POLITECNICO DI MILANO

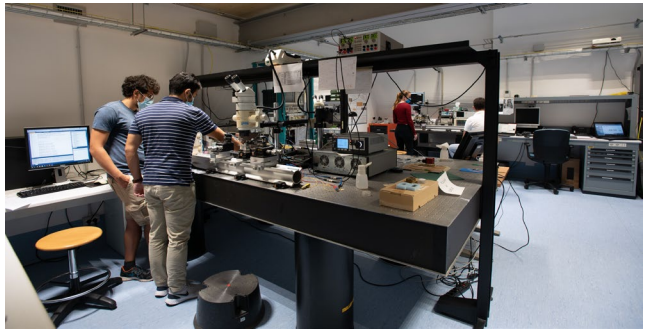
The need to peep light

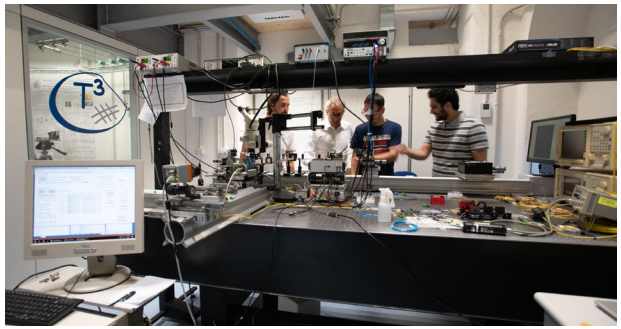
(Electronic (sensing) in Si-photonics)

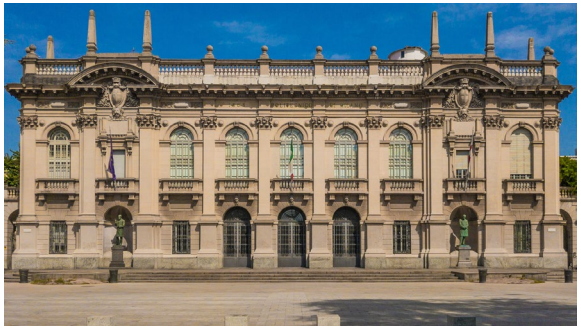
Andrea Melloni

F. Morichetti, S. Seyedinnavadeh, M. Milanizadeh, M. Petrini, C. De Vita, V. Grimaldi, F. Toso, G. Ferrari, F. Zanetto, M. Sampietro …

DEIB, Politecnico di Milano, Milano, Italy







Photonic Devices Lab

Andrea Melloni

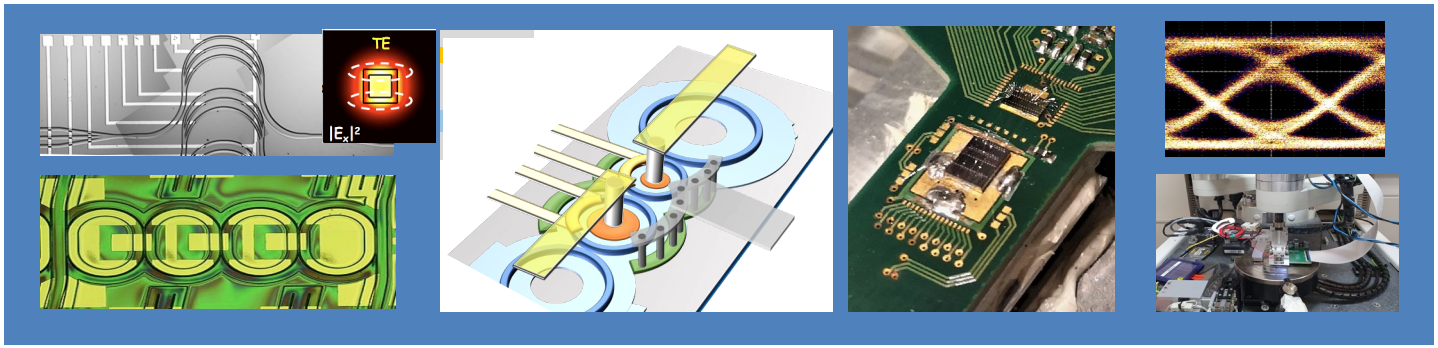
Francesco Morichetti

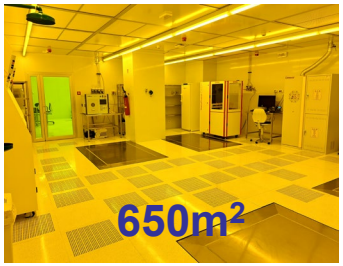
http://photonics.deib.polimi.it

POLITECNICO DI MILANO

polifab POLITECNICO DI MILANO

PoliMi micro- nano-technology center





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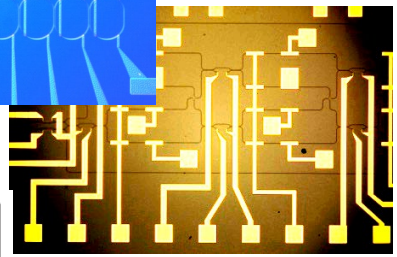
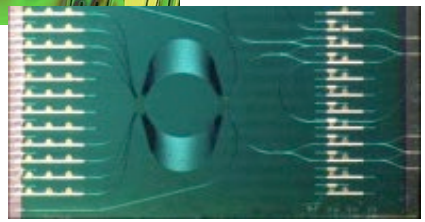
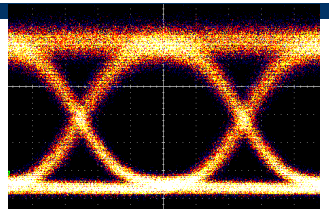
25 years of Multidisciplinary photonics@ PoliMi

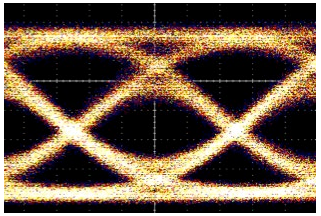
Silicon photonics



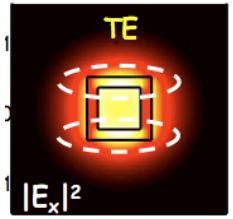
Indium phosphide

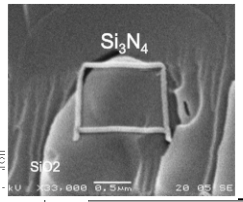


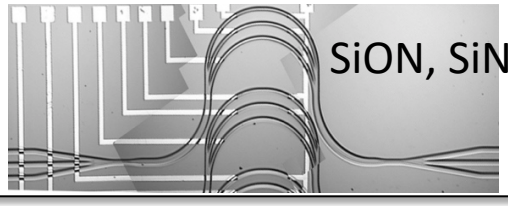




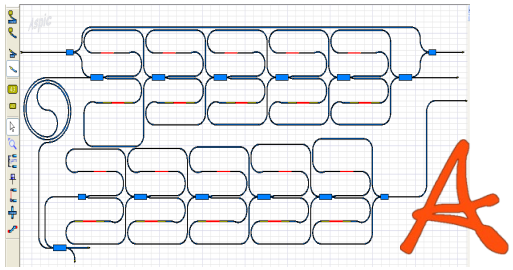
WDM up to 200 Gb/s

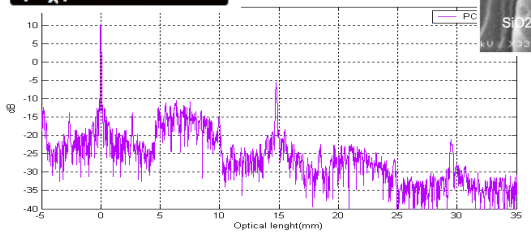






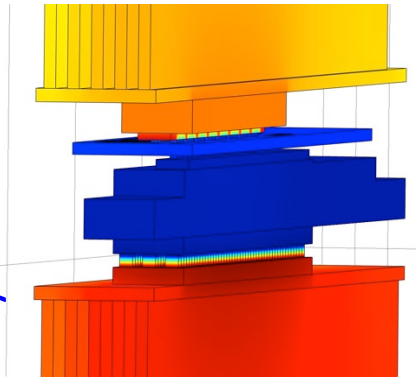
Commercial Circuit simulator

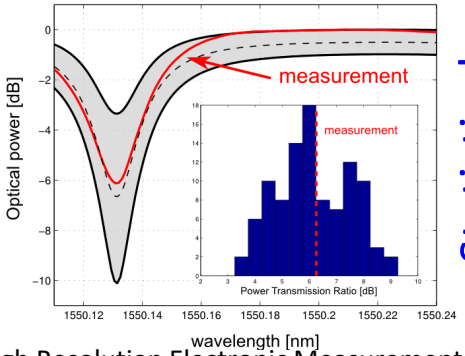




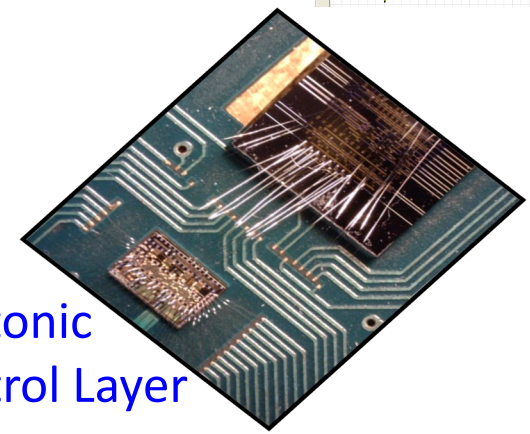
Characterization techniques

Thermal & Stress analysis





Statistical analysis



Photonic Control Layer

Biosensing

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The European Technology Platform Photonics21 represents the photonics community of industry and research organisations. Jointly with the European Commission our members develop and implement a common photonics strategy in a Horizon2020 **Public Private Partnership (PPP)** to spur growth and jobs in Europe.

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2020-2030

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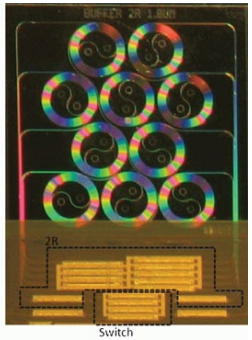
Photonics

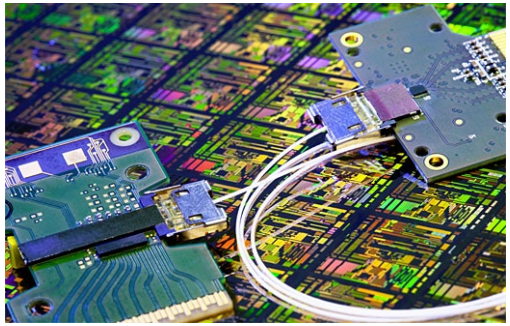
A Key Enabling Technology for Europe

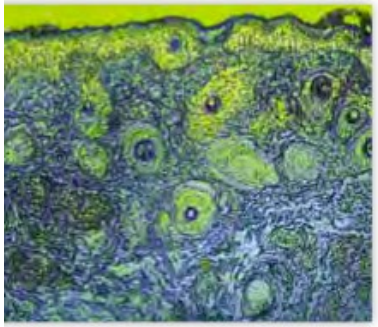
The European Technology Platform Photonics21 represents the photonics community of industry and research organisations. Jointly with the European Commission our members develop and implement a common photonics strategy in a Horizon2020 **Public Private Partnership (PPP)** to spur growth and jobs in Europe.

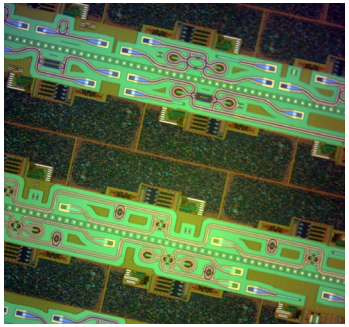
EPIC European Photonics Industry Consortium

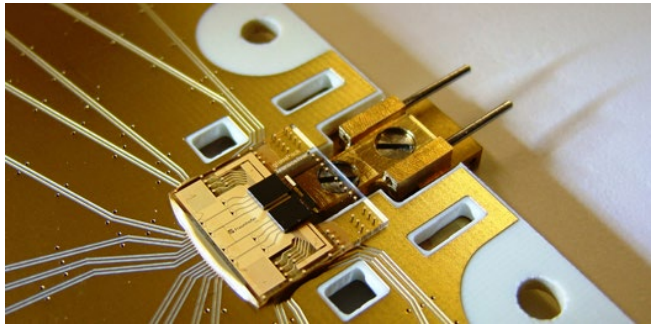
PHOTONICS21











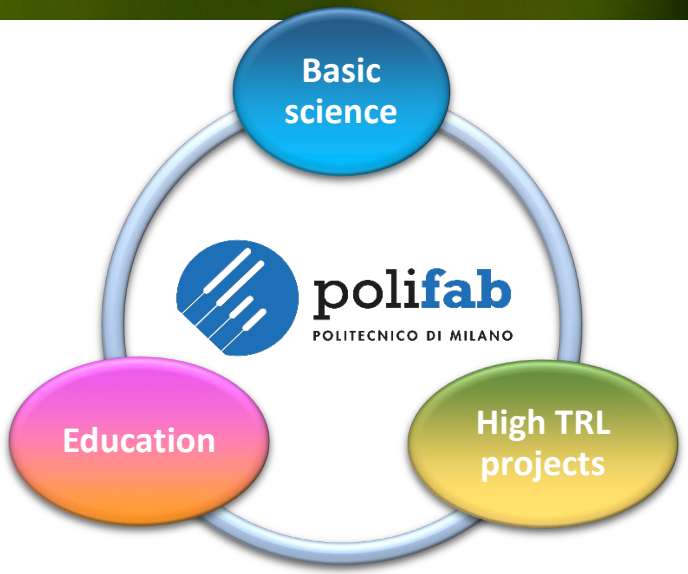
POLIFAB MISSION

Polifab is the **micro and nano technology center** of the Politecnico di Milano created to provide the highest technological standards for a wide range of applications and processes involving **all the Key Enabling Technologies**: photonics, micro and nanoelectronics, biotechnologies, advanced materials and nanotechnology

Polifab: **aggregating and enabling open infrastructure**

Polifab works with:

- Academic research groups
- External research institutions
- Startups
- Companies



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POLITECNICO DI MILANO

Lithography

- Photolithography
- Maskless photolitho
- Electron beam lithography
- Thermal scanning lithography

Deposition

- Electron beam evaporation
- Thermal evaporation
- Sputtering
- Chemical vapor deposition
- Electrodeposition

Etching

- Reactive ion etching
- Ion beam etching
- Plasma ashing
- Wet etching

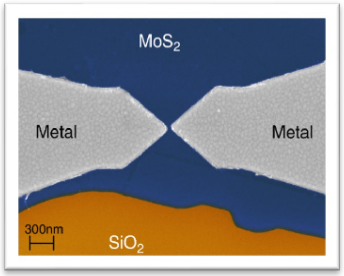
Characterization

- Optical microscopy
- Stylus profilometry
- Optical profilometry
- SEM, AFM
- Ellipsometry
- Electrical measurements
- X-ray diffraction
- EDX

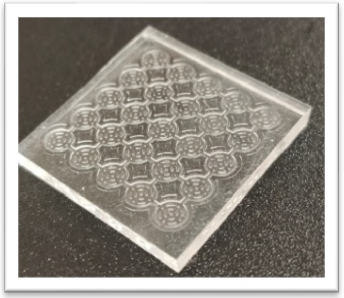
Backend

- Annealing ovens
- Rapid thermal annealing
- Wire bonding
- Dicing
- Pick & Place
- Alignements tools

FROM NANO TO MILLI



D. Ielmini, DEIB



E. Bianchi, DCMIC

Available in near future:

- Two-photon polymerization tool
- Sputtering for metals and oxides
- Electron beam lithography
- Micro-Raman spectroscopy
- .....

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Contents

- ✓ (very short) Overview on integrated photonics
- ✓ The photonic chip as system
  - ✓ Monitors
  - ✓ Actuators
  - ✓ Feedback and Control
- ✓ CLIPP: non-invasive integrated light monitor
- ✓ Applications: routing, tuning and bio sensing,…

1969: 54 years of integrated optics …

THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48 September 1969 Number 7

Integrated Optics: An Introduction

By STEWART E. MILLER

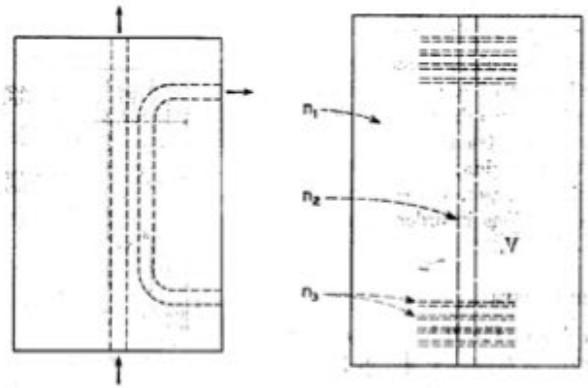


Fig. 6 — Directional coupler type hybrid. ; 3 — Resonator using planar waveguide.

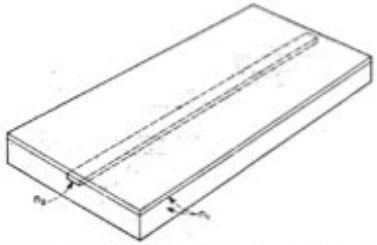


Fig. 2 — Planar waveguide formed using photolithographic techniques.

Bends in Optical Dielectric Guides

By E. A. J. MARCATILI

(Manuscript received March 3, 1969)

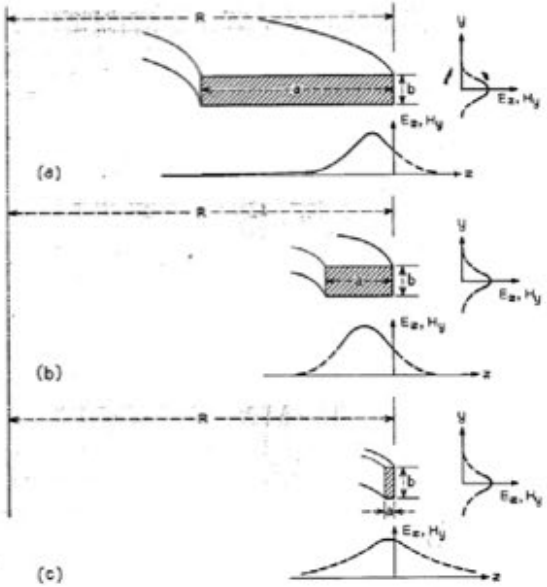


Fig. 6 — Field distribution as a function of guide width a with (a) $a/\Lambda \gg 1$, (b) $a/\Lambda \cong 1$, and (c) $a/\Lambda \ll 1$.

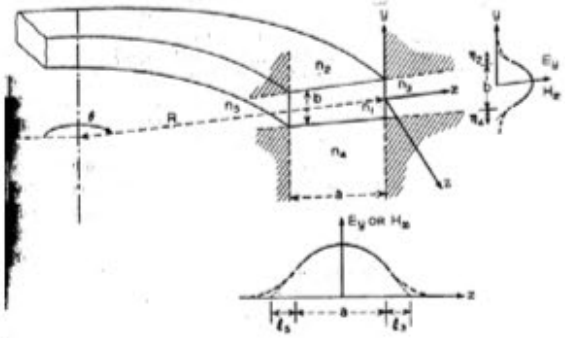


Fig. 2 — Curved dielectric guide.

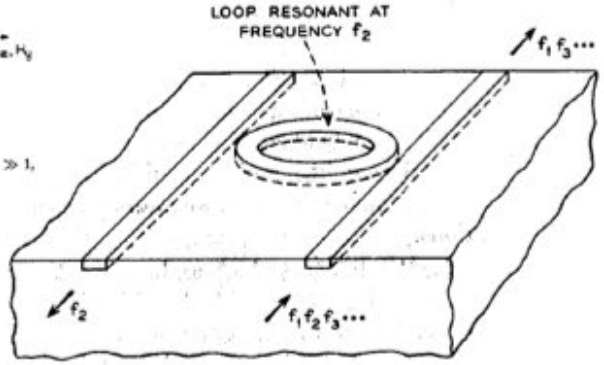
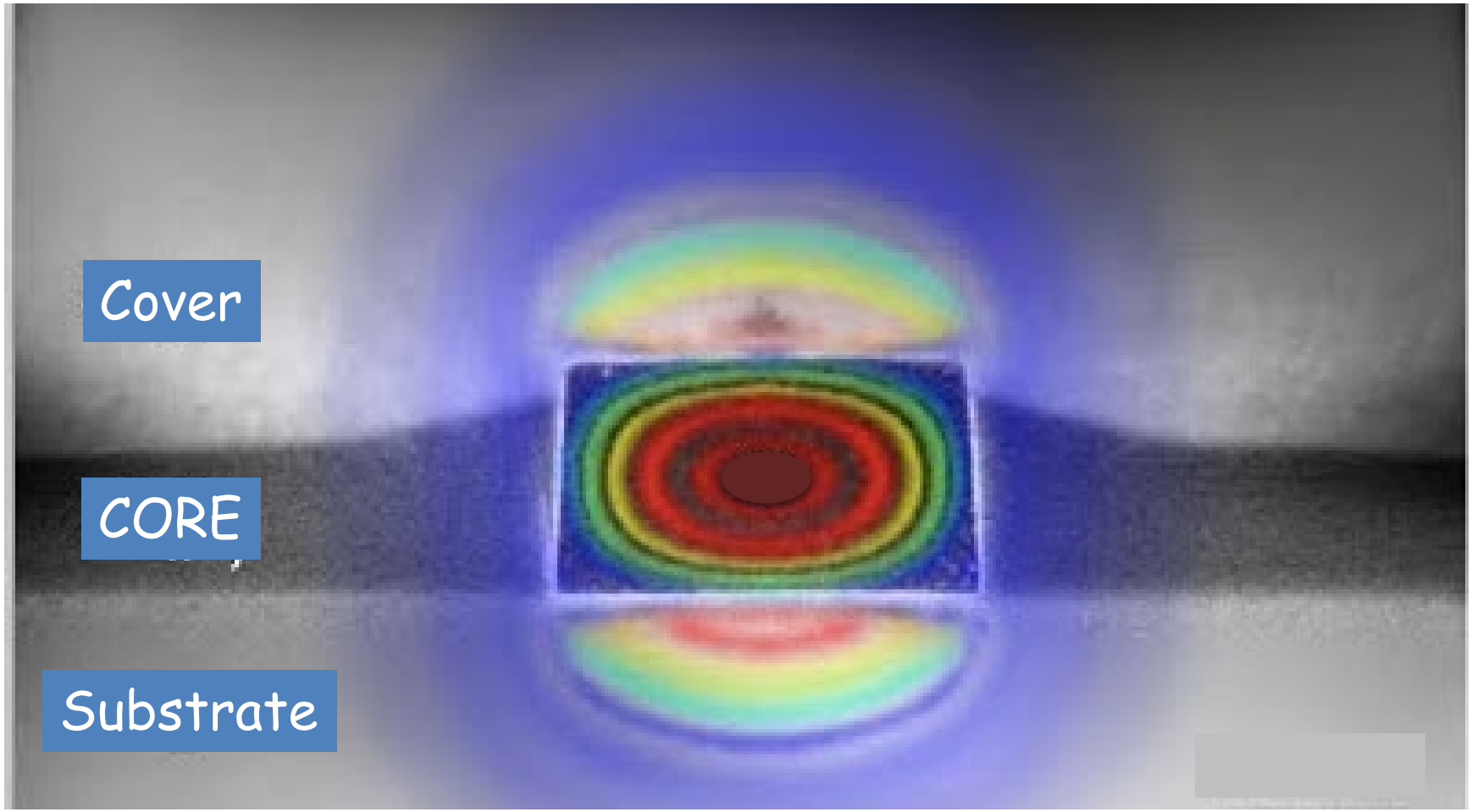
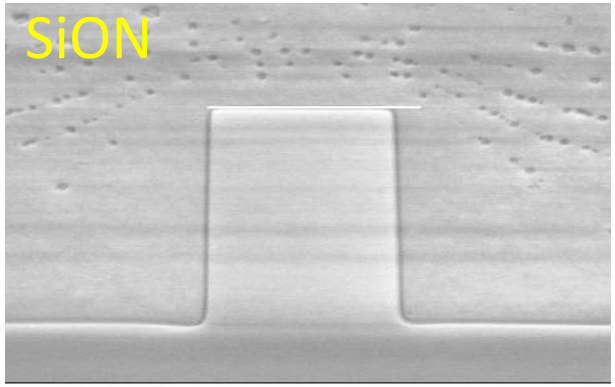


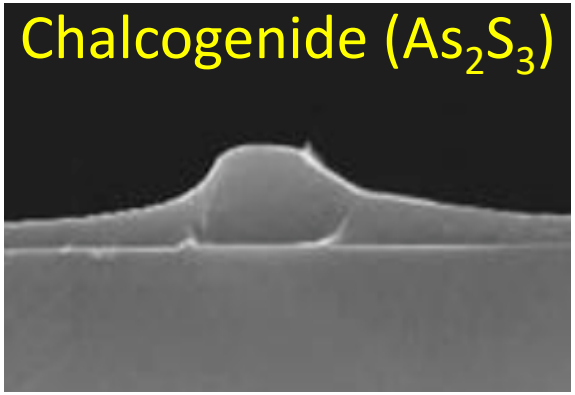
Fig. 1 — Channel dropping filter (ring type).

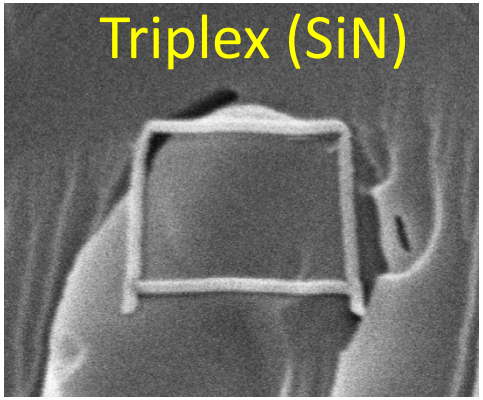
WAVEGUIDE

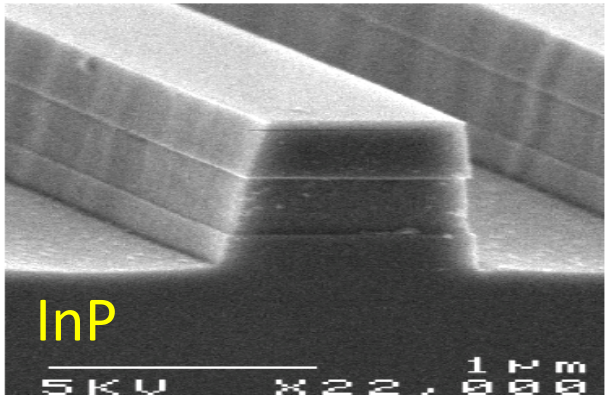


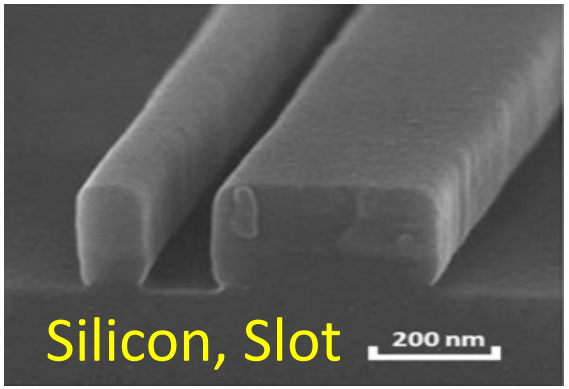
Waveguides...

