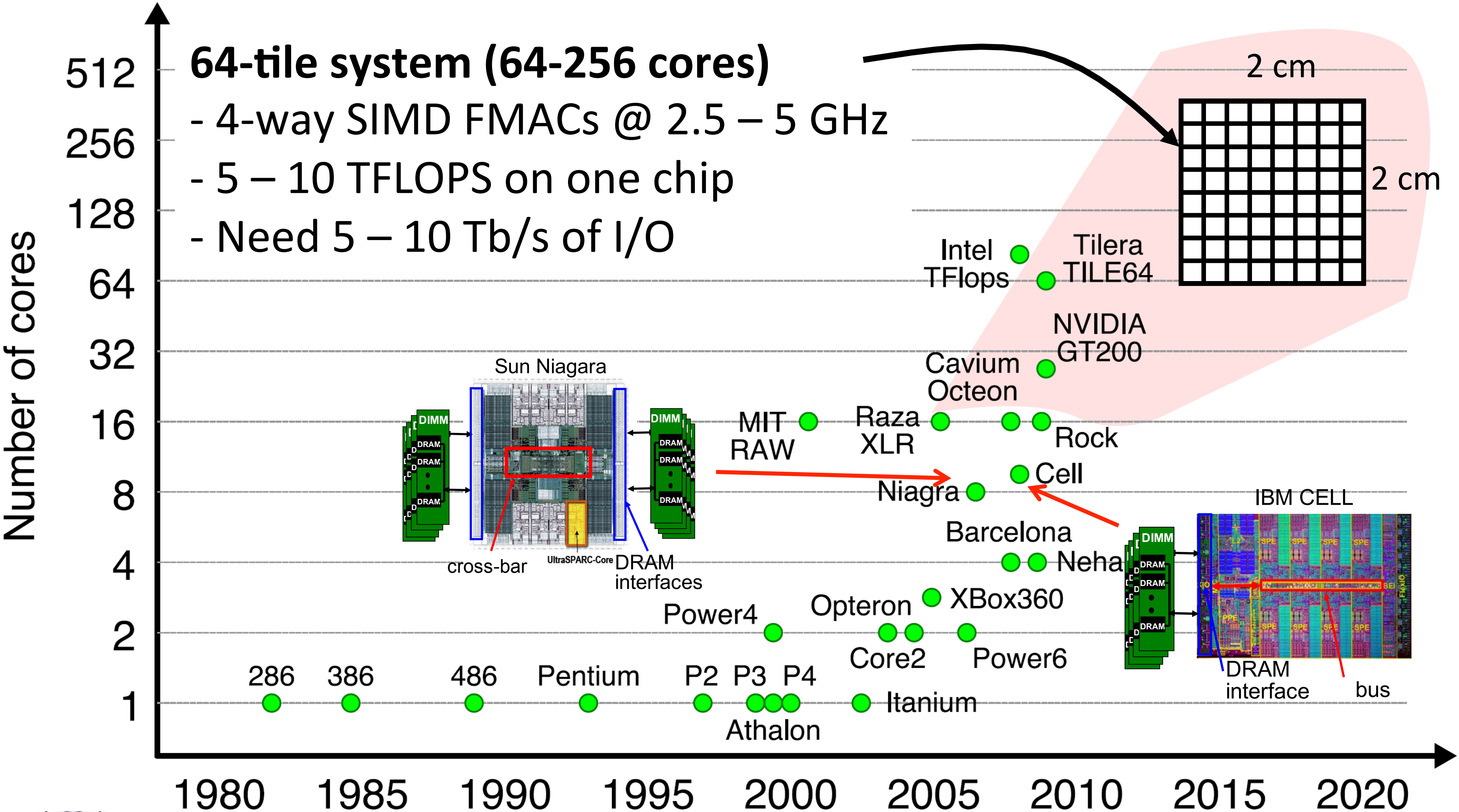
RISC-V Microprocessor Chip with Photonic I/O

Chen Sun

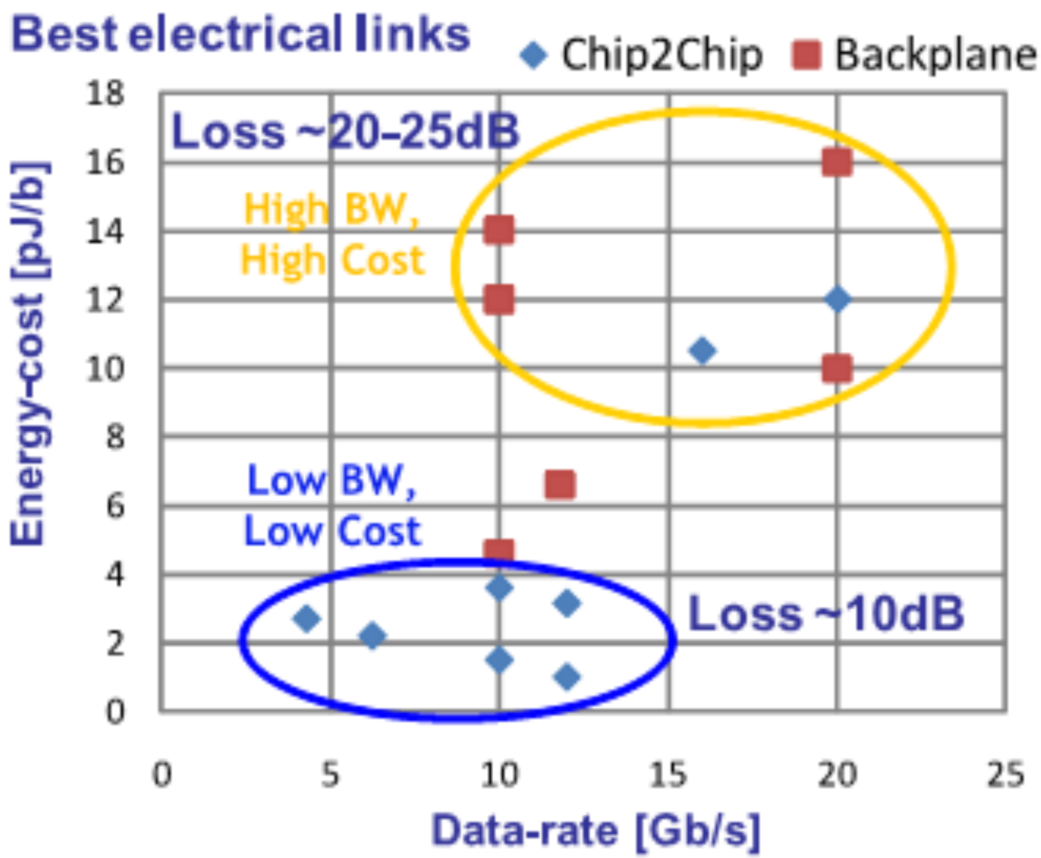
RISC-V Workshop

1/6/2016

Many-Core Systems Scaling



I/O Wall

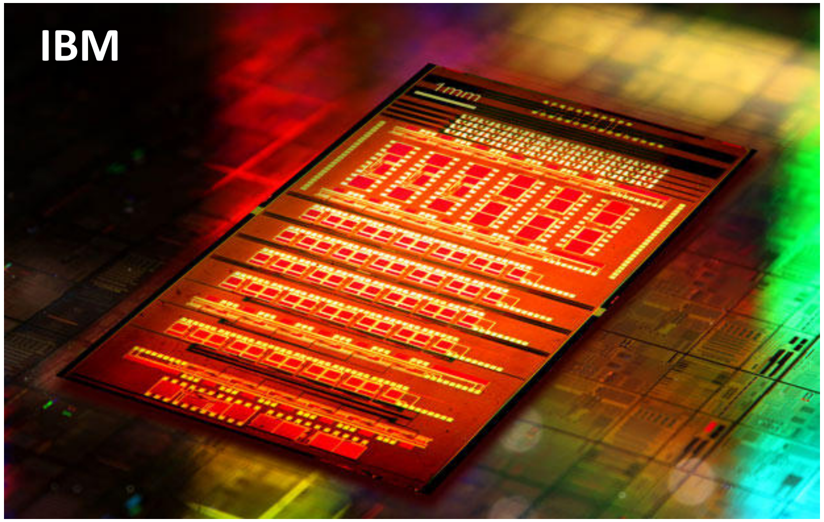


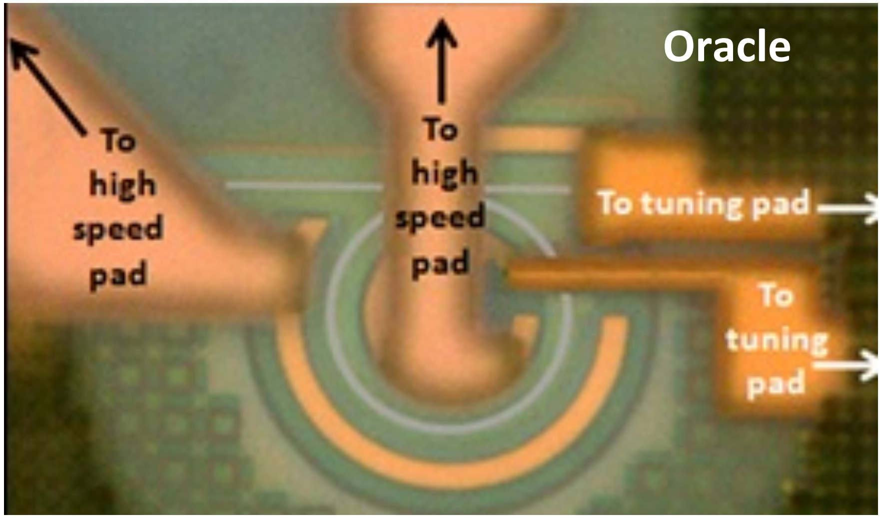
10 Tb/s @ 10 pJ/bit is 100 W

10 Tb/s requires 2000 pins (50% are for power/ground)

Used up all of your power budget, just for I/O!

Silicon Photonics

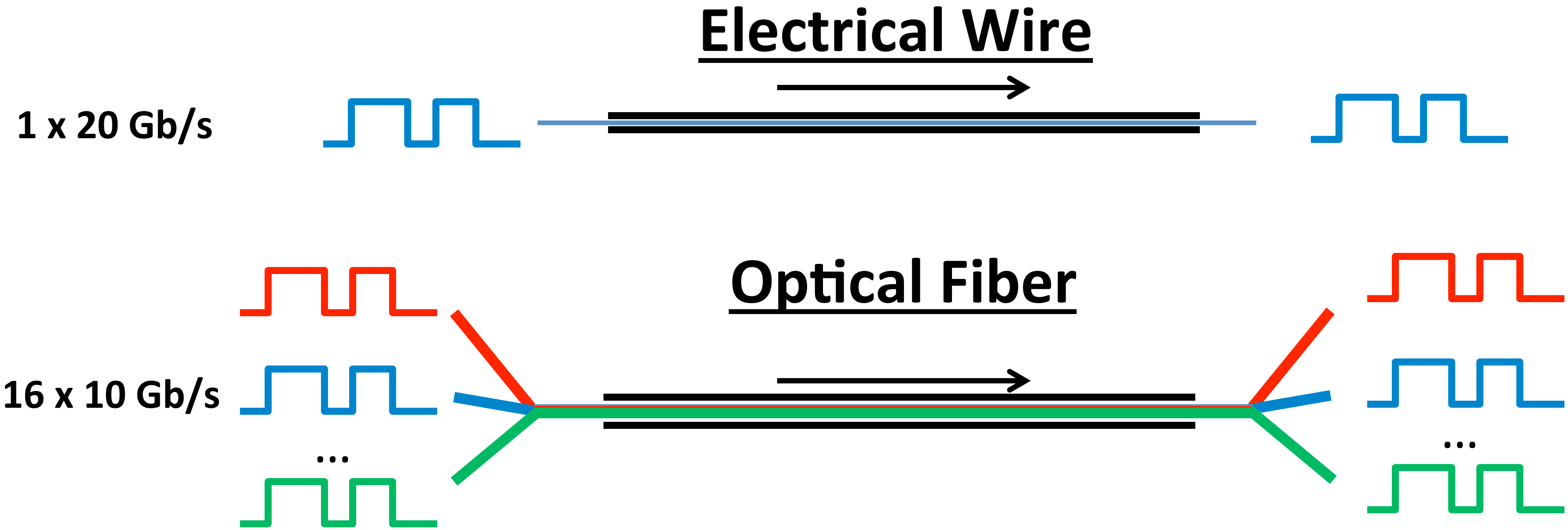




- Promising for overcoming I/O bandwidth limitations of current electrical systems
  - Industry already starting to develop the technology, however they are more conservative on their approaches

BWRC

Optical Signaling



- Photonic links use dense wavelength division multiplexing (DWDM) to improve bandwidth density
  - Fit multiple channels of data onto the same waveguide/fiber
- Distance insensitive loss, low distortion optical signaling
  - Better energy-efficiency

BWRC

How can optics help architecture?

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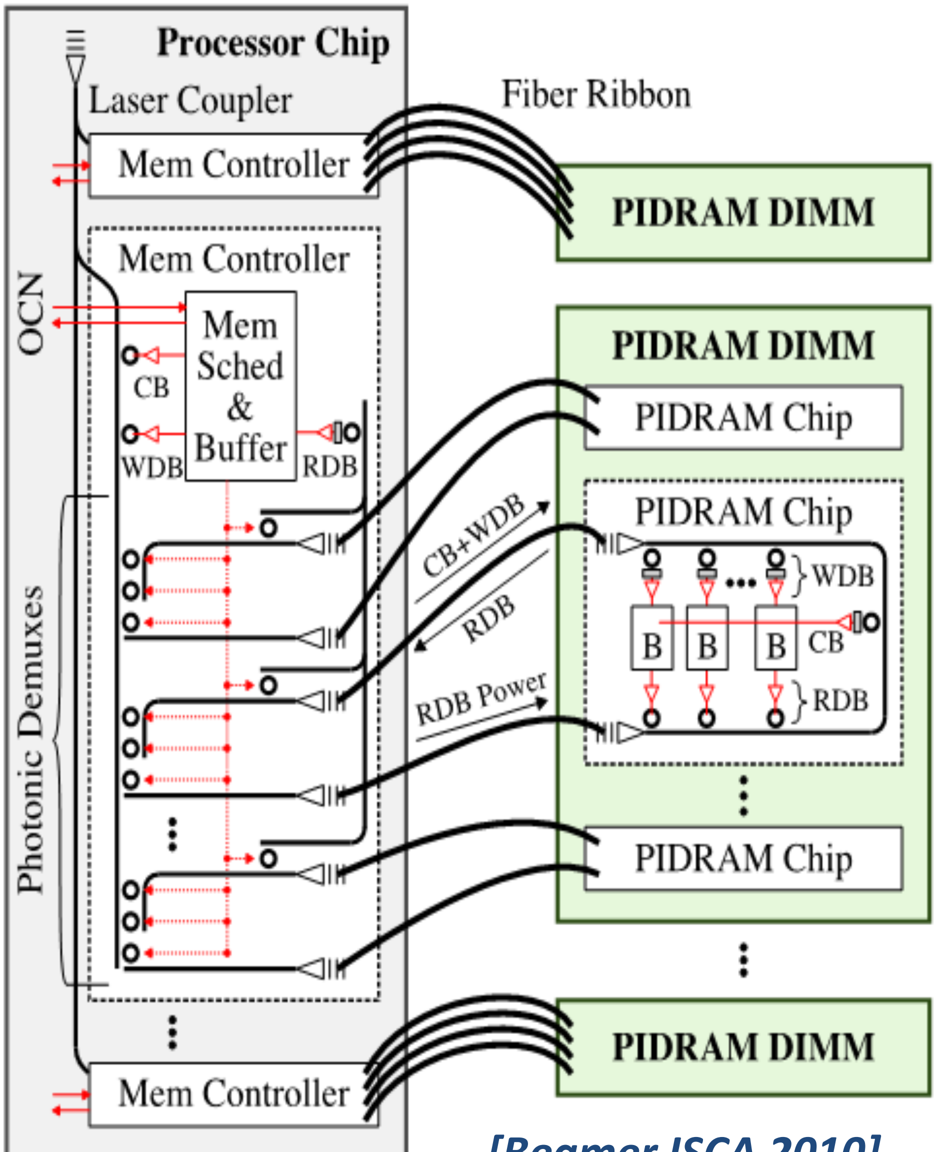
Scott Beamer

How can optics help architecture?

