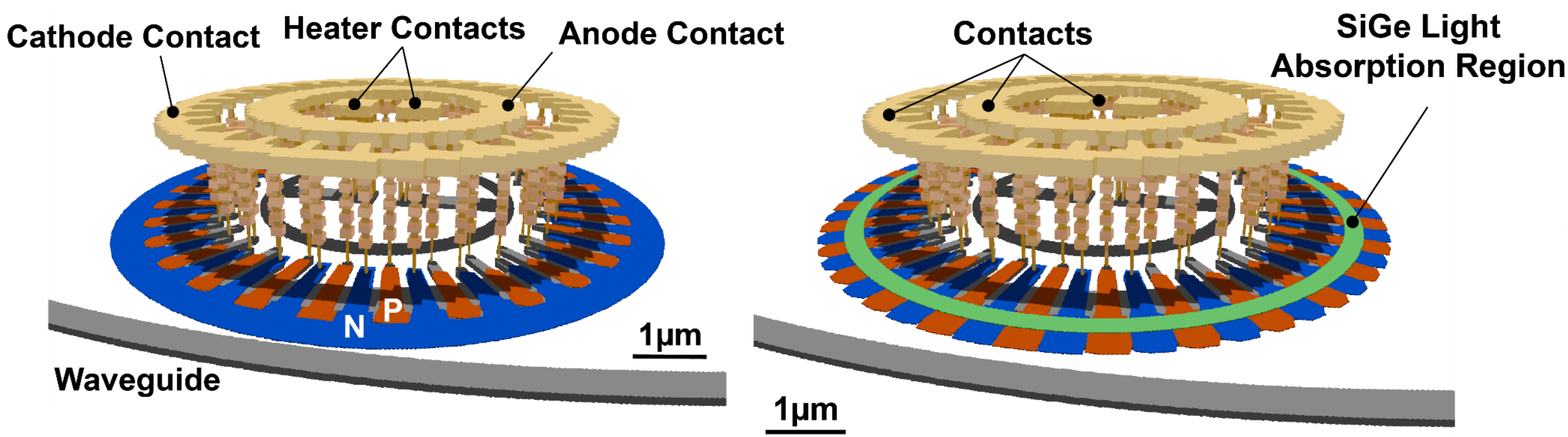
[Orcutt 2013, Alloatti APL 2015]

Key Device Components

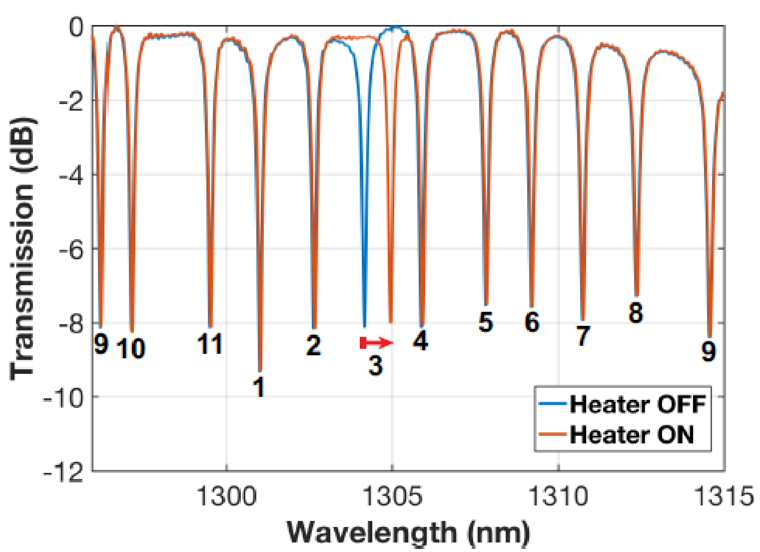


[Shainline OL 2013, Wade OFC 2014]

Resonant-Rings

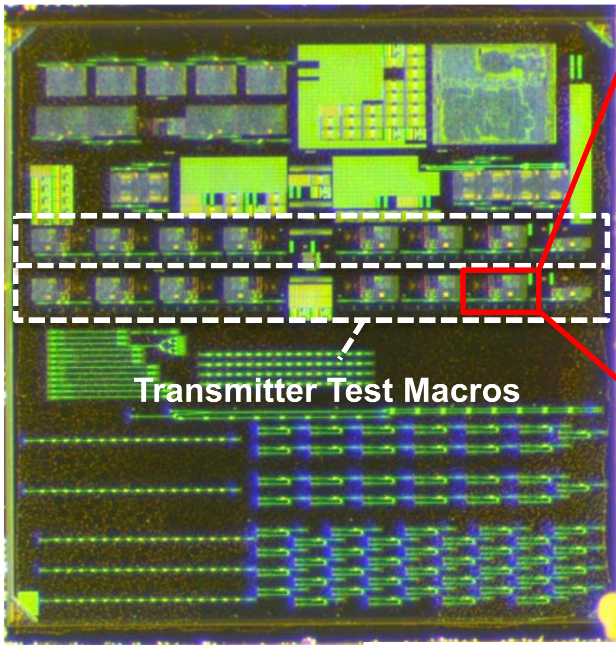


- Interleaved planar PN junctions
  - Enabled by advanced lithography of this process
- Highly sensitive structures that can be used in a number of applications
  - Q factors up to 200k



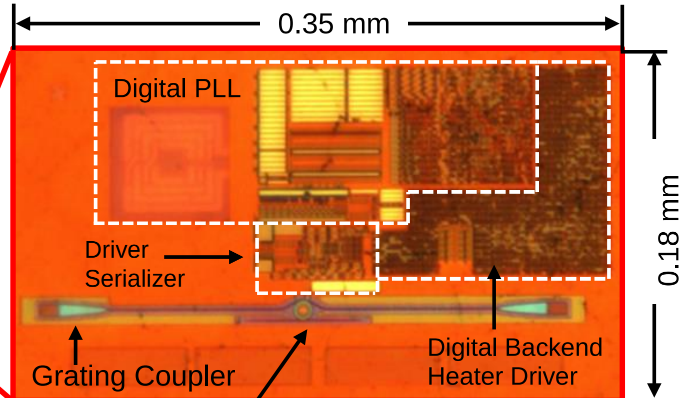
Higher-speed and higher-order modulation

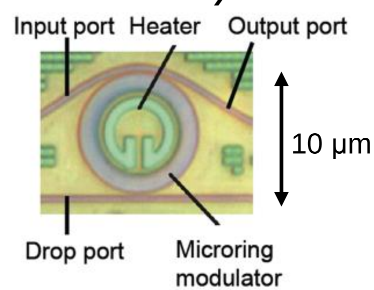
Moazeni and Lin et al [ISSCC17, JSSC17, OptEx18]