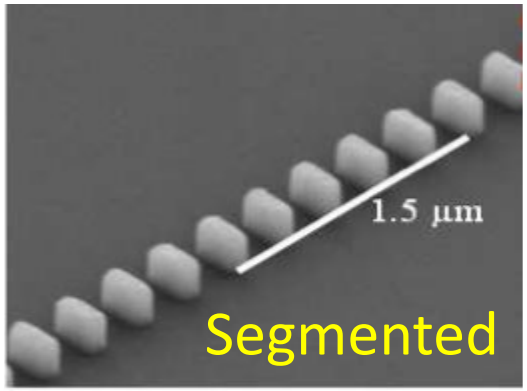

SiON

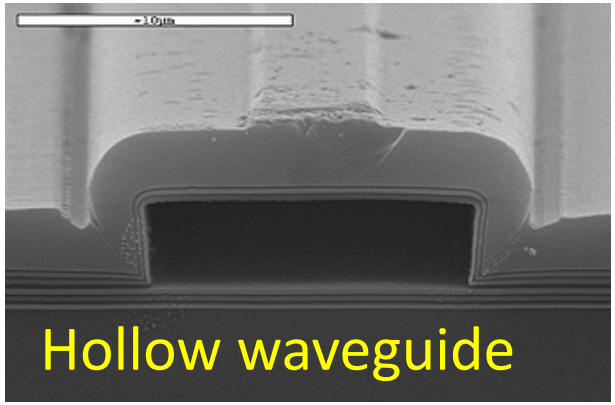

Chalcogenide (As_2S_3)

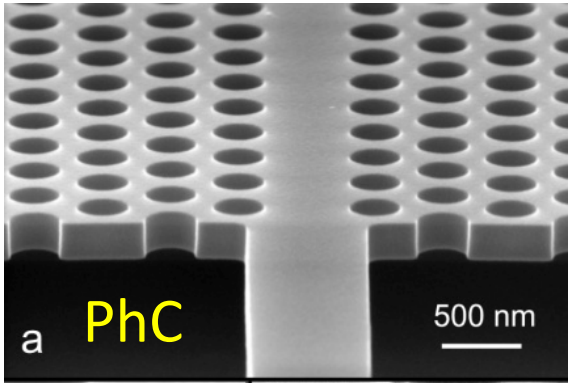

Triplex (SiN)

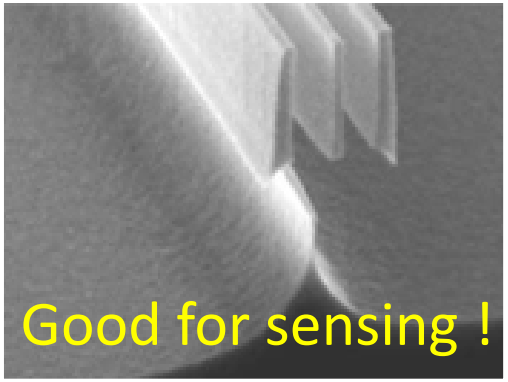

InP
1 µm
5KV X22,000


Silicon, Slot
200 nm

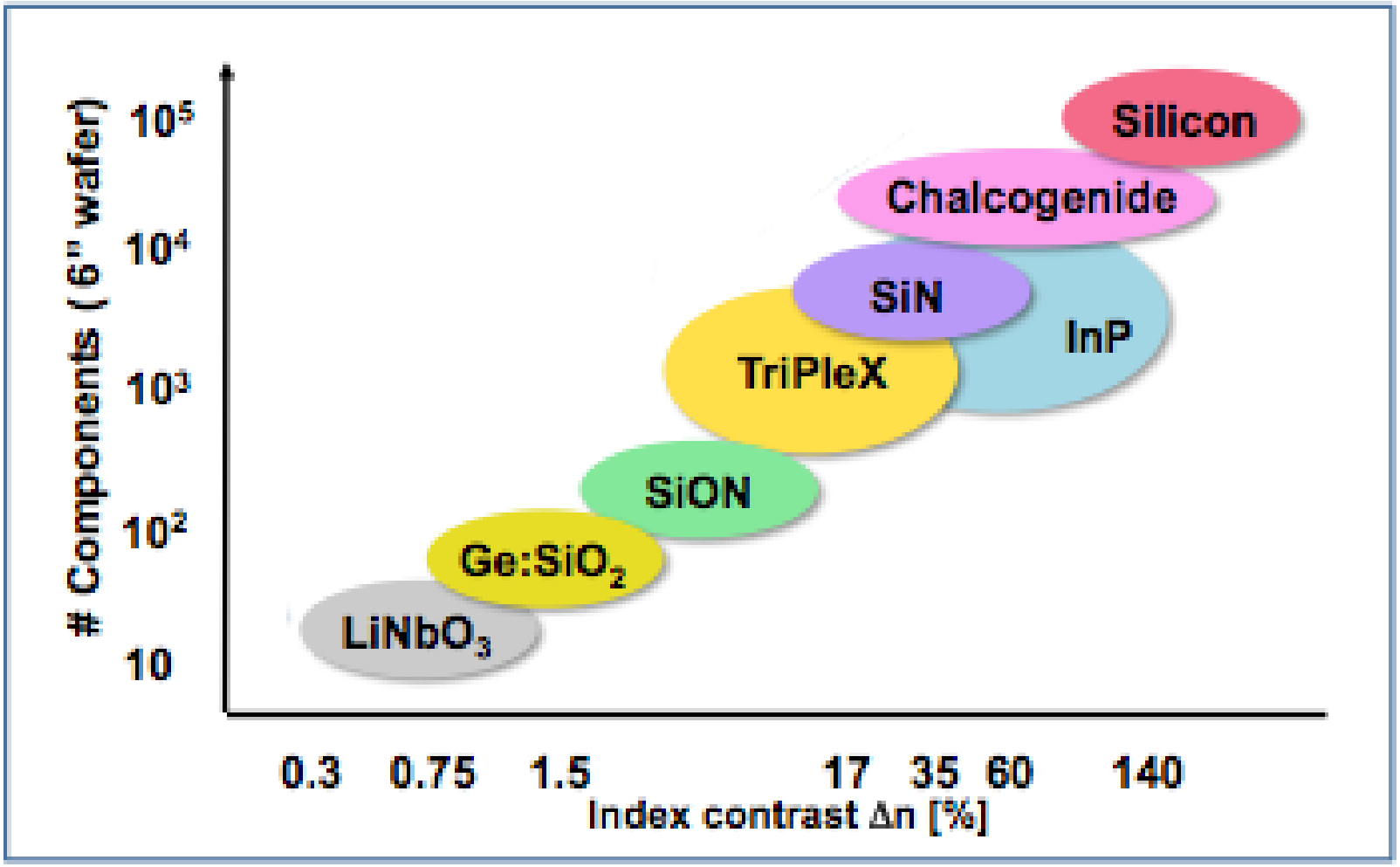

1.5 µm
Segmented


Hollow waveguide

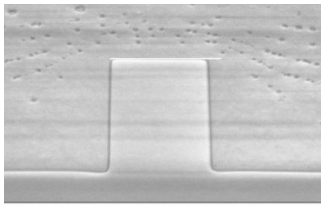
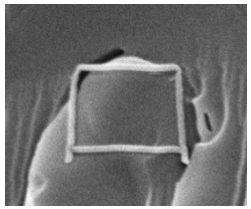
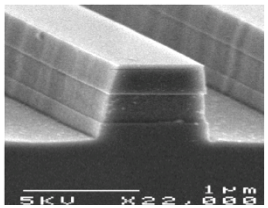
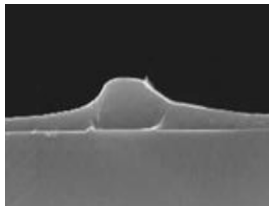
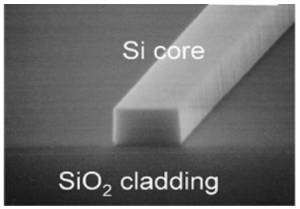

a
PhC
500 nm


Good for sensing ! !

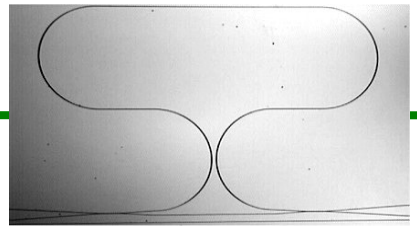
Materials for Photonic circuits



Technologies and Waveguides

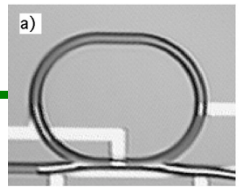






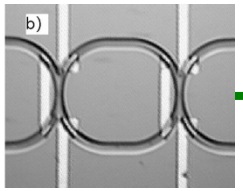
$Ge:SiO_2$	SiON	Si_3N_4	InP	As_2S_3	Silicon	Δn
0.5…3 %	2…8 %	38 %	3 / 70 %	60…100 %	140%	



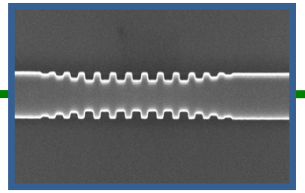
Mach-Zehnder

Dir. Couplers, Y, MMI, Star couplers



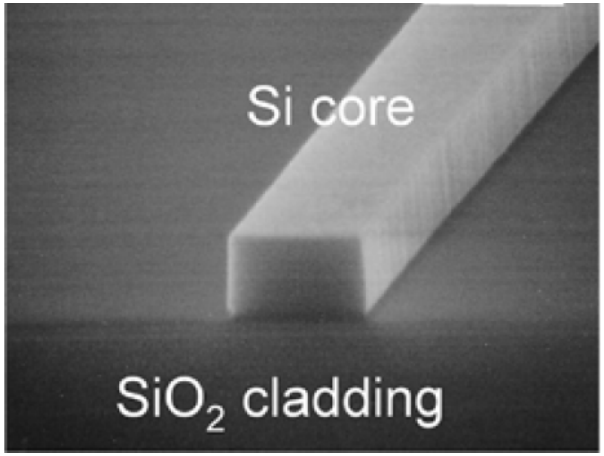


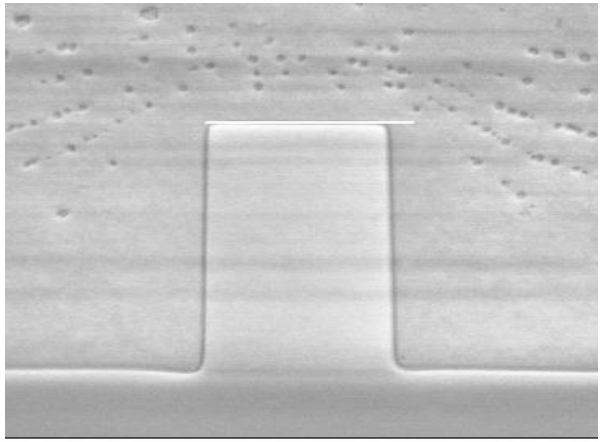
Ring Resonators

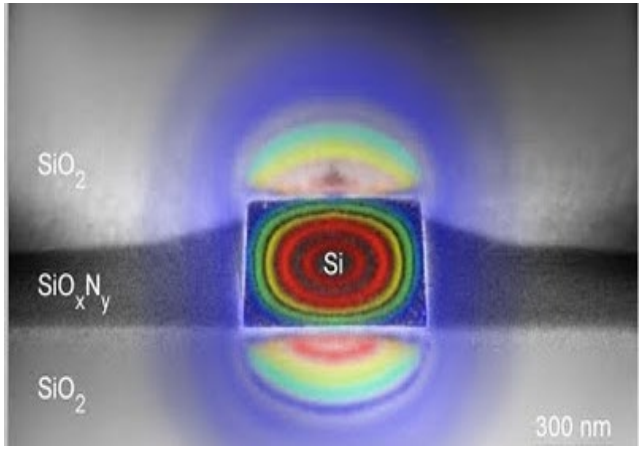


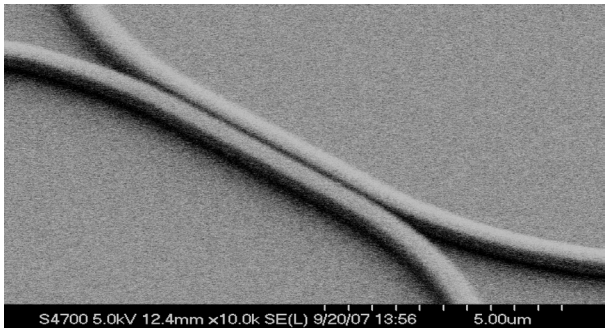
Gratings

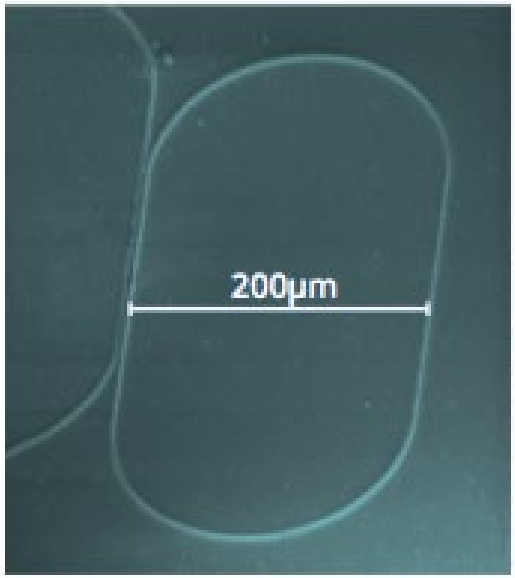
Integrated Photonics

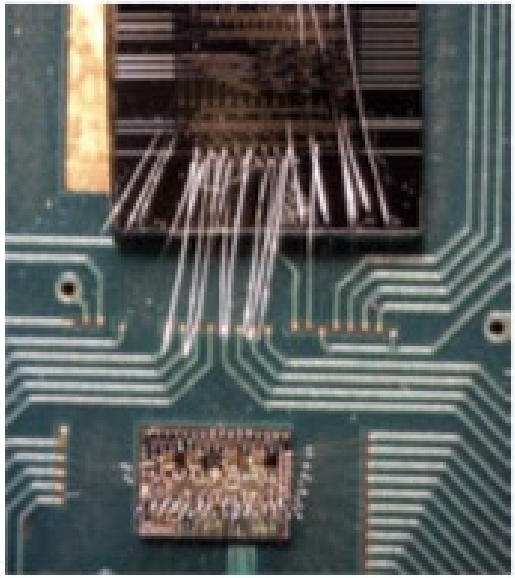




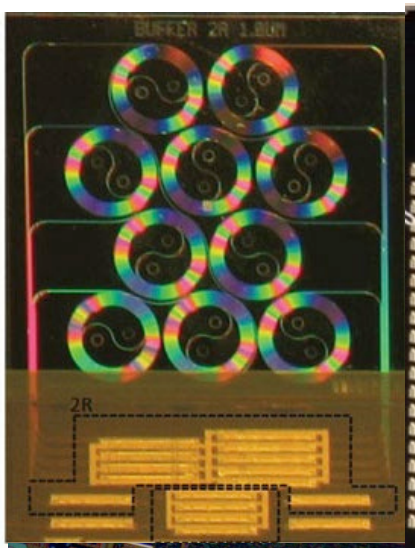


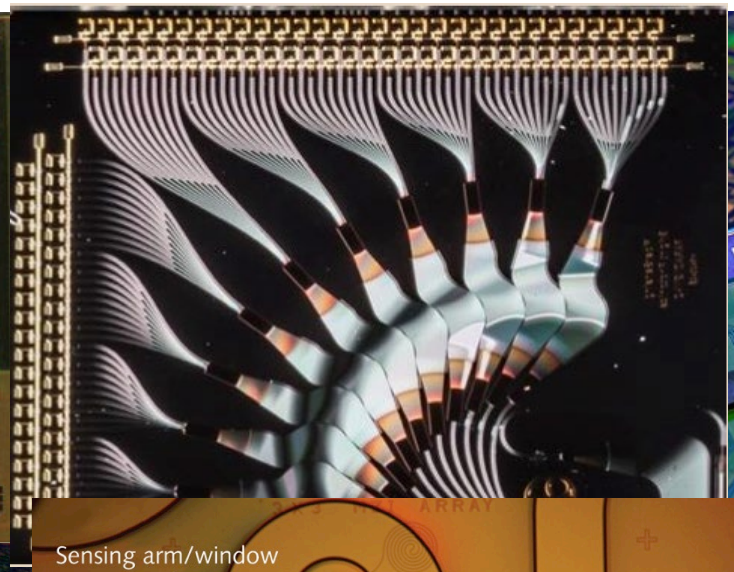


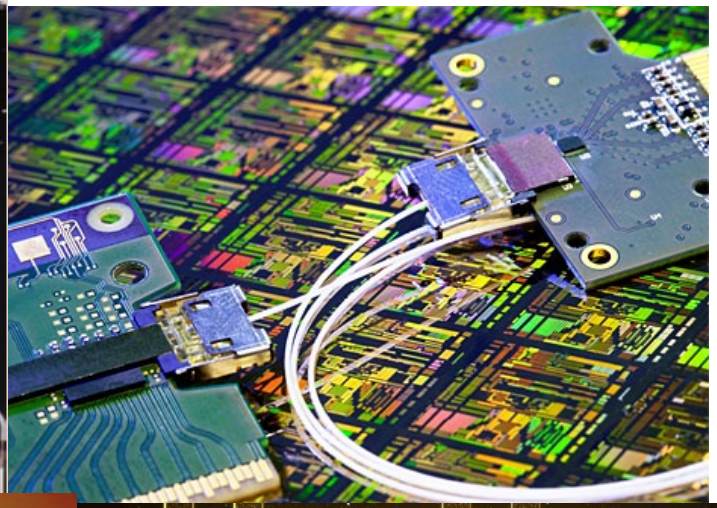


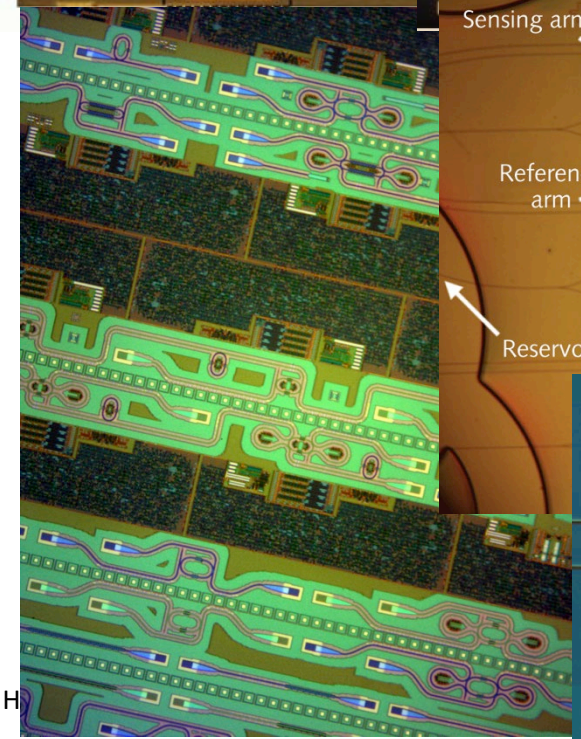


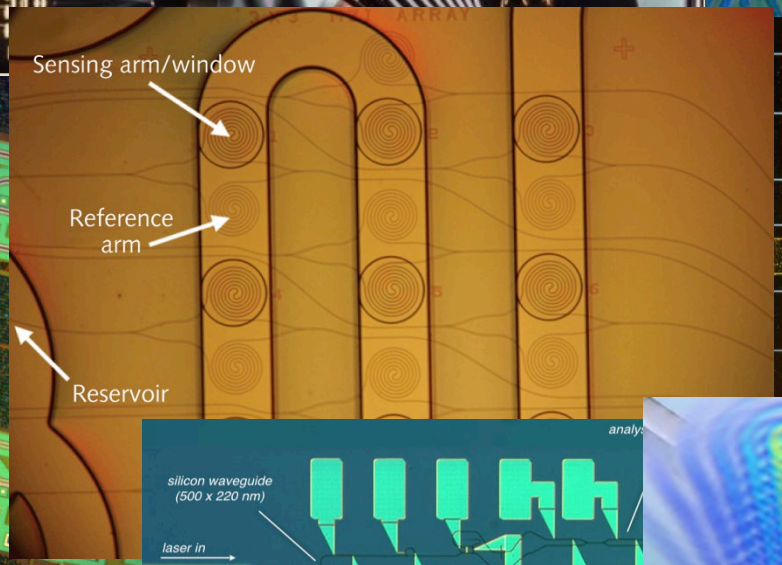
Integrated photonics: towards ubiquitousness