Scott Beamer

Me 6 years ago

Photonically-connected memory



[Beamer ISCA 2010]

Scott Beamer

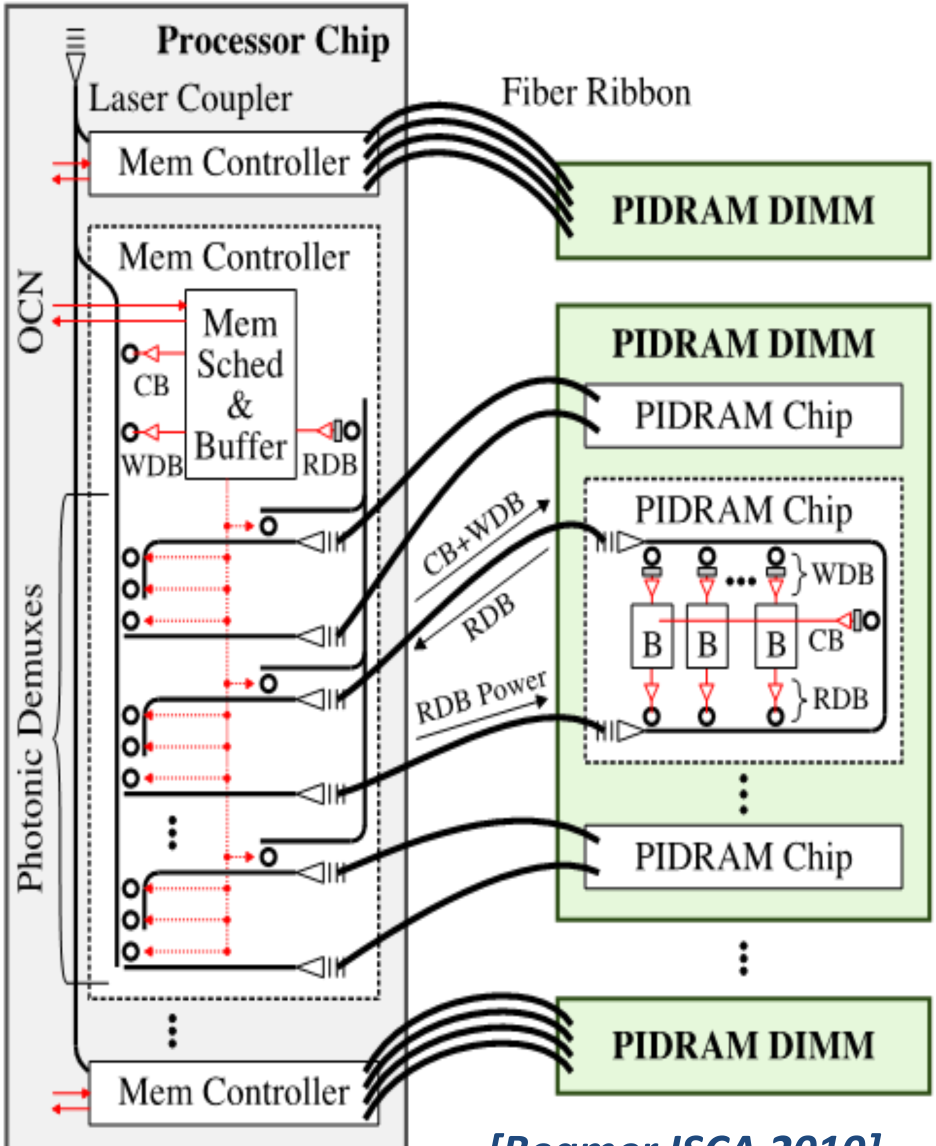
Me 6 years ago

Proposed

- Energy-efficient, enable >10Tb/s of memory I/O
- Decouple tradeoff between memory capacity and memory bandwidth

Little did I know…

DARPA POEM Project



[Beamer ISCA 2010]

DARPA POEM:

Build "this"

DARPA Program Challenges

DARPA Question 1: Photonics projects need a dedicated process and foundry development, where are you going to get a foundry?

DARPA Program Challenges

DARPA Question 1: Photonics projects need a dedicated process and foundry development, where are you going to get a foundry?

Prof. Rajeev Ram

Rajeev:
"We can do it **without** a dedicated foundry!"

DARPA Program Challenges

DARPA Question 2: What about electronics, how will you connect electronics and photonics together with low overhead?

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Prof. Vladimir Stojanovic

Vladimir:
"We will build electronics **on the same chip** as the photonics!"

BWRC

DARPA Program Challenges

DARPA Question 3: Optical chip-to-chip links will always compete with electronics, will your devices perform well enough to be competitive?

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Prof. Milos Popovic

Milos:
"Leave that up to **me.**"

DARPA Program Challenges

DARPA Question 4: Where are you going to get a processor?

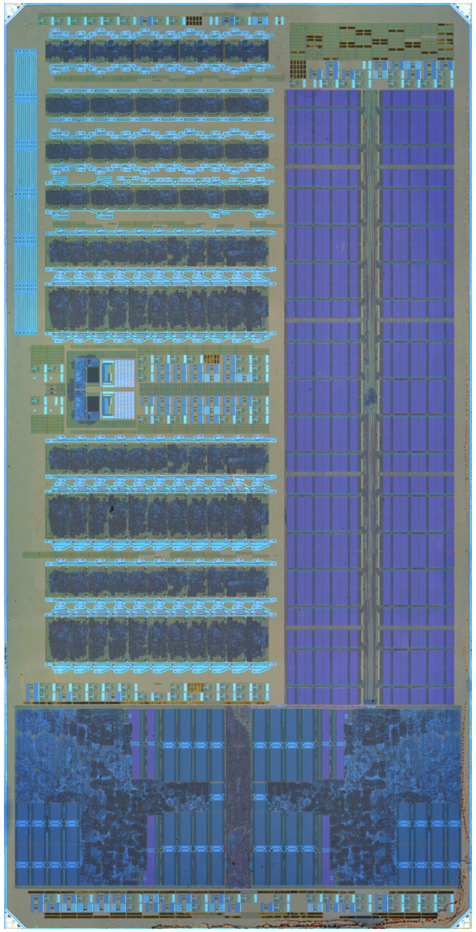
DARPA Program Challenges

DARPA Question 4: Where are you going to get a processor?

Prof. Krste Asanovic

Krste:
"Hey, why not **RISC-V**?"

We built it and made it work



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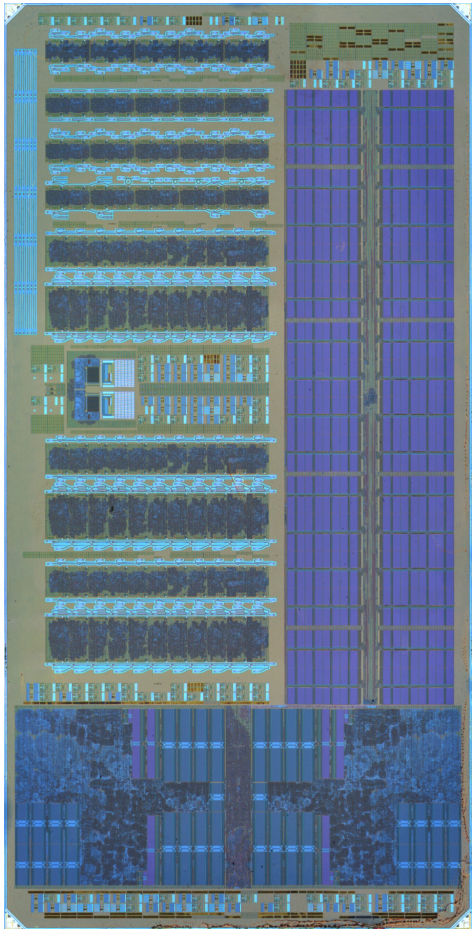

[Sun et al Nature 2015]

- First microprocessor chip to communicate using light

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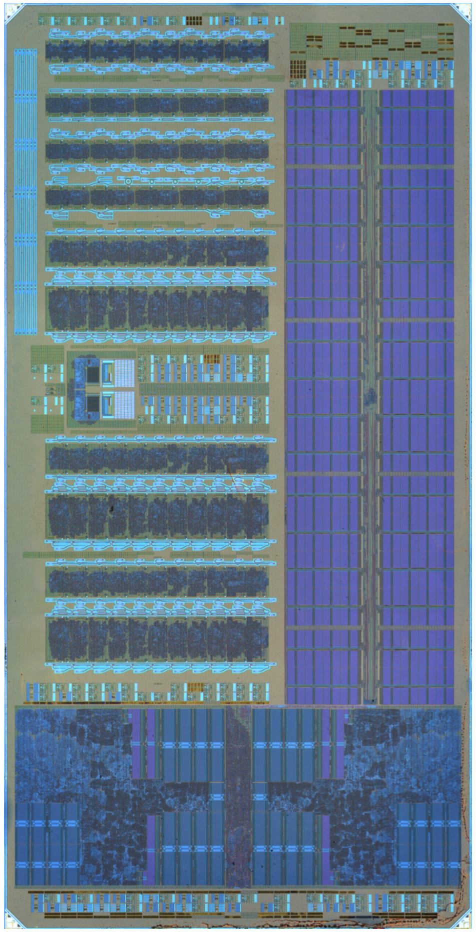

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- Manufactured in a commercial CMOS SOI Single chip with both electronics and optics

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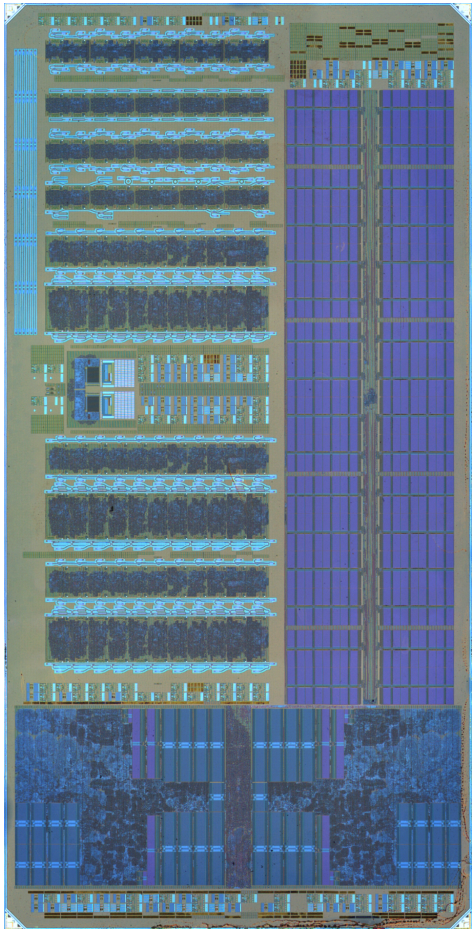

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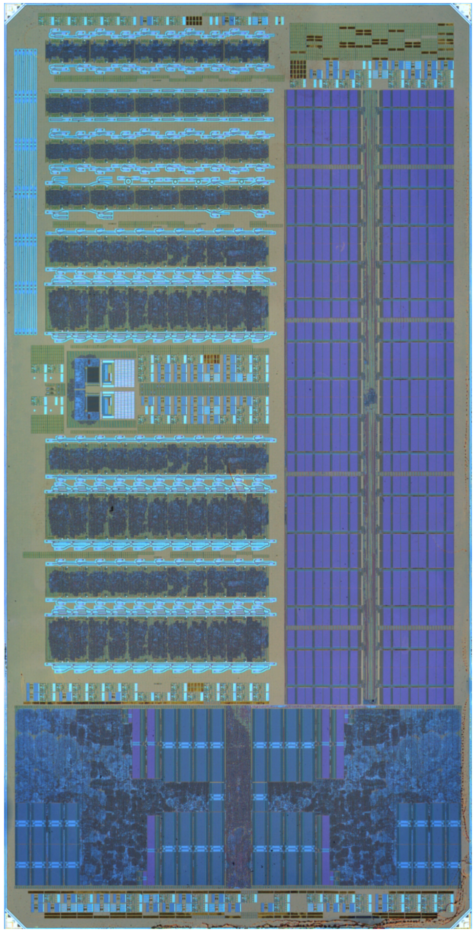
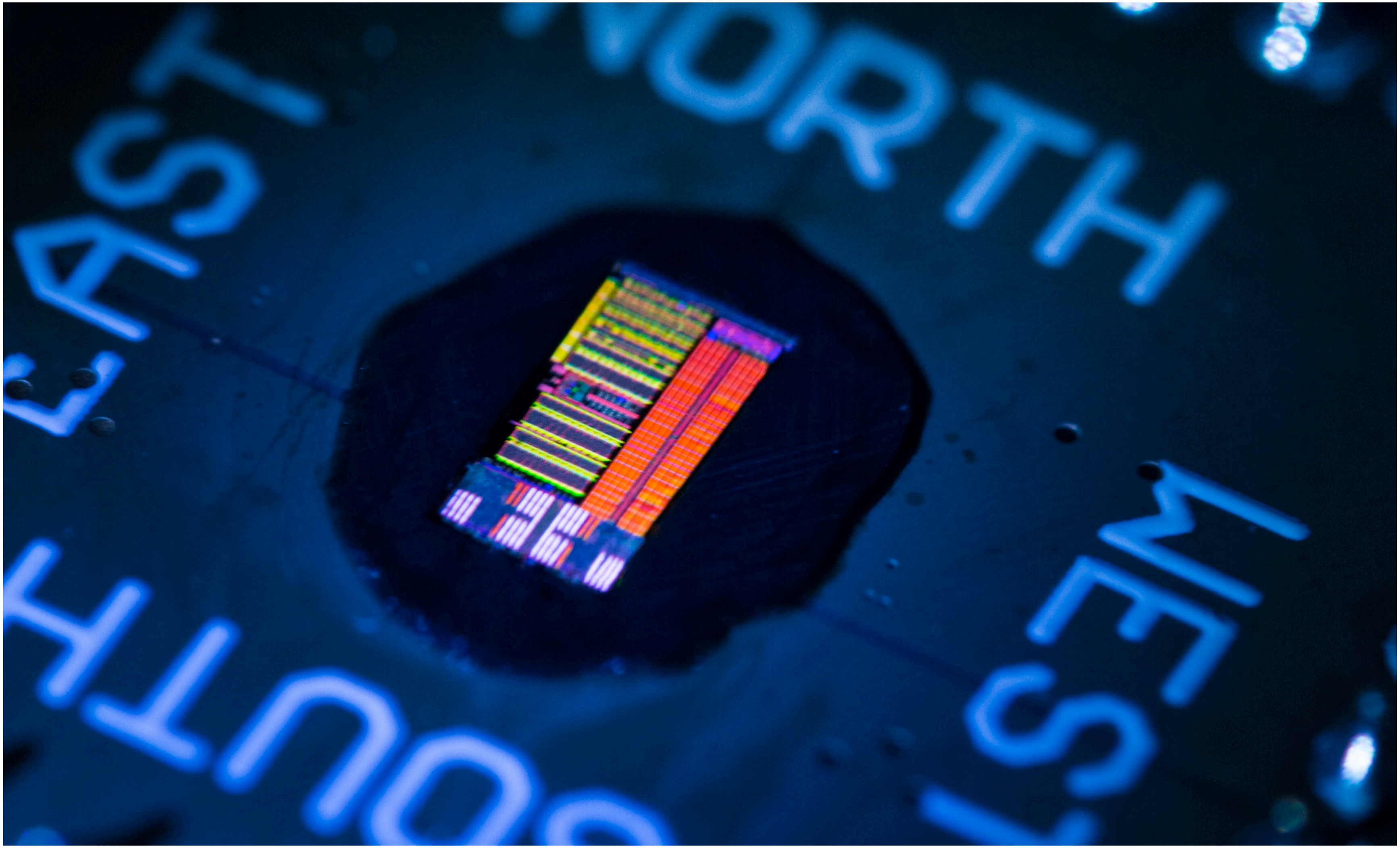


[Sun et al Nature 2015]

- First microprocessor chip to communicate using light
- Manufactured in a commercial CMOS SOI Single chip with both electronics and optics
- Competitive performance
- Processor is a dual-core 1.65GHz RISC-V