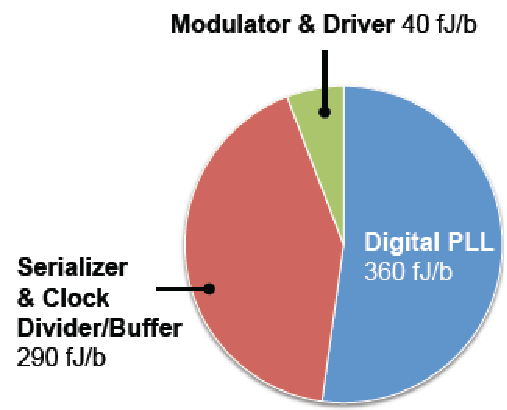


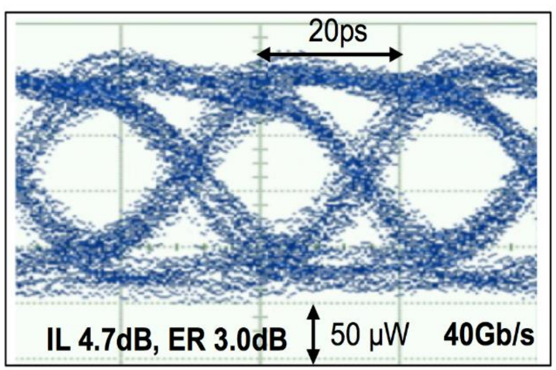
Chip 3.0x3.0mm

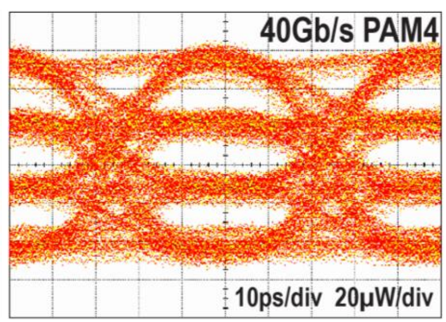
Transmitter Macro





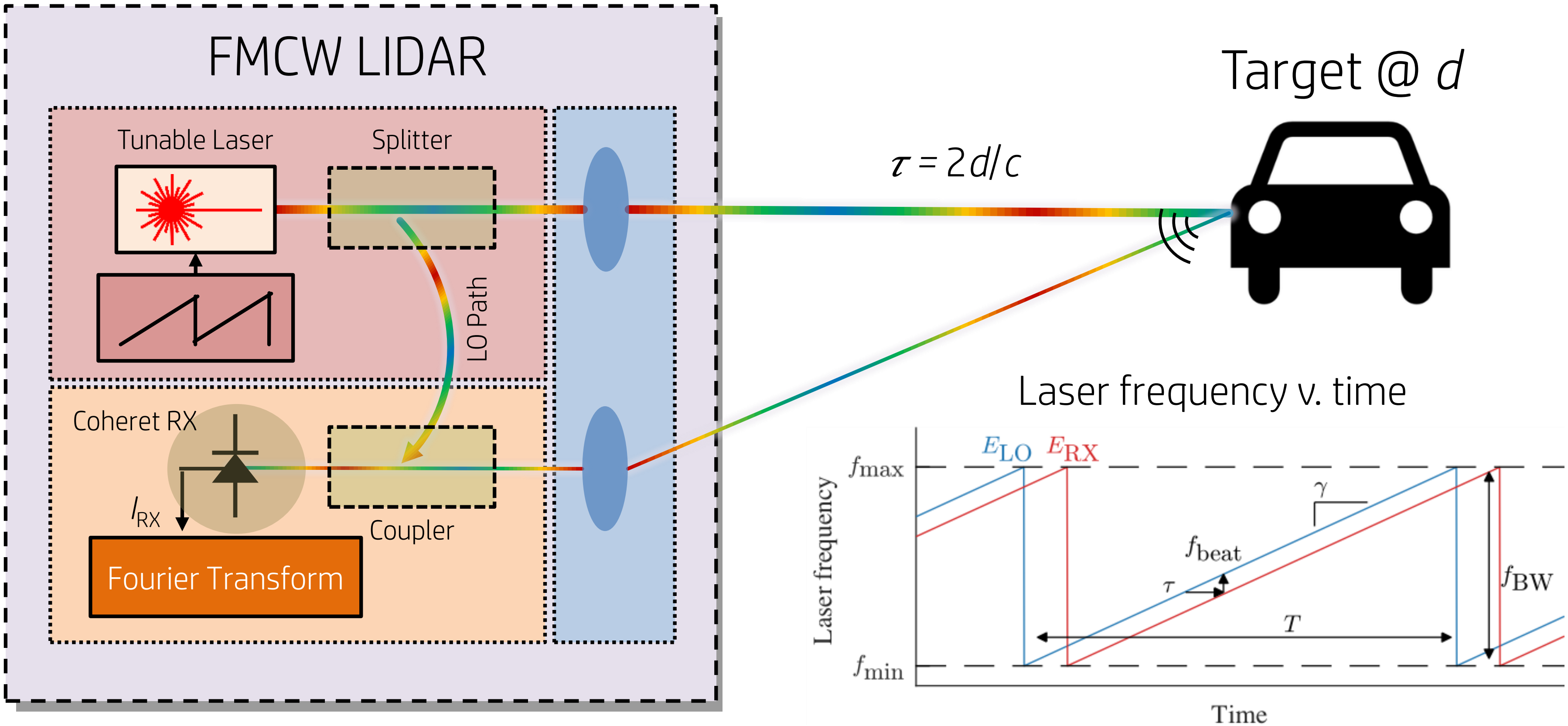






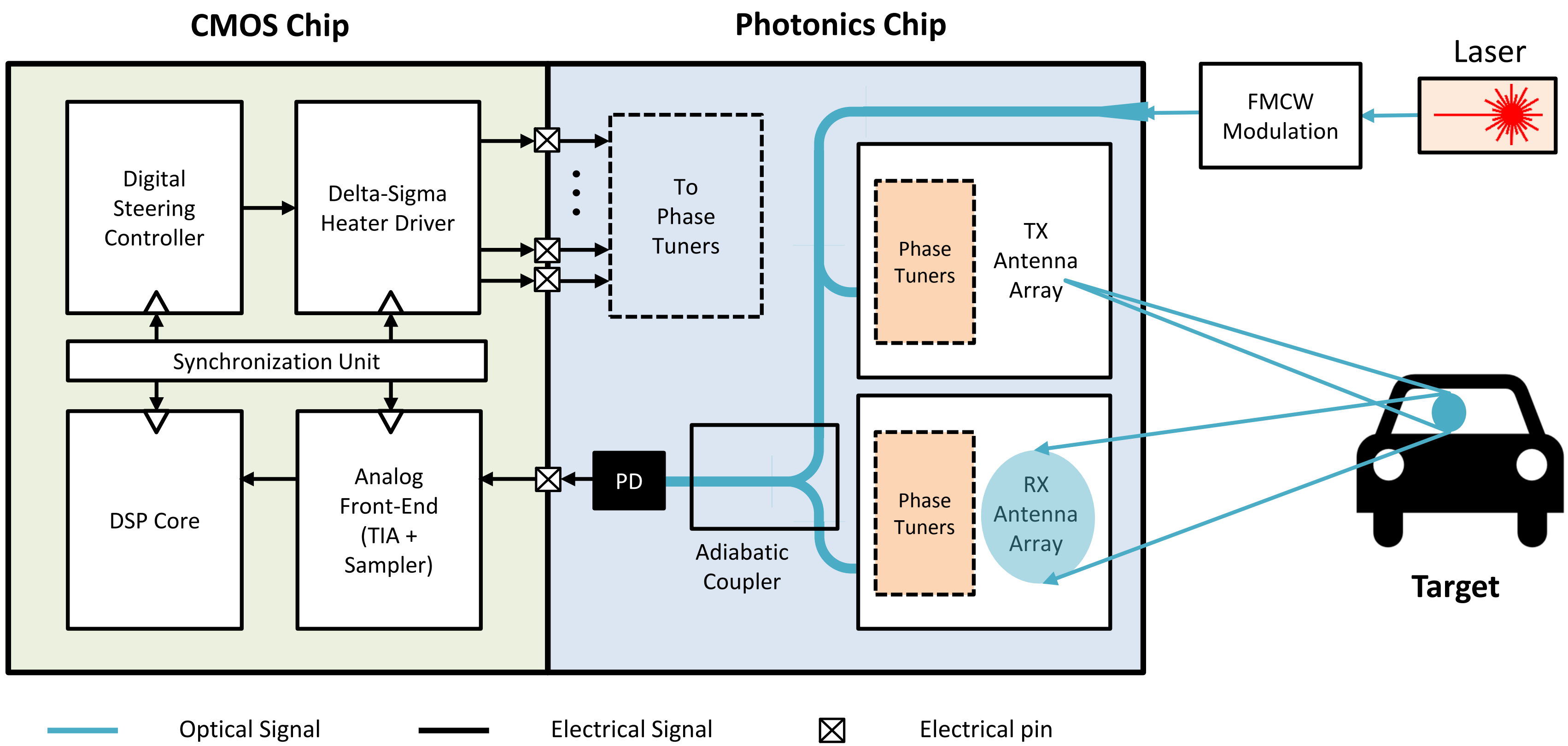
Modulation	40 Gb/s NRZ
Full TX Energy	0.33 pJ/b
Full TX + PLL	0.69 pJ/b