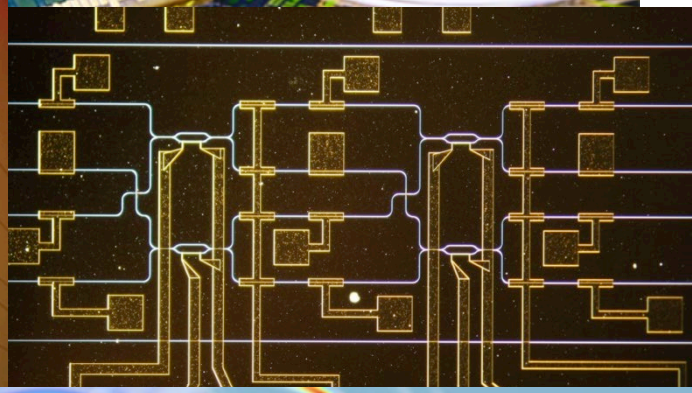


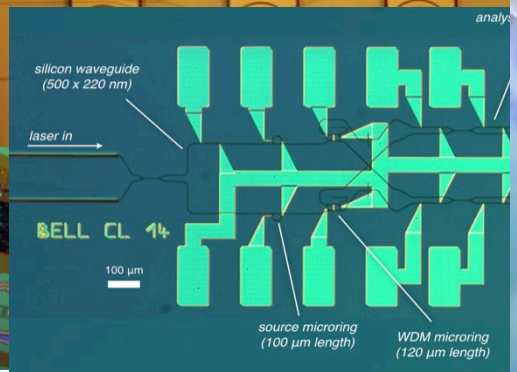


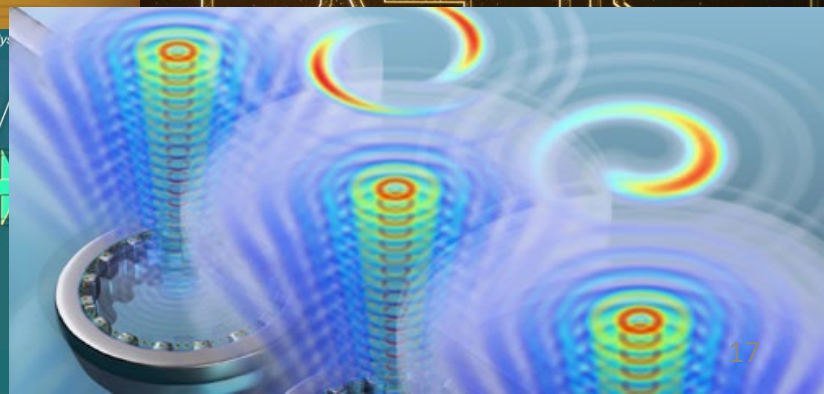




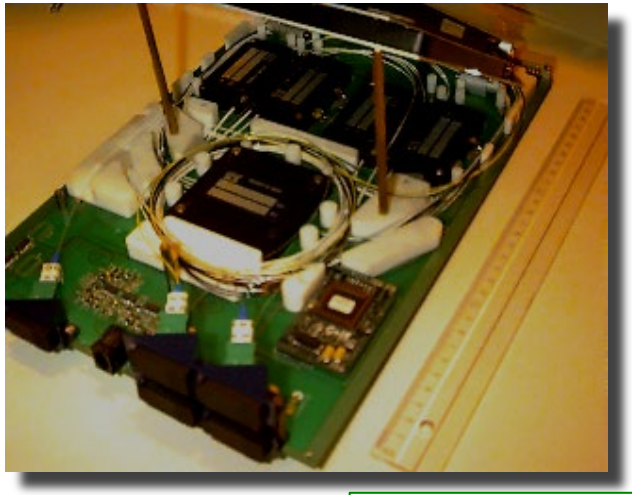




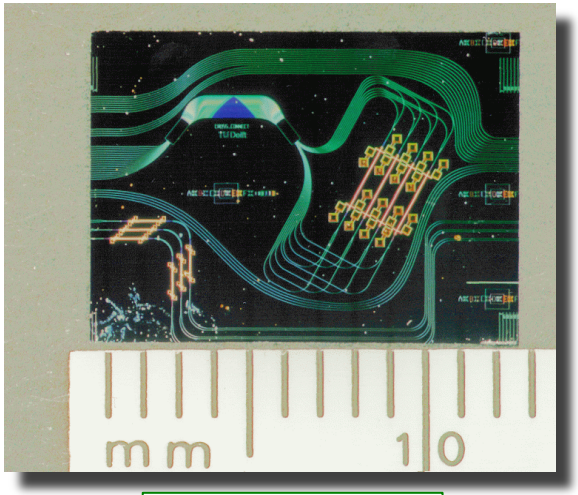




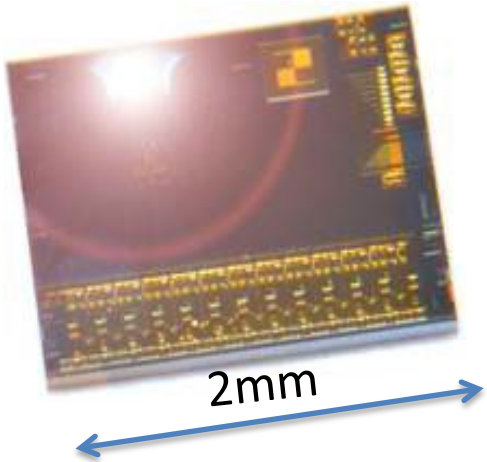
The need of Integrated Photonics



1994
4-λ 2x2 OXC

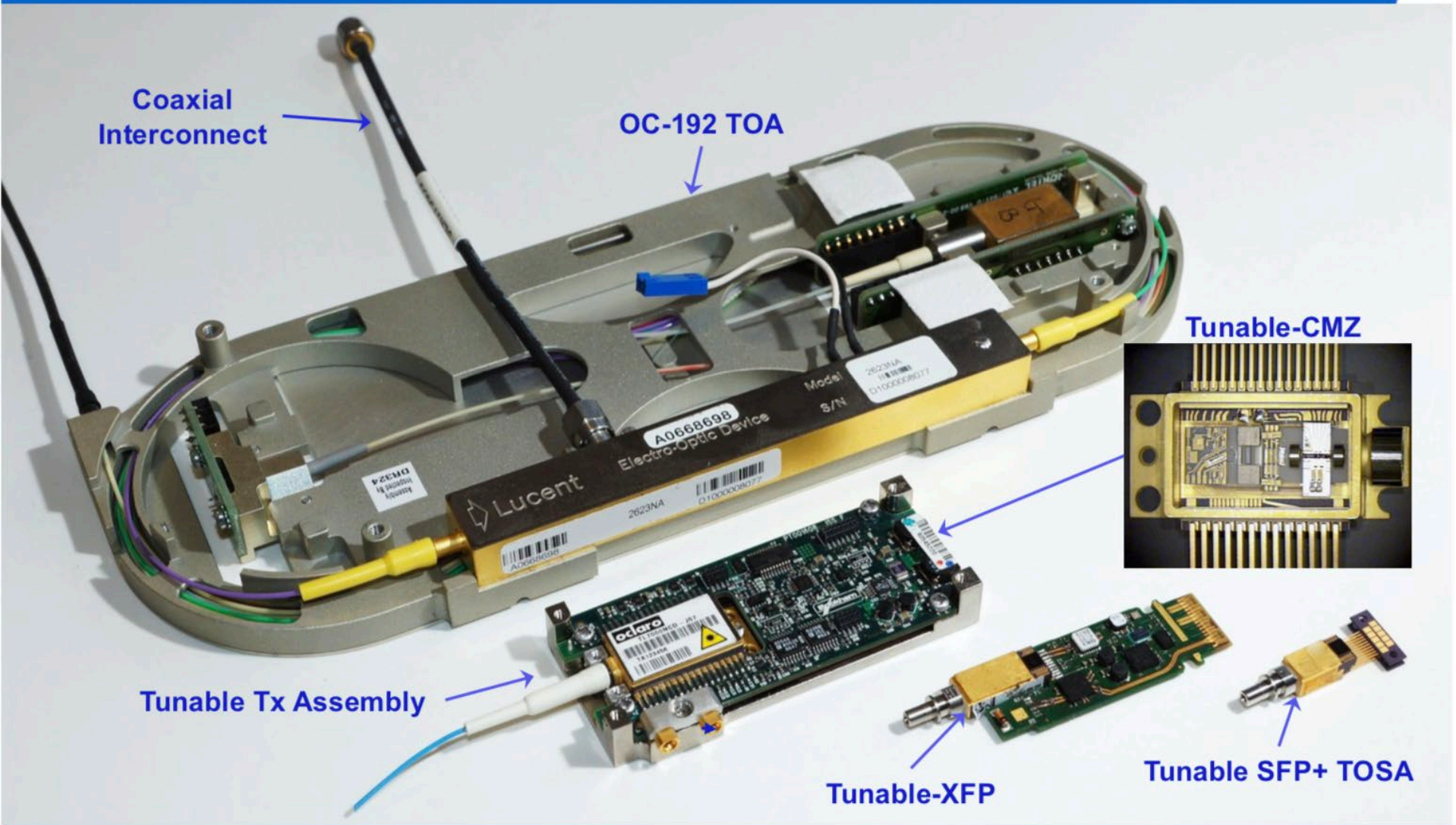


1998
4-λ 2x2 OXC



2018 Transceiver
2.4Tb/s, 12000km

Integration

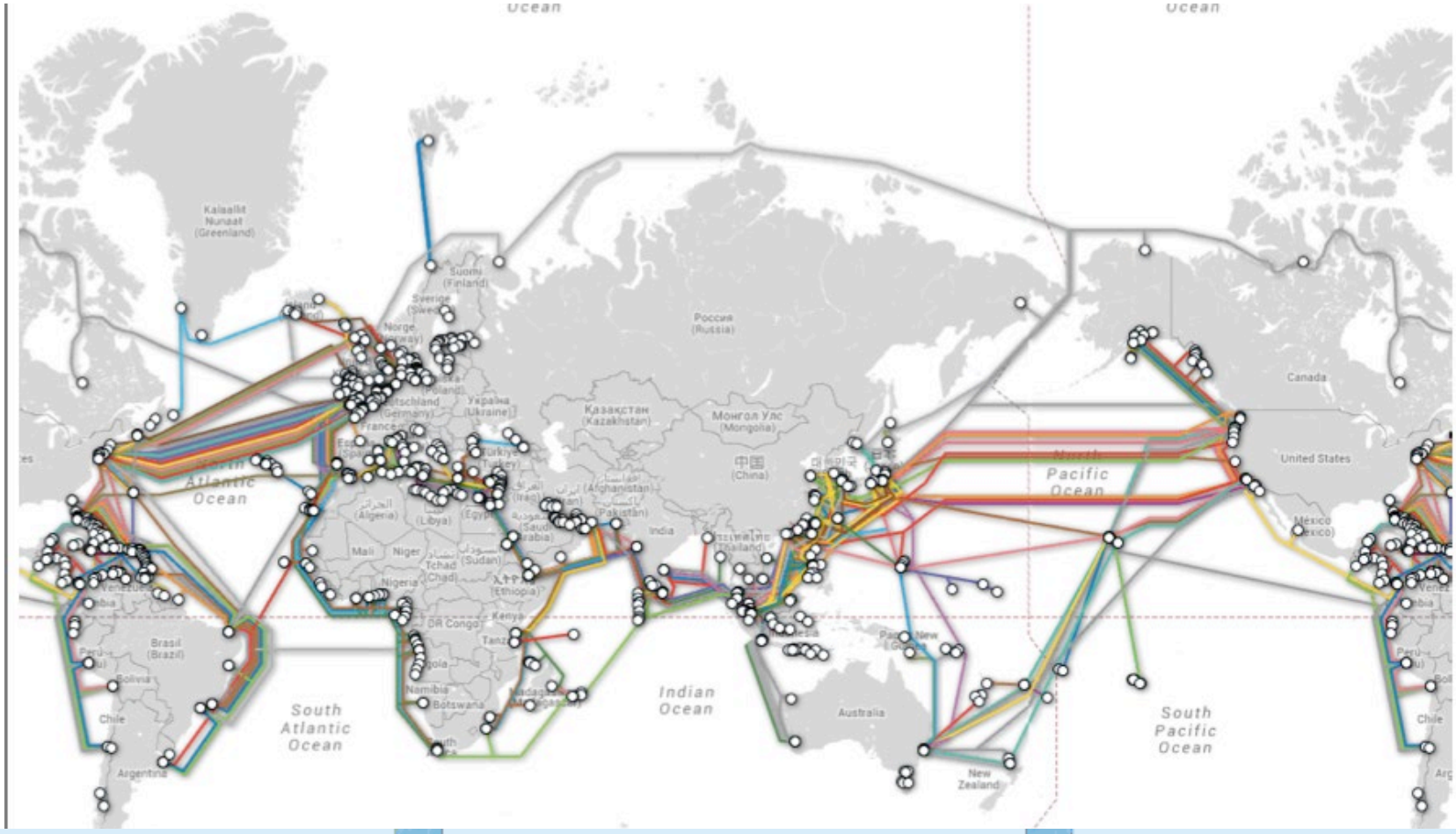


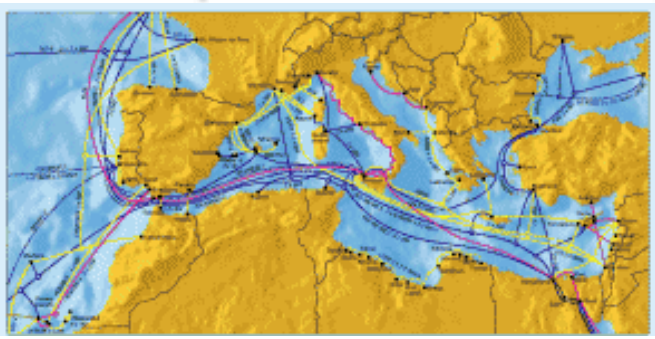
T-SFP+ TOSA has full TOA functionality plus wavelength tunability & control

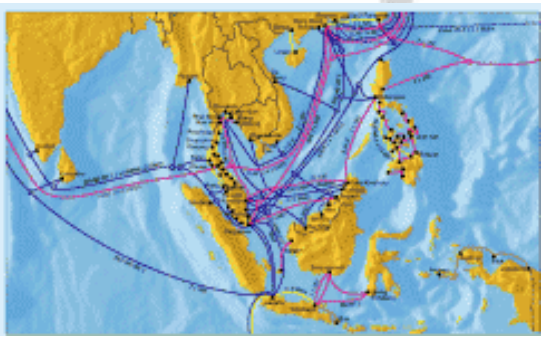
Photonic Integration: Motivation

- Greatly reduced component cost
  - Monolithic interconnection of device elements
  - Simpler packaging and assembly, standard processes
- High reliability
  - Less interfaces
- High functionality
  - Many more functional elements per chip, higher creativity in design
- High phase stability, excellent device matching
  - Permits interferometric structures
- Robust
  - Single chip designs with minimal optical interfaces are ideal for demanding environments
- Higher power efficiency
  - Minimize optical power loss at interfaces between device elements

Submarine cables, optical fibers



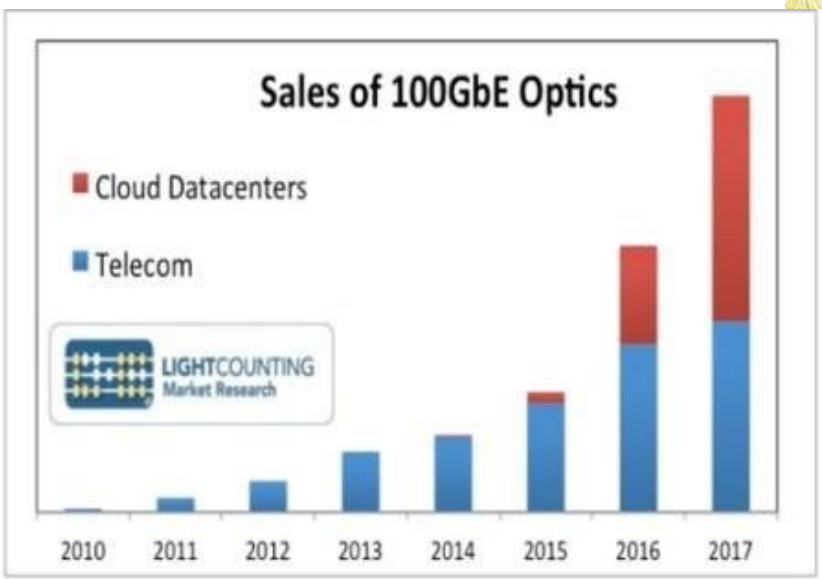


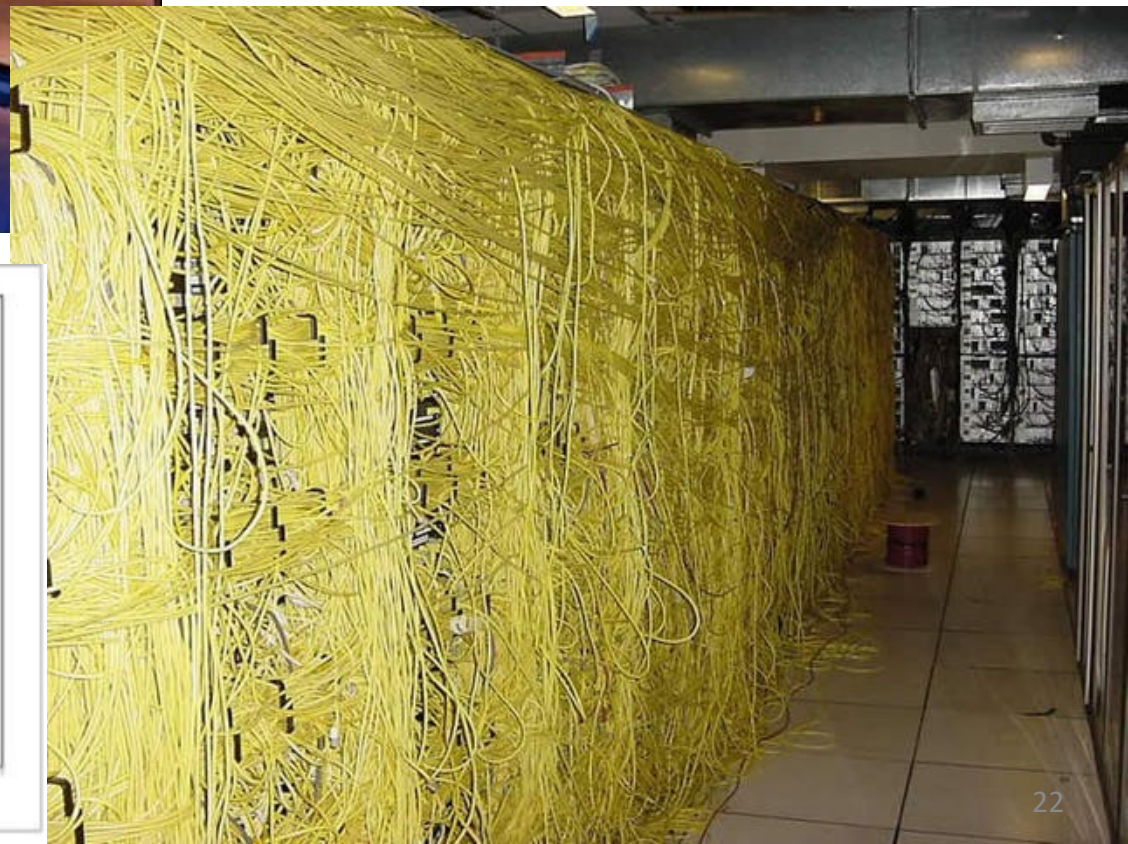


Optical Interconnects = Datacenters

Cisco reports total bit rate for internet traffic > 320 Tb/s

Datacenters....





HPC wire

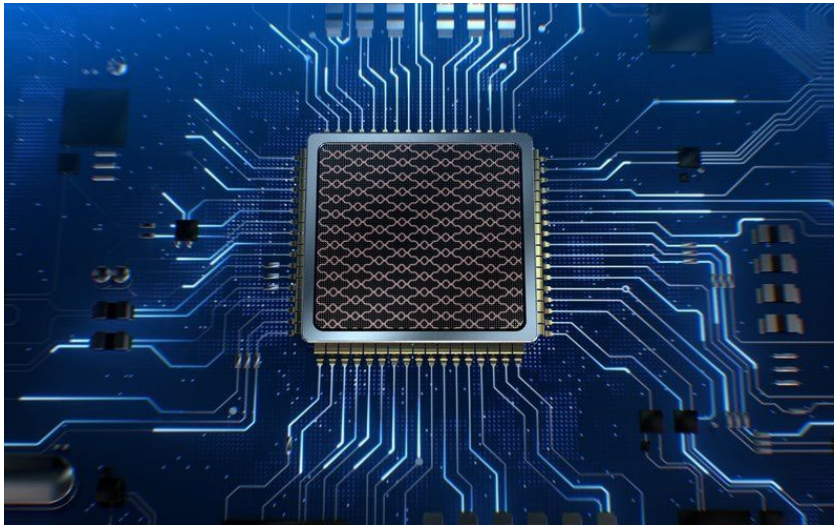
Since 1987 - Covering the Fastest Computers in the World and the People Who Run Them

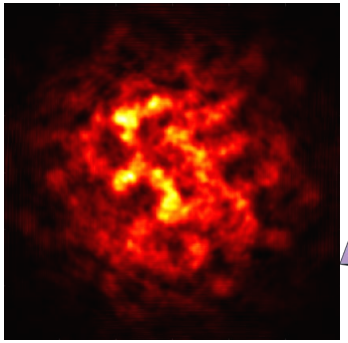
- Home
- Technologies
- Sectors

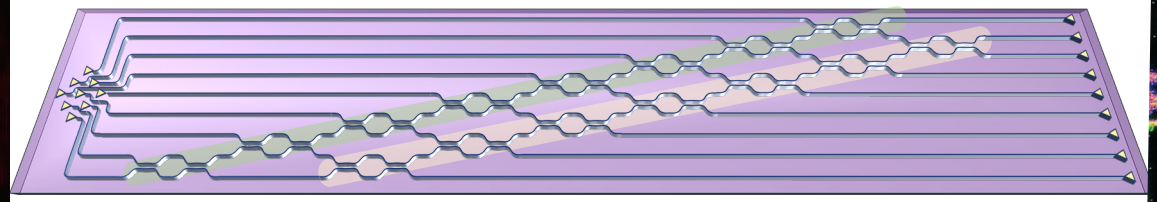
Researchers Develop Novel Analog Processor for High Performance Computing

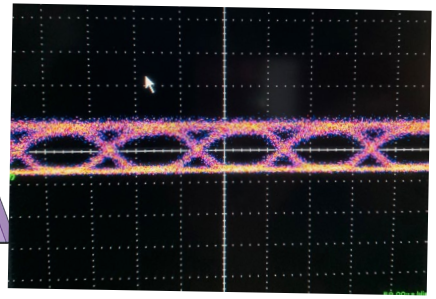
August 30, 2021

Aug. 30, 2021 — Analog photonic solutions offer unique opportunities to address complex computational tasks with unprecedented performance in terms of energy dissipation and speeds, overcoming current limitations of modern computing architectures based on electron flows and digital approaches.







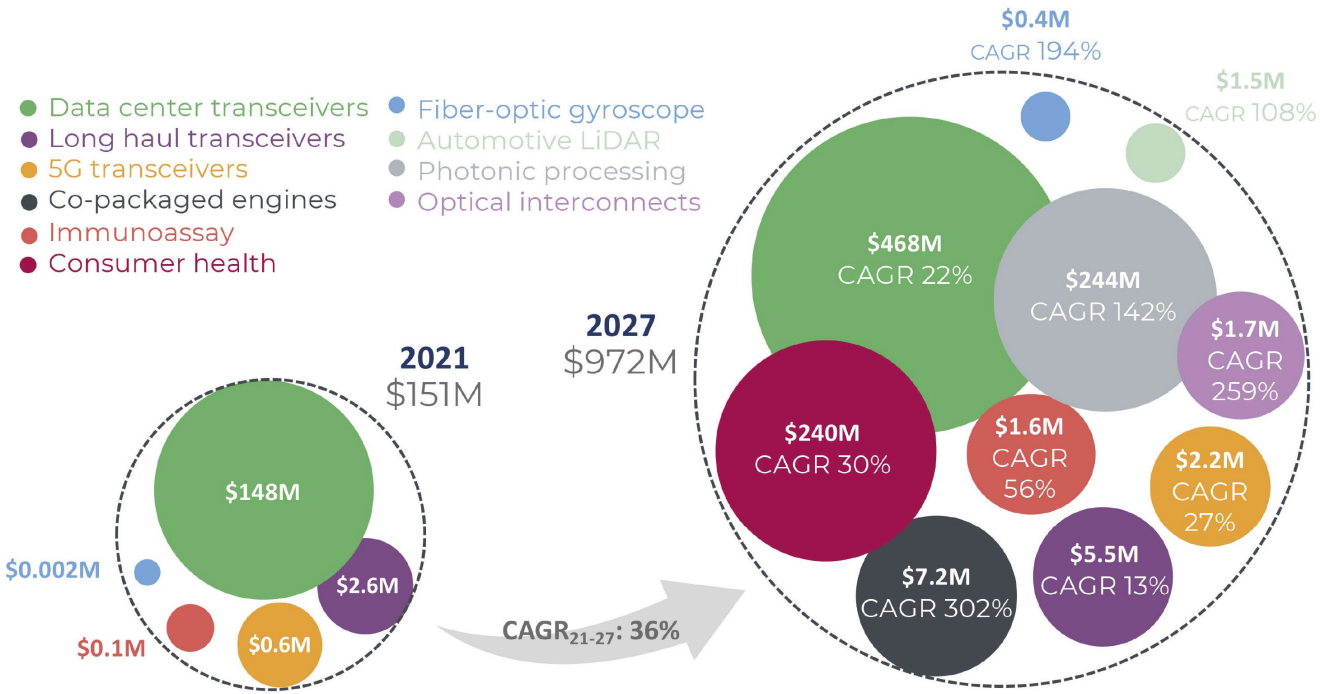


S.Pai, … A.Melloni, Science 380, 398–404, 2023
W. Bogaerts, … A. Melloni, Nature 586, 207–216, 2020

Silicon Photonics: roadmap and markets

2021-2027 SILICON PHOTONIC DIE FORECAST BY APPLICATION

Source: Silicon Photonics 2022 Report, Yole Intelligence, 2022



YOLE Intelligence

www.y

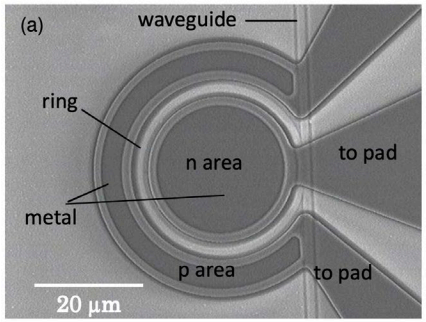
Datacom is main market

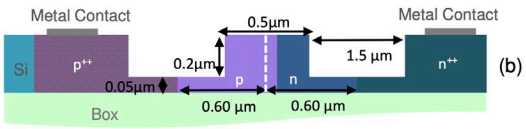
(20% transceiver → 30% by 2027)

Emerging markets:

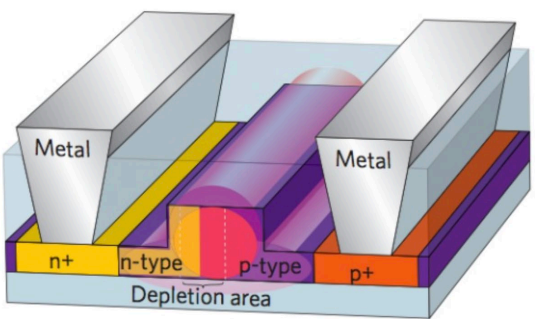
- medical & biosensing
- disaggregated data centers
- high-performance computing (HPC)
- analog artificial intelligence (AI)
- automotive (LiDAR and gyroscopes)
- Co-Packaged Optics engines
- …

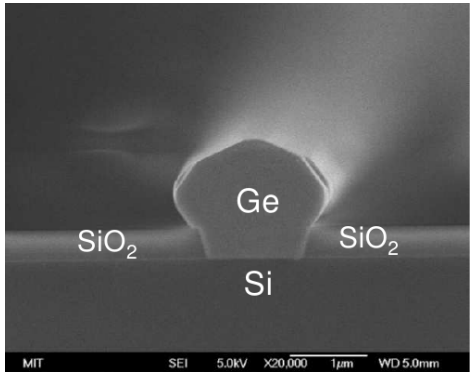
How Much Electronics in Photonics?



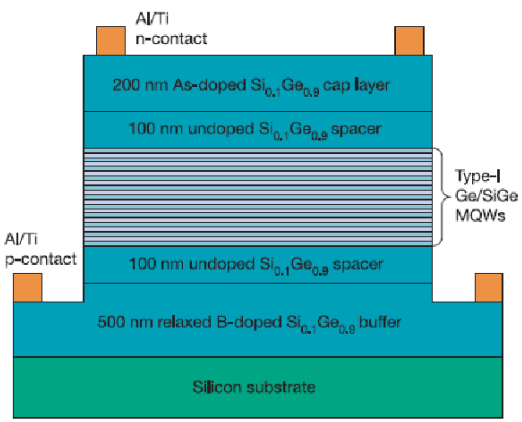


Modulator/Switch

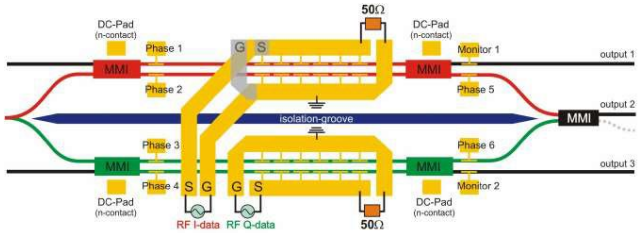




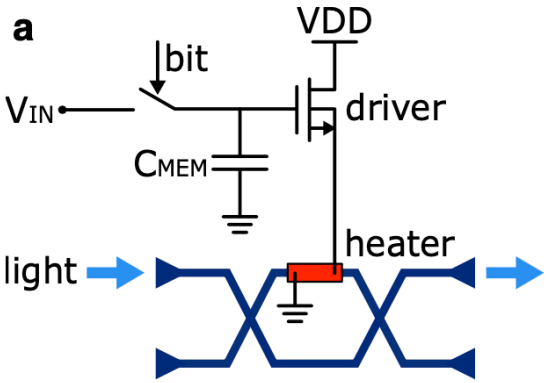
Photodetector



Laser



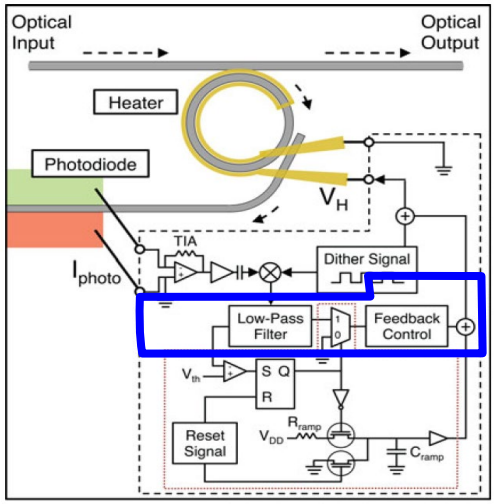
Drivers (microwave)



Control Layer

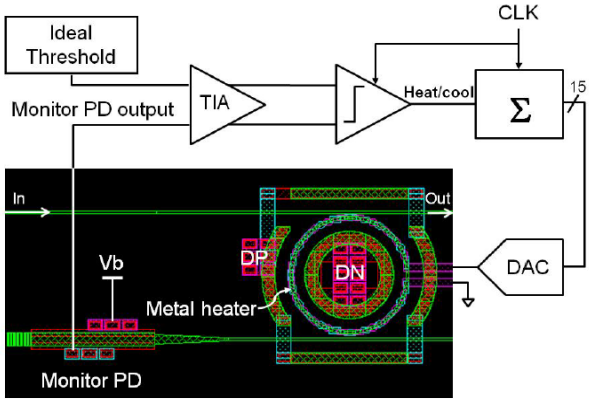
How Much Electronics in Photonics?