Demo Video



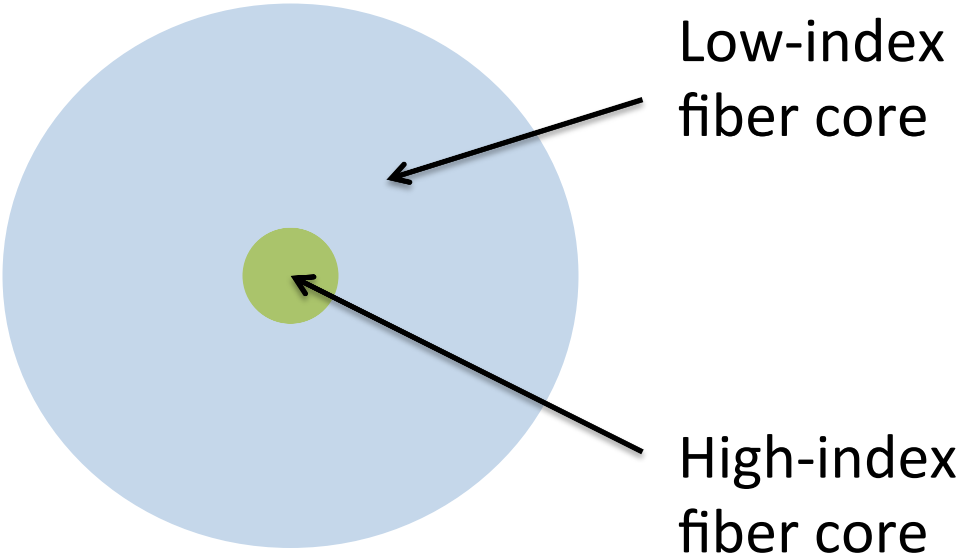
Outline

- Introduction to “zero-change” photonics
- Optical transceivers using microring resonators
- Electronic-photonic processor demonstration
- Conclusions

BWRC

Optical Fibers

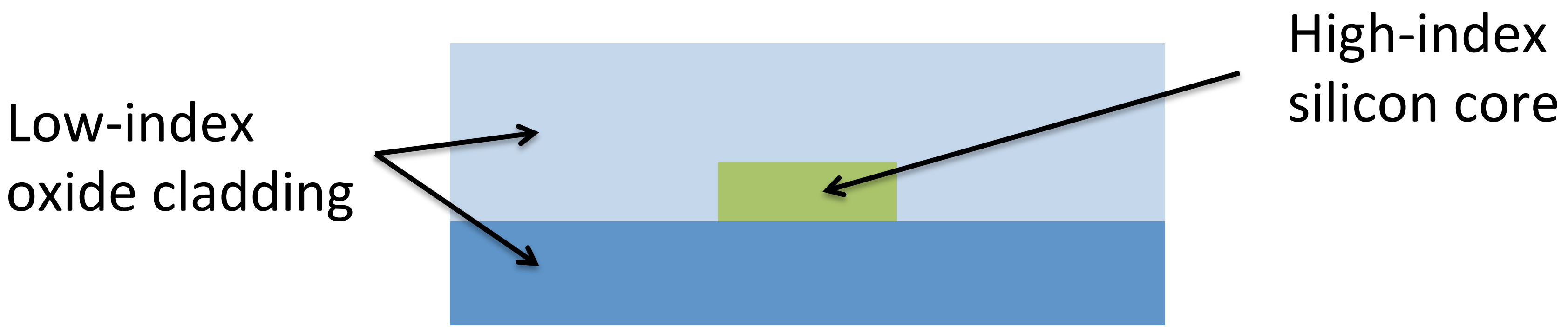
- Total internal reflection due to index of refraction contrast between core and cladding
- Typically low contrast, need >1cm bend radii



Cross-section of an optical fiber

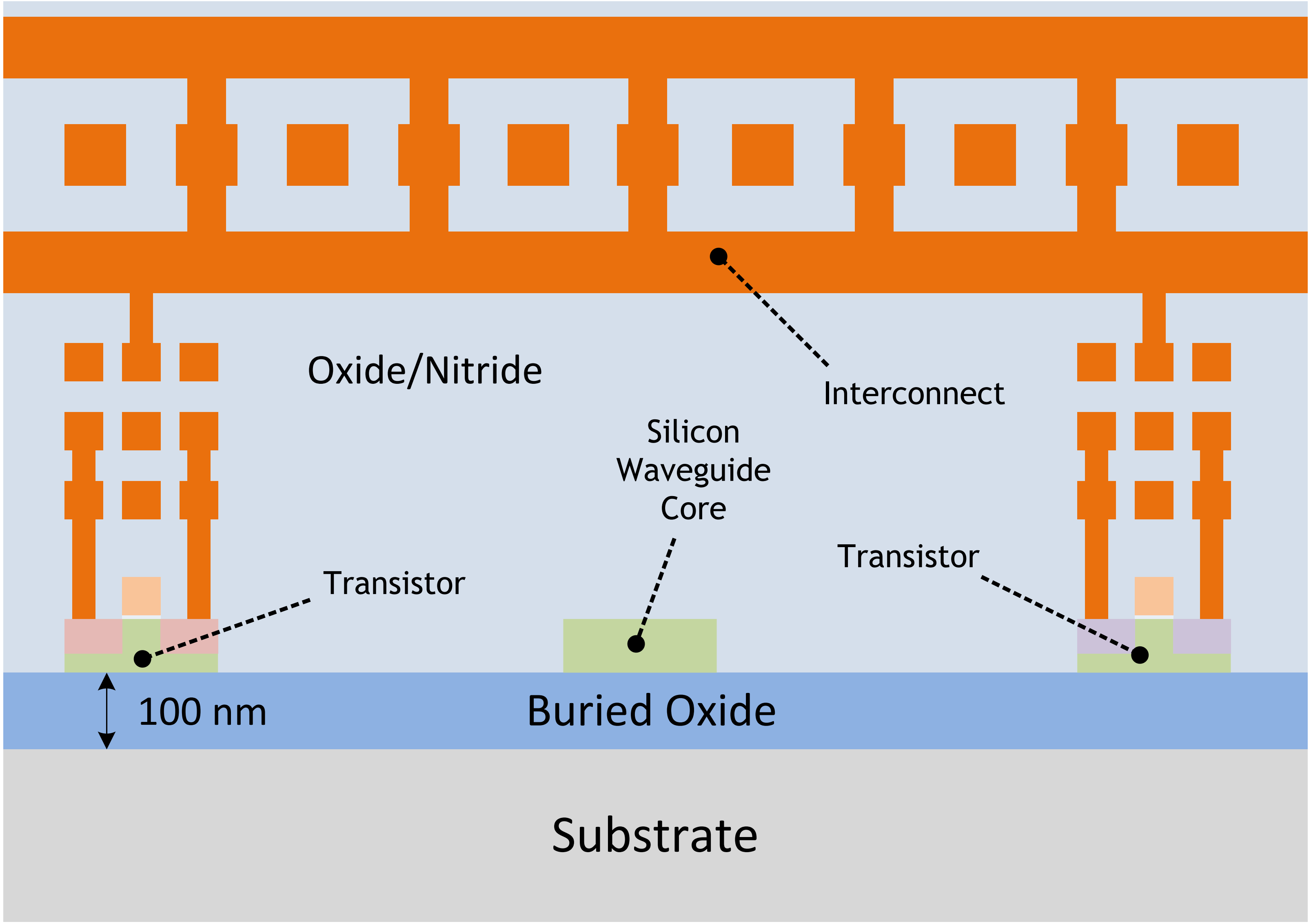
Waveguides in silicon

- Waveguides with planar silicon processing
- Silicon is the high-index core, oxides form the low-index cladding
- High index contrast, bend radii ~2um

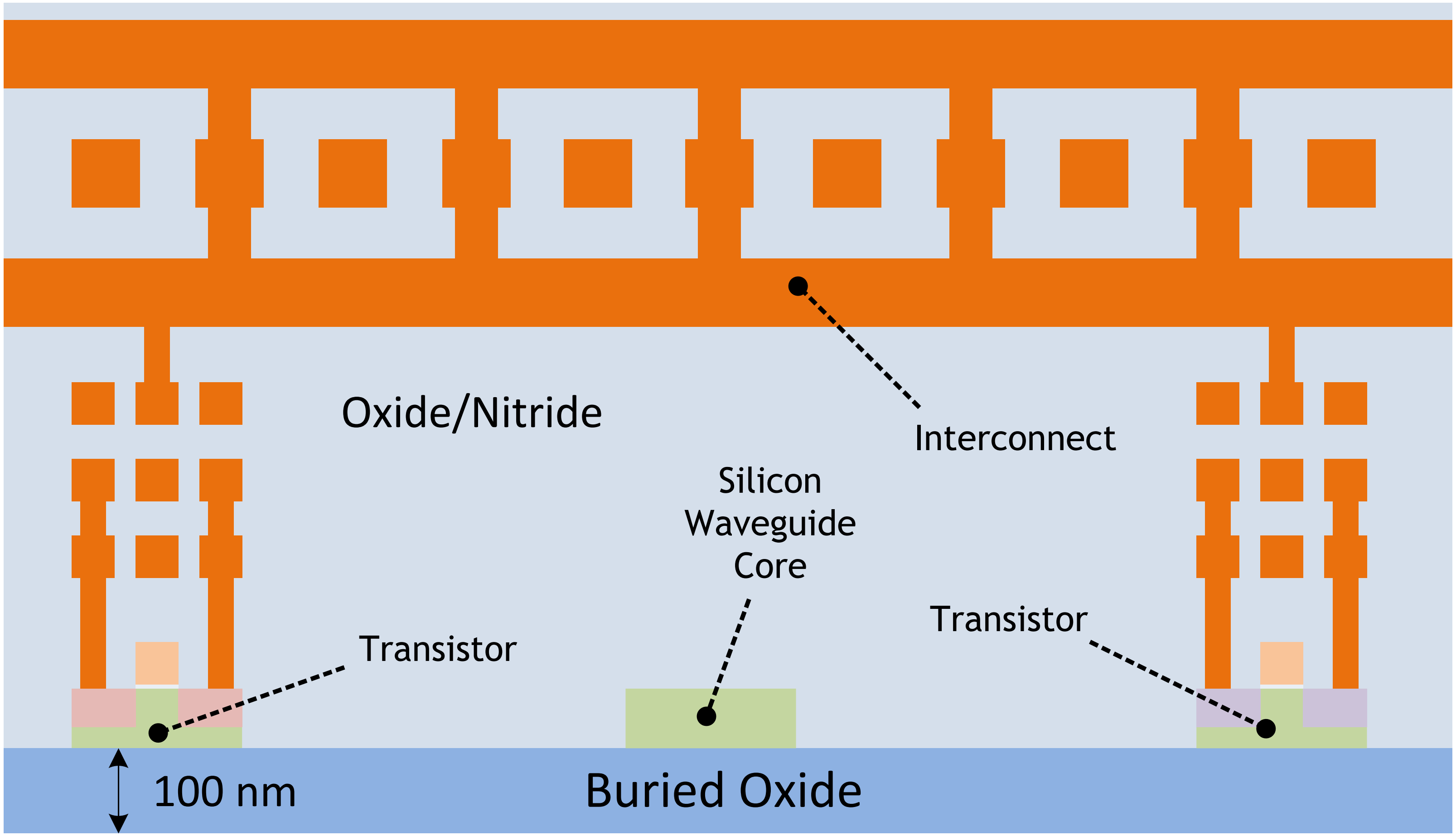


Cross-section of an planar silicon waveguide

“Zero-Change” Photonics in 45nm SOI



"Zero-Change" Photonics in 45nm SOI



Substrate Removal to use air low-index isolation

Air

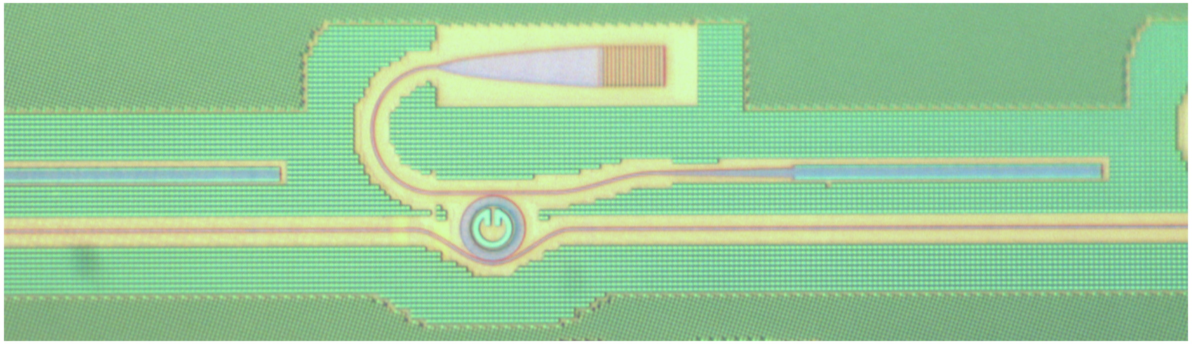
[Orcutt Opt. Ex. 2012]