Anatomy of FMCW LIDAR

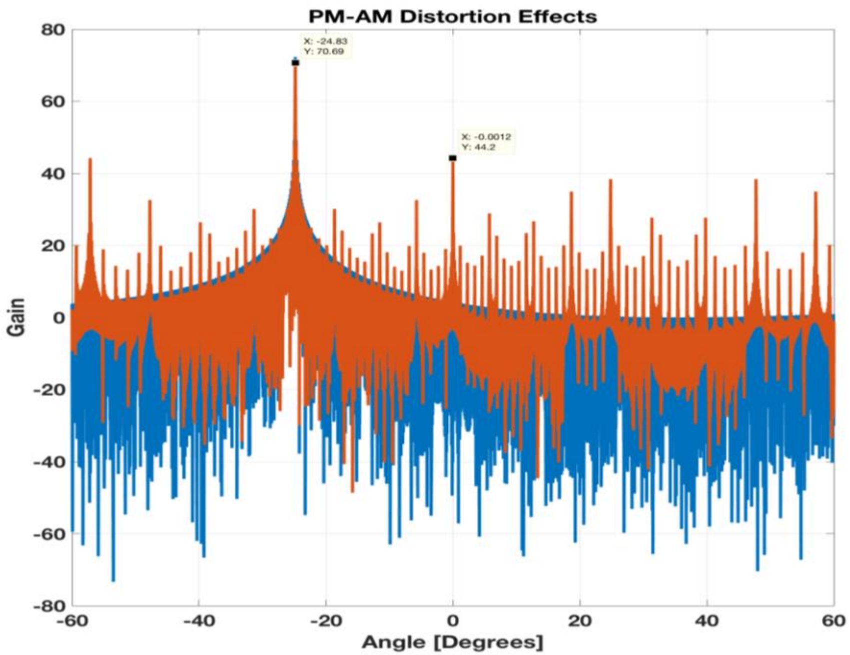


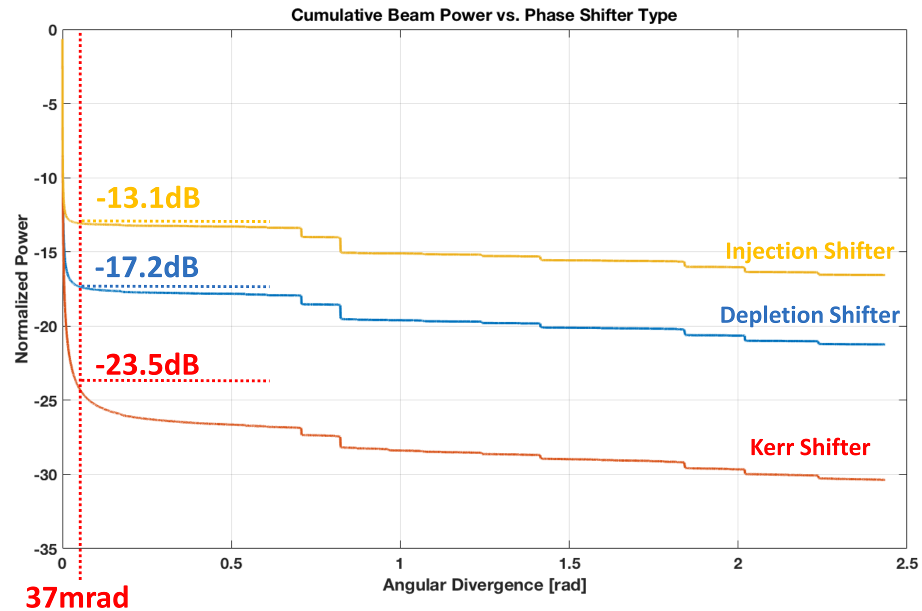
- Advantages over pulsed LIDAR
  - Sensitivity shot-noise limited
  - Less sensitive to background noise

FMCW LIDAR – System Architecture

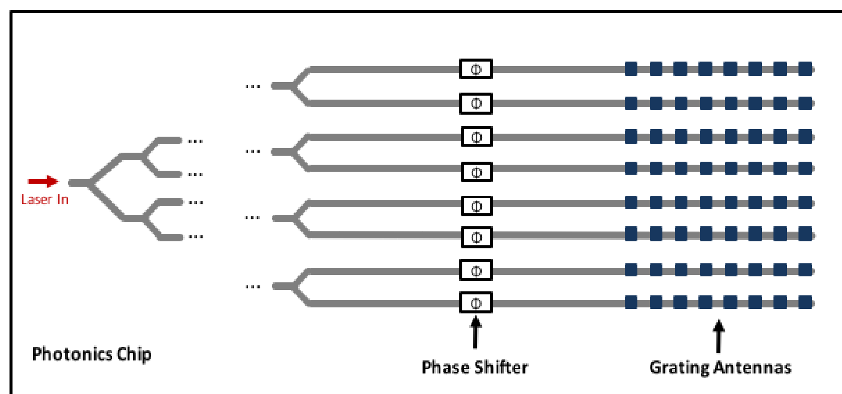


Photonic array distortions



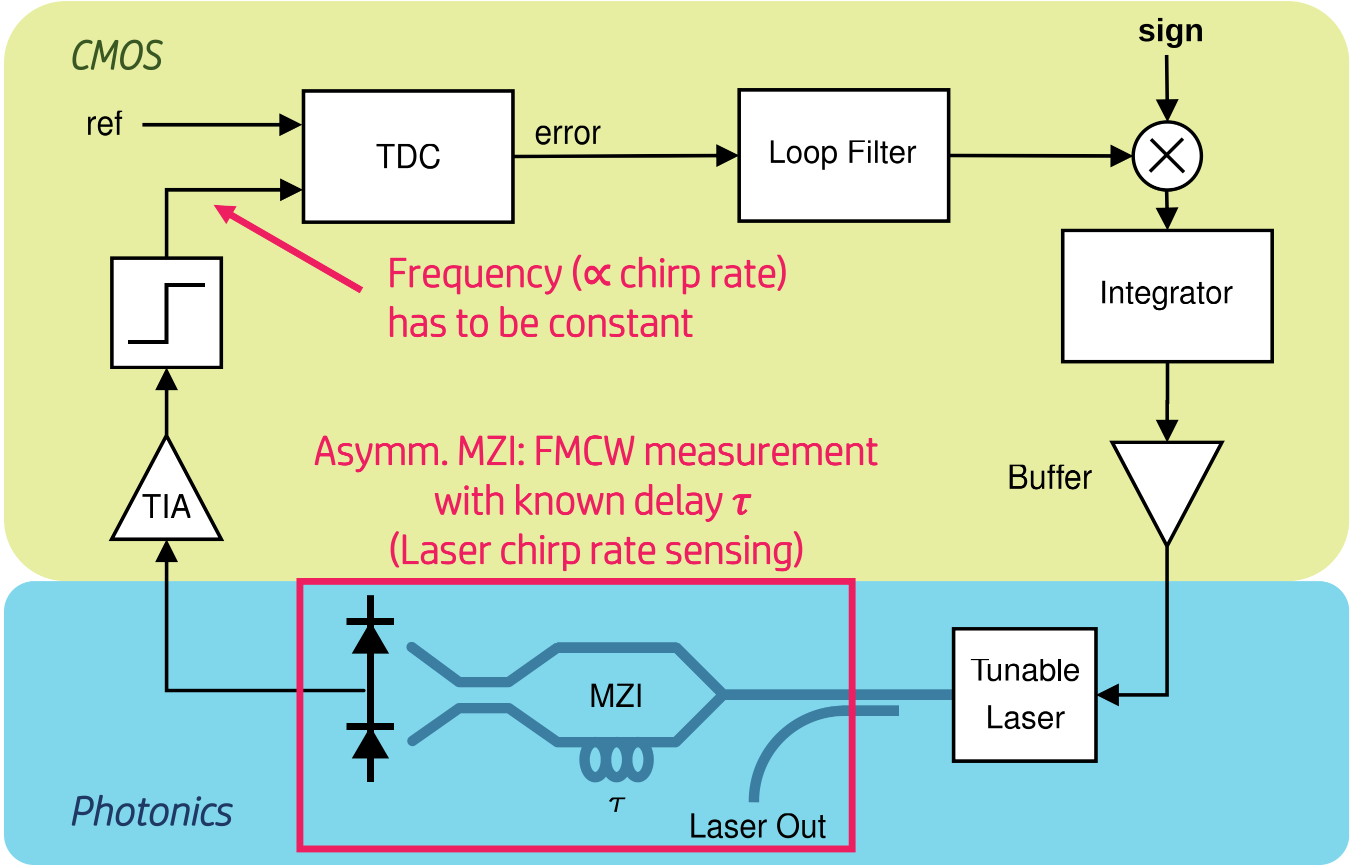


- Extensive modeling framework
  - Various phase-shifter types (AM/PM distortion)
  - Quantization
  - Index variations, coupling and pitch mismatch, etc



Laser chirp control via optical PLL

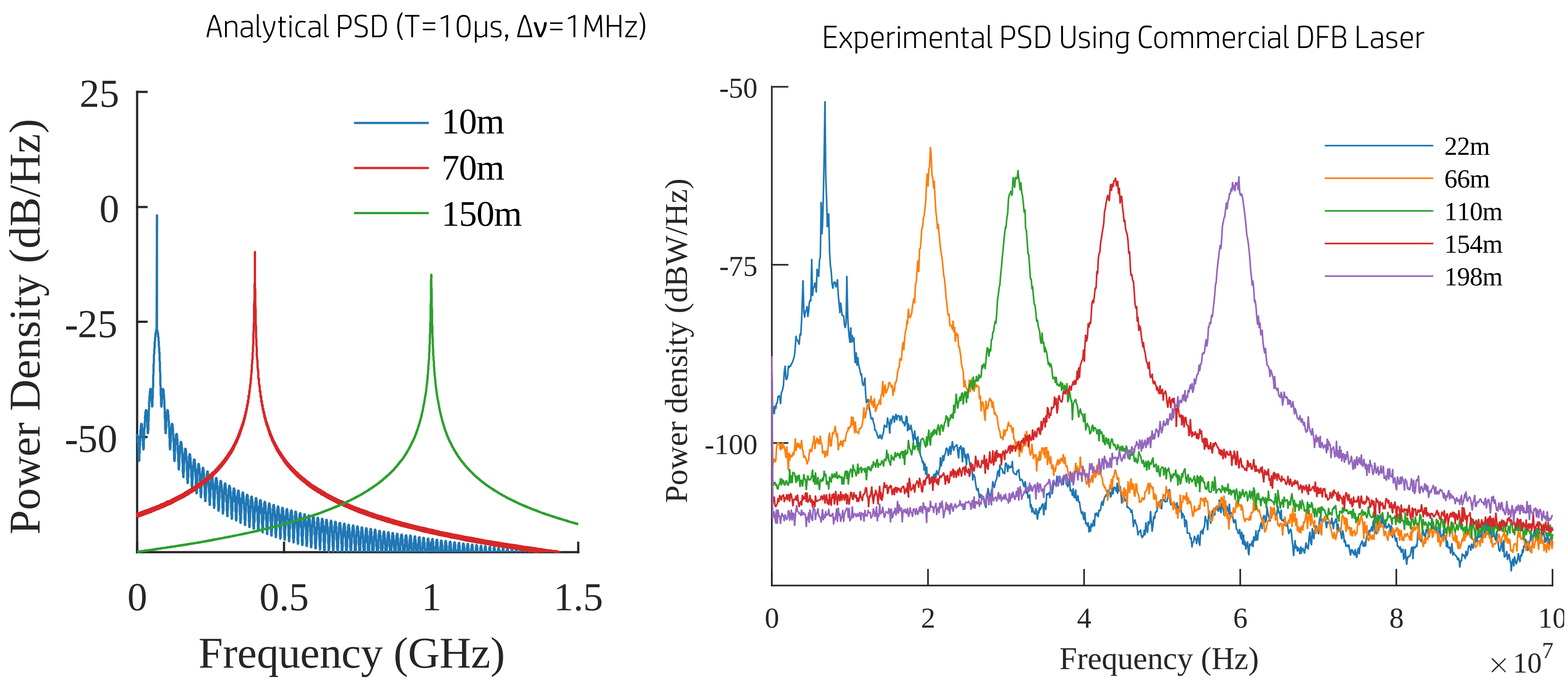
- Optical PLL enables closed-loop control of laser wavelength