Dithering, analog
Columbia Univ. 2014



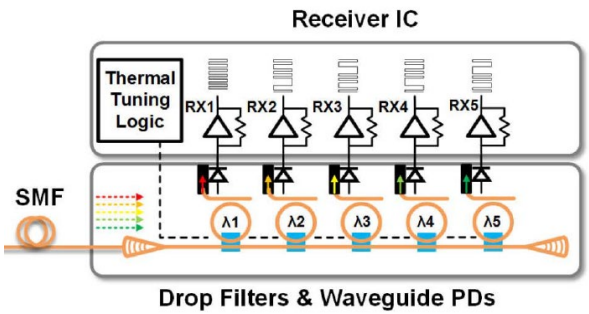
K. Padmaraju, et al, JLT 32(3), 2014

Bang-bang, digital 15 bits
Oracle 2014



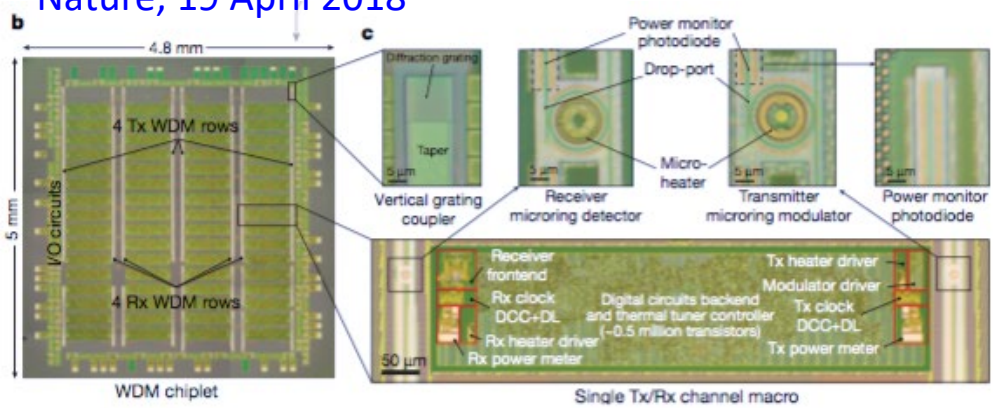
X. Zheng, Opt. Express, 22(10) 2014

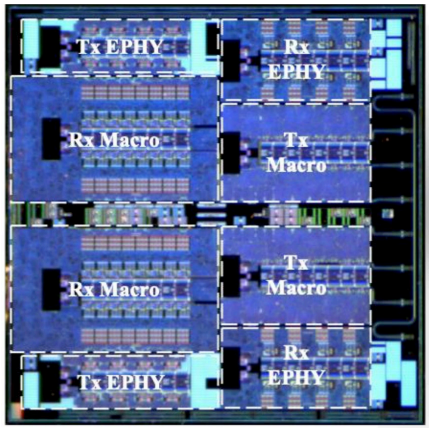
Tuning (peak search, analog) + locking (bang-bang, digital) HP 2016



K. Yu, et al., JSSC, 51(09) 2016

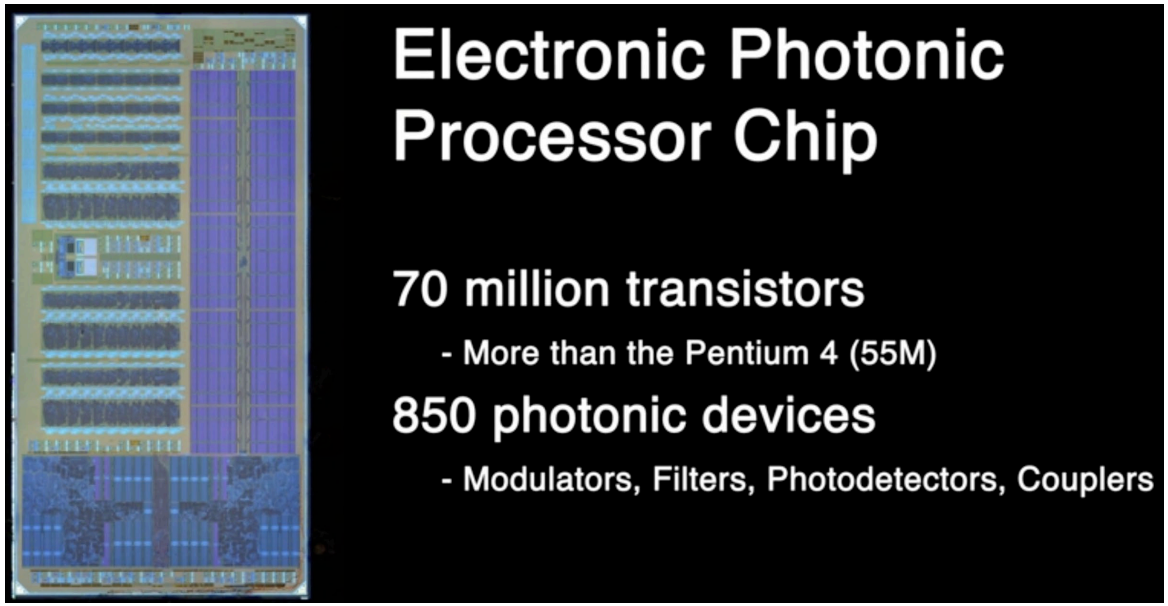
Integrating photonics with silicon nanoelectronics
Nature, 19 April 2018



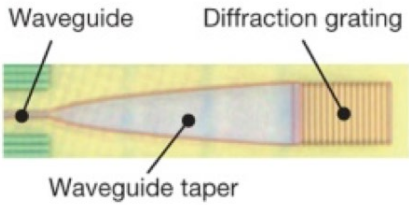


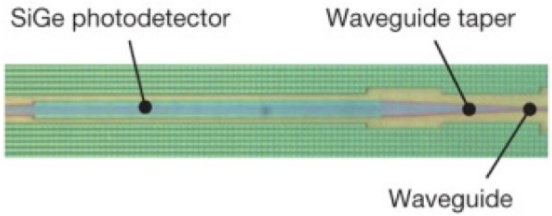
TeraPHY: A High-density Electronic-Photonic Chiplet, OFC 2019 - *Ayar Labs, Inc.*

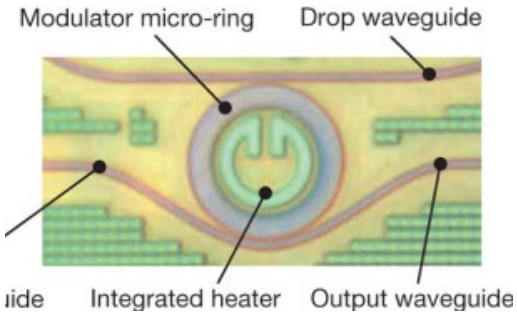
How Much Photonics in Electronics?



Sun, C. *et al.* Single-chip microprocessor that communicates directly using light. *Nature* **528,** 534–538 (2015). https://doi.org/10.1038/nature16454



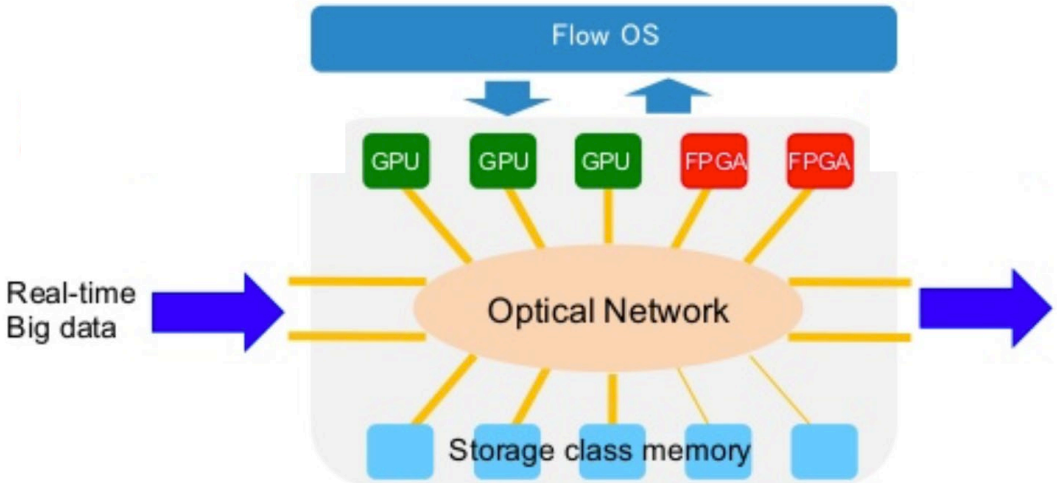




Tx / Rx wavelength de-multiplexer

How Much Photonics in Electronics?

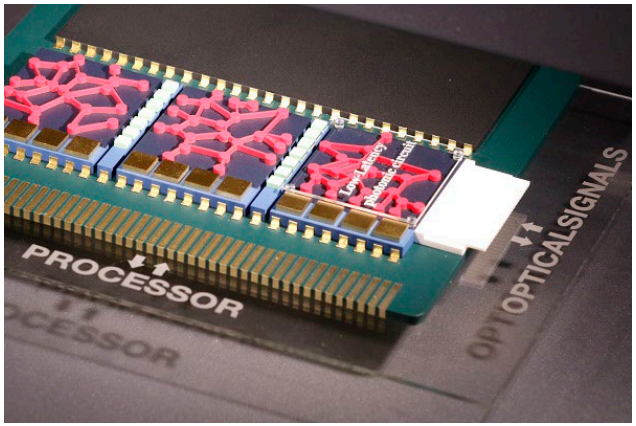
https://www.slideshare.net/oraccha/flowcentric-computing-a-datacenter-architecture-in-the-post-moore-era



NTT DATA
Trusted Global Innovator

14, January 2020

What comes after electronics?



https://ro.nttdata.com/News/The-future-of-photonics-presented-at-the-recent-NTT-Research-and-Development-Forum

Energy per bit

Operation	Energy per bit
Wireless data	10 – 30μJ
Internet: access	40 – 80nJ
Internet: routing	20nJ
Internet: optical WDM links	3nJ
Reading DRAM	5pJ
Communicating off chip	1 – 20 pJ
Data link multiplexing and timing circuits	~ 2 pJ
Communicating across chip	600 fJ
Floating point operation	100fJ
Energy in DRAM cell	10fJ
Switching CMOS gate	~50aJ – 3fJ

10^{-6} J

10^{-9} J

10^{-12} J

10^{-15} J

Transmit a signal (bit) across a chip requires charging/discharging the capacity of the electrical link

$C \approx 1$ pF/cm

Average length of the link
1 mm – 1 cm

$C \approx 0.1 - 1$ pF

Energy per bit (1 V)

$E \approx CV^2$
= 0.1 - 1 pJ

→ Energy required to transmit data across electronic chips has not scaled down much in the last years

→ Energy consumption of (super)computers is mainly due to short-distance signal transmission inside electrical chips

David A. B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications», J. of Lightwave Technology 35(3), Feb. 2017

Energy consumption of hyperscale computing

Supercomputers can achieve **hundreds of peta FLOPS** (floating point operations per second) in processing data

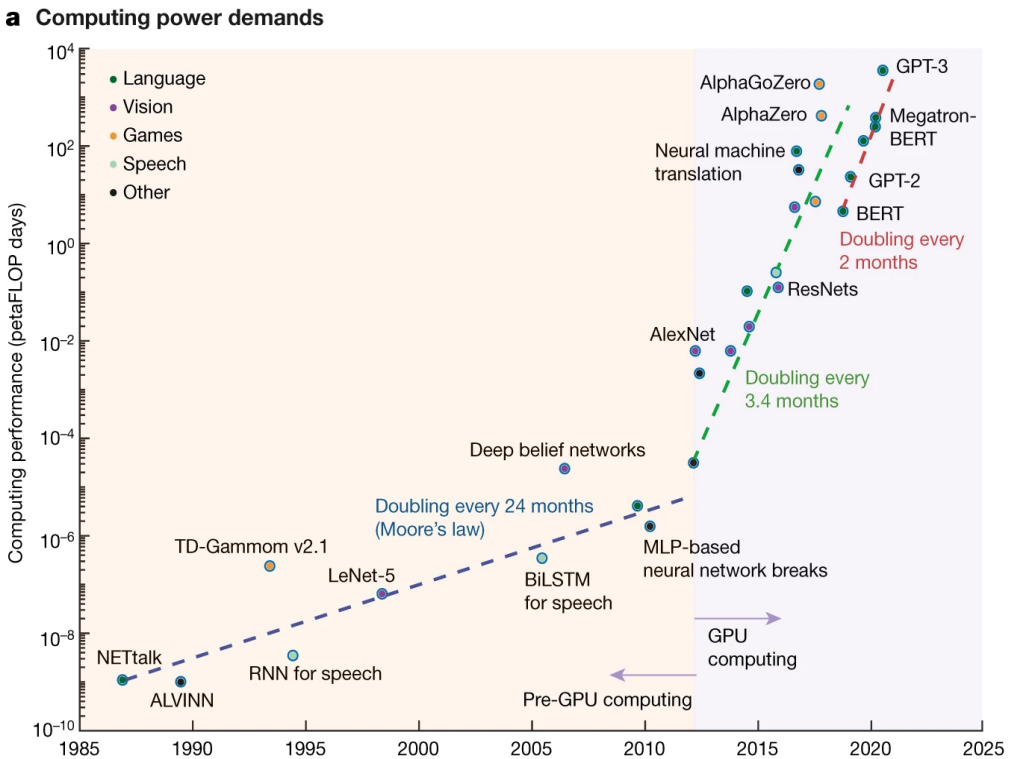
 # FLOP/s = 10^{17} FLOP/s **(# FLOP/day ≈ 10^{22})**

Energy per FLOP & Communication **E_{FLOP} = 1 - 10 pJ**

Total power consumption **>1 MW**

New computing technologies (→ «Silicon» Photonics)

- Remove (or reduce) energy consumption associated with data trasmission and processing in digital electronics
- Transmit and compute in the optical domains



JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 35, NO. 3, FEBRUARY 1, 2017

Attojoule Optoelectronics for Low-Energy Information Processing and Communications

David A. B. Miller, *Fellow, IEEE, Fellow, OSA*

[13], [14]. But, now we are facing a need to have optics help at shorter distances, and not just to enable higher interconnect densities. Now a key question is whether optics can reduce energy in interconnects inside cabinets, racks, and circuit boards, down at least to the edges of the chips themselves, and possibly even on the chip. This question is critical: if we cannot solve these problems with optics, it is not clear that we have any other way of tackling them.

D.A.B. Miller, "Attojoule Optoelectronics for Low-Energy Information Processing and Communications», J. of Lightwave Technology 35(3), Feb. 2017

What can we do (easily & conveniently) in photonics?

Function	Electronics	Photonics
MAC & MVM	CV^2 Energy Cost	Easy $O(N^2)$
Communication		Free
Gain	Easy	Easy (but off-chip)
Nonlinearity	Easy (Transistor)	Hard $O(N)$
Memory	Easy (DRAM, SRAM)	Hard

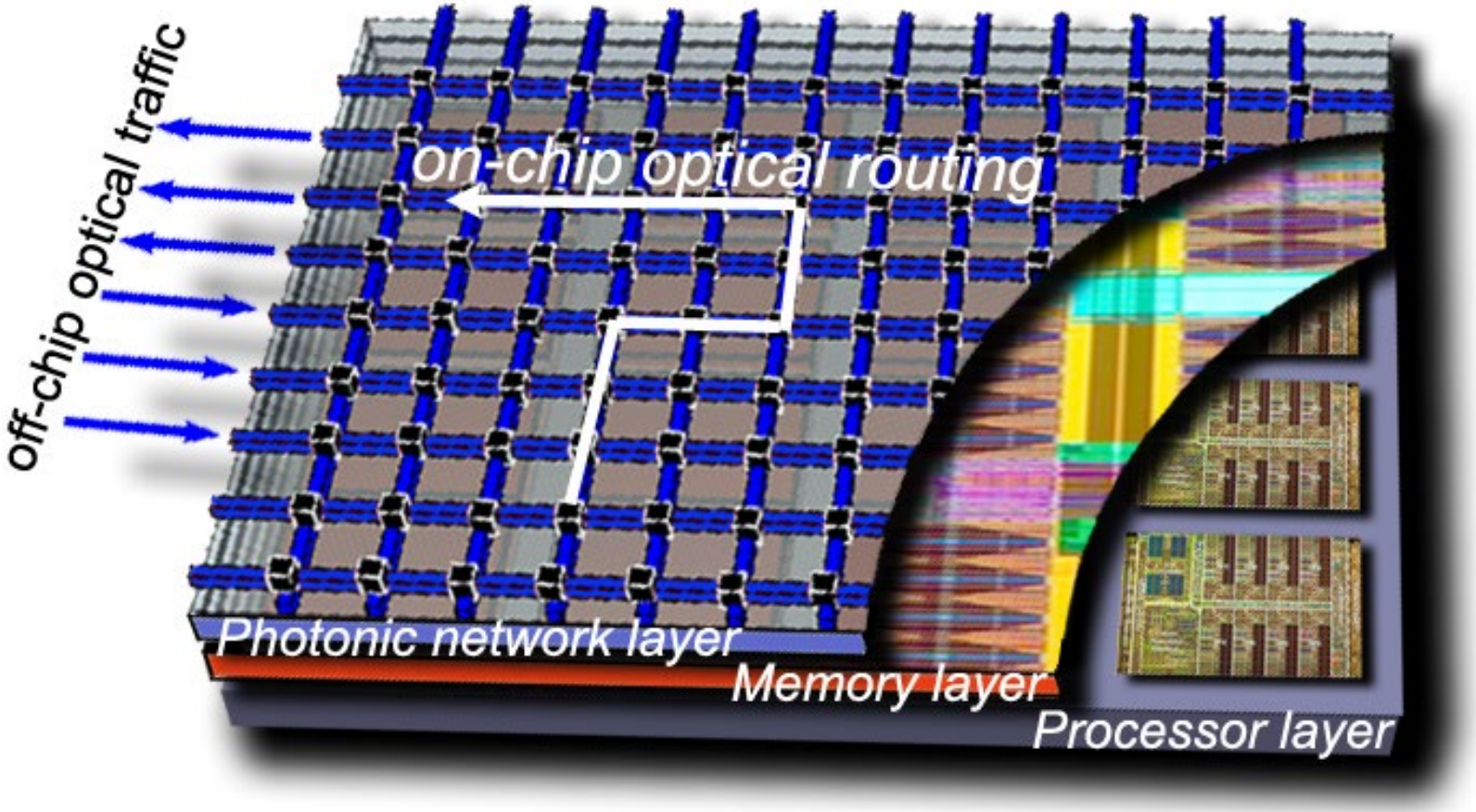
In neural networks, the convolutional part based on MVM occupies > 80% of the total processing time

Matrix-vector multiplication (MVM) & multiplications & accumulation (MAC) is everywhere in data processing:
- *convolution, factorization, linear equalization, filtering, Fourier transform…*
- *neuro-inspired computing (weighted interconnections between adjacent photonic neurons)*

Advantages of photonic computing
- high speed (THz) & low latency (< ns) in solving linear mathematical operations
- low energy/bit consumption (<< pJ/bit)

→ optical computing is a competitive candidate for **artificial intelligence accelerators**
→ acceleration is achieved by matching math operations and photonic hardware

Photonics Integration – Optical interconnect



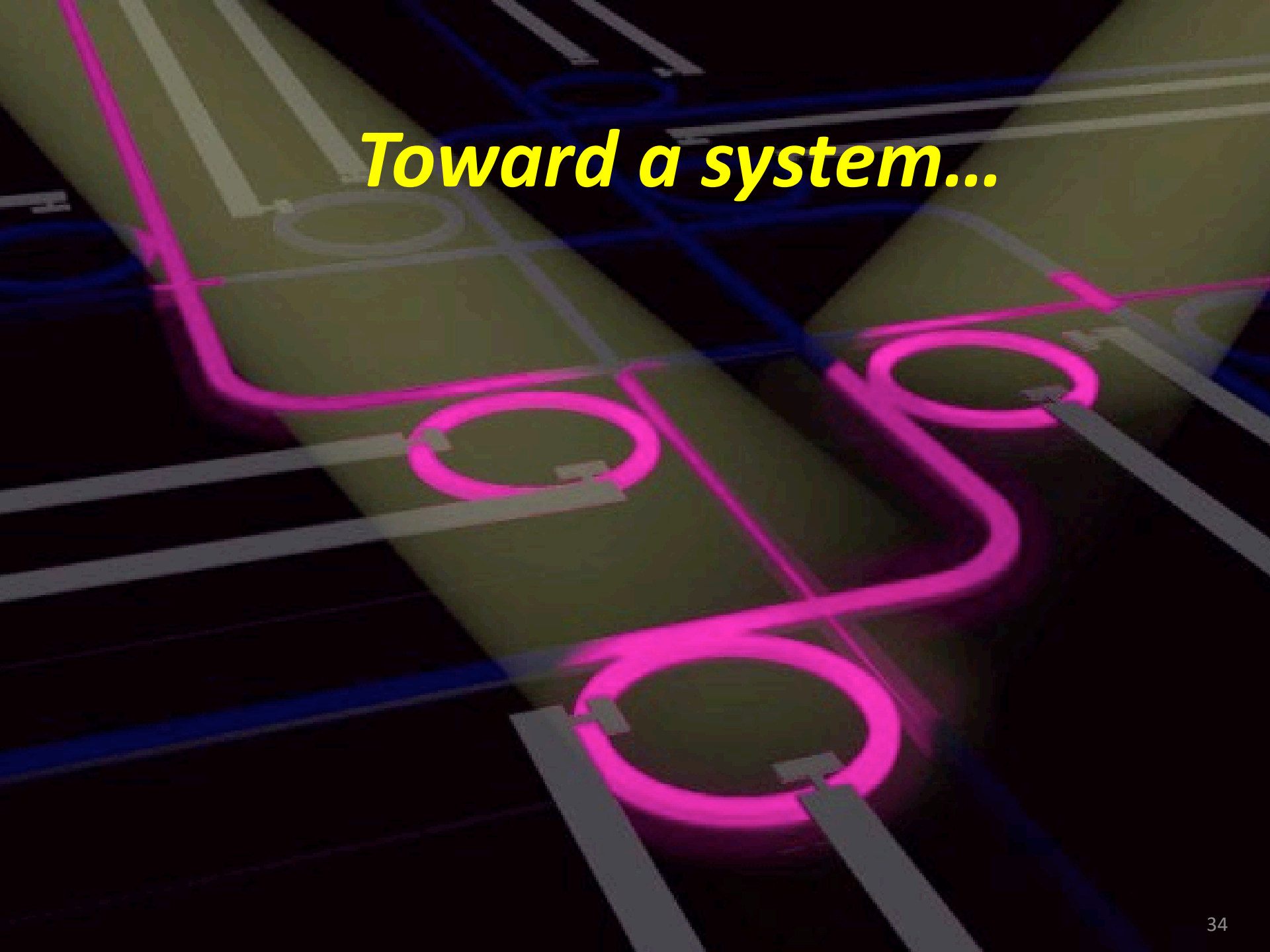
IBM, 2008

Monolithic Photonic-Electronic Integration

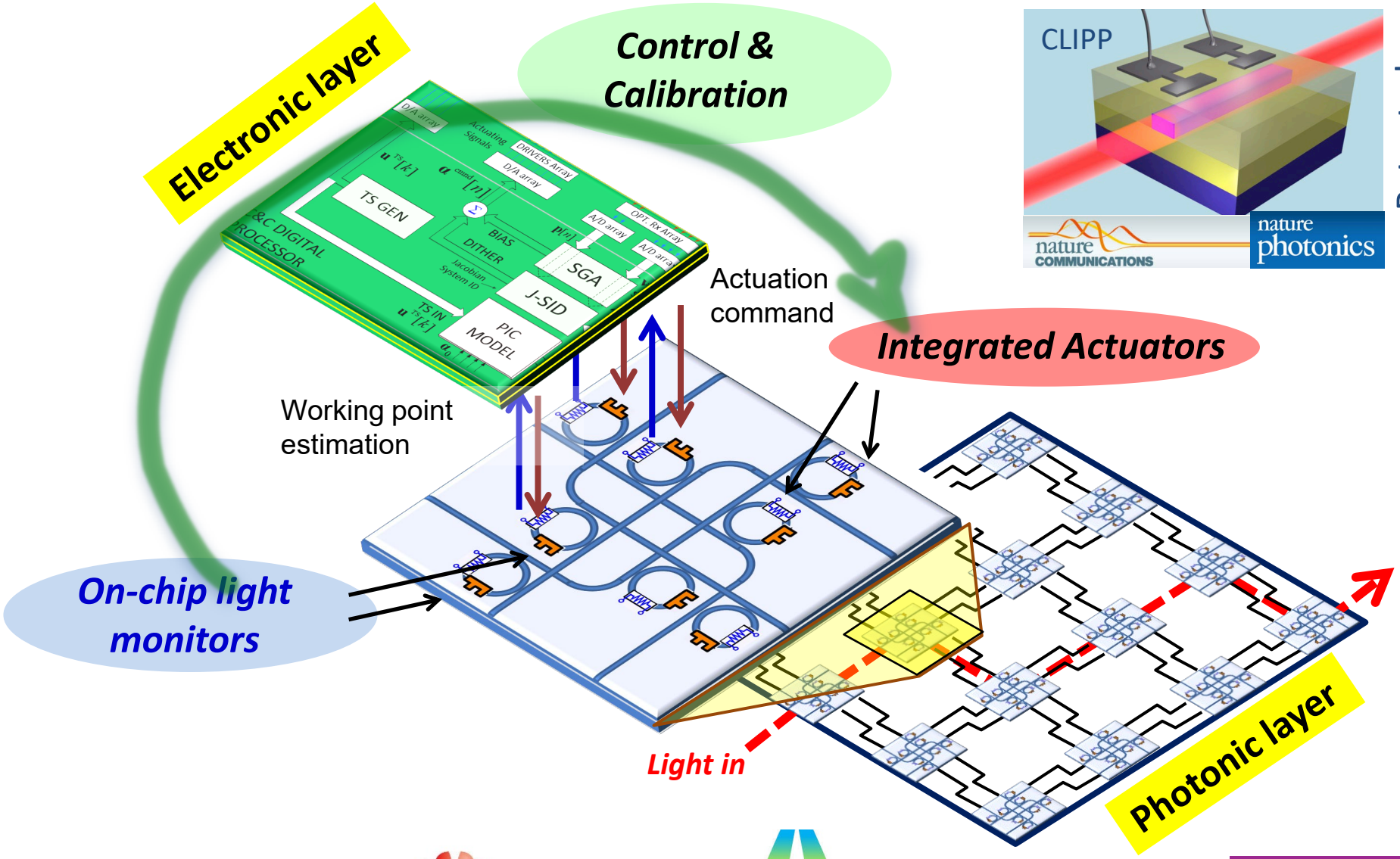
Exploiting existing fundries

 33

Toward a system…



Control layer for photonic integrated circuits



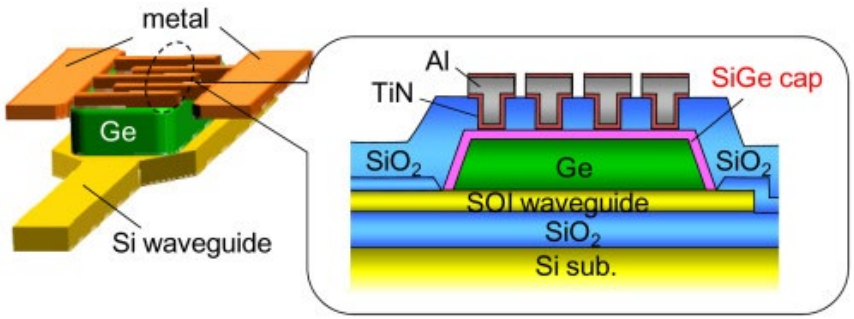
Patented

(Non Perturbative) Probes

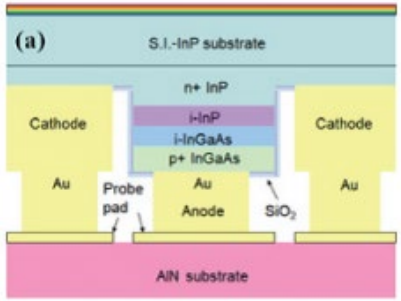
Monitor to detect light level in waveguides and provide feedback (test pin)
Hitless (transparent), small, low power…

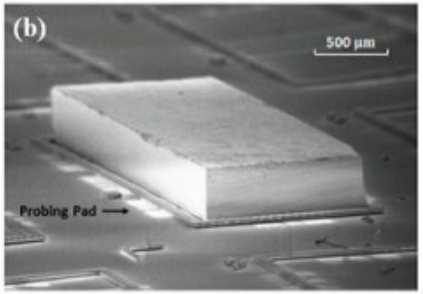
Light monitors: Ge, InP, hybrid, monolithic...