Monolithic photonics platform with the fastest transistors

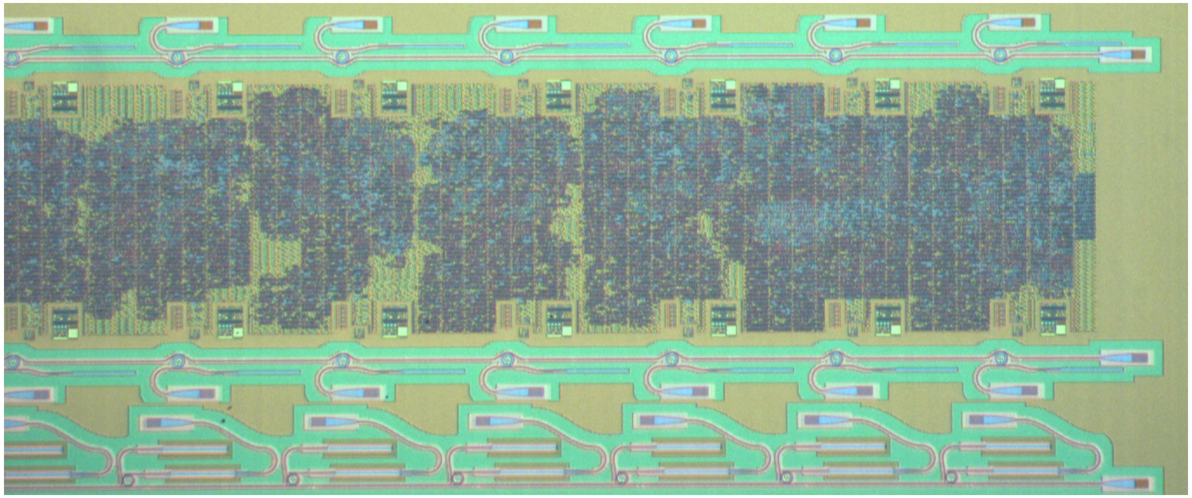
Optical devices using waveguides

- Working waveguide gets you 90% of the way towards an optical transceiver

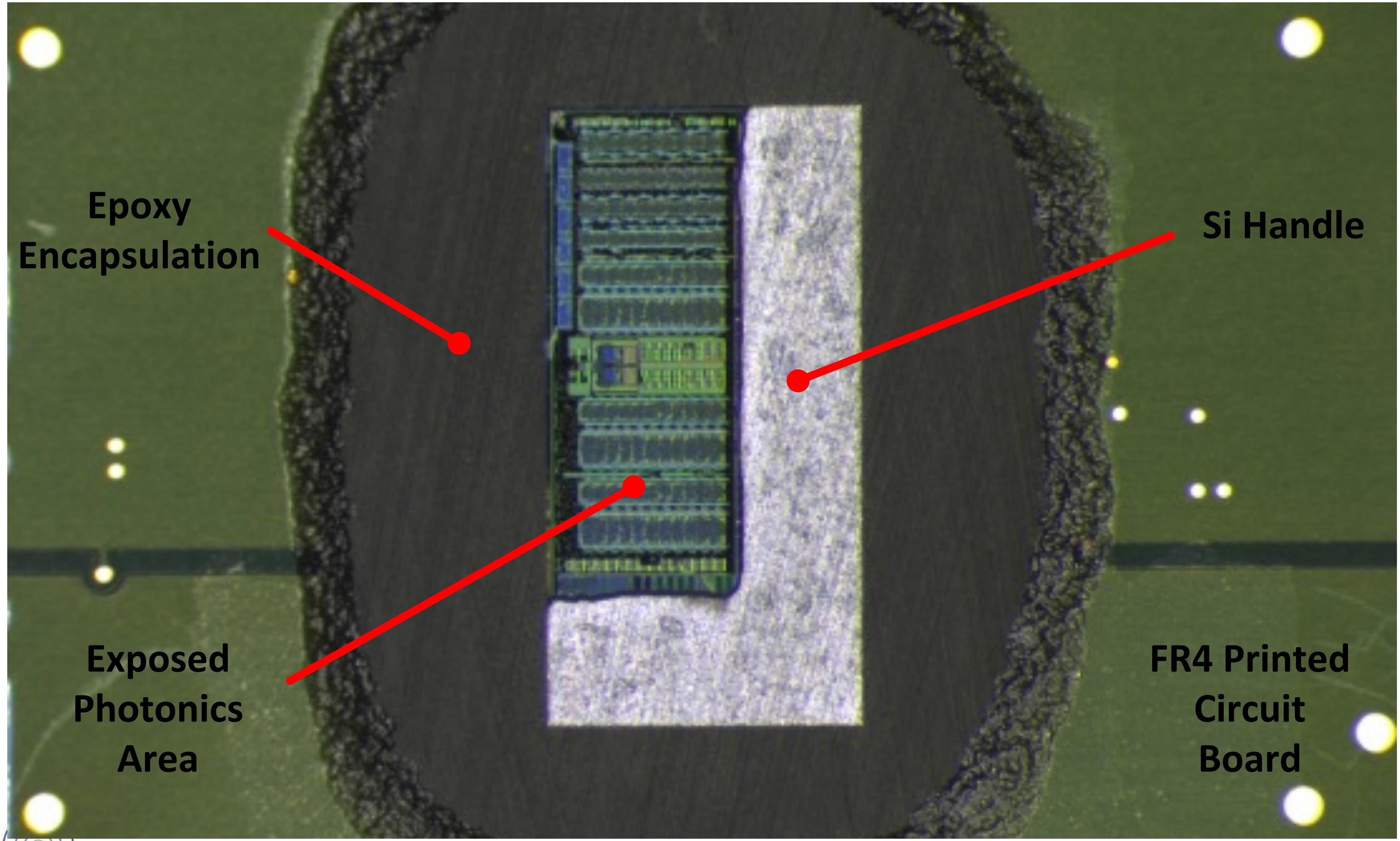
Waveguides in a transmitter



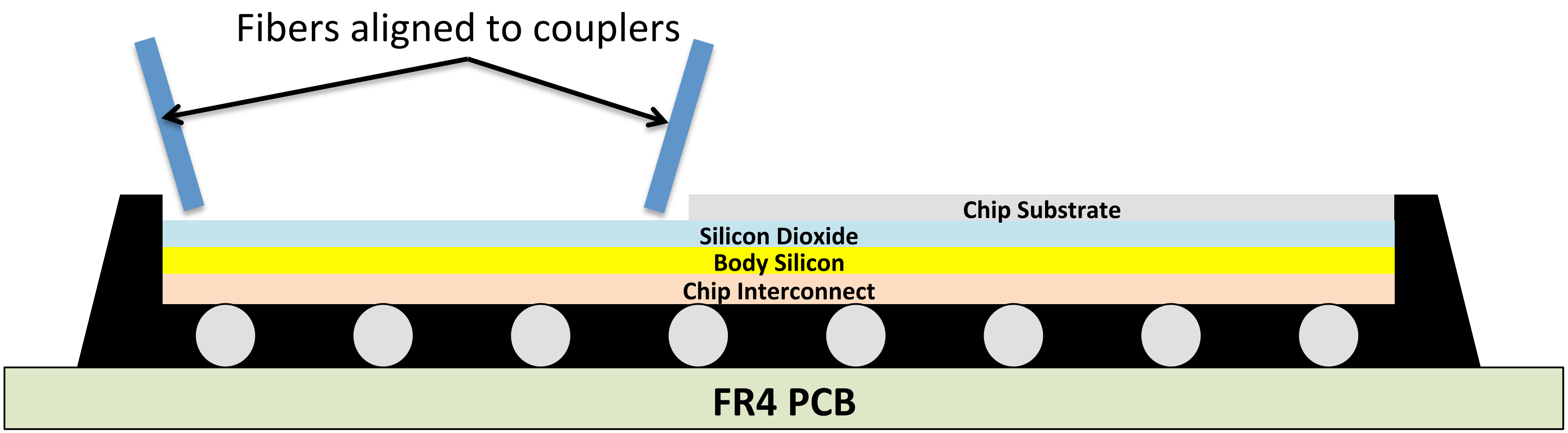
Waveguides routing light across the chip



Packaged Partial-Released Processor

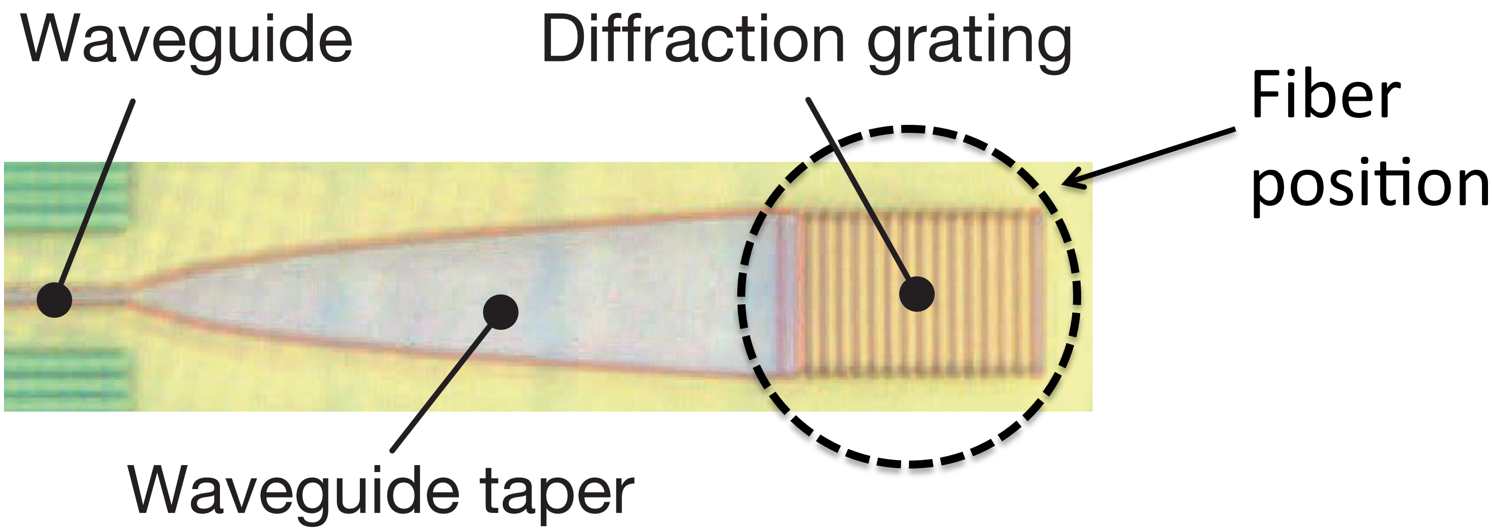


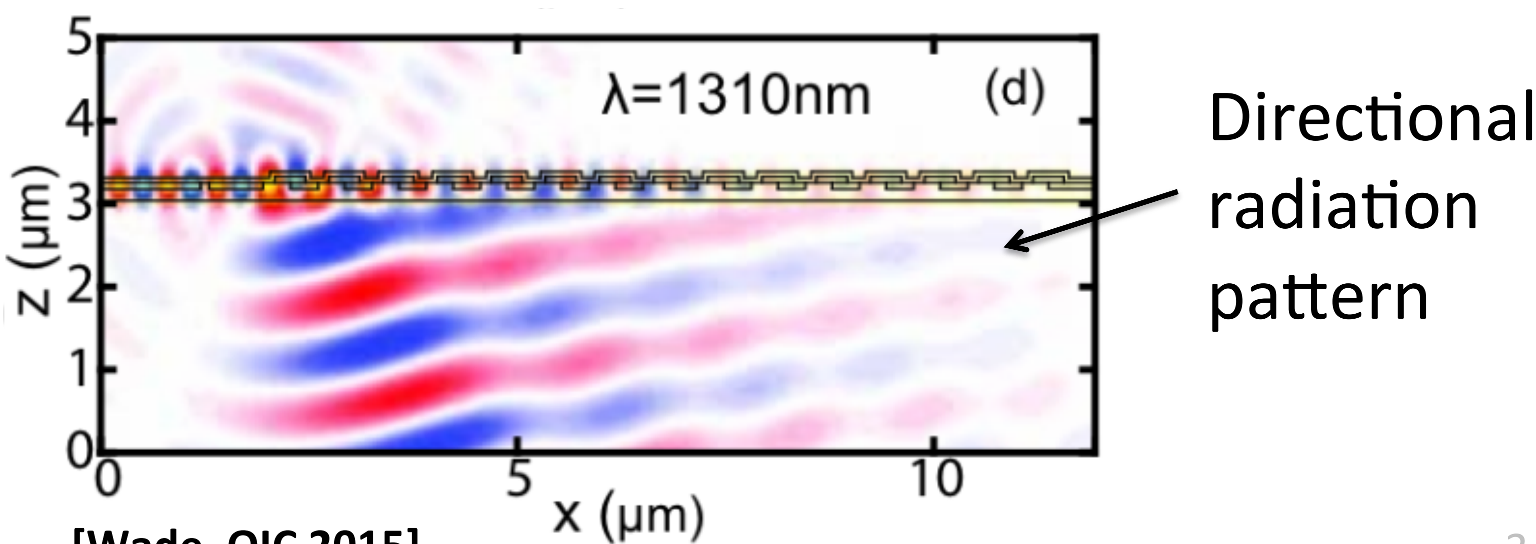
Electrical/Optical I/Os



- Electrical connections made through standard C4 bump attach to a PCB
- Optical fibers couple to on-chip waveguides through the exposed chip back-side

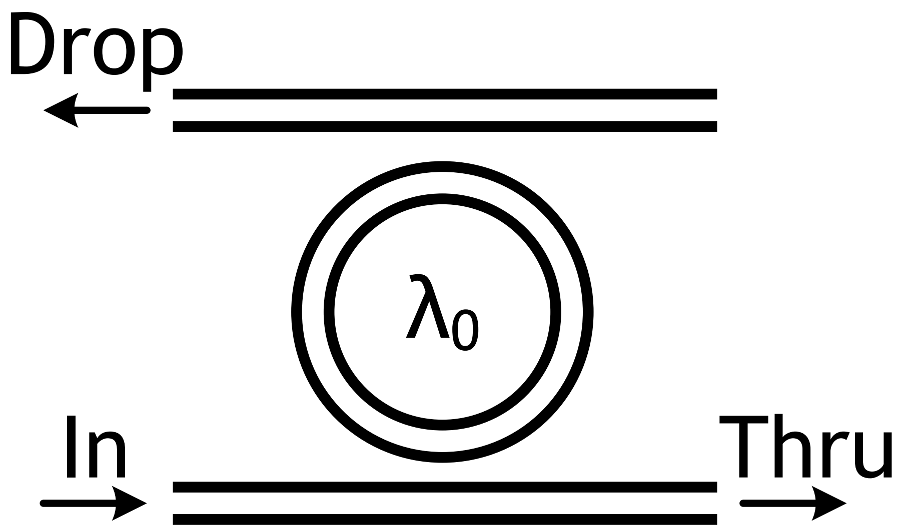
Fiber-to-Waveguide Couplers





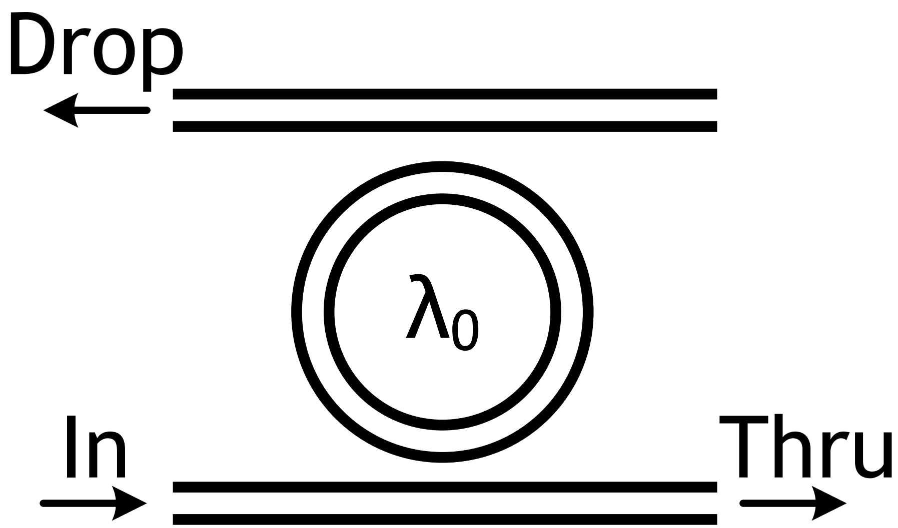
[Wade, OIC 2015]