All-digital implementation enables the loop to address multiple different chirp rates & optimize phase noise through loop filter reconfiguration

- Chips currently in packaging
  - CMOS: GF 45nm SOI process
  - Photonics: CNSE 300mm process

Coherence distance barrier



- Spectral peak degrades as distance increases ($\propto e^{-\Delta\omega\tau}$)
  - Beyond "coherence distance," lineshape converges to laser lineshape (e.g. Lorentzian)
  - Big challenge for using compact semiconductor lasers (>1MHz linewidth) for long-distance (>100m) LIDAR

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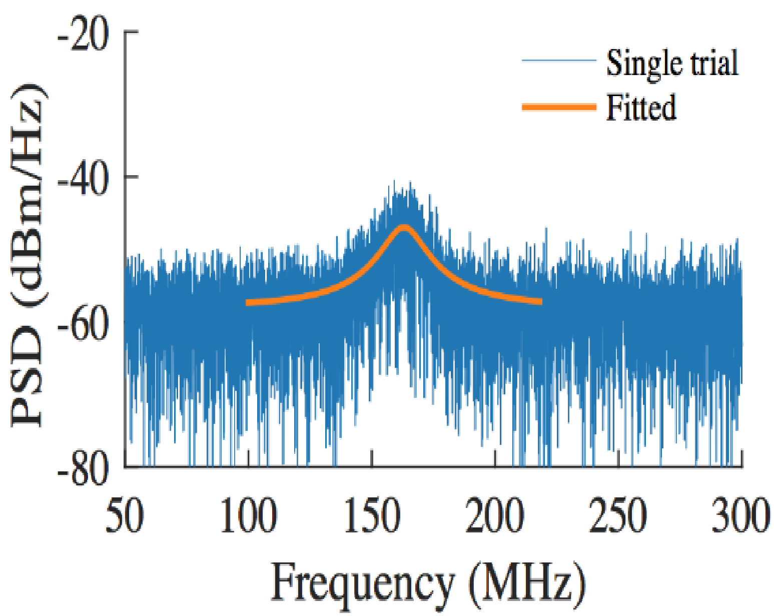
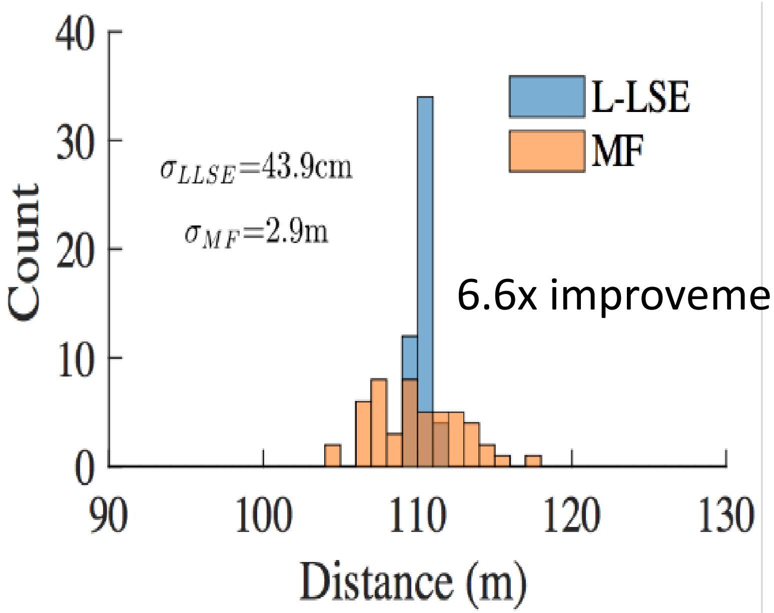
Beyond the coherence limit with optimized detection

[Kim et al ICASSP18, CLEO18]





6.6x improvement

- Improved detection algorithm
  - Take into account the phase-noise basis shape
    - Wide-range tunable laser with DBR mirror used (Δv~1MHz)
    - Path delay (110m) emulated by long fiber, path loss emulated by VOA
    - Simulated path loss ~ -80dB (corresponding to 110m target, 3x3mm aperture)

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Electronic-Photonic Massive MIMO Systems

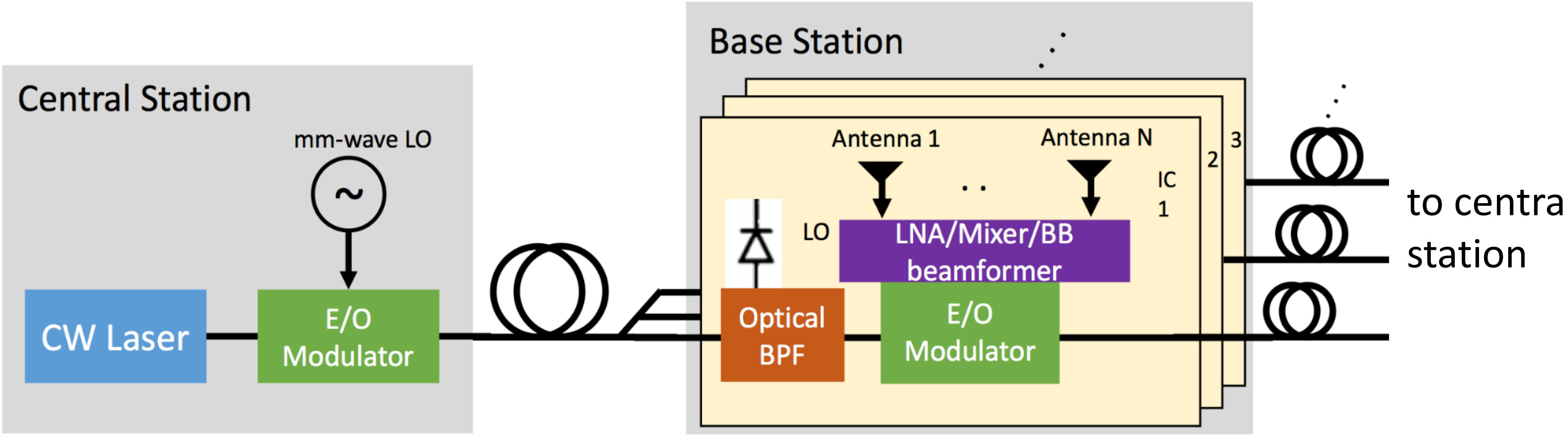
Future MIMO System Challenges

- mm-wave operating frequency
- 100’s of beams, 1000’s of antennas
- Power
- Density
- Chip-to-chip communication