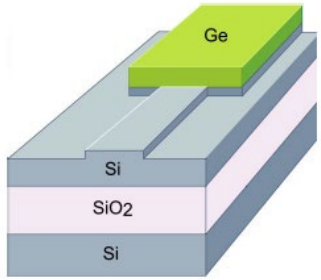
Ge on Silicon



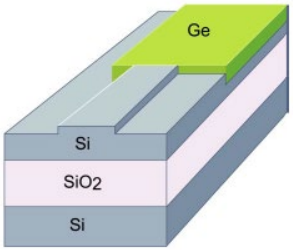
III-V compounds



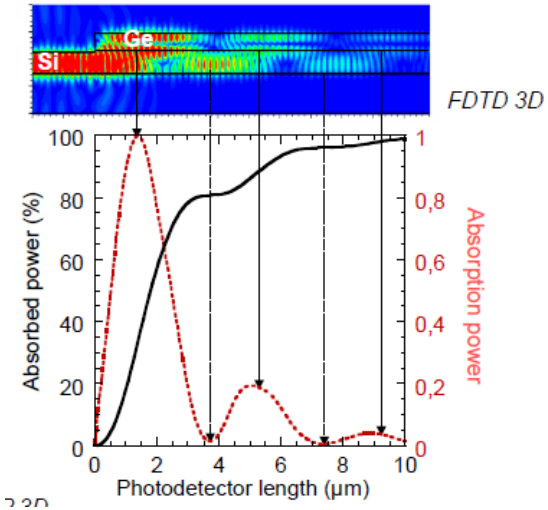


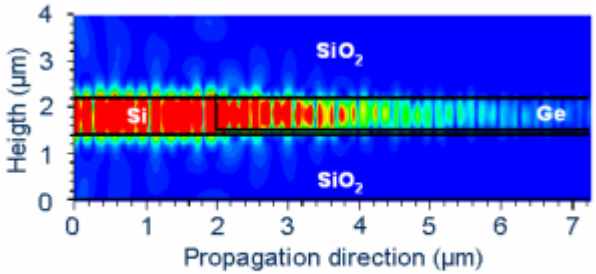


Vertical coupling



Butt coupling





95% absorption length < 4µm

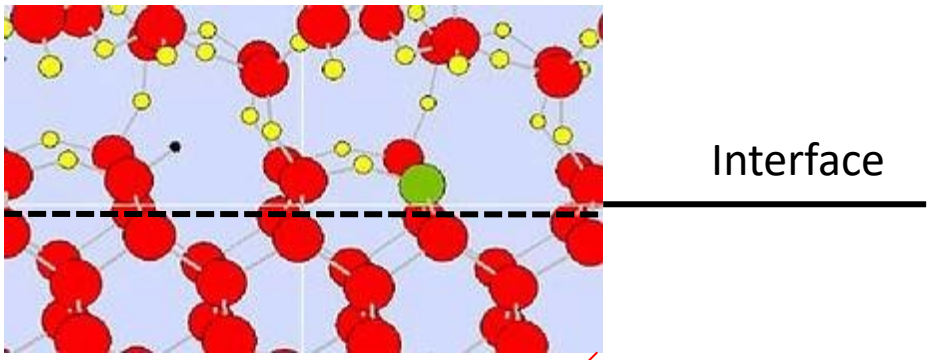
4.2% Ge-Si Lattice mismatch
⇒ specific growth strategies required
⇒ growth on thin SiGe buffers
⇒ multi step growth process
⇒ thermal annealing (reduce dislocation density)

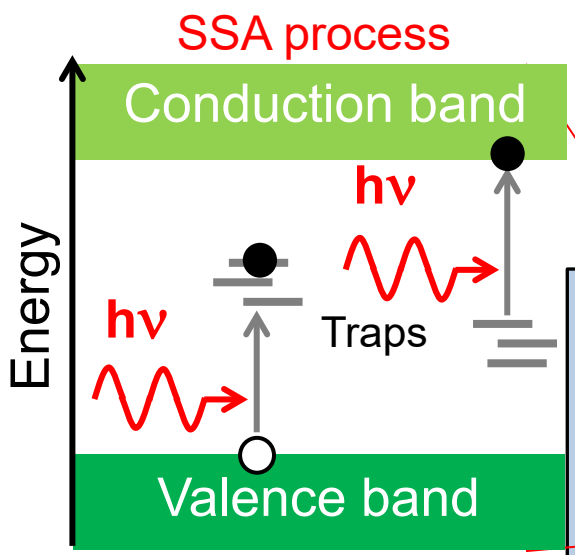
Light-waveguide interaction

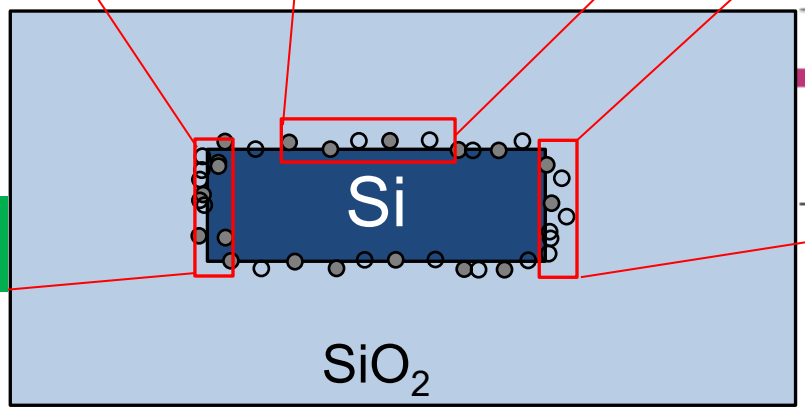
- Surface State Absorption

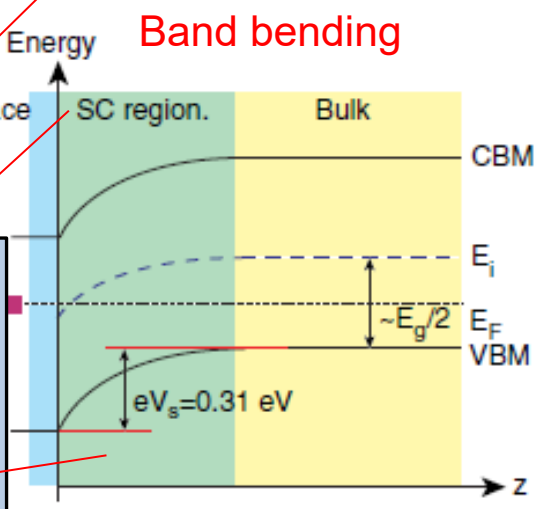
- Surface states are located typically within the first two/three silicon atomic layers (≈ 1 nm)

- Intra-gap energy states create a free carrier and a corresponding recombination center



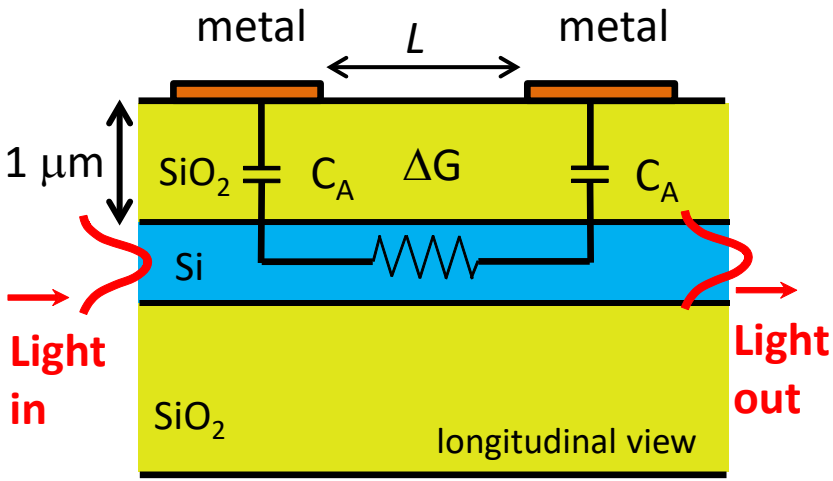


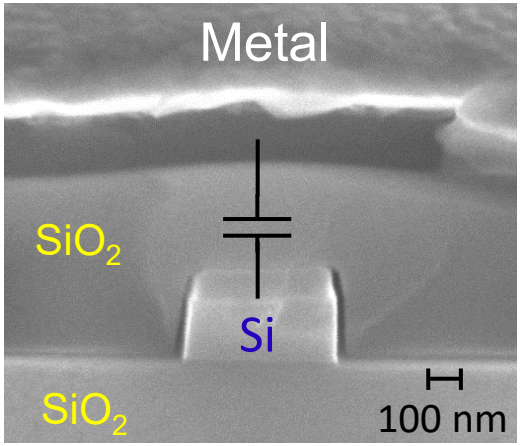




The CLIPP concept

ContacLess Integrated Photonic Probe (CLIPP)





Contactless capacitive access to the waveguide

Measuring the SSA induced waveguide **conductance change ΔG** through an ultrasensitive electric **detection circuit**

Light dependent conductance variation

$$\Delta G = \Delta\sigma \frac{A}{L} = q\left(\frac{\mu_{e,s} + \mu_{h,s}}{2}\right)\frac{A}{L}\Delta N_s$$

Free carriers generated on the surface by SSA

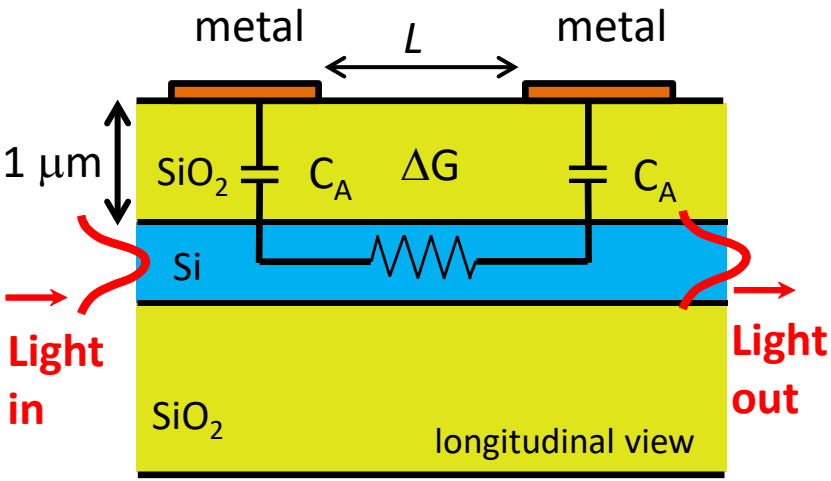
Si conductivity change induced by light

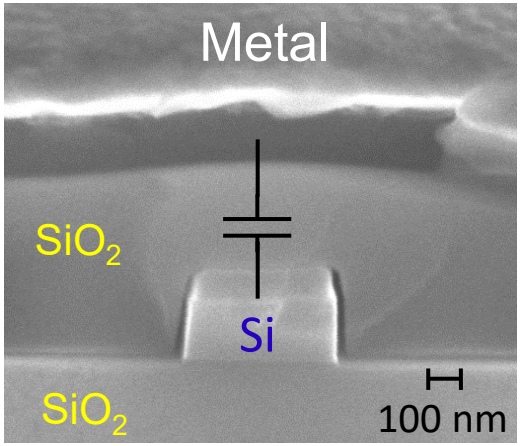
Carrier mobility is typically lower on the surface compared to the bulk

A	Si waveguide cross section
L	CLIPP length
ΔN_s	surface free-carrier density
μ_s	carrier mobility

The CLIPP concept

ContacLess Integrated Photonic Probe (CLIPP)





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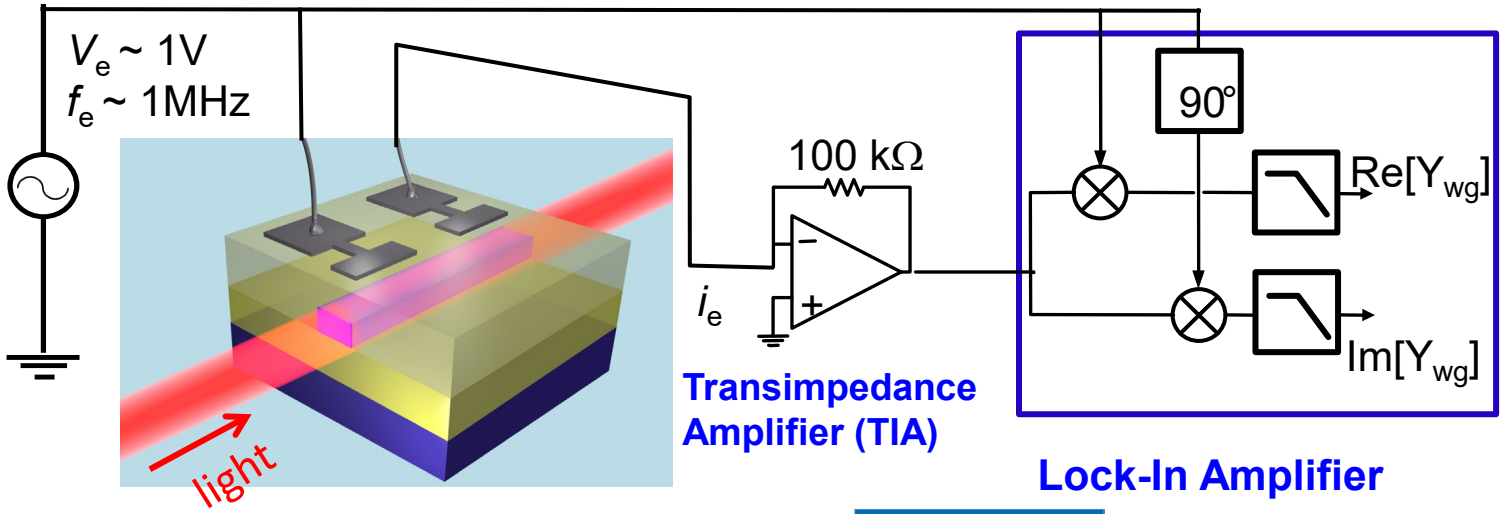
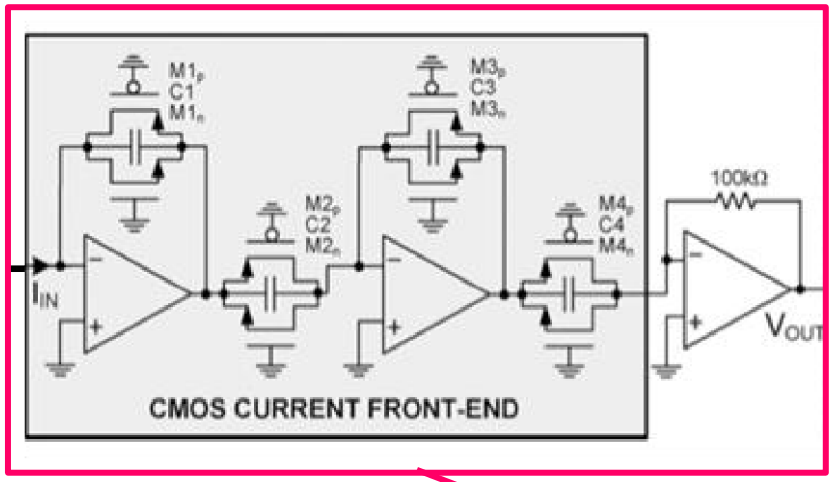


Patented

"Silicon Photonics: Stalking Light," Nature Photonics **8**, 2014

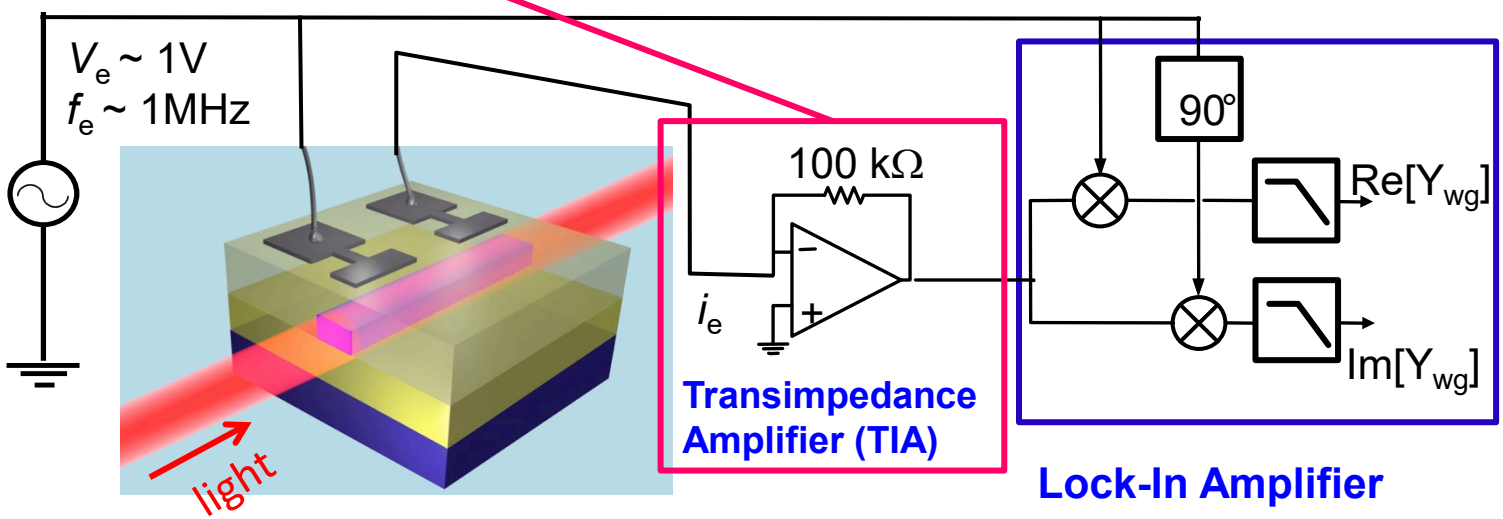
research highlights nature photonics nature COMMUNICATIONS

The CLIPP readout system



Realization:

- AMS 0.35μm CMOS
- Vsupply 3.3V
- Crosstalk < -60dB
- Modular motherboard
- >50MHz bandwidth
- Low current noise 100fA/√Hz @ 1MHz

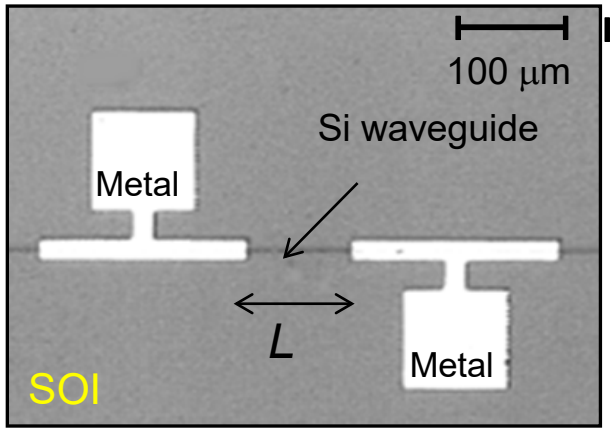


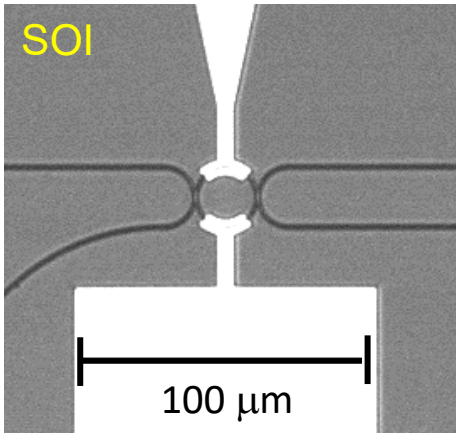
Patented

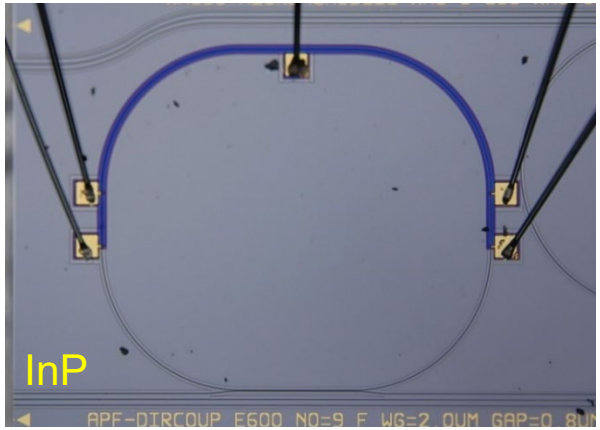
F. Morichetti et. al, J. Selected Topics in Quantum Electronics, July 2014

Stalking light, Nature Photonics, Vol. 8 April 2014

CLIPP performance in Si waveguides

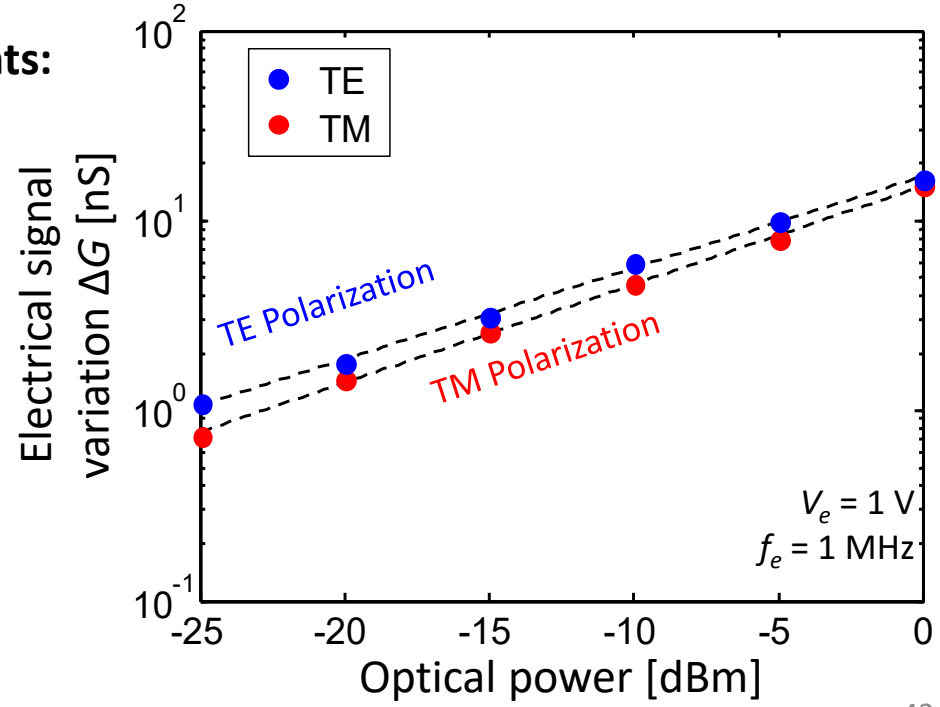




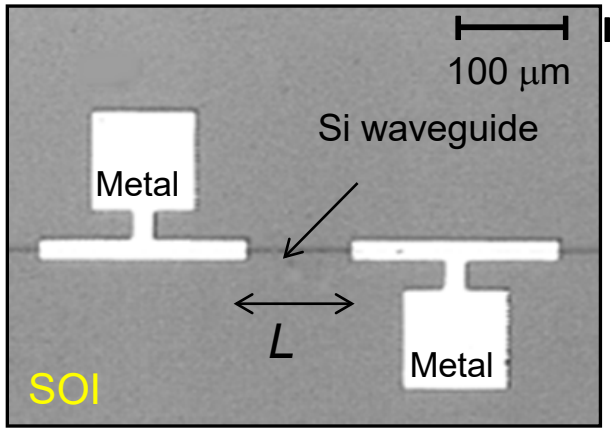


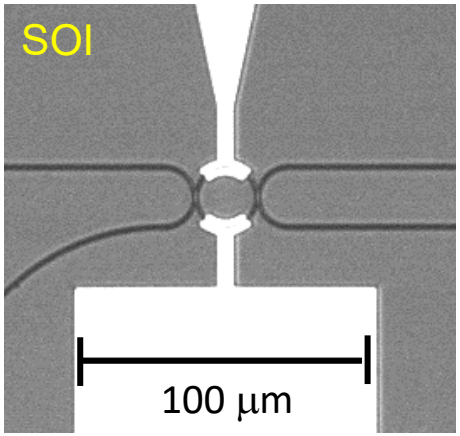
Performance match monitoring requirements:

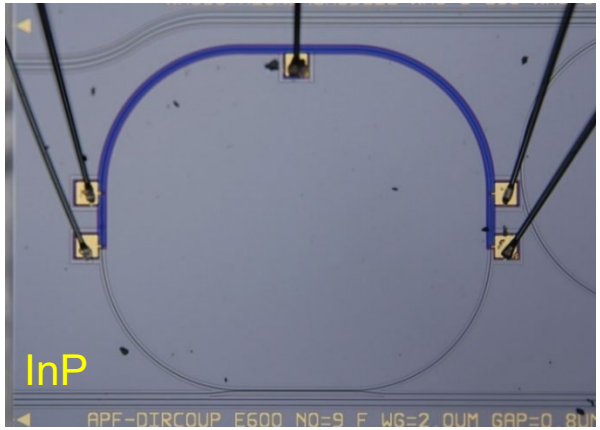
- Single-mode and multimode waveguides
- Compact size: *L* down to 25 μm
- Both TE/TM polarizations
- Sensitivity down to -30 dBm
- 40 dB dynamic range
- Speed down to 20 μs
- No loss, no backreflection, no amplitude/phase perturbation



CLIPP performance in Si waveguides







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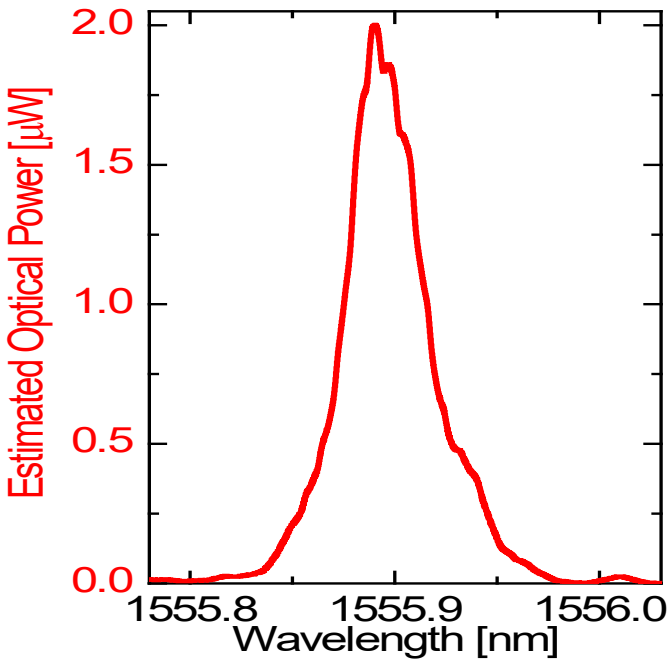
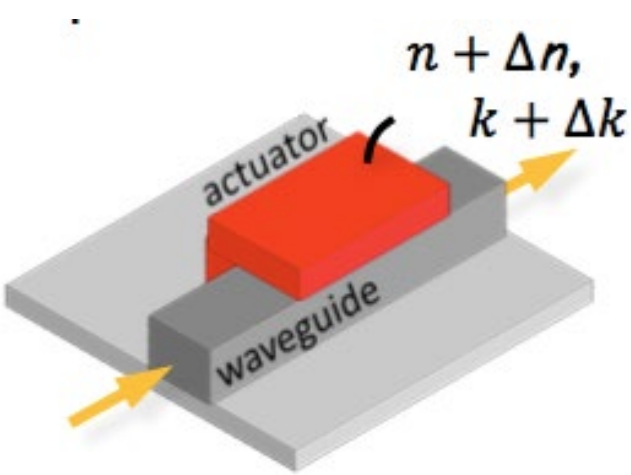
Light intensity inside a ring



Actuators

Low Power Electronic, algoritmhs and strategies for trimming, tuning, locking, adaptive …

Actuators



Phase / Amplitude

Fast (MHz for tuning and reconfiguration)

Compact (10-100 μm)

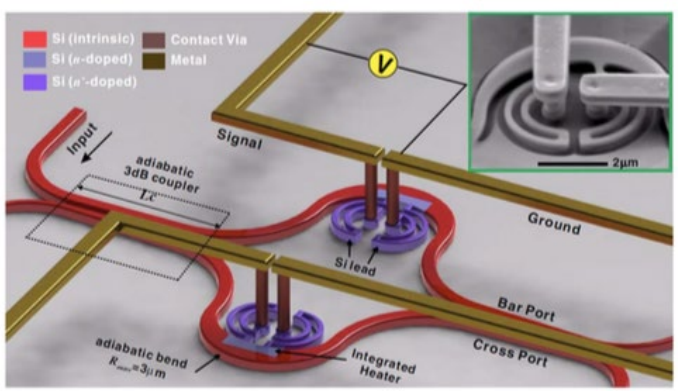
Low Power consumption (< mW)