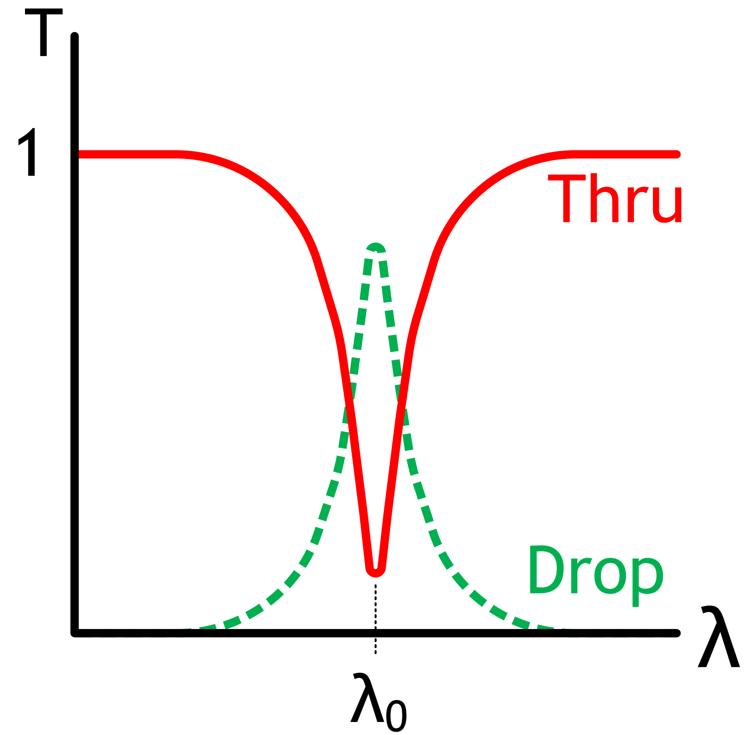
Ring Resonators



- Enabler of compact silicon-photonic devices

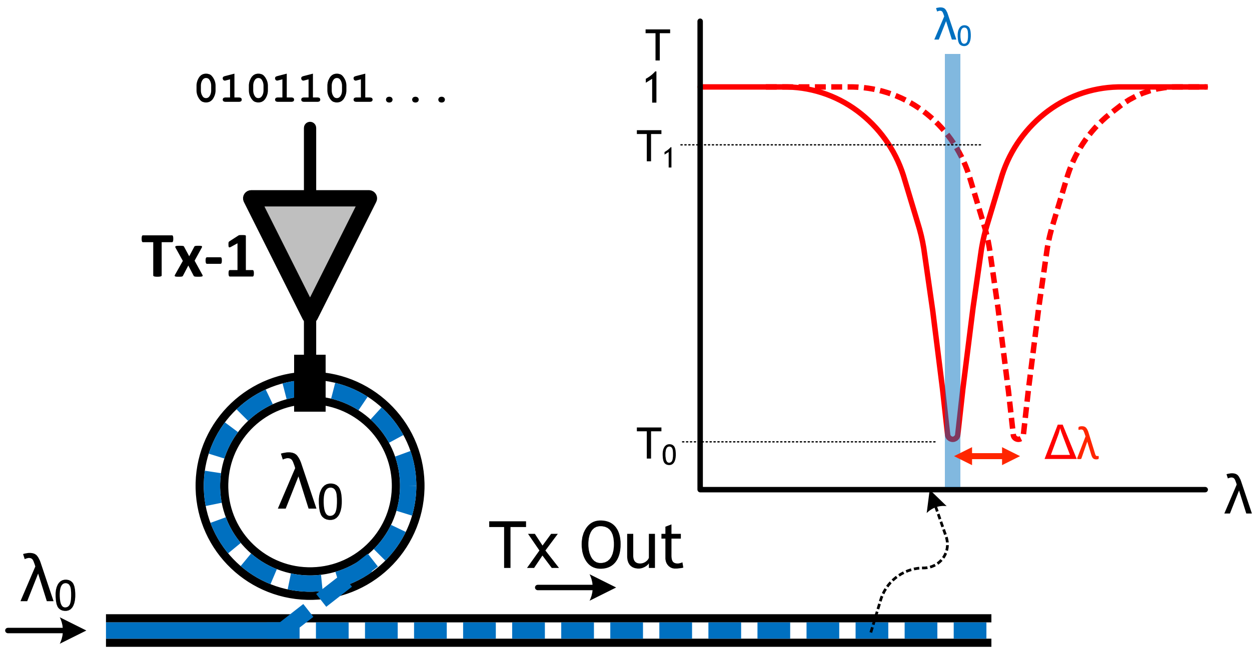
Ring Resonators





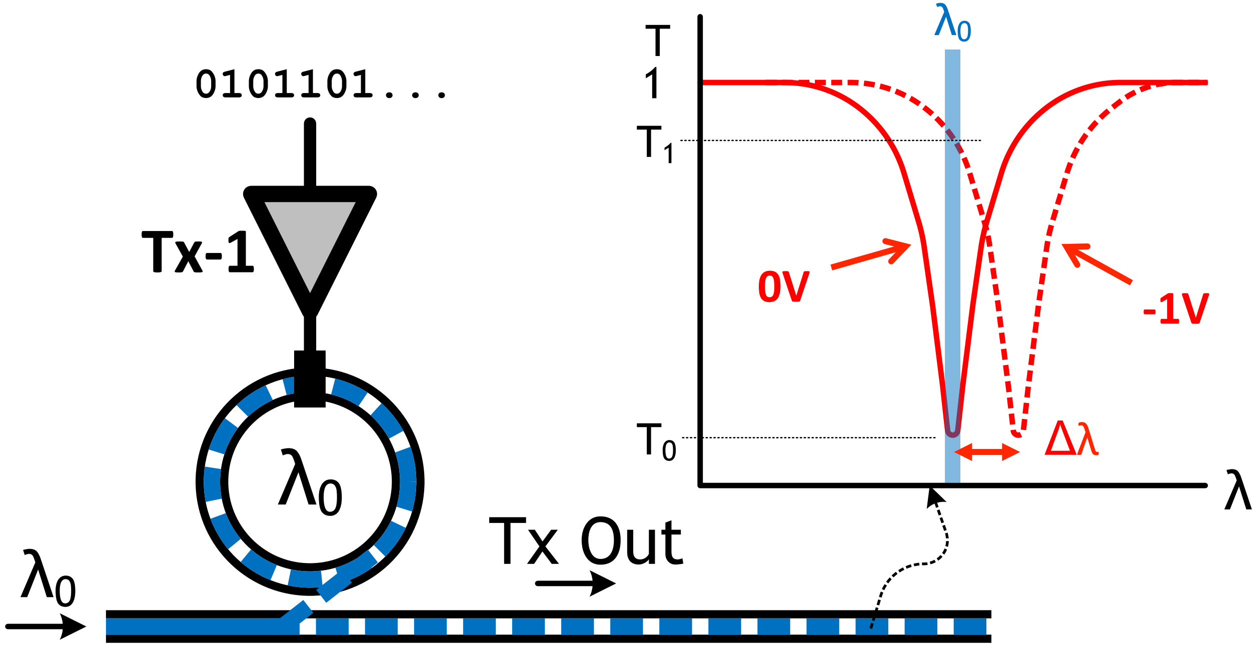
- Enabler of compact silicon-photonic devices
- Very high-Q resonant notch filter

Modulators and Receivers



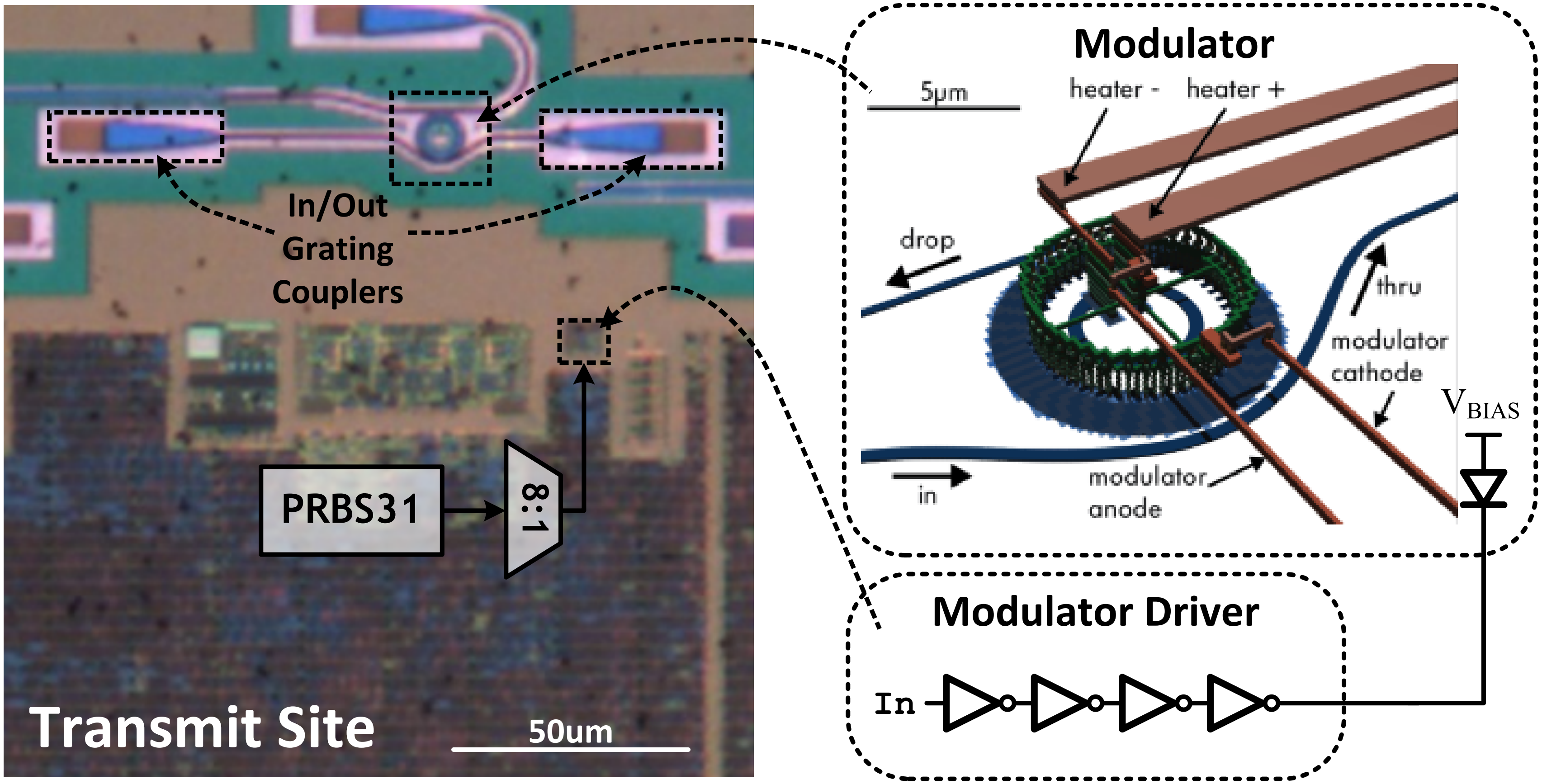
- Modulation:
  - On-off key the laser by electrically shifting notch wavelength

Modulators and Receivers



- Modulation:
  - On-off key the laser by electrically shifting notch wavelength
  - Modulator ring is a PN diode
  - Free carrier dispersion (Δfree carriers => Δindex of refraction)

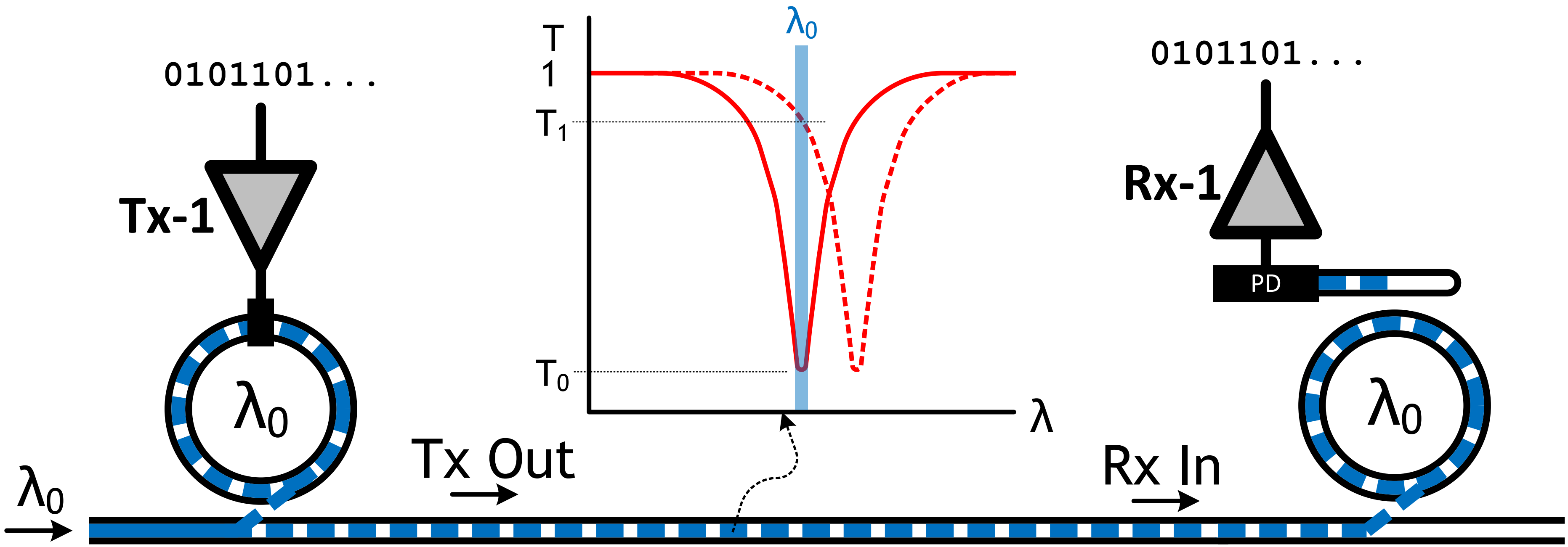
Transmitter



- Driven by a CMOS logic inverter (1.2V_{pp})
- 5 Gb/s data rate at ~30fJ/b
  - Newer devices are >14 Gb/s

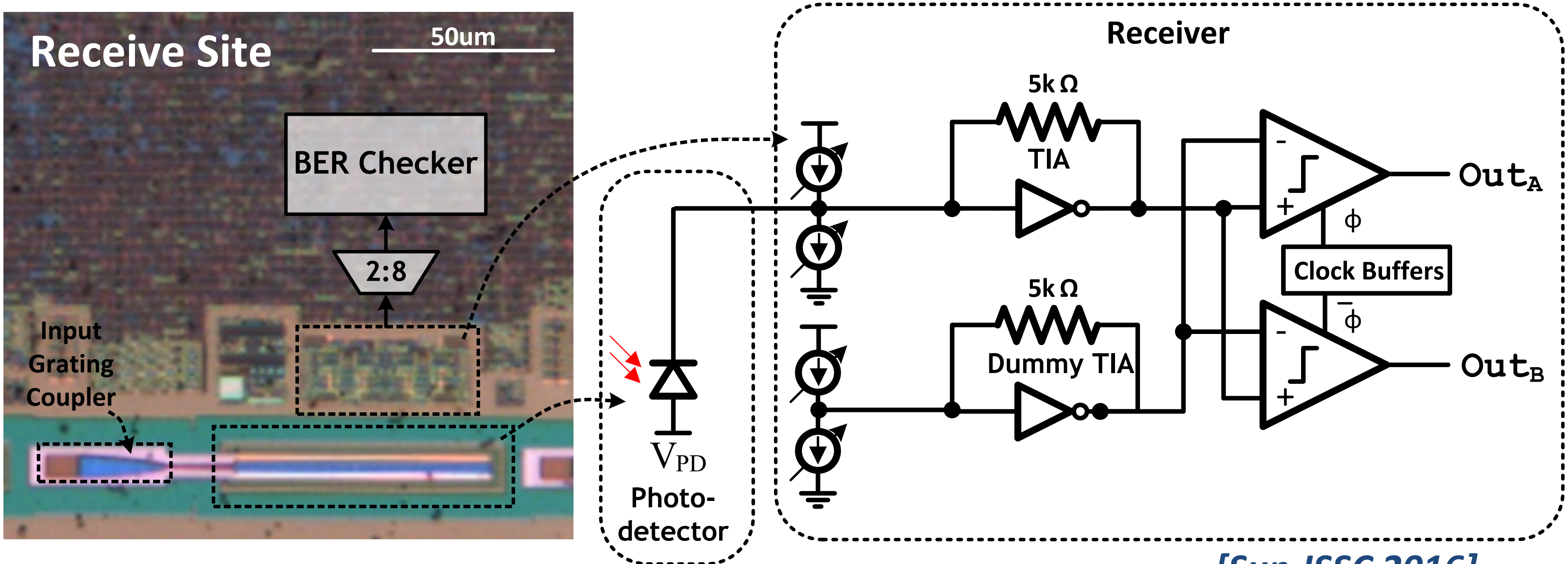
[Wade OFC 2014]
[Sun JSSC 2016]

Modulators and Receivers



- Receive:
  - Ring captures light of a specific wavelength, drops light onto a wideband photodetector

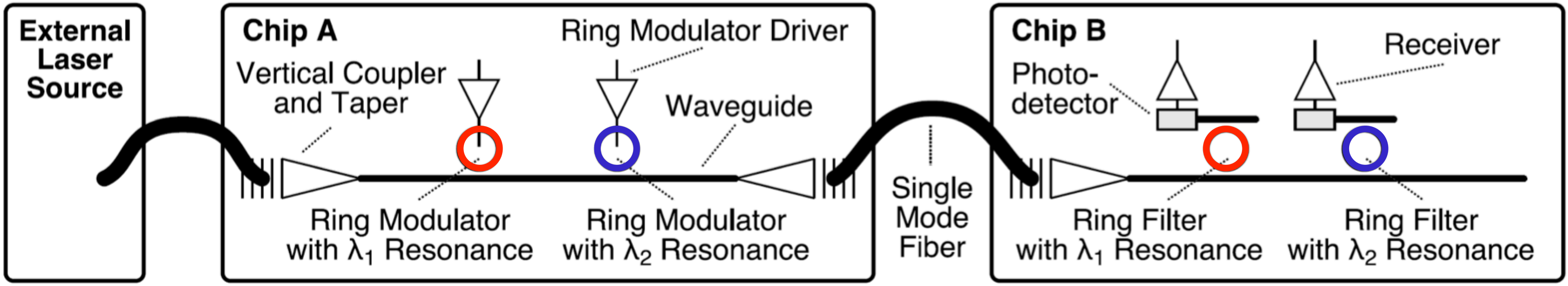
Receiver



[Sun JSSC 2016]

- SiGe from PMOS strain engineering used as PDs
- Low parasitics from monolithic integration enable single-stage TIA receiver design with 5kΩ feedback resistance
- 10 Gb/s operation at 330 fJ/bit with 8.3uA sensitivity