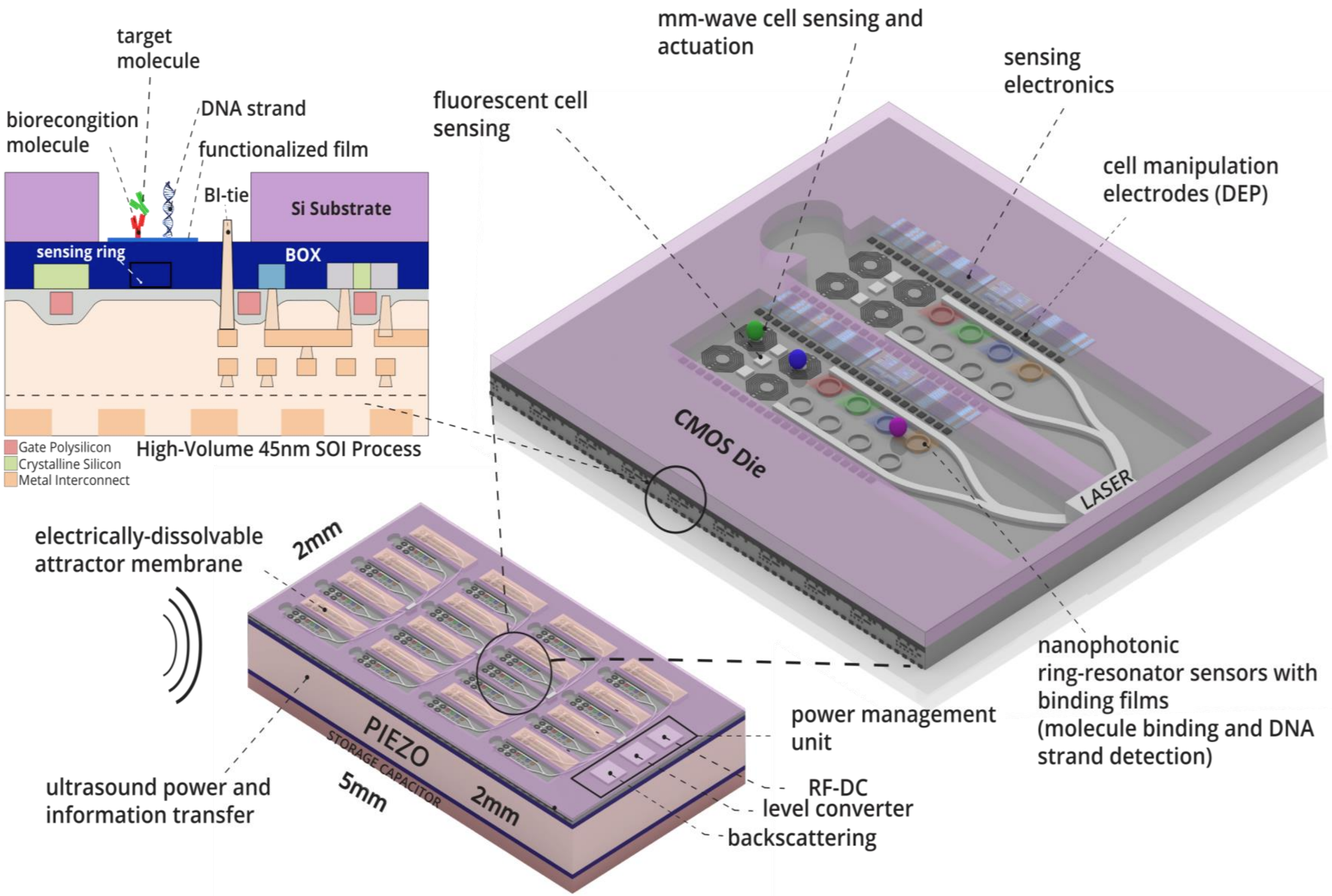
Electronic-Photonic System Goals

- mm-wave LO distribution
- Direct mm-wave photonic link from antenna to remote hub

NF and SNDR relaxed in massive MIMO systems

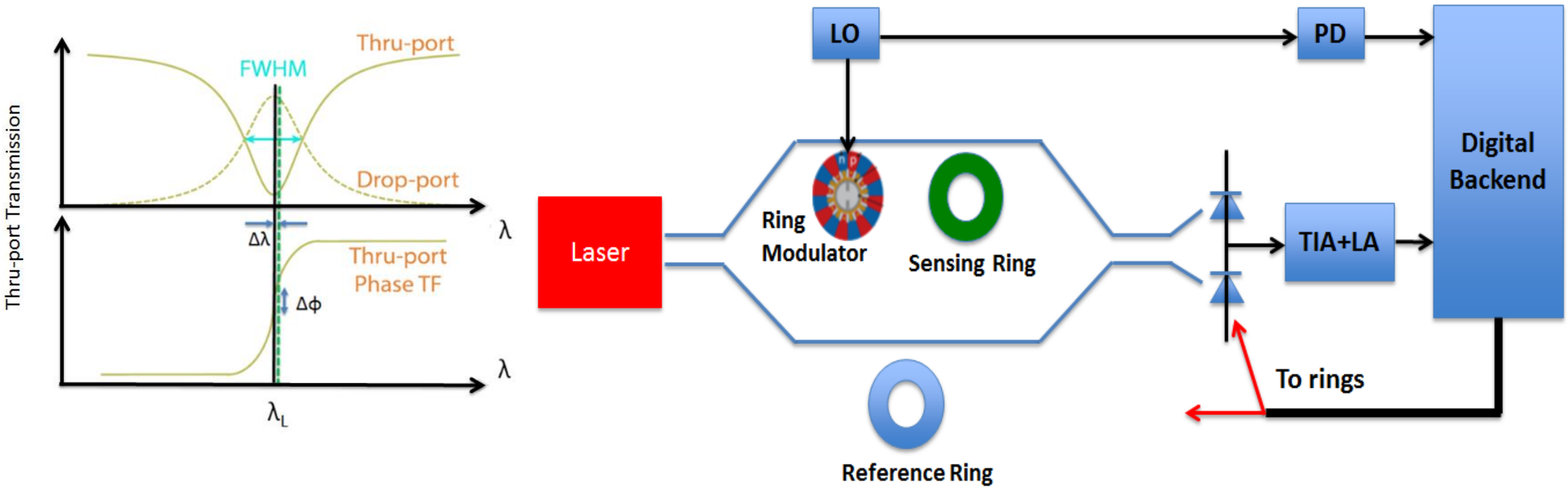


Cellular and Molecular Sensing



[Anwar, Stojanovic, Niknejad]

Coherent detection

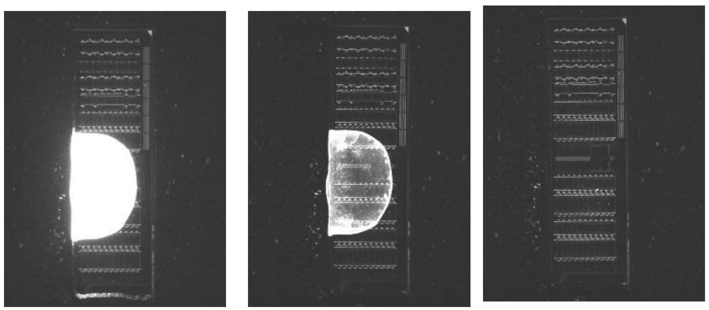


- Reduced measurement time (sub 1s)
  - Capture faster kinetics
- Increased SNR (allows lower ring Q factors)
- Integrated thermal tracking

[Anwar, Stojanovic, Niknejad]

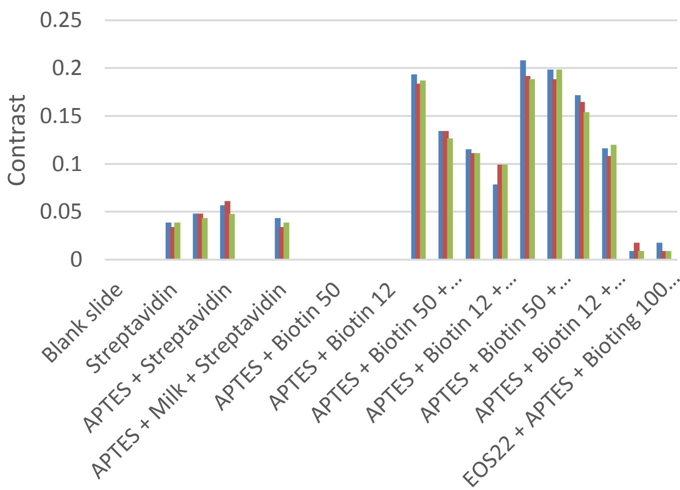
Packaging and functionalization

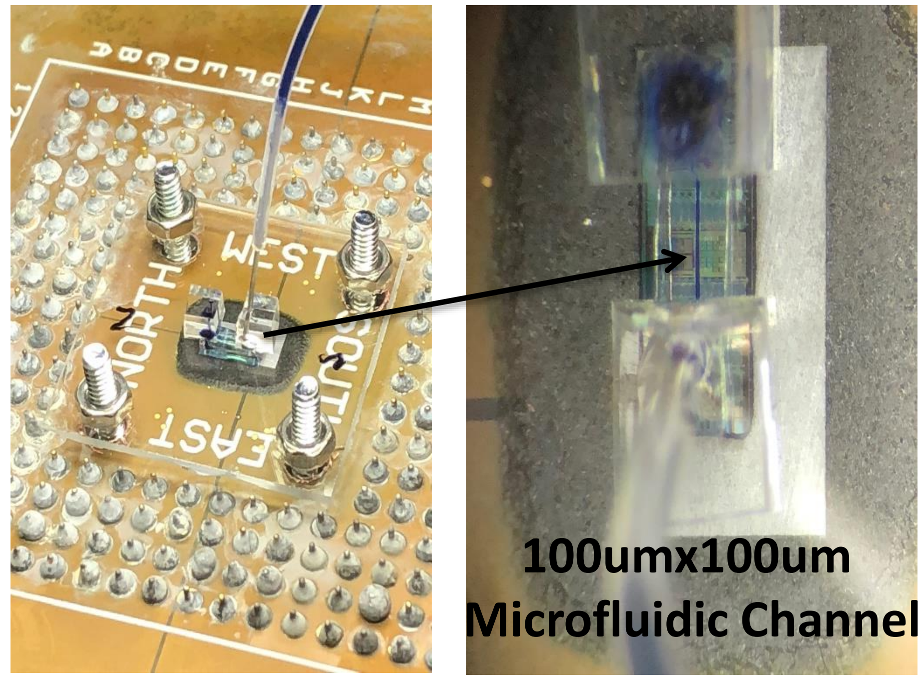
Wet Streptavidin - fluorophore	Dry Streptavidin - fluorophore	Post Wash