Permanent, self holding to avoid to continuous feed

Analog / Digital

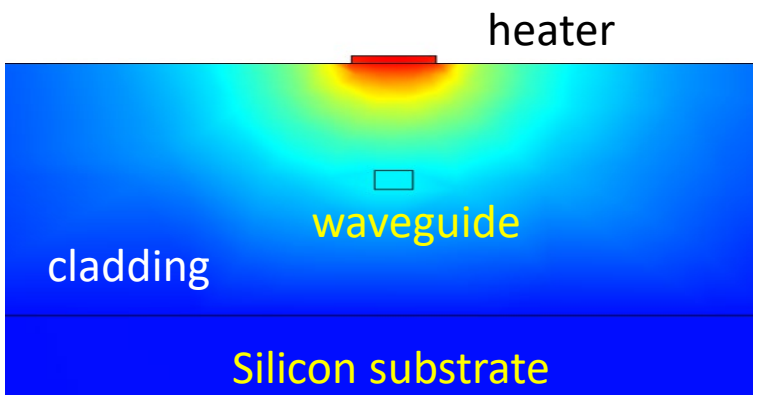
Thermal actuators, mature technology, power hungry

M. R. Watts, et al. Opt. Lett. 38, (2013)



Si channel waveguide with embedded Si heater (n-doped)

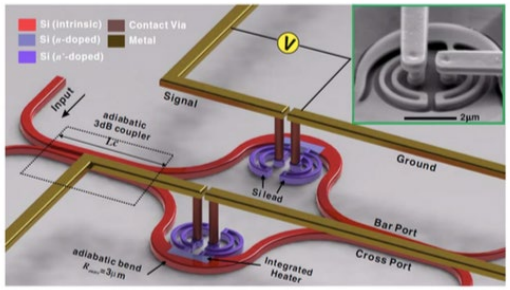
Thermal field induced by heater



Integrated optical **actuators**

Thermal actuators

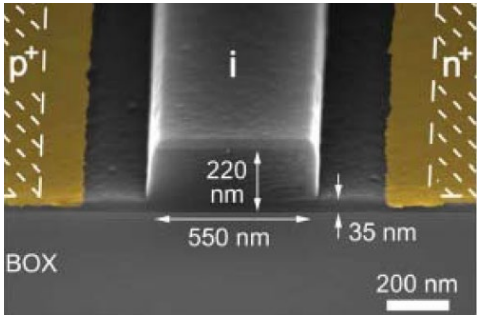
M. R. Watts, et al. Opt. Lett. 38, (2013)



Si channel waveguide with embedded Si heater (n-doped)

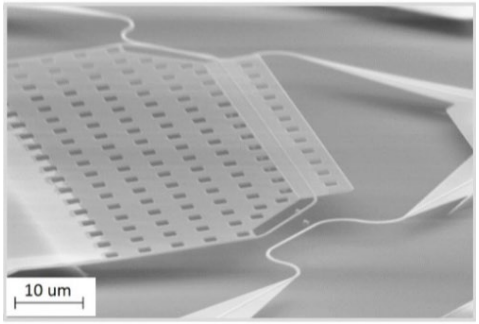
p-n junctions

Carrier injection/depletion



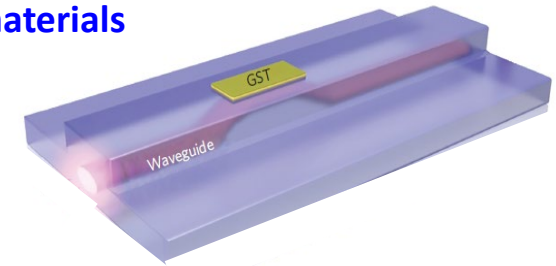
W.M. Green *et al.*, Opt. Express 15 (2007)

MEMS based switches



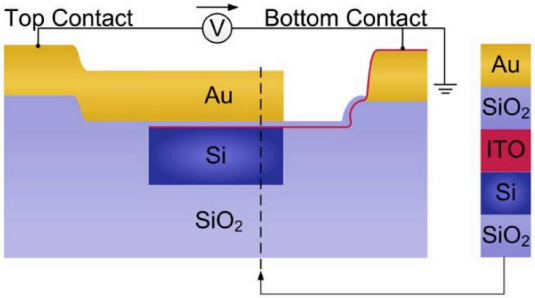
S. Han *et al.*, Berkeley, (2015)

Phase-change materials



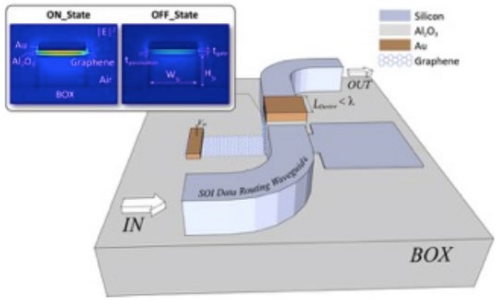
C. Rãos *et al*, Nature Photonics **6** (2015)
A. Joushaghani et al, APL, 102, 061101 (2013)

Plasmonic memristor



C. Hoessbacher *et al.*, Optica **1** (2014)

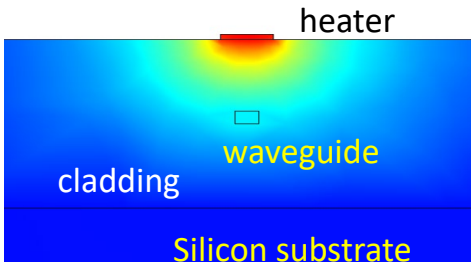
Graphene, $MoTe_2$, ITO modulators



R. Amin *et al.*, arxiv (2018)

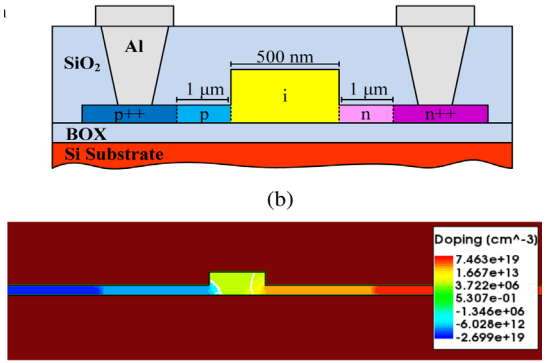
Integrated optical **actuators**

Thermal field induced by heater

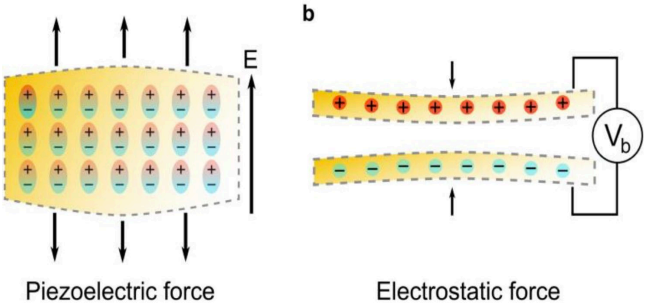


p-n junctions

Carrier injection/depletion

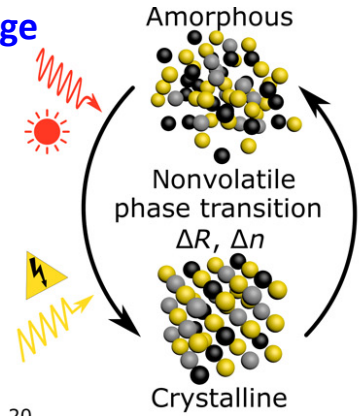


MEMS based switches



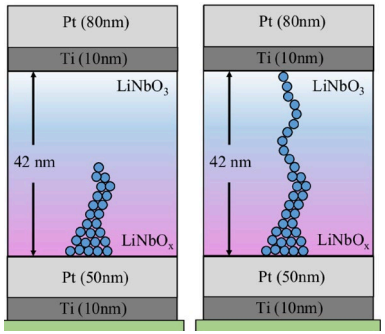
A. Fiore, TU/e

Phase-change materials



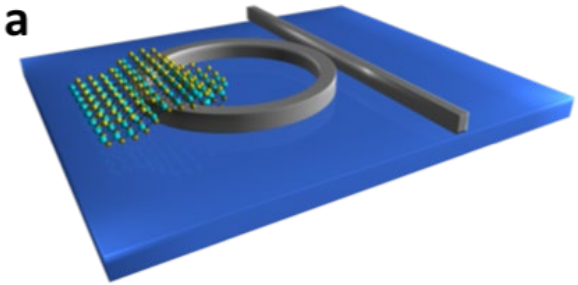
N. Farmakidis et al.
Sci Adv 2019; 5

Plasmonic memristor



Yacopcic, 2017

Graphene, $MoTe_2$, ITO modulators

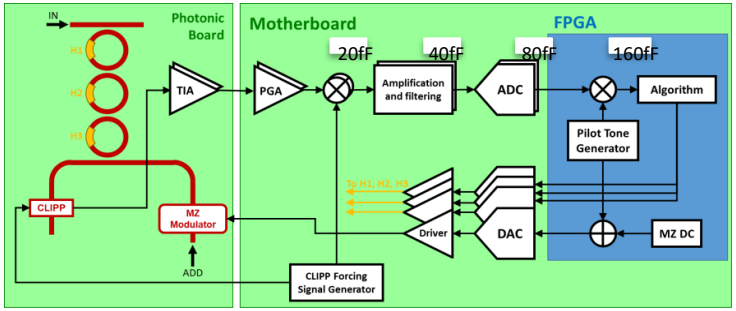


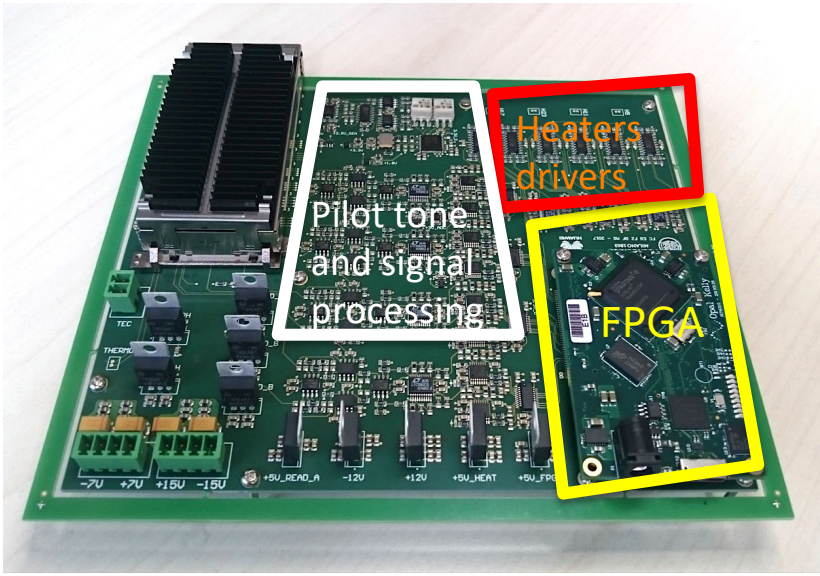
Feedback and control

Low Power Electronic, algoriths and strategies for trimming, tuning, locking, adaptive …

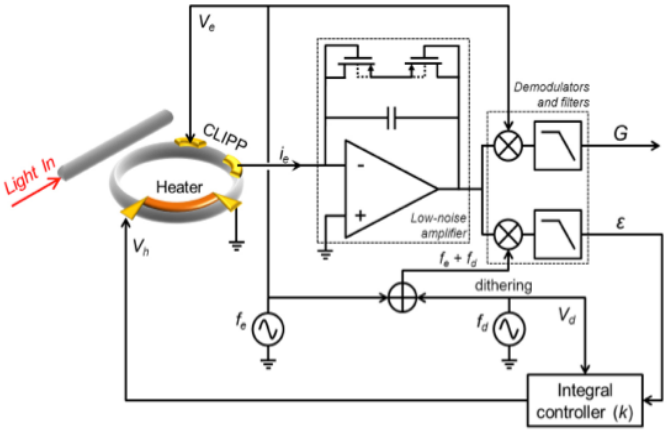
Electronics at service of photonics

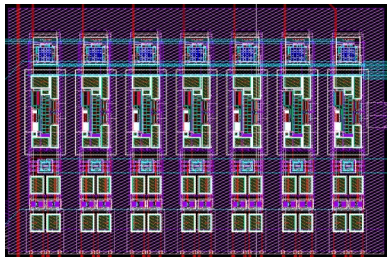
BRAIN – Central Control Unit





REFLEX ARC– Local Analog Control



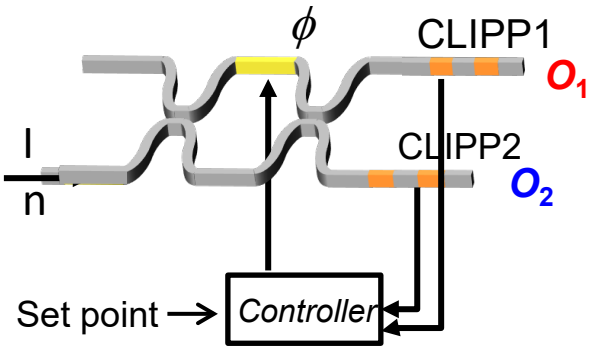


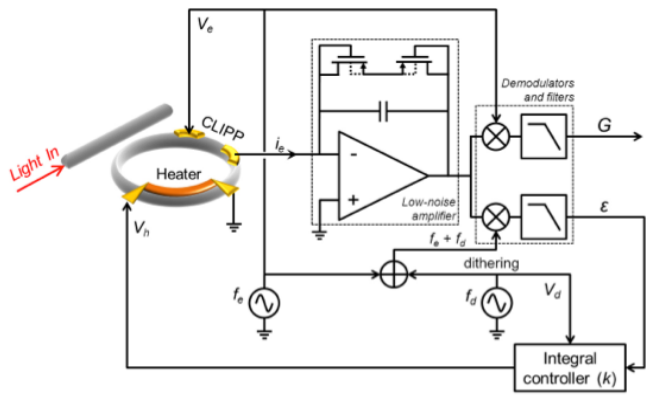
STm BCD8sp ASIC

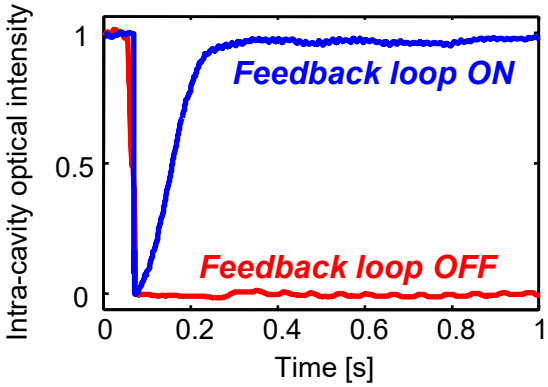
Feedback and control

Local feedback loop

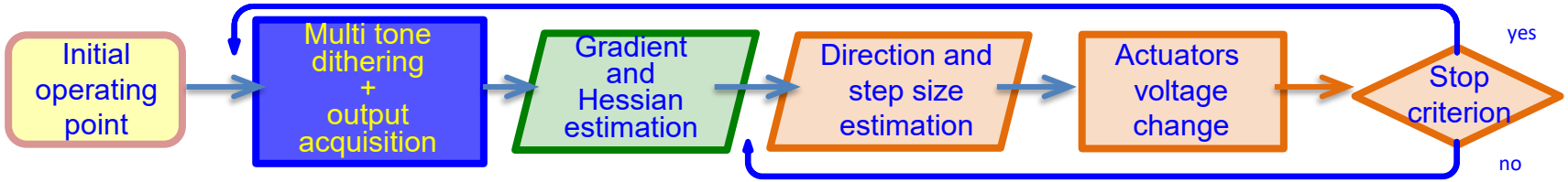
1-DOF





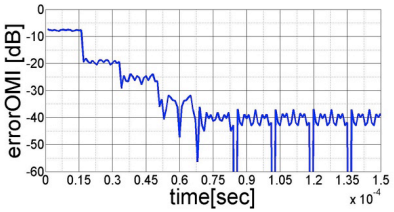


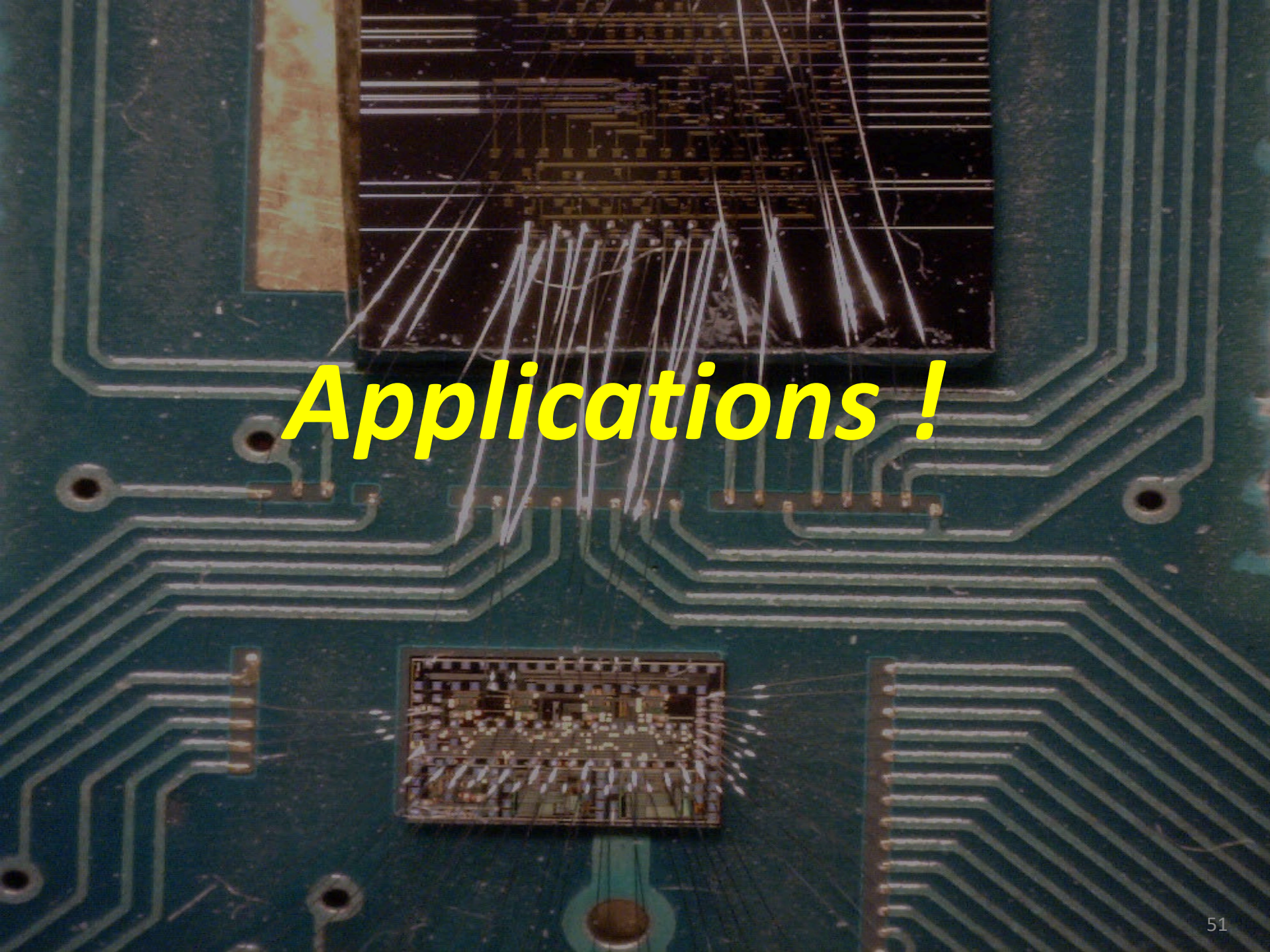
M-DOF



Control **many degrees-of-freedom** (DOFs) using a **single monitoring point**

Several DOFs **simultaneously dithered at orthogonal frequencies** generated from a discrete-multi-tone generator

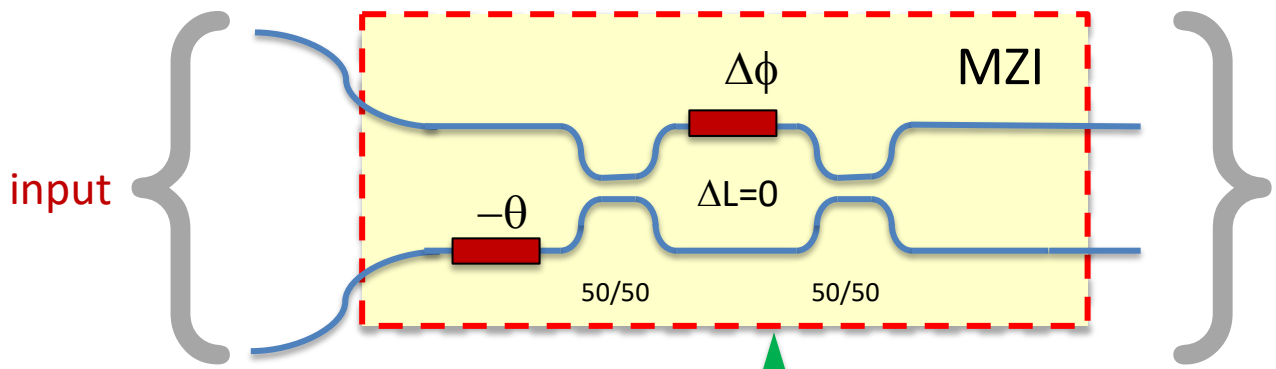




Applications !

The simplest Programmable Optical Processor (2 input apertures)

Photonic Analog Combiner



Unitary trasformation

Mach-Zehnder Interferometer (MZI)

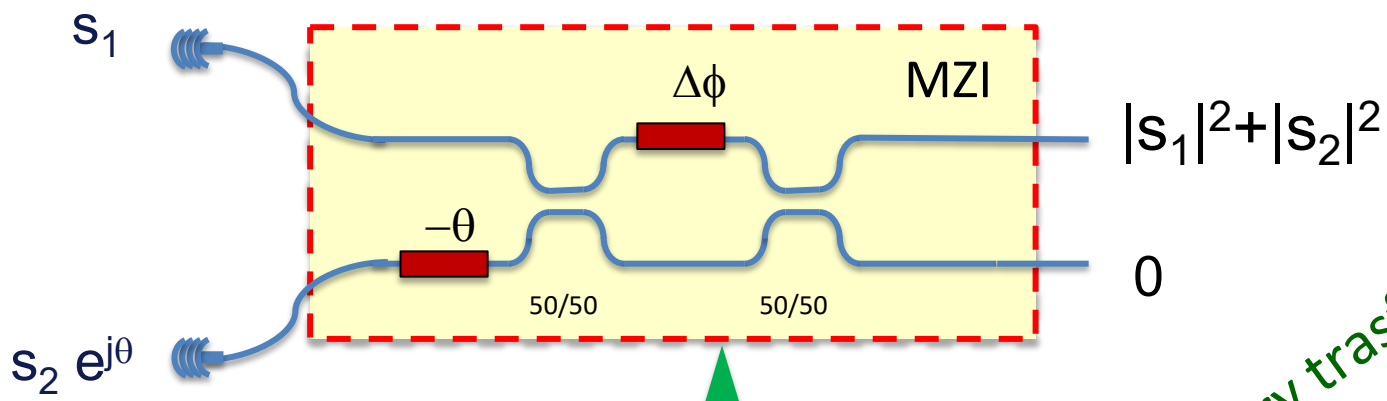
Phase shifters

$$\mathbf{H} = \begin{bmatrix} \sin(\Delta\phi/2) & e^{-j\theta}\cos(\Delta\phi/2) \\ -\cos(\Delta\phi/2) & e^{-j\theta}\sin(\Delta\phi/2) \end{bmatrix}$$

det (**H**)=1

The simplest Programmable Optical Processor (2 input apertures)

Photonic Analog Combiner



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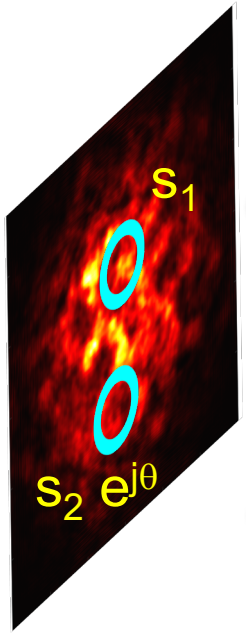
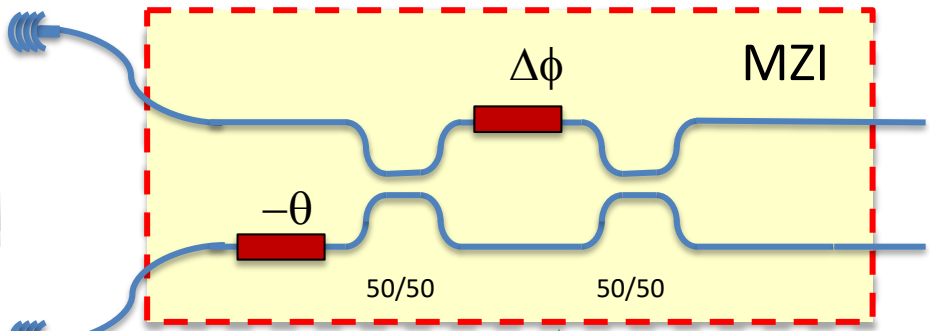
The simplest Programmable Optical Processor (2 input apertures)



Photonic Analog Combiner



$|s_1|^2+|s_2|^2$

0

Unitary trasformation

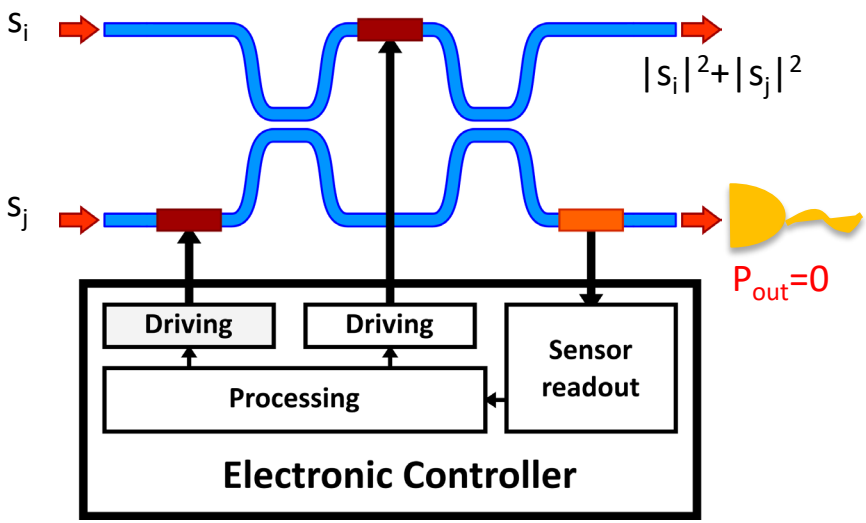
Mach-Zehnder Interferometer (MZI)

Phase shifters

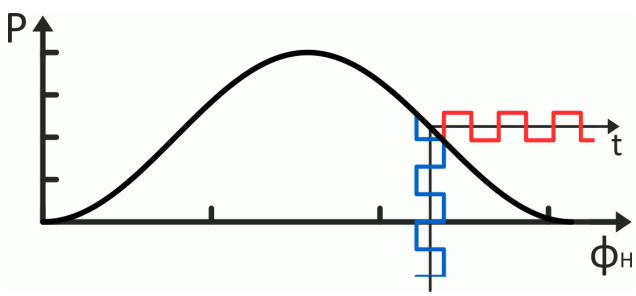
$$\mathbf{H} = \begin{bmatrix} \sin(\Delta\phi/2) & e^{-j\theta}\cos(\Delta\phi/2) \\ -\cos(\Delta\phi/2) & e^{-j\theta}\sin(\Delta\phi/2) \end{bmatrix}$$