Chip-to-Chip DWDM Links



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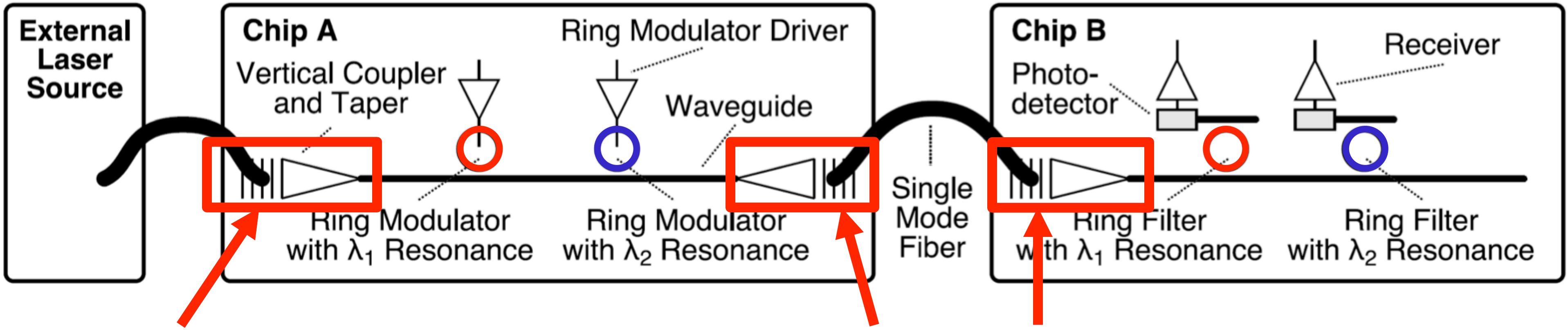
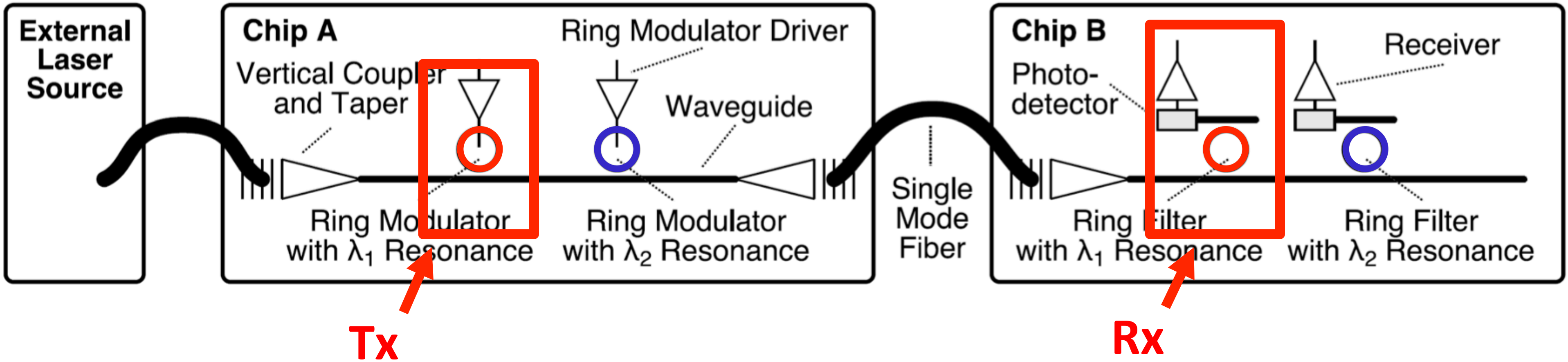


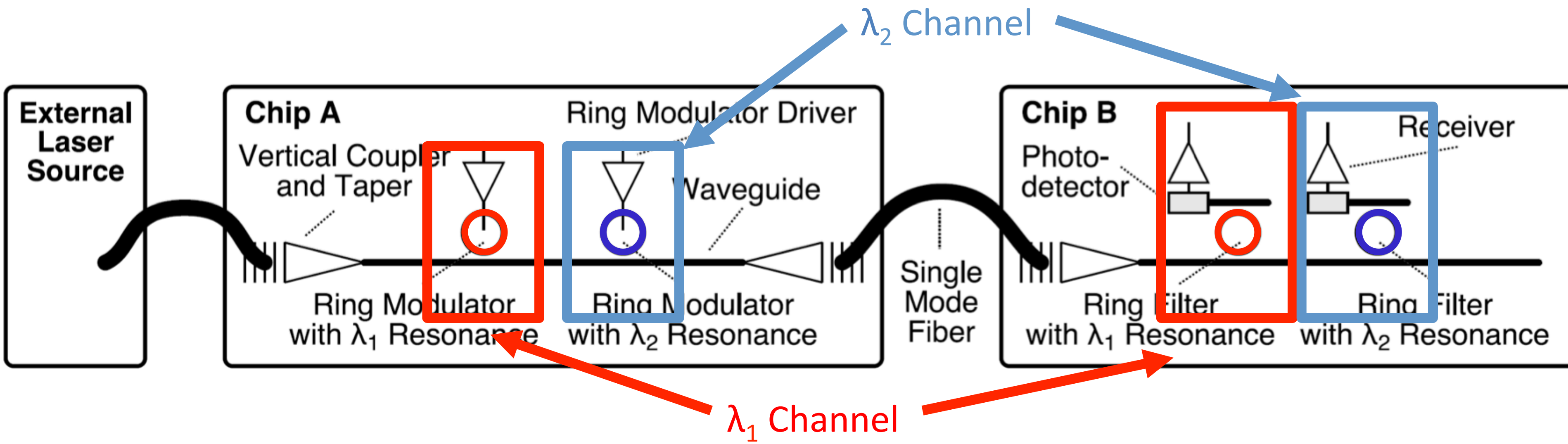
- Vertical grating couplers couple light from a fiber into or out of a chip

Chip-to-Chip DWDM Links



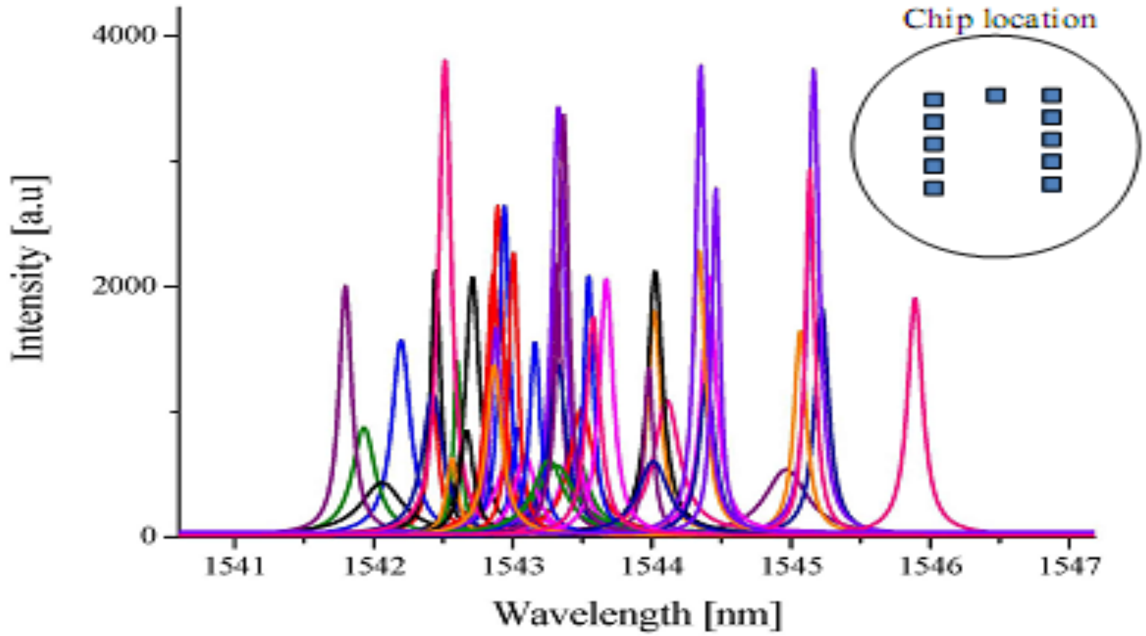
- Vertical grating couplers couple light from a fiber into or out of a chip
- A pair of resonators aligned to the same wavelength form a wavelength channel

Chip-to-Chip DWDM Links



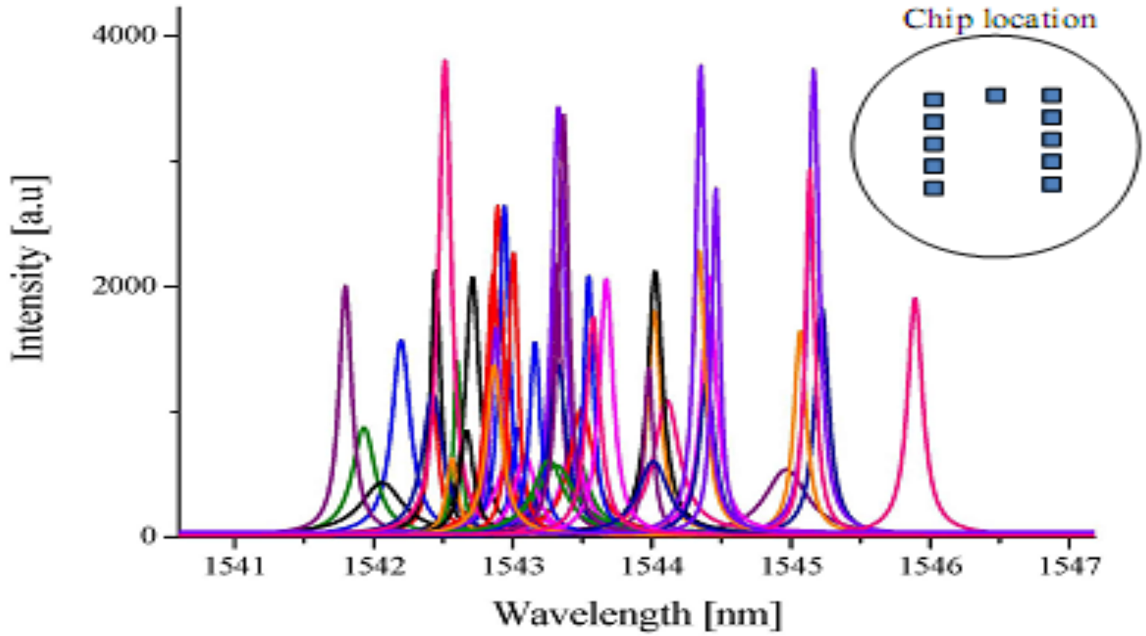
- Vertical grating couplers couple light from a fiber into or out of a chip
- A pair of resonators aligned to the same wavelength form a wavelength channel
- High selectivity (Q ~10000) enables many channels on the same waveguide

Drawback of Ring Resonators



Drop-port spectra of 55 nominally identical rings [Selvaraja IEEE LEOS 2009]

Drawback of Ring Resonators



Drop-port spectra of 55 nominally identical rings [Selvaraja IEEE LEOS 2009]

- Wavelength alignment critical to functionality, but resonance is sensitive to process, temperature variations
  - Can thermally tune away the process variations (0.05nm/K)

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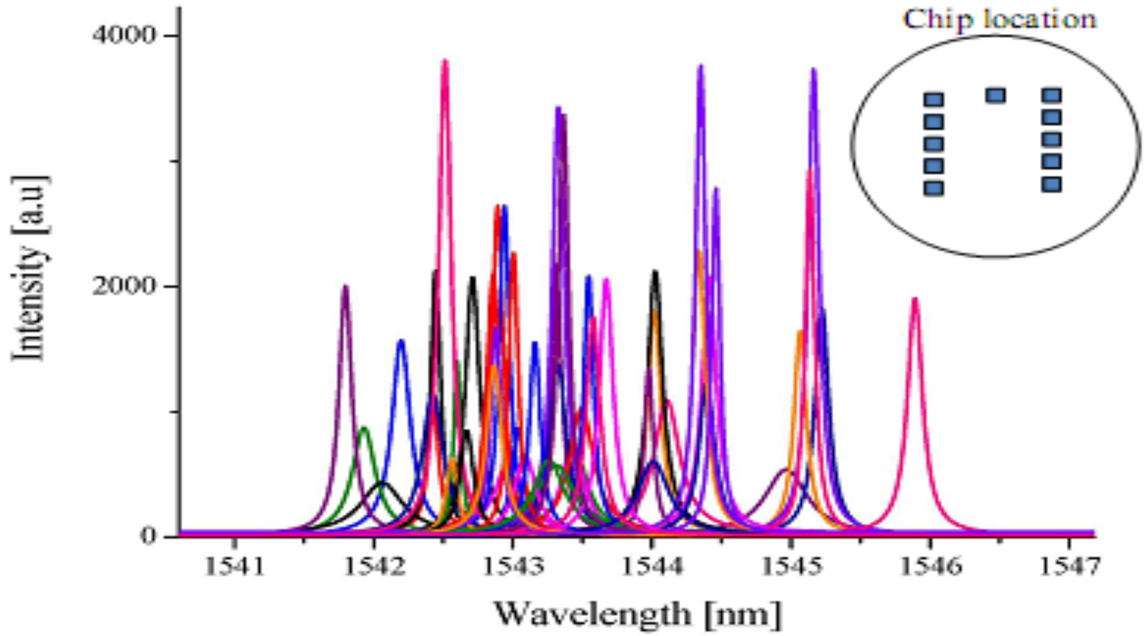
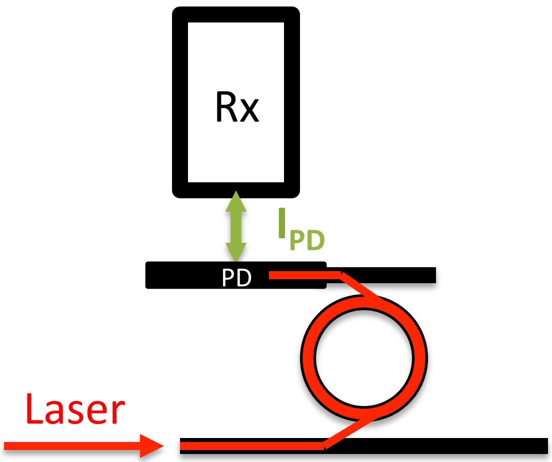
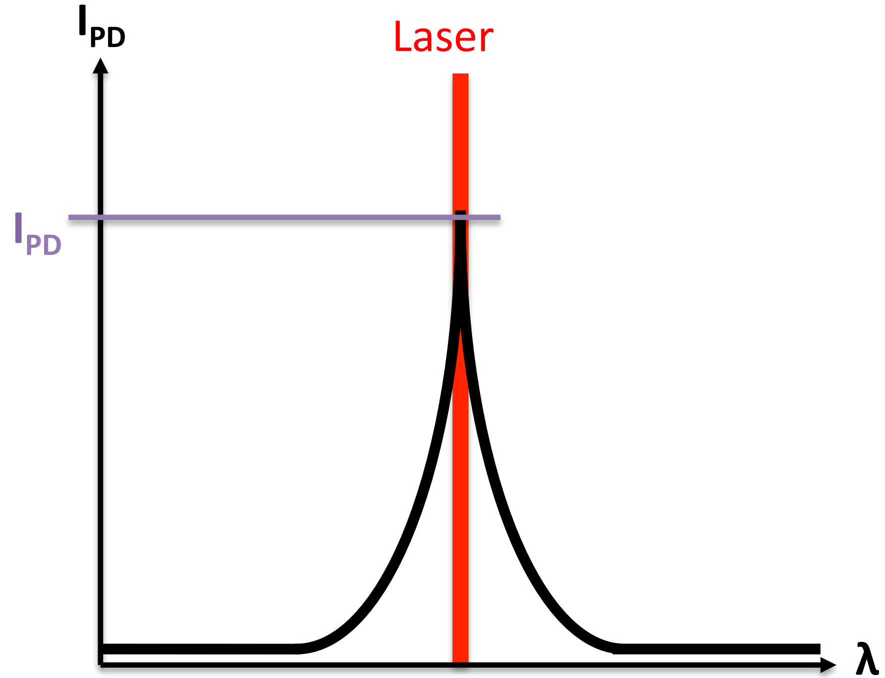


Drop-port spectra of 55 nominally identical rings [Selvaraja IEEE LEOS 2009]

- Wavelength alignment critical to functionality, but resonance is sensitive to process, temperature variations
  - Can thermally tune away the process variations (0.05nm/K)
  - Many consider rings unusable in a real system
  - We will explore how to make them work in a real system