APTES Chip

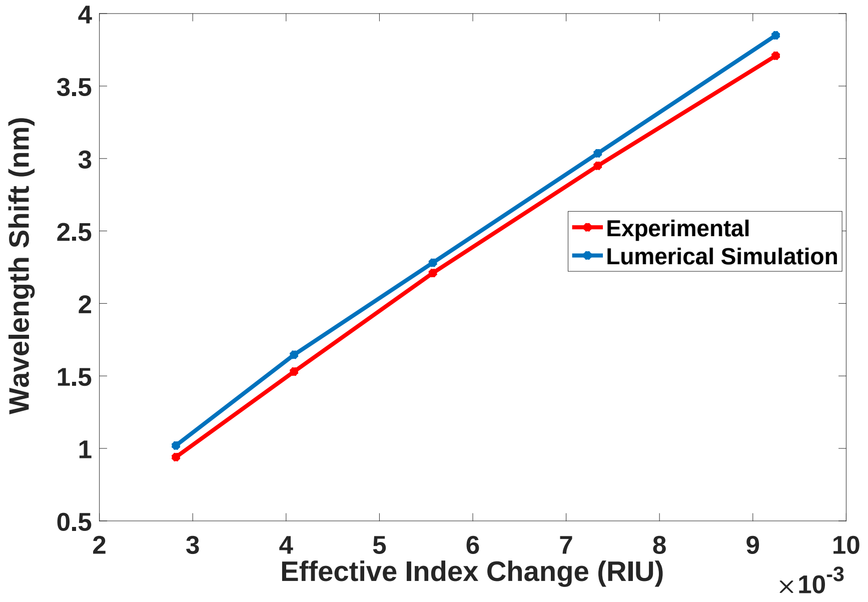
Fluorescence at various conditions

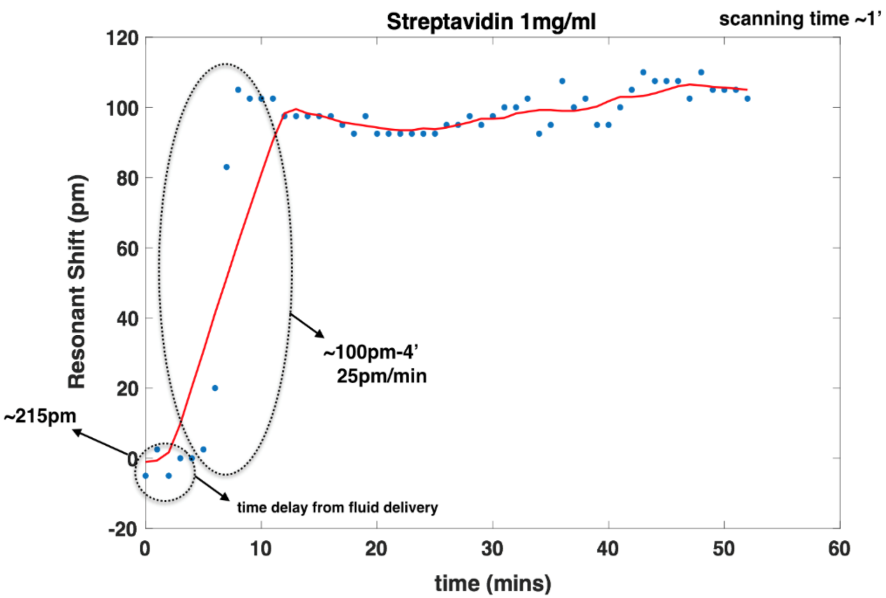




- Substrate released chip (45nm SOI)
  - Successful functionalization with APTES/biotin and biotin-streptavidin binding