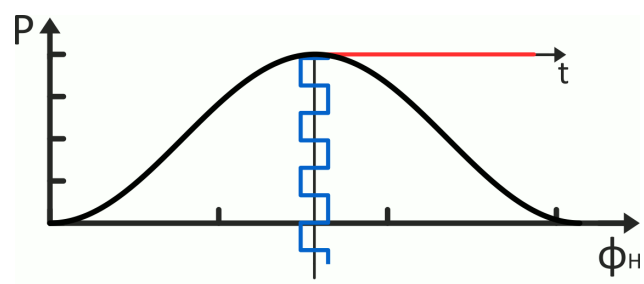
det (**H**)=1

Control electronics for self-configuring MZI



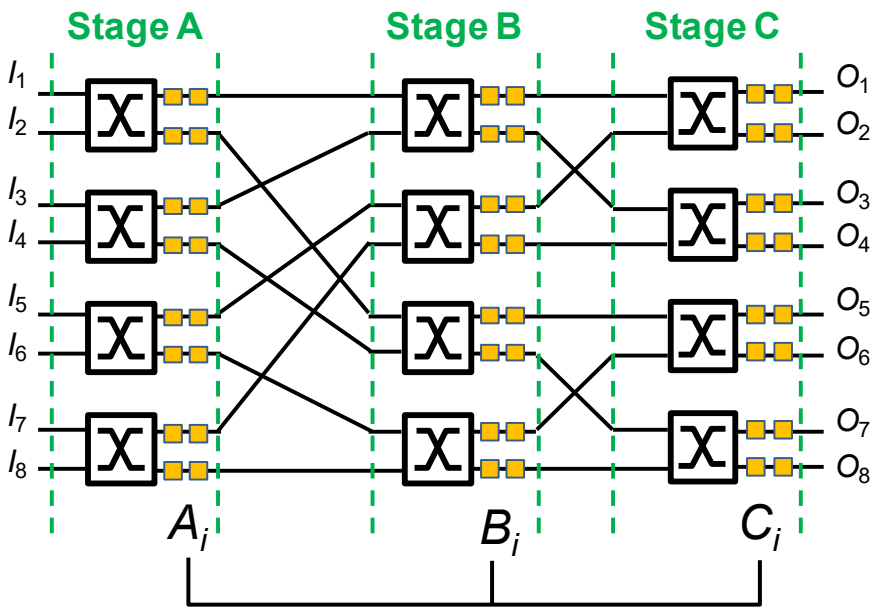
- Automatic (dithering-based) self-configuration of a MZI from any initial condition
- Track input signal changes (amplitude/phase)
- Compensate thermal fluctuation & fabrication variability
- Control in parallel of N MZIs (not sequential)
- Full processor stabilization in ms scale



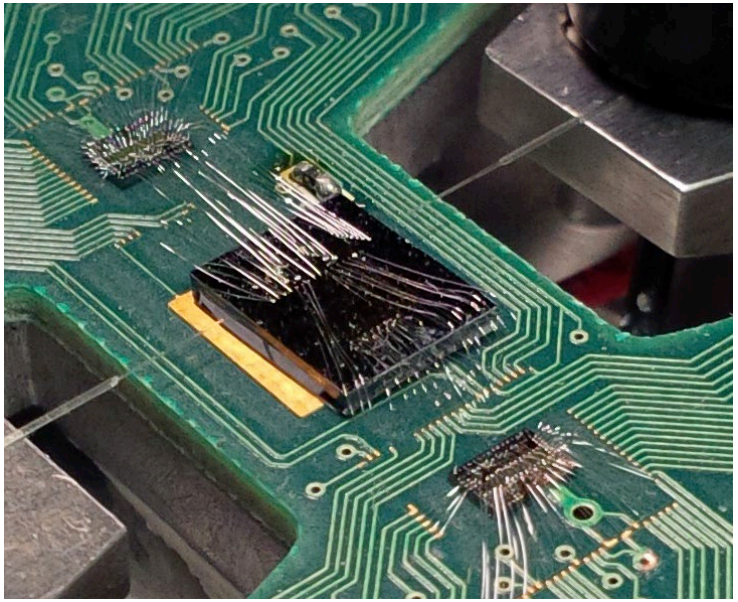


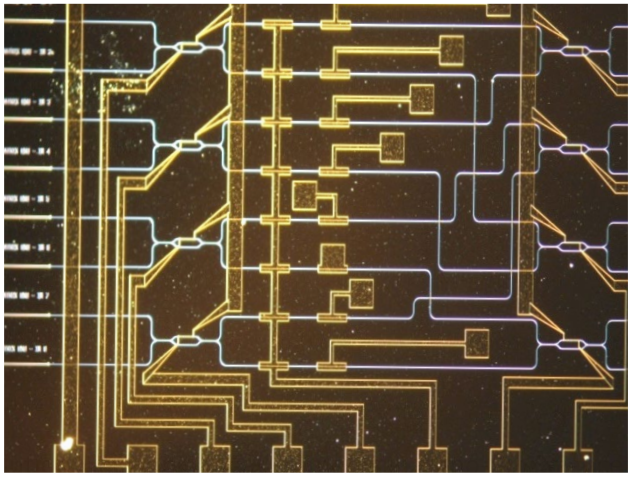
Lightpath tracking and feedback control routing

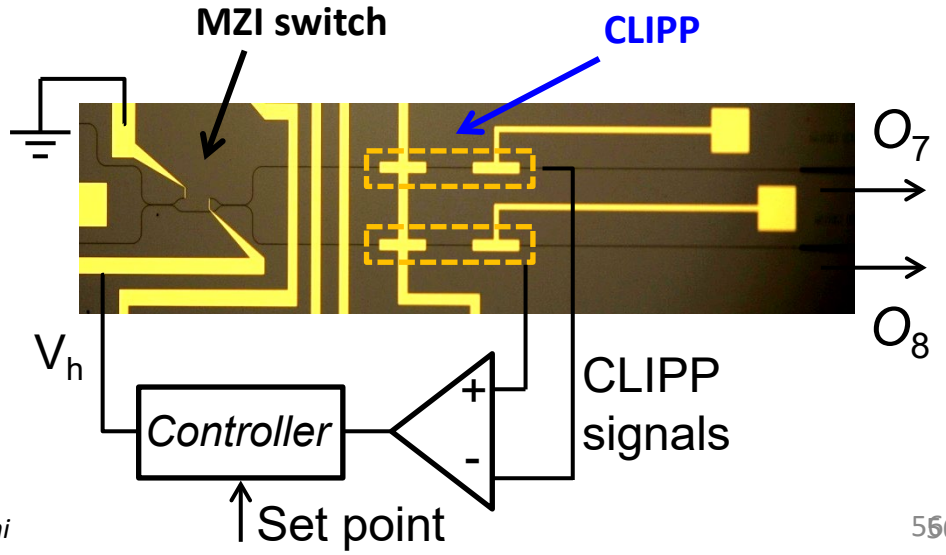
A. Annoni et al, JSTQE, 22(6)2016



2 x 12 CLIPPs
12 heaters



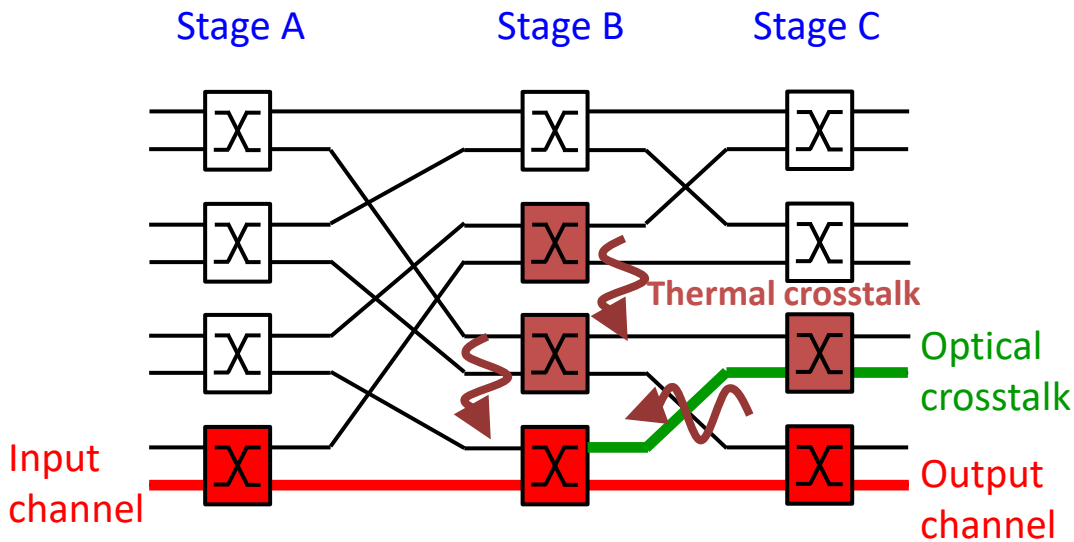


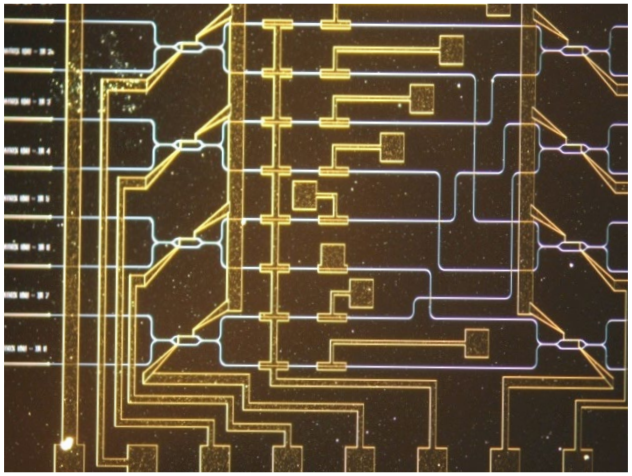


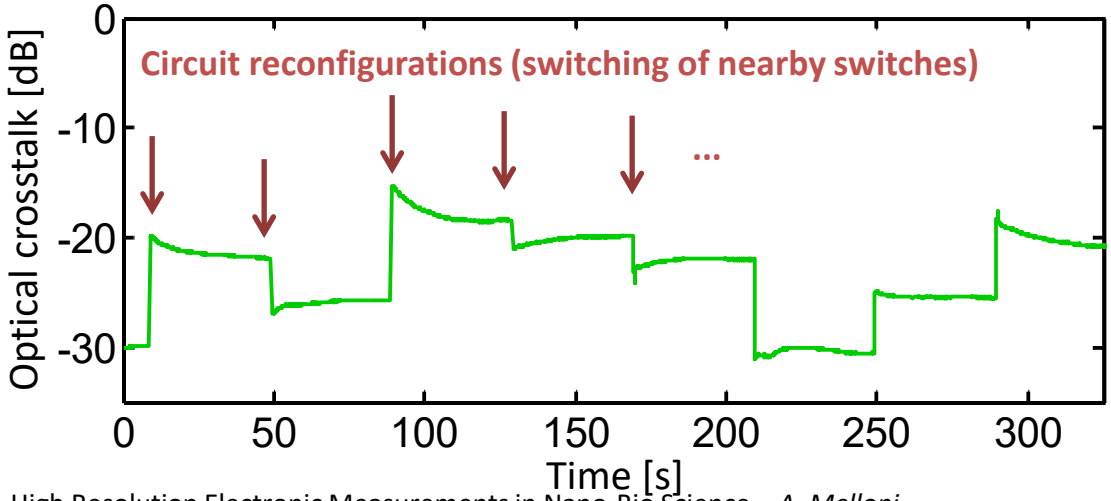
Feedback control

A. Annoni et al, JSTQE, 22(6)2016

8x8 Si photonic switch matrix



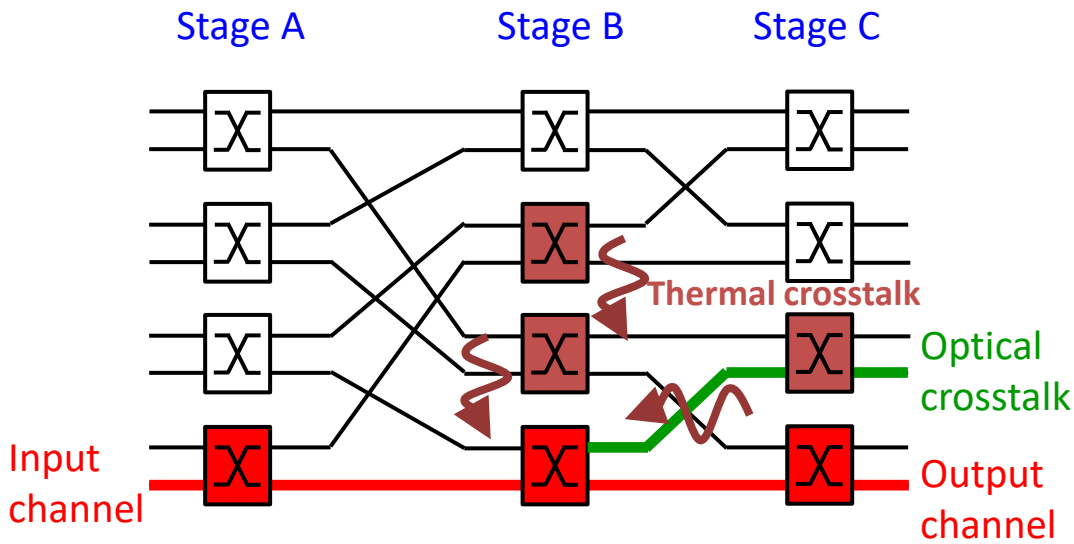


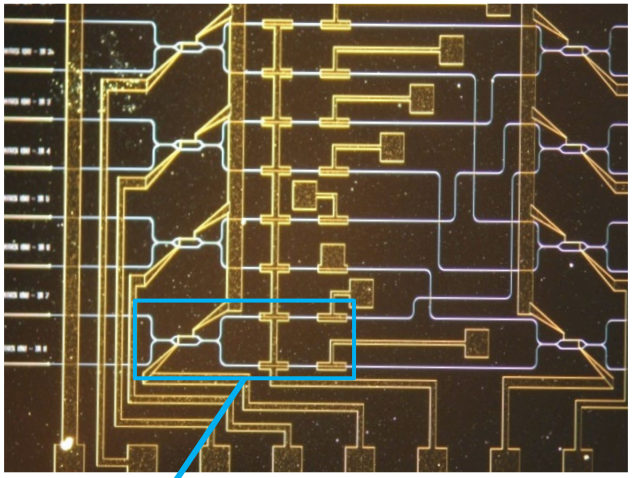


Feedback control

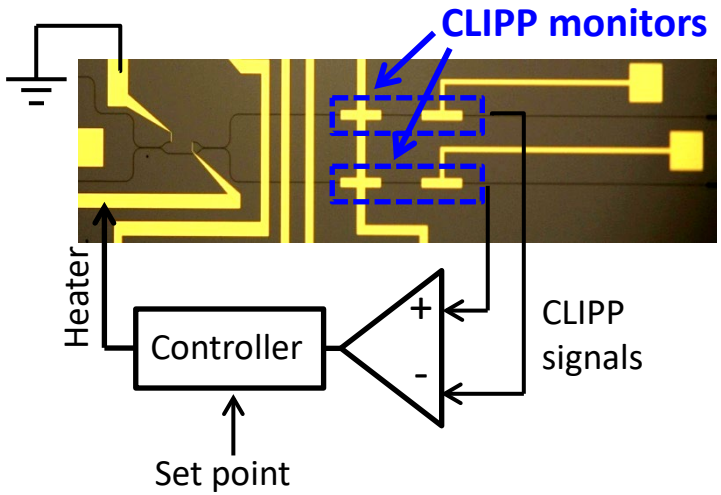
A. Annoni et al, JSTQE, 22(6)2016

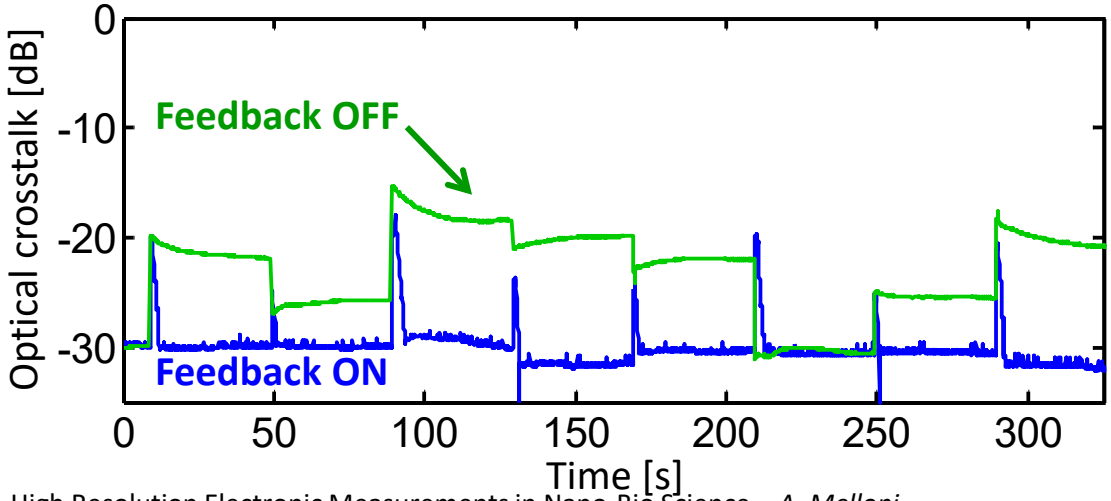
8x8 Si photonic switch matrix



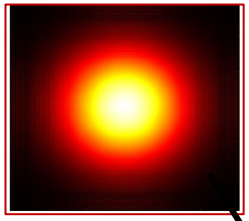


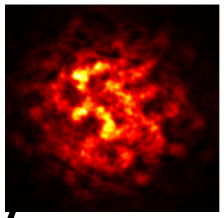
Feedback on every switch





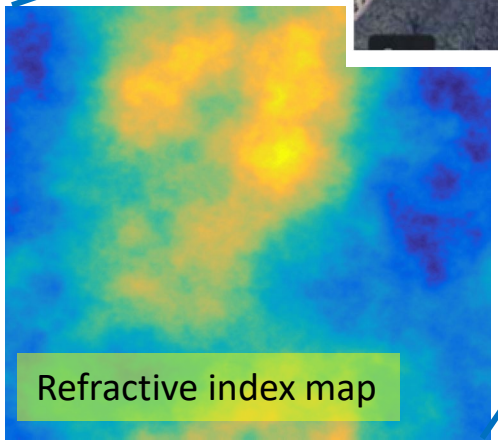
Free Space Optical (FSO) Link





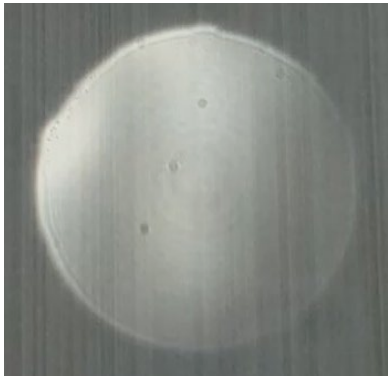
Transmitter - TX
Alignment/stability
Collimating Optics
Divergence
Launch power
Modulation format
Multichannel
Beam shaping
Beam Diversity

Receiver - RX
Alignment/stability
Collimating Optics
Geometrical aperture
Position/Beam Diversity
Direct/Coherent Detection
Sensitivity
Adaptive Optics
Turbulence compensation



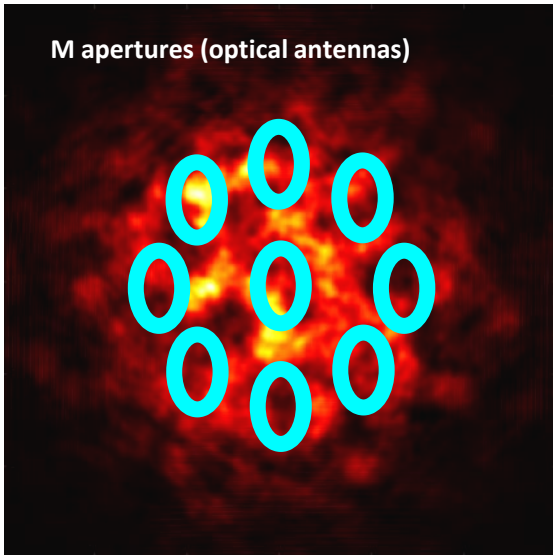
Free Space Channel
- Attenuation
- Multipath
- Time varying channel
- **Turbulence** (scintillation & wander)
- Polarization

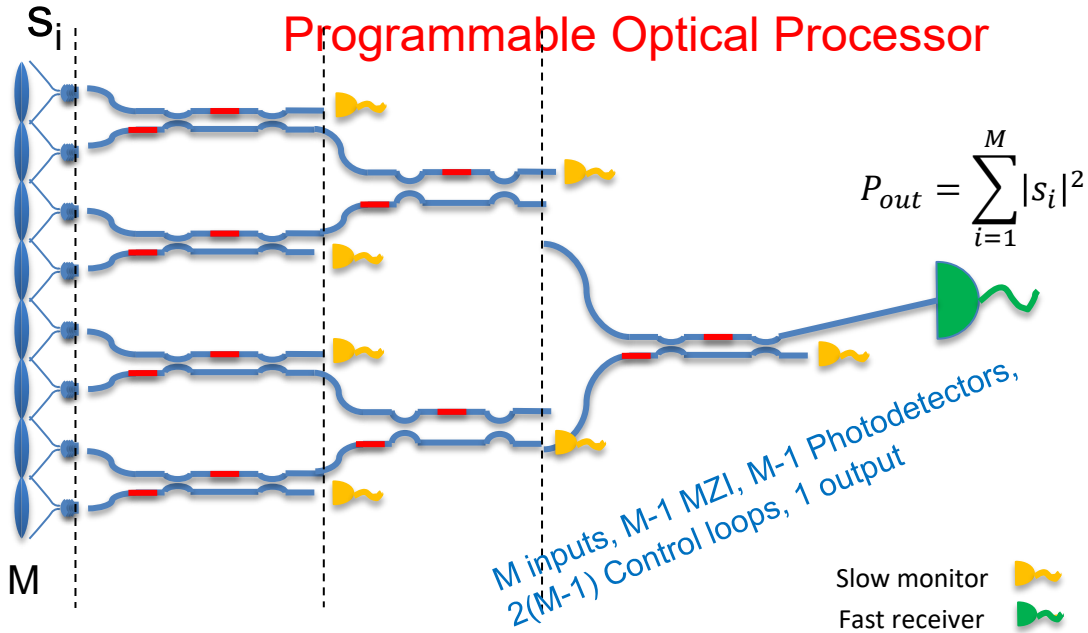
320 m FSO link
100 fps



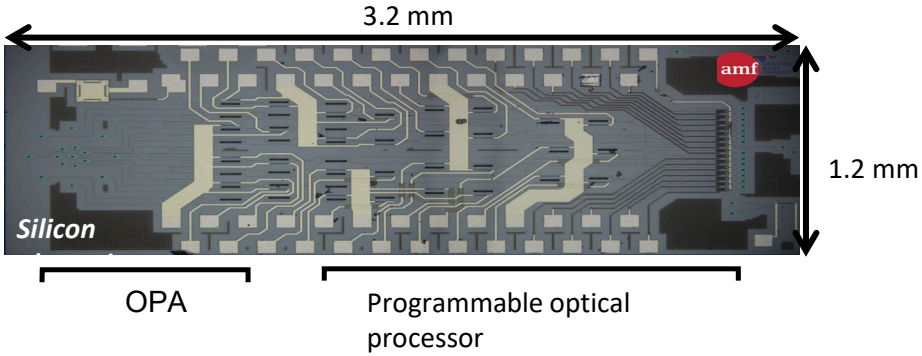
A. Trichili et al., **Roadmap to Free Space Optics,** JOSA B, July 2020

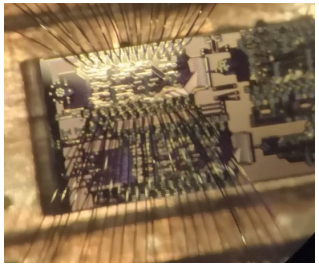
The Optical Analog Processor based receiver





A device capable of coupling an arbitrary free-space beam (non-spatially coherent → "multimode") into a specific output beam (spatially coherent → ""single-mode")



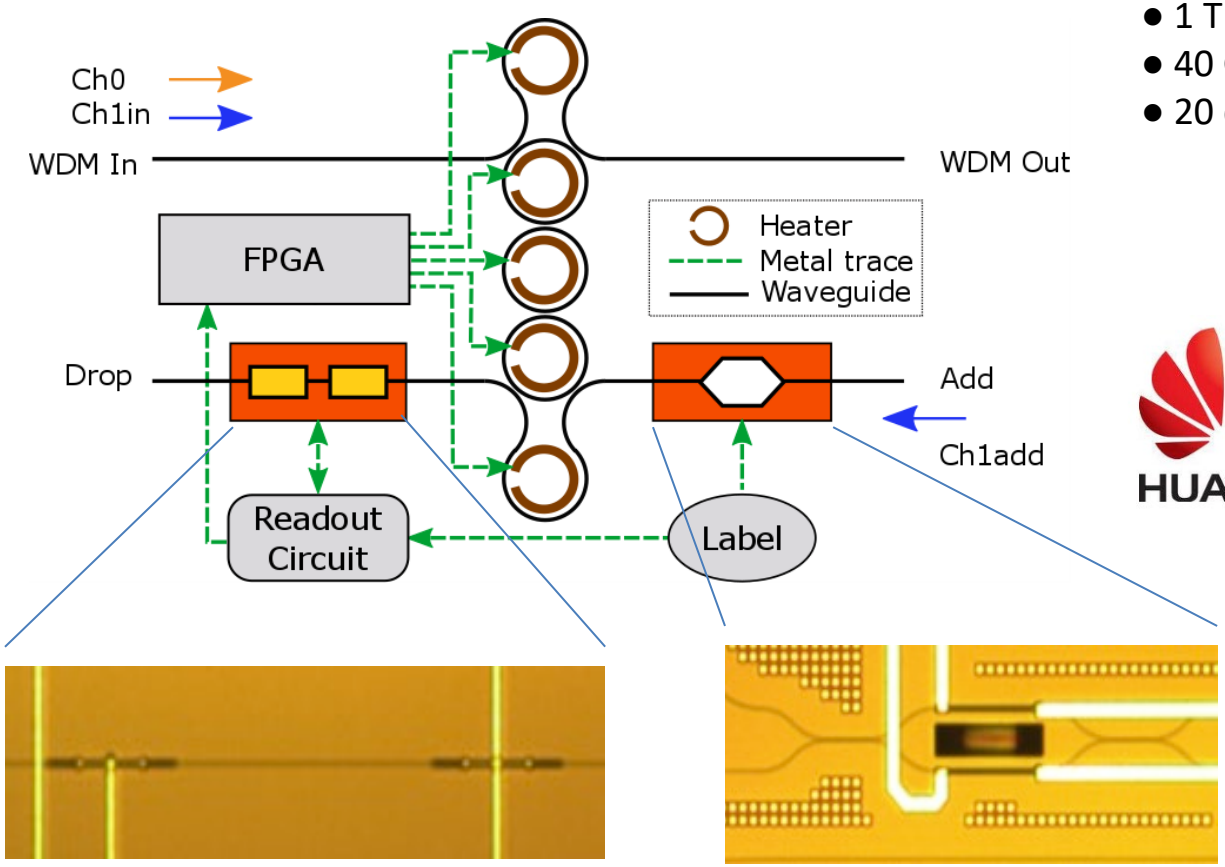


W. Bogaerts, … F. Morichetti, A. Melloni
Programmable photonic circuits, Nature 586, 207–216 (2020)

Reconfigurable hitless filter

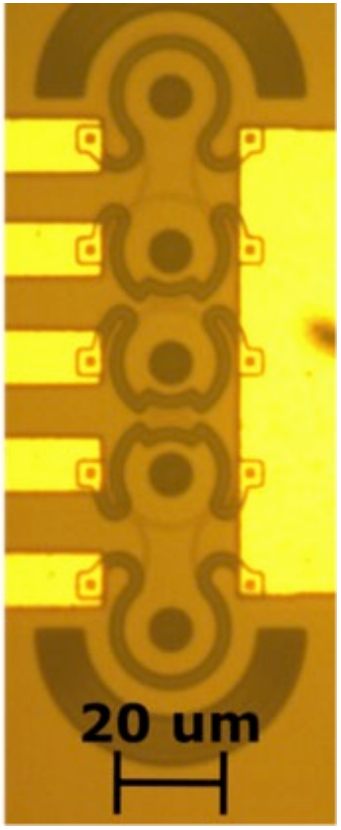
Filter characteristics:

- Hitless tuning
- 1 THz (8 nm) of Free Spectral Range (FSR)
- 40 GHz of 3 dB bandwidth
- 20 dB in band isolation

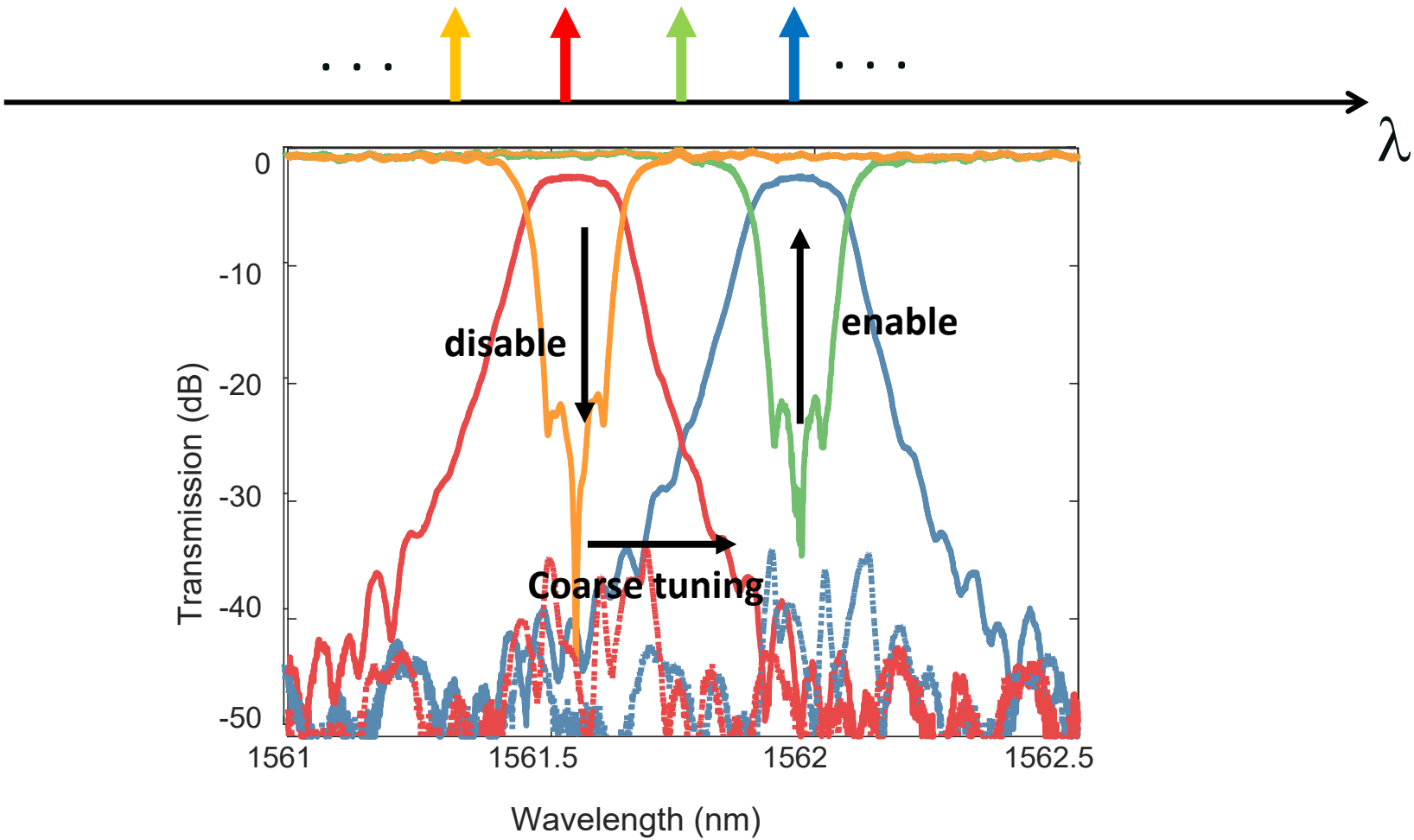


CLIPP at the Drop port to read optical label

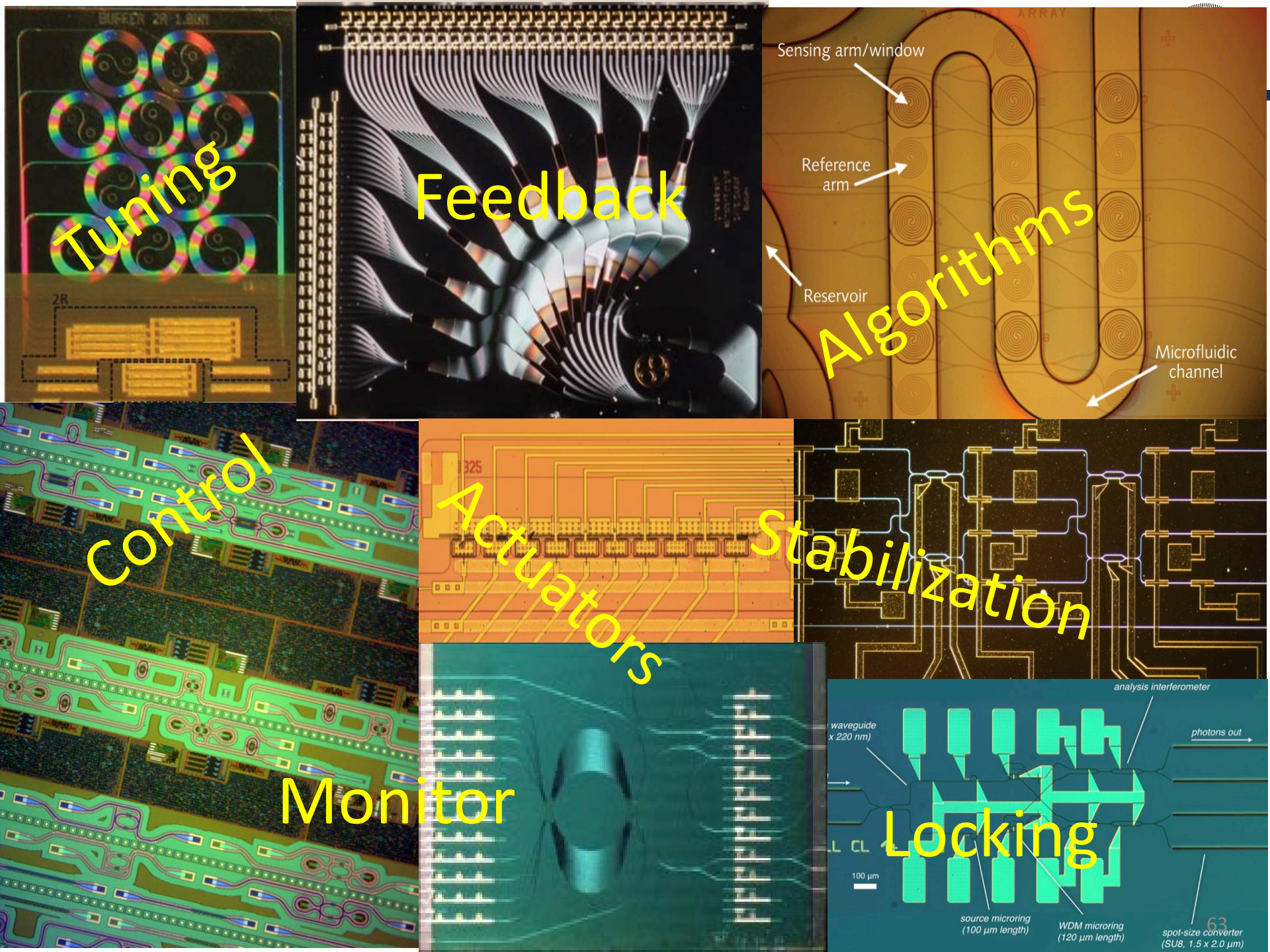
Mach-Zehnder Modulators (MZM) in the add port to apply optical label



Filter Reconfigurability

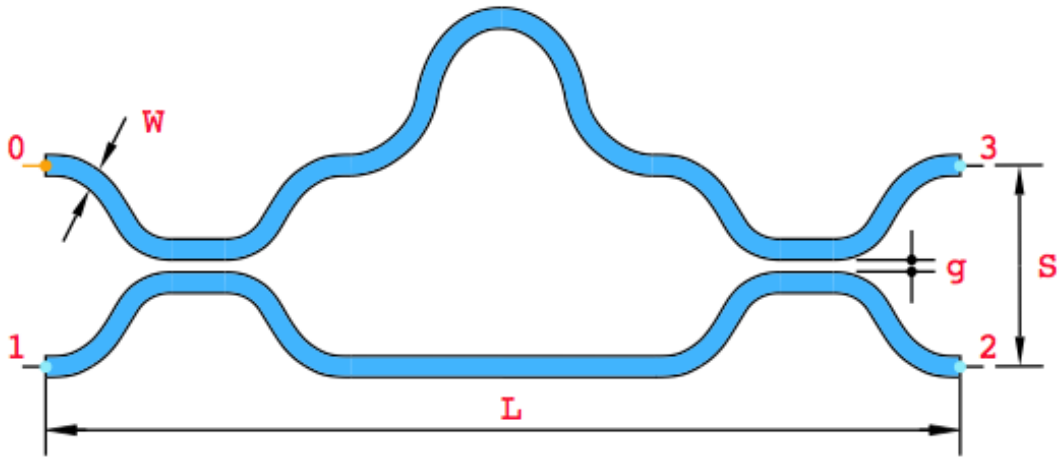


Aguiar, Douglas, et al. "Automatic Tuning of Microring-Based Hitless Reconfigurable Add-Drop Filters." *2018 OFC*. IEEE, 2018.


Tuning
Feedback
Sensing arm/window
Reference arm
Reservoir
Microfluidic channel
Algorithms
Control
Actuators
Stabilization
Monitor
analysis interferometer
photons out
waveguide
x 220 nm)
100 µm
source microring
(100 µm length)
WDM microring
(120 µm length)
spot-size converter
(SU8, 1.5 x 2.0 µm)
Locking

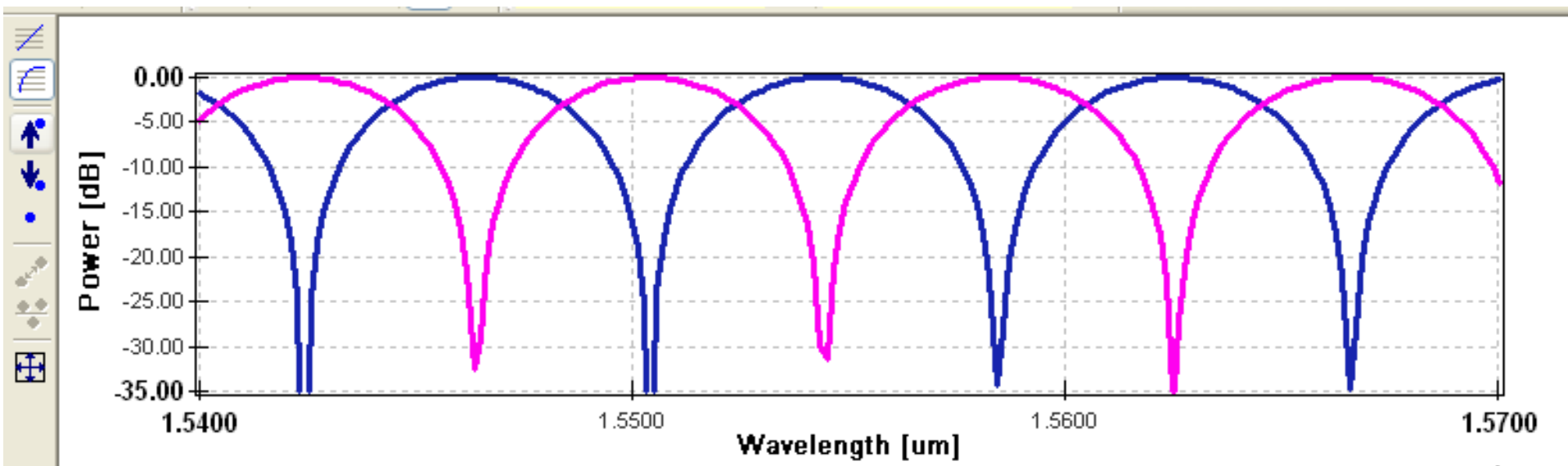
Mach-Zehnder interferometer (Filter)

Finite Impulse Response filter, FIR



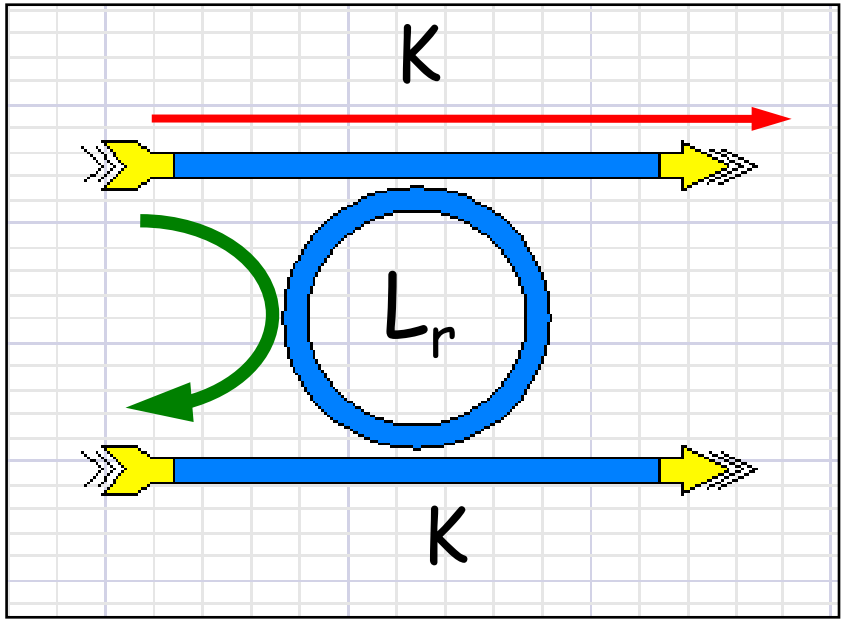
$$FSR = \frac{c}{n_g \Delta L}$$

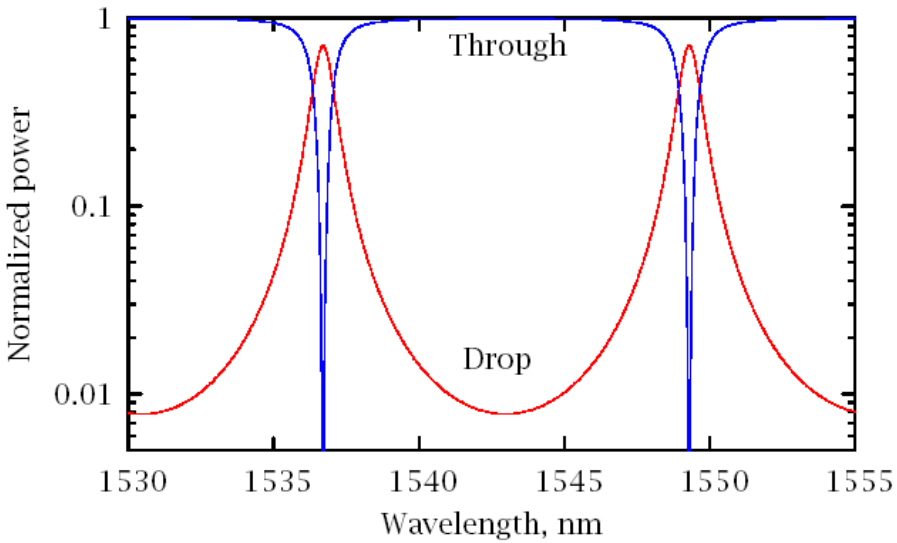
$$\frac{2\pi}{\lambda} n_{eff} \Delta L = 2M\pi$$



Ring resonators = Fabry-Perot

Infinite Impulse Response filter, IIR





$$\lambda_0 = N n_{eff} L_r$$

$$\mathcal{F} = \frac{\pi\sqrt{1-\kappa}}{\kappa} = \frac{\mathrm{FSR}}{B}$$

$$\mathrm{FSR} = \frac{c}{n_g L_r}$$

$$Q = \frac{f_0}{B}$$

$$\kappa = \sqrt{K}$$

Acknowledgments

Many people behind:

Photonics Devices Group
F. Morichetti, S. Grillanda, A. Annoni, D. Melati, N. Peserico, A. Melloni

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University of Glasgow, Glasgow, UK

James Watt Nanofabrication Center
(University of Glasgow)

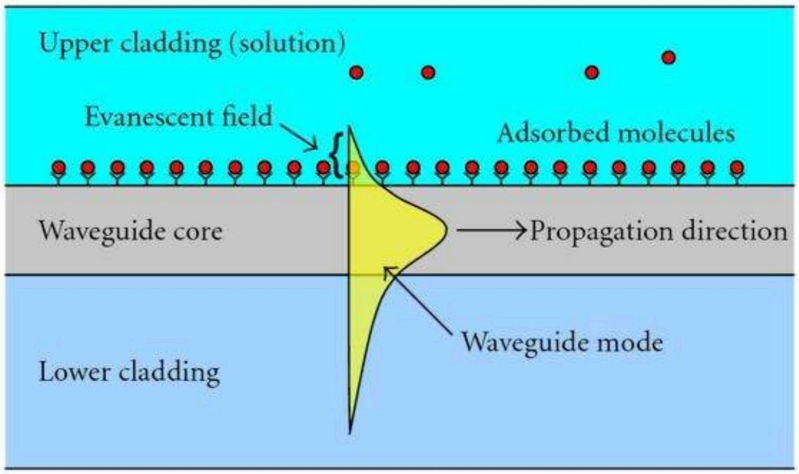
M. Nazarathy, J. Fisher
Technion University, Haifa, Israel

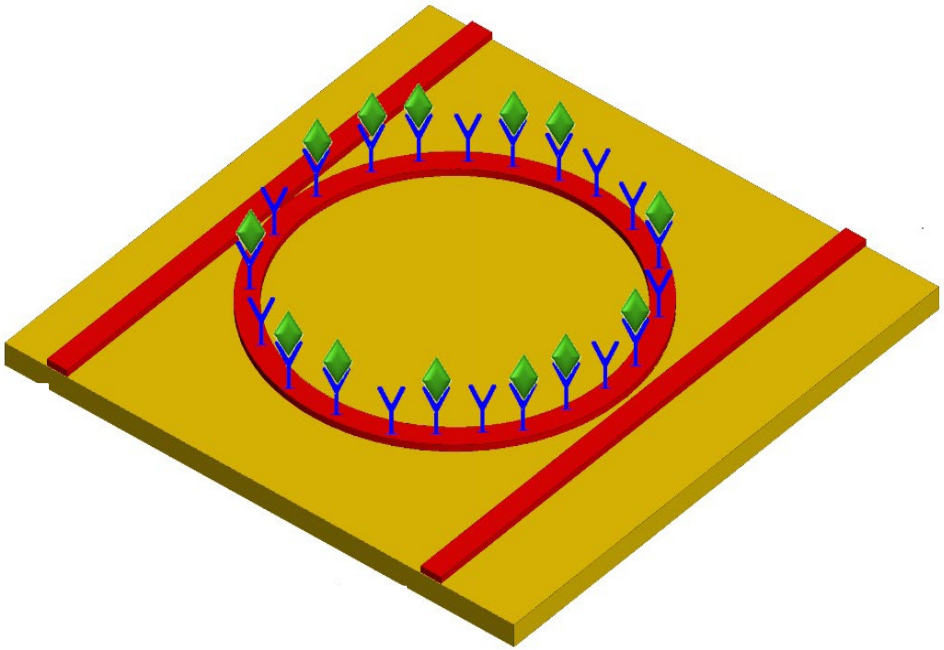
ICT_FET EU Project **BBOI**
Breaking the barriers of Optical Integration

http://www.bboi.eu

Advanced control technologies for integrated optics (ACTIO)
Fondazione Cariplo (grant 2016-0881)

Biosensing and integrated photonics

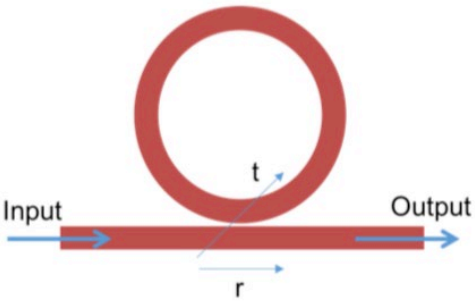


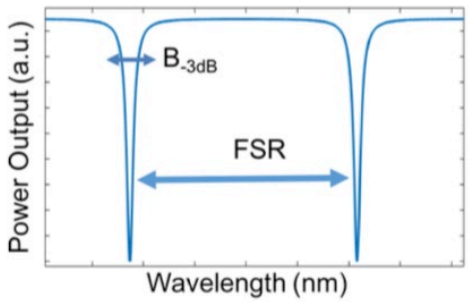


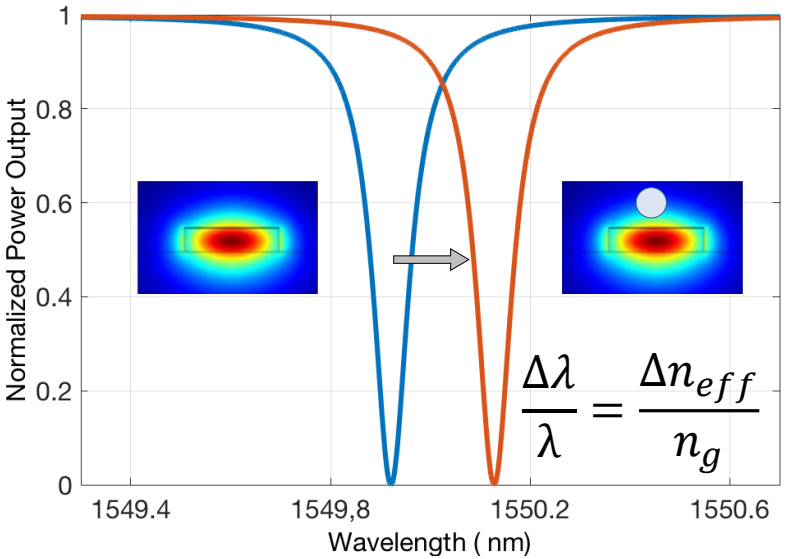
Evanescent field detection
Negligible absorbtion
Phase change of the light

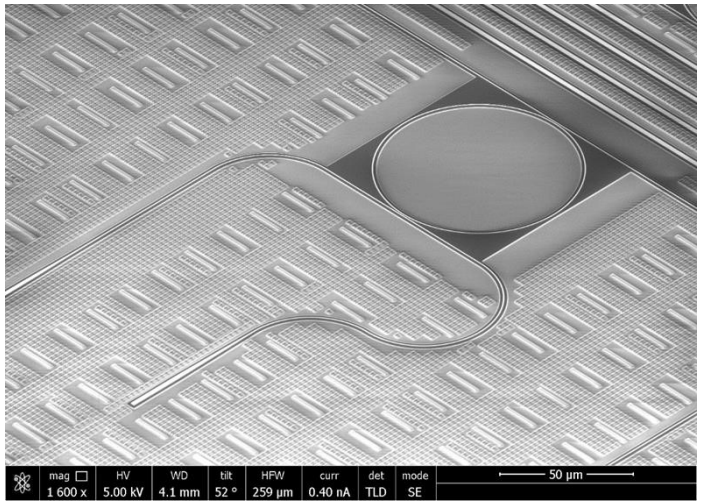
Phase-intensity conversion with an "interferometer" (ring resonator)

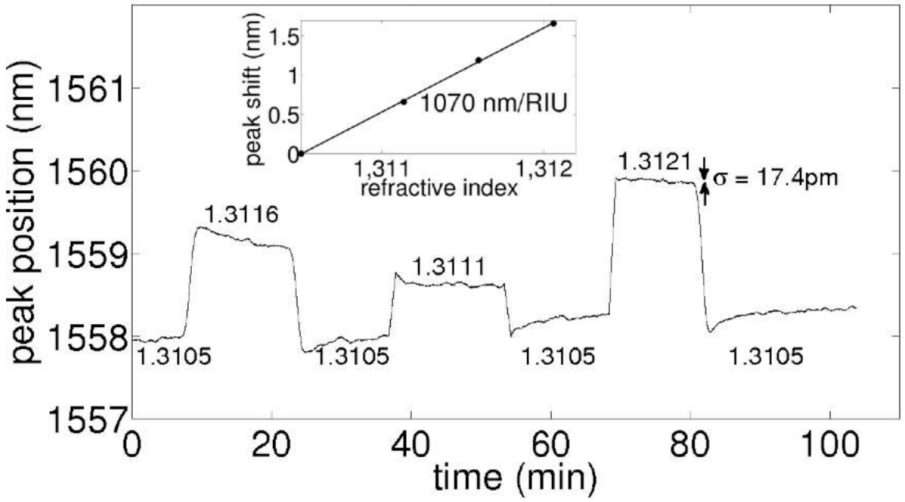
Biosensing and integrated photonics



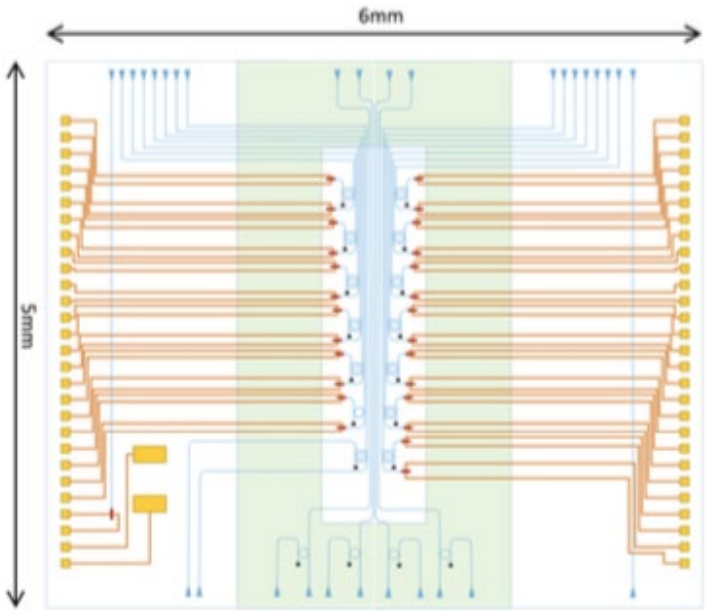