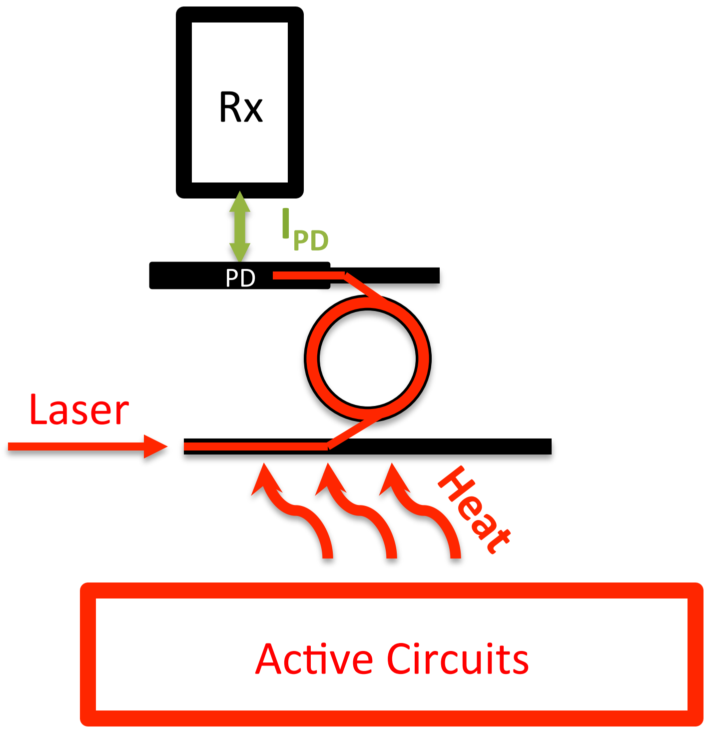
Gating Issue: Thermal Perturbations

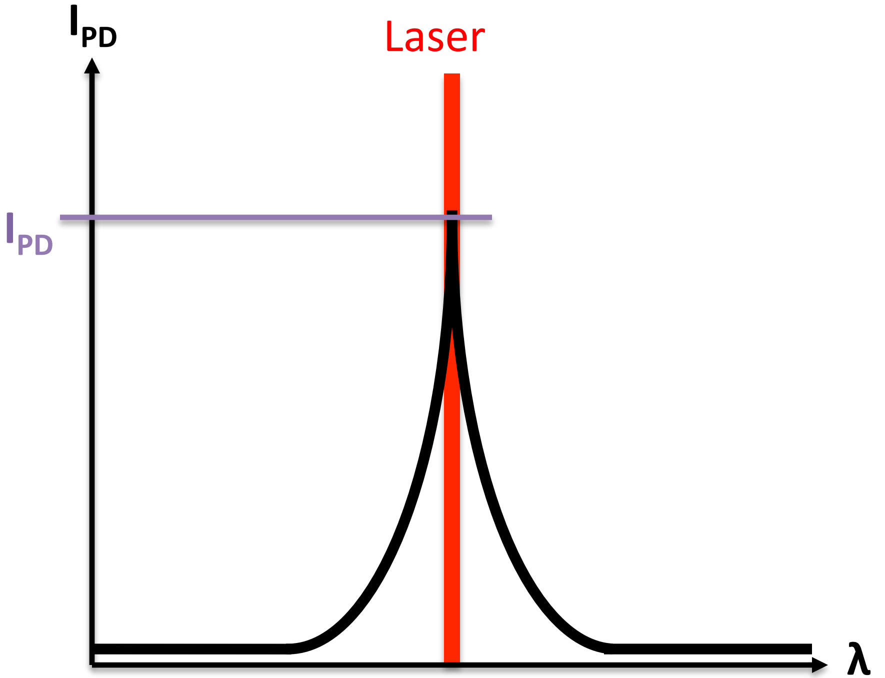




- Ring resonator resonances are sensitive to temperature!

Gating Issue: Thermal Perturbations





- Nearby circuit turns on and burns a lot of power

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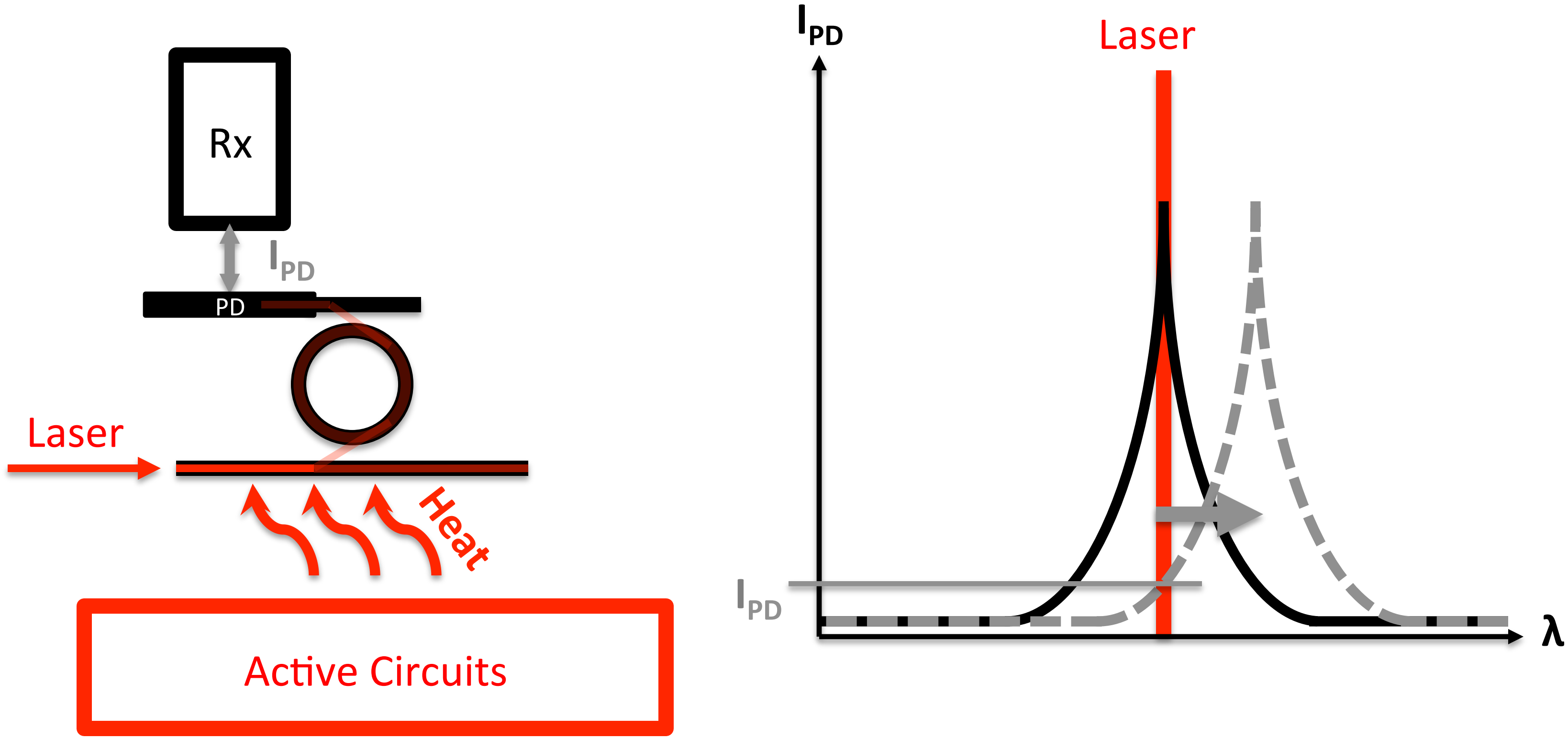
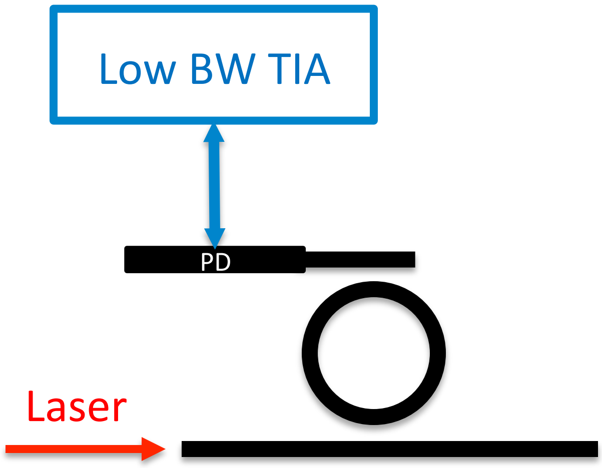


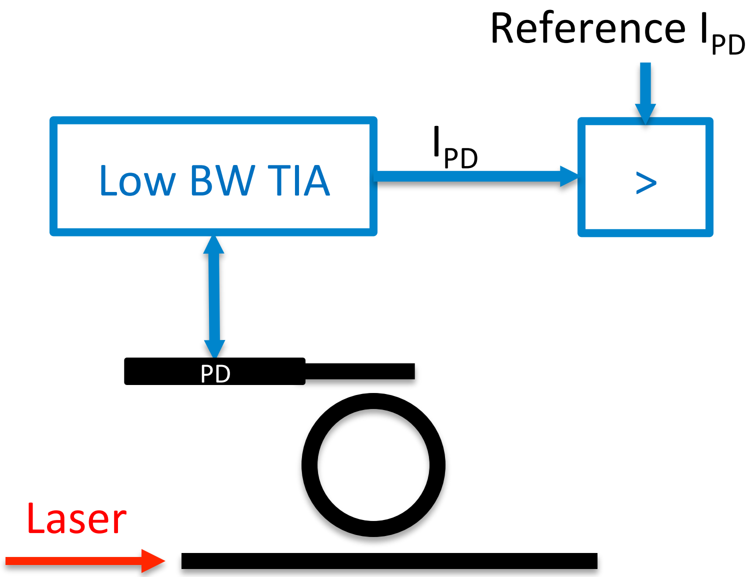
- Nearby circuit turns on and burns a lot of power
- Ring heats up, the resonance moves (red-shift)
- Dynamic / Active tracking is needed

Thermal Tuning: Drop-Port Sensing



- Track average drop-port photocurrent as sensing signal
  - When ring is on resonance, PD illuminated

Thermal Tuning: Drop-Port Sensing



- Track average drop-port photocurrent as sensing signal
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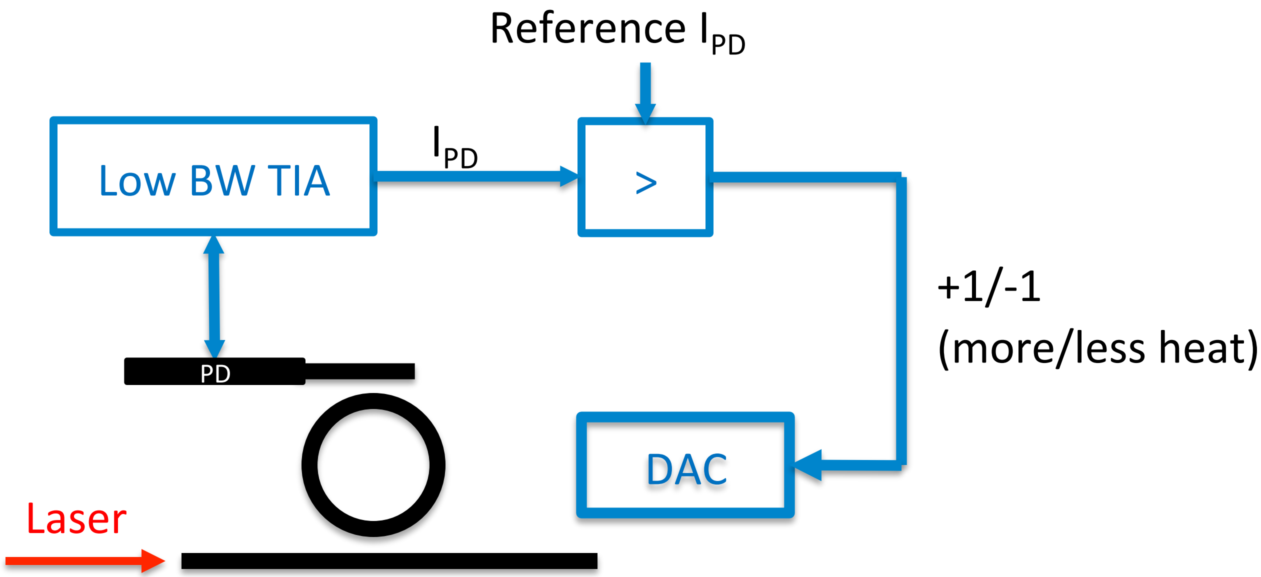
- Compare to reference I_{PD}

Thermal Tuning: Drop-Port Sensing



- Track average drop-port photocurrent as sensing signal
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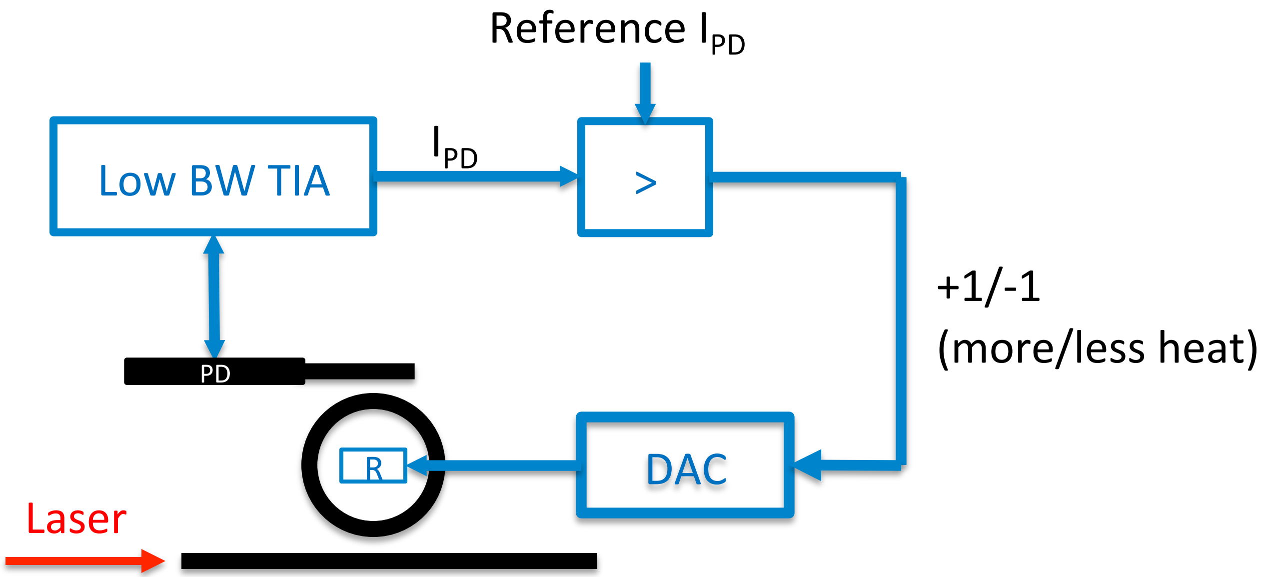
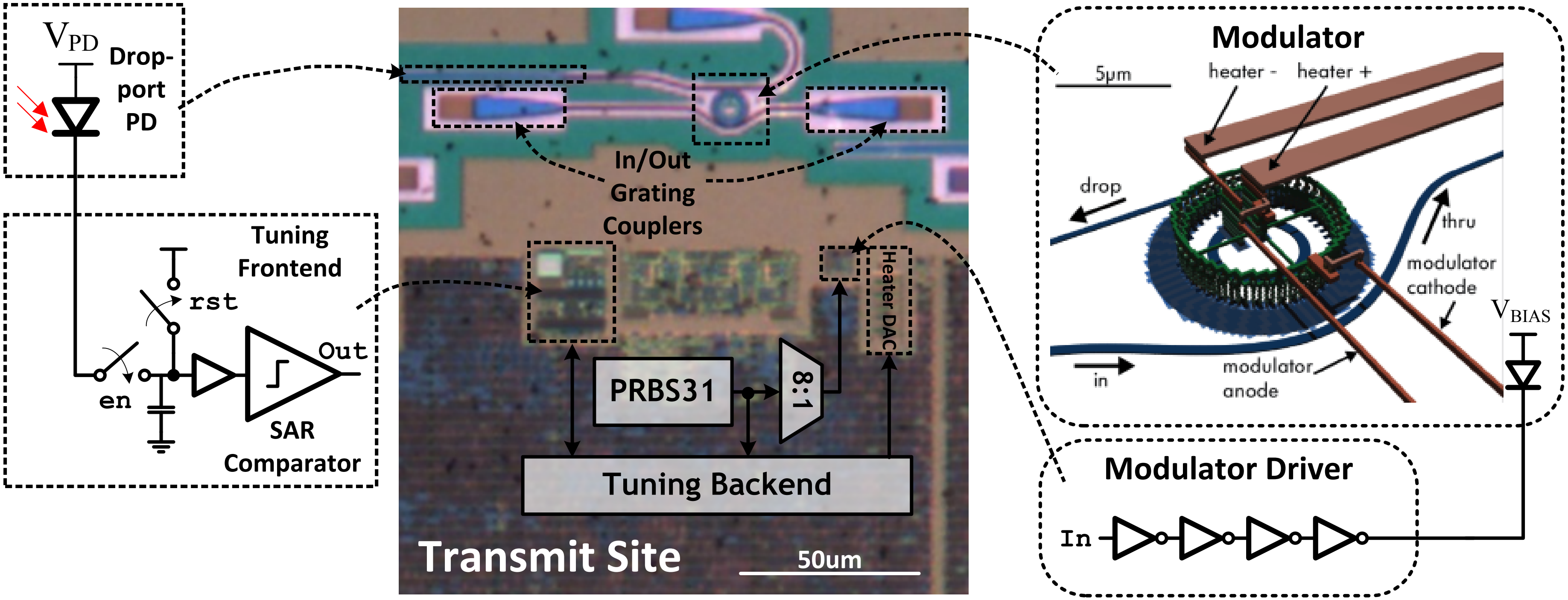
- Heat more or heat less decision