First sensitivity and kinetics results

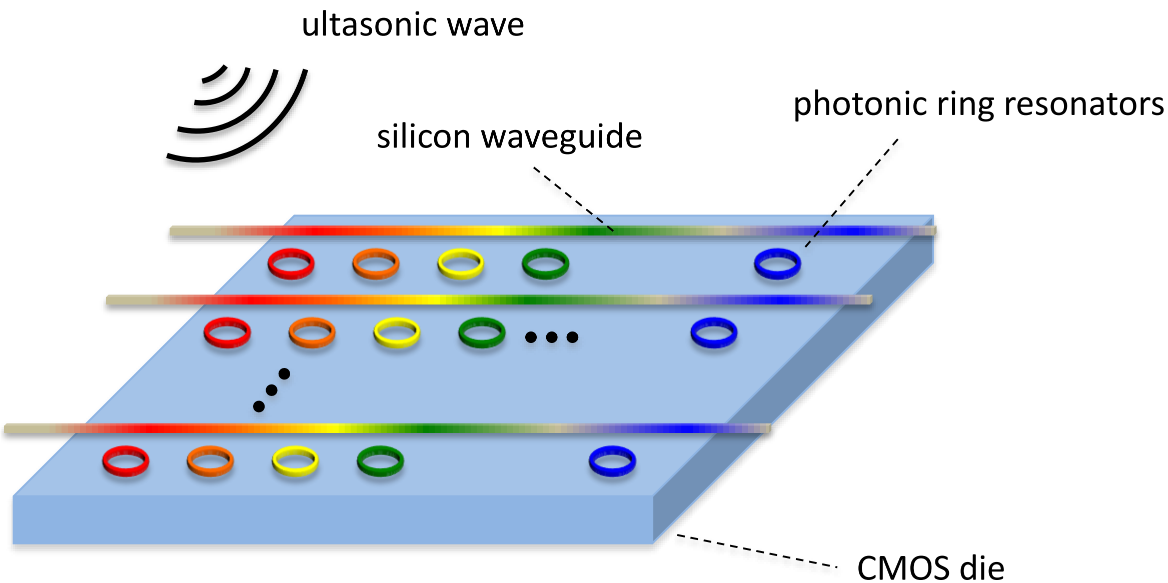


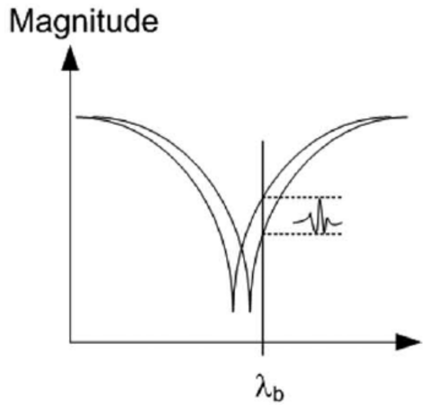


Bulk RI Sensitivity : 5nm/RIU

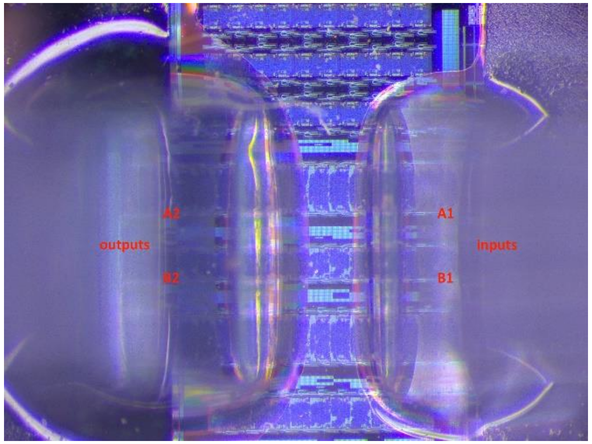
First kinetic binding results

Ring resonator based Ultrasound Imaging

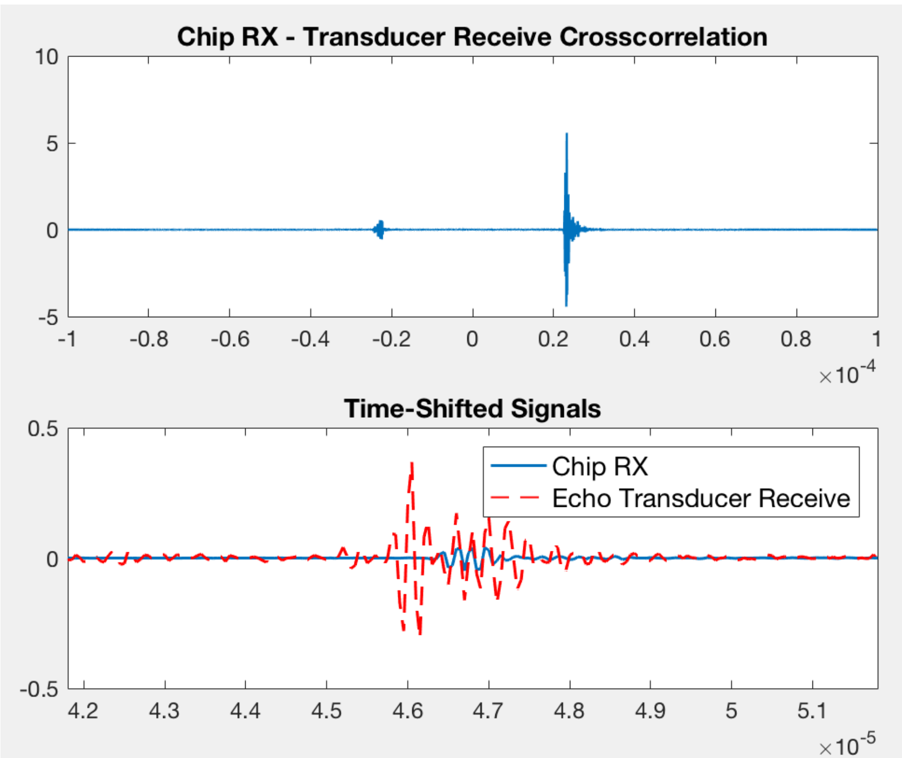


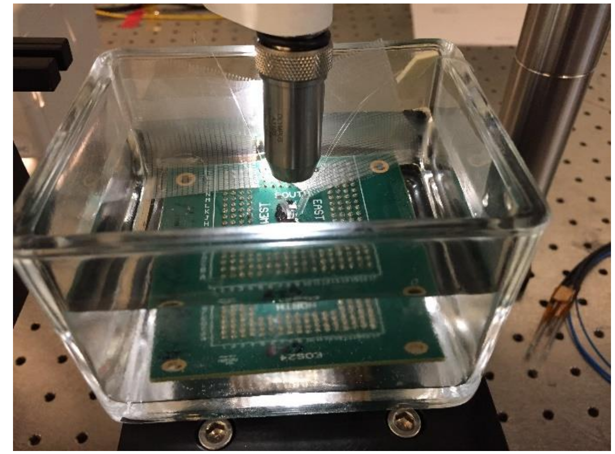


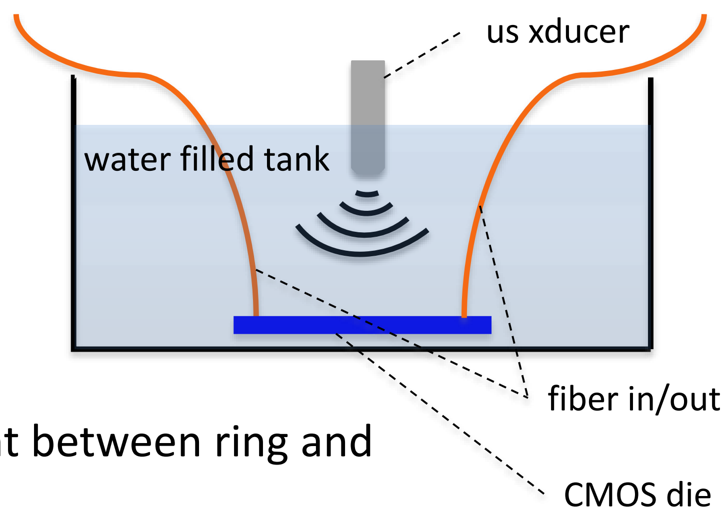
- Ultrasound RX phased array
  - Real-time 3D ultrasound imaging
- Reduced cable count and pitch compared to piezo/cmut alternatives
  - more aggressive scaling of ultrasound probes targeting IVUS, TEE
- Resonant shift induced by
  - Acoustic pressure wave straining the waveguide and causing Δn_{eff}
  - Acoustic resonance vibration



Preliminary Results





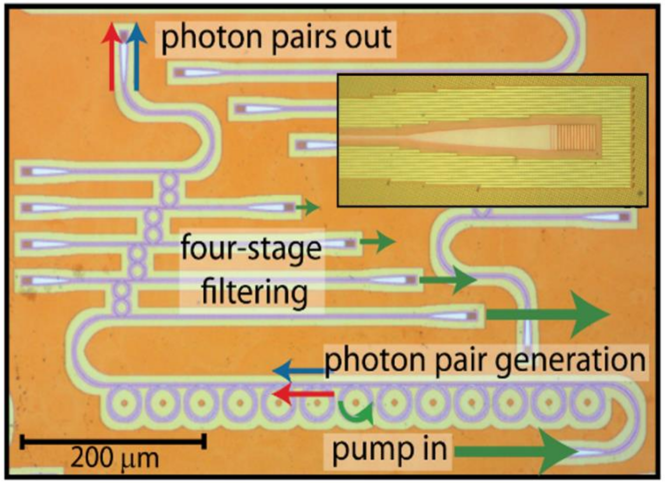


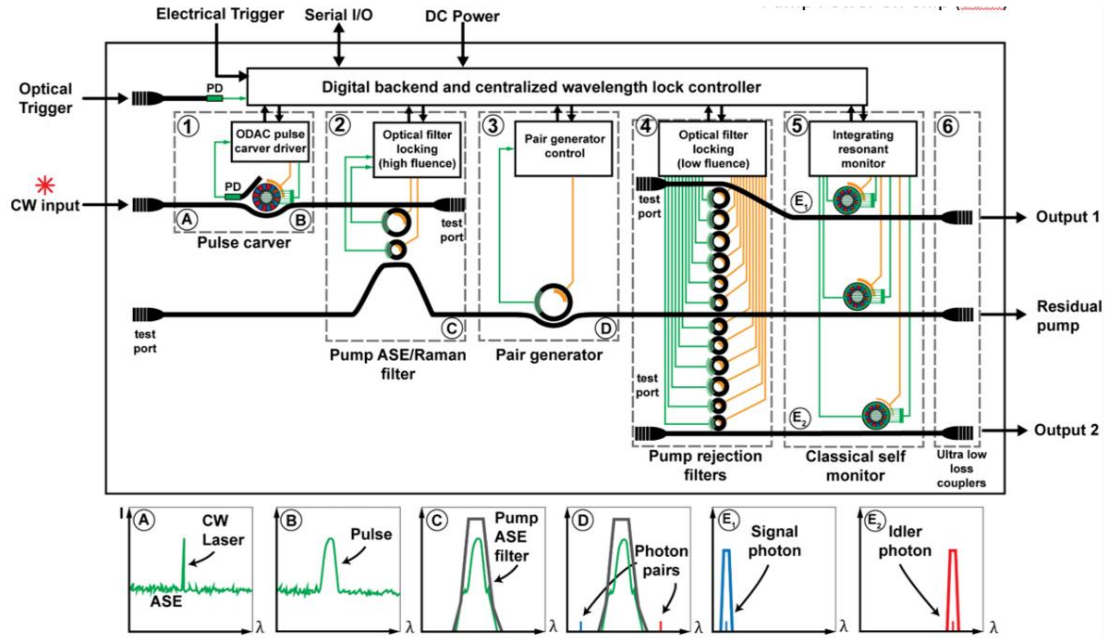
- Ring picks up the ultrasound (good agreement between ring and transducer receive response)
- Intrinsic sensitivity S_i = 60fm/kPa – comparable to existing polymer based ring related work (ring is not optimized for this application)

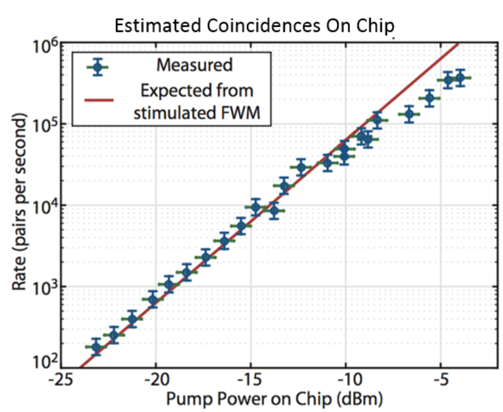
BWRC

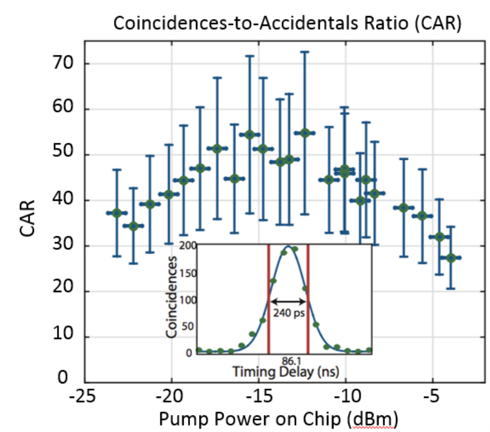
Electronic-Photonic Quantum SoCs

45nm SOI







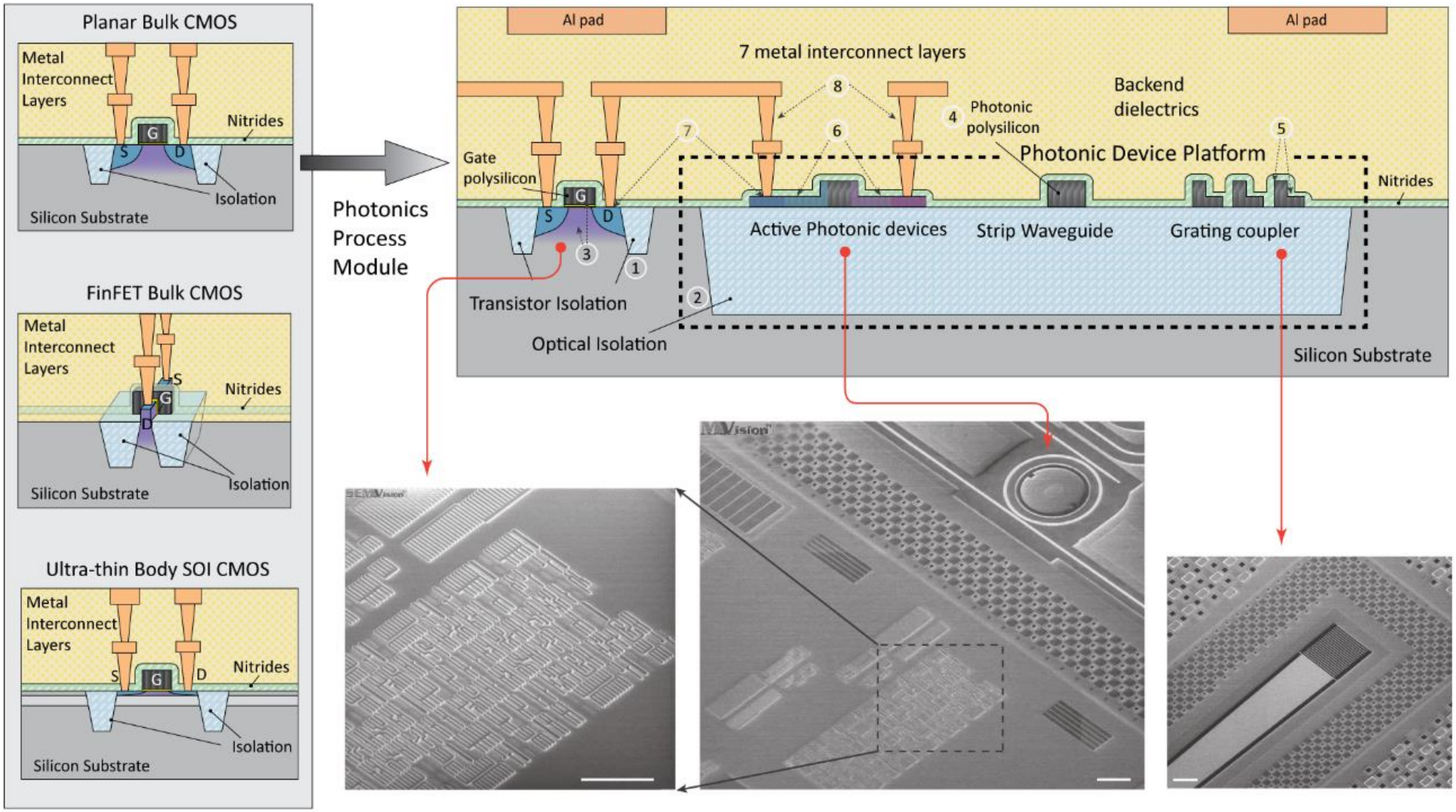


Electrical Trigger Serial I/O DC Power

[Gentry et al, Optica'15, CLEO'18]

[Popovic, Stojanovic, Kumar]

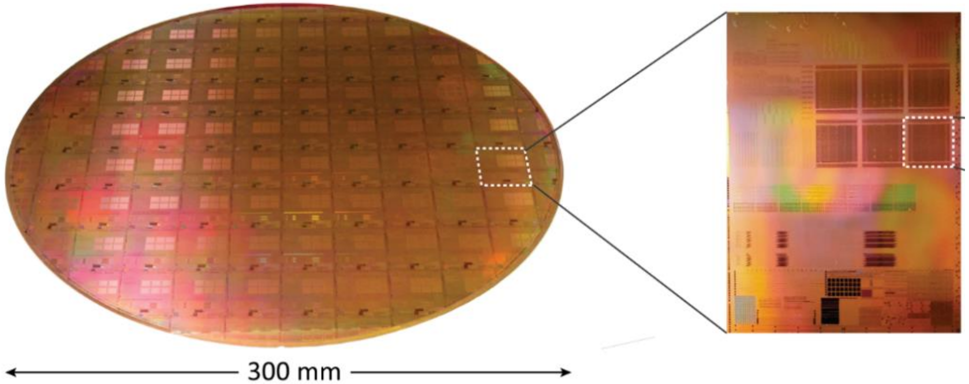
Deposited polySi photonic platform

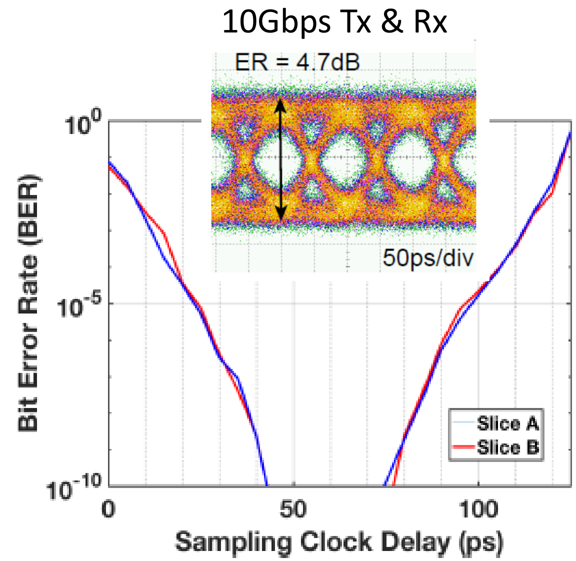


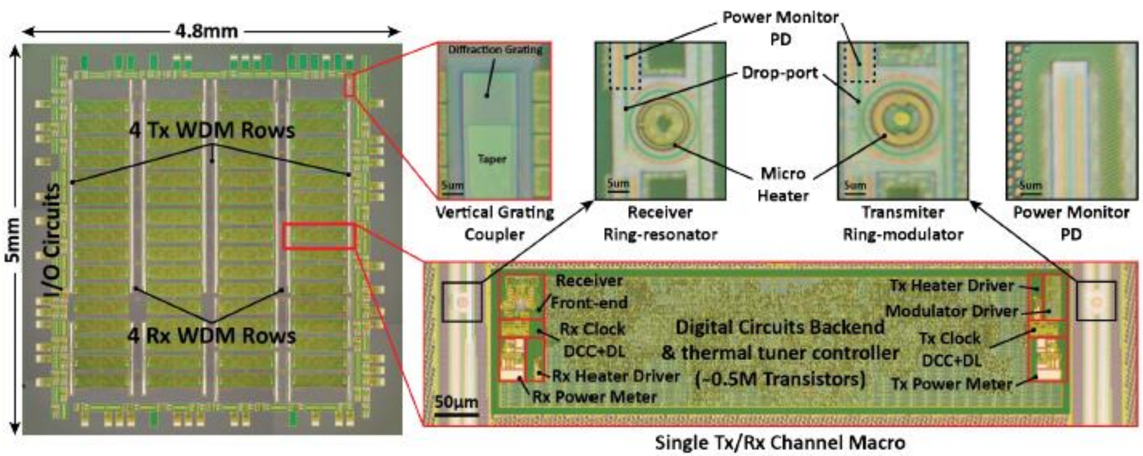
- Deposited on deep-trench oxide
- The only way to integrate photonics in advanced nodes

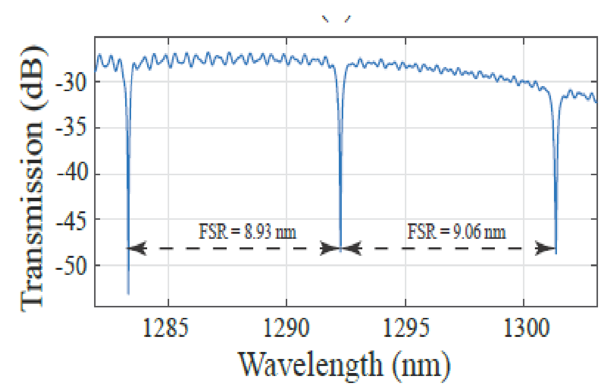
Already in a 300mm fab

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









Conclusions

- Silicon-photonics – enabler of new capabilities
  - Think "new on-chip inductor" or "new on-chip t-line"
- Potentially revolutionize many applications despite slowdown in CMOS scaling
- Deposited polySi-photonics key to monolithic integration with advanced transistors