Thermal Tuning: Drop-Port Sensing



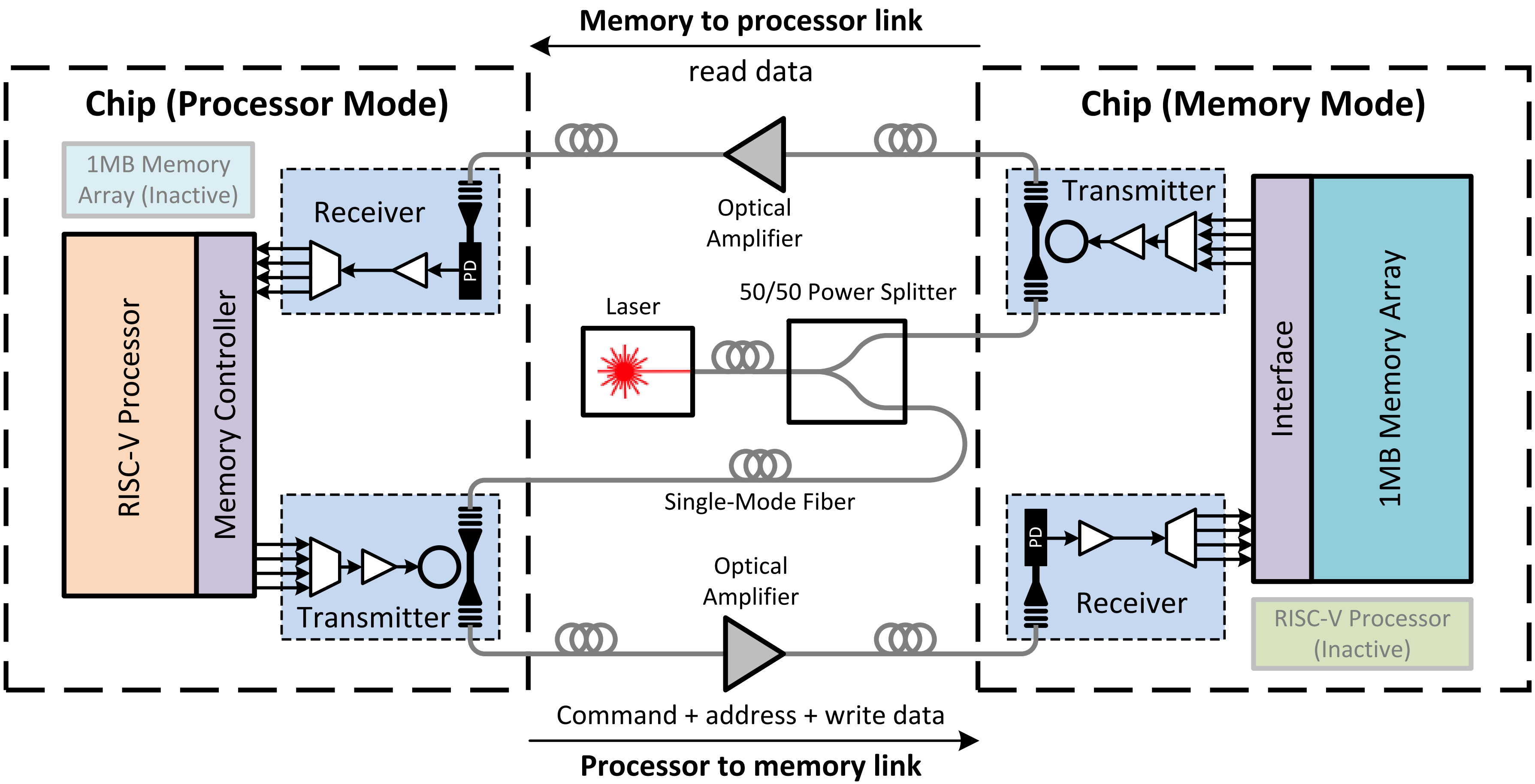
- Track average drop-port photocurrent as sensing signal
  - When ring is on resonance, PD illuminated
- Compare to reference I_{PD}
- Heat more or heat less decision
- Integrated ring heater driven by DAC to move temperature

Auto-Locked Transmitter / Receiver



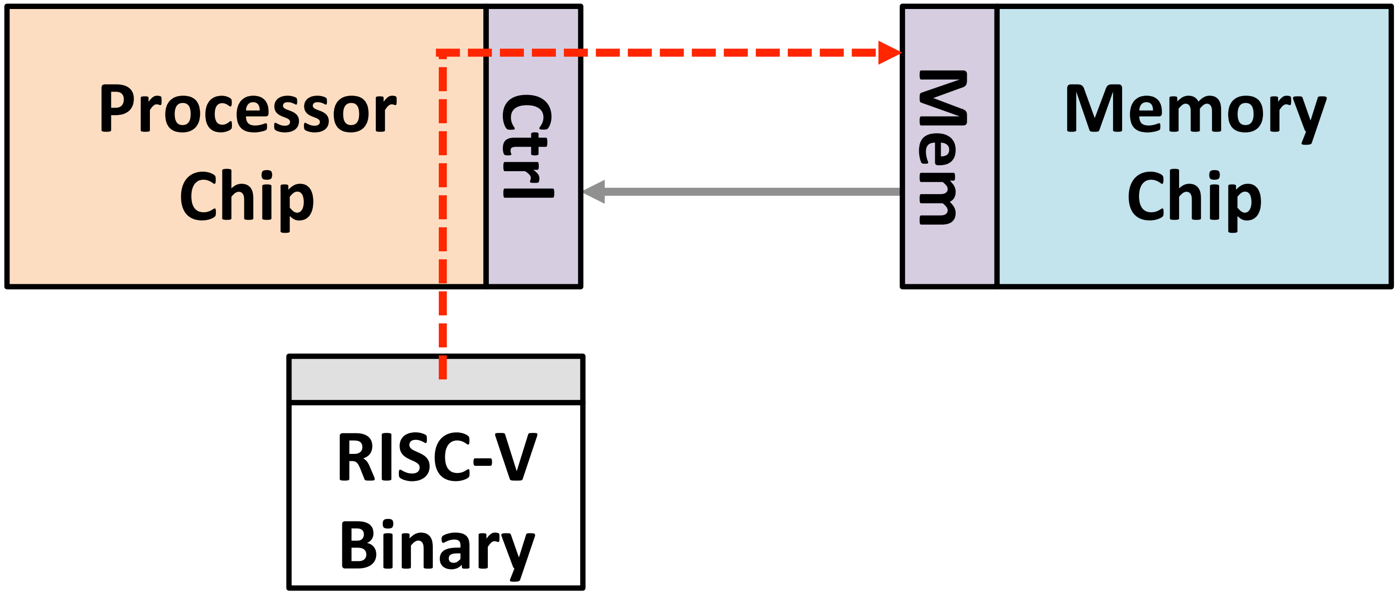
- Integrate the tuning circuitry
- Highly-wavelength tunable (3.8μW/GHz), auto-locking transmitters and receivers

Optical Memory System Demo



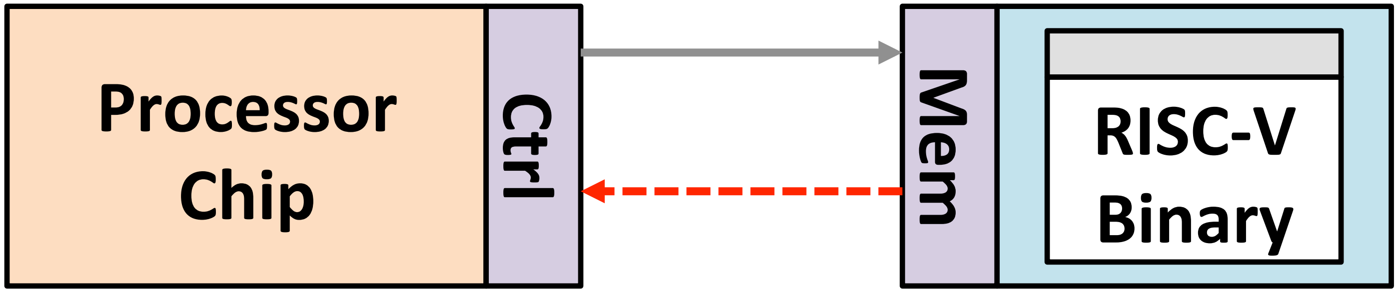
- Chip 1 acts as processor, Chip 2 acts as memory
- Custom memory controller, DRAM interface emulator
  - Takes advantage of full duplex (as opposed to half-duplex) memory interface

Loading Programs



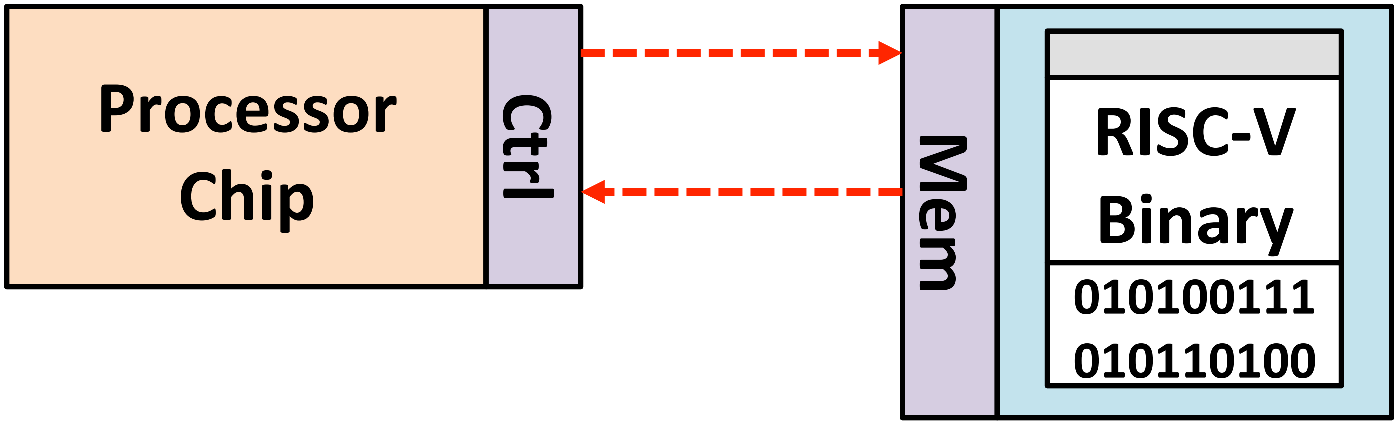
Load program into memory

Loading Programs



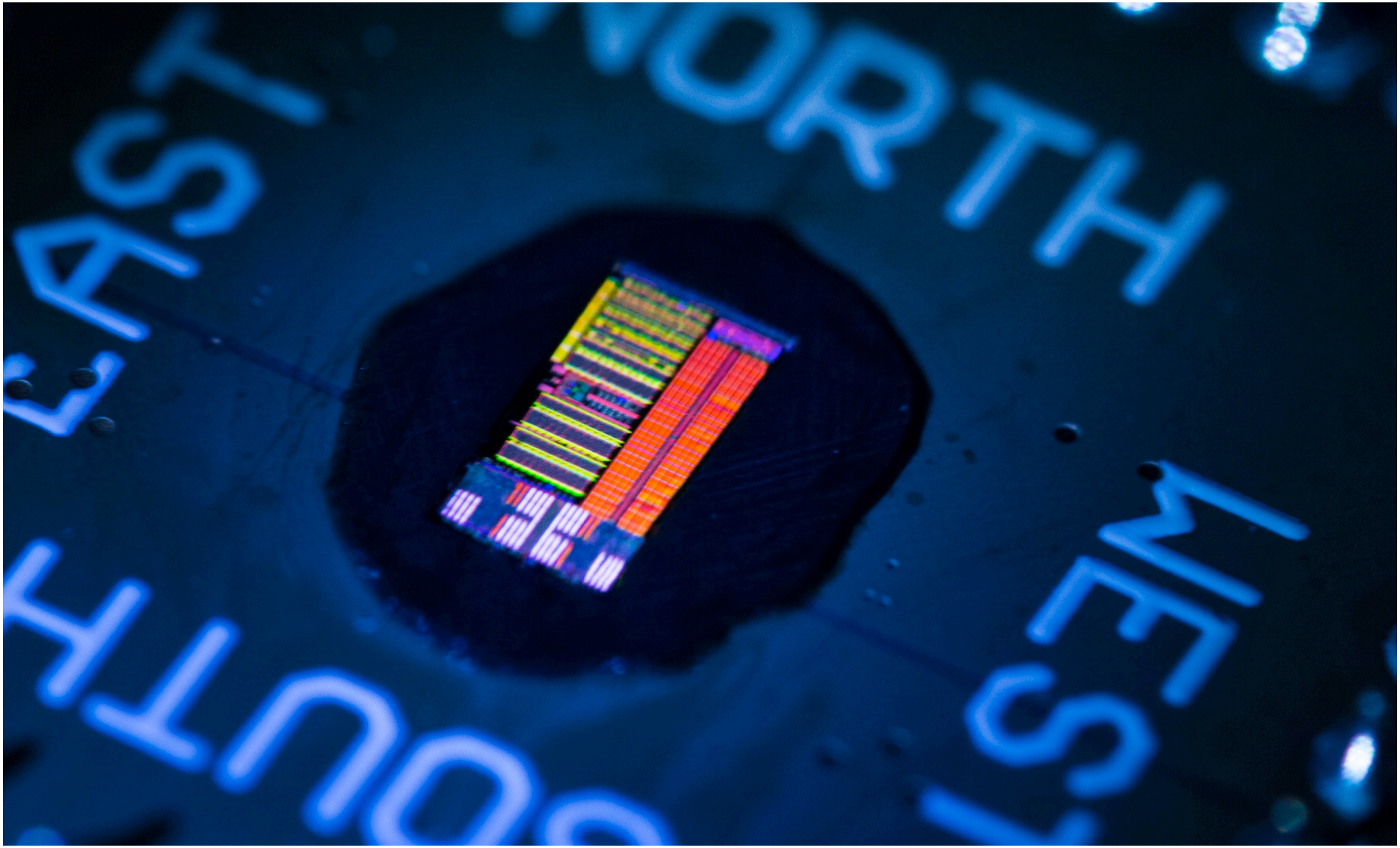
After reset, processor begins execution at address **`0x2000`**

Loading Programs



During execution, instructions and data are read from or written to memory

Demo Video



Conclusion

- We demonstrated the first microprocessor chip which communicates with light
- Design of photonics in CMOS, as opposed to changing CMOS to enable photonics, enabled a electronic-photonic platform in a CMOS foundry that produces processors
- Enabled microring-based transmitters and receivers for compact, energy-efficient, and high-density chip-to-chip communication

A look back…

Metric	[Beamer ISCA 2010] Conservative Estimates	In processor chip (Feb. 2014)	Current devices (March 2015)
Waveguide Loss	4 dB/cm	3.7dB/cm	3.7 dB/cm
Vertical Coupler Loss	1 dB	4-6dB	1 dB
Tx Data Rate	10 Gb/s	2.5 Gb/s	>14 Gb/s
Tx Energy Per Bit	120 fJ/b	30fJ/b	60 fJ/b
Rx Data Rate	10 Gb/s	10 Gb/s	12.5 Gb/s
Rx Energy Per Bit	80 fJ/b	330 fJ/b	330 fJ/b
Rx Sensitivity	10 µA	8.3uA	<8 µA
PD Responsivity	0.9 A/W	0.024 A/W	0.55 A/W
Thermal Tuning Efficiency	1.6 µW/GHz	3.8 µW/GHz	3.8 µW/GHz

- Meeting/exceeding most of specs we assumed in our arch proposal!

Thank You!

- POEM Teams at MIT, CU Boulder, and UC Berkeley, and Micron Technology
  - Device designers at CU Boulder, MIT
  - Circuit designers at UC Berkeley, MIT
  - RISC-V processor team
- DARPA, NSF, BWRC and ASPIRE Lab sponsors

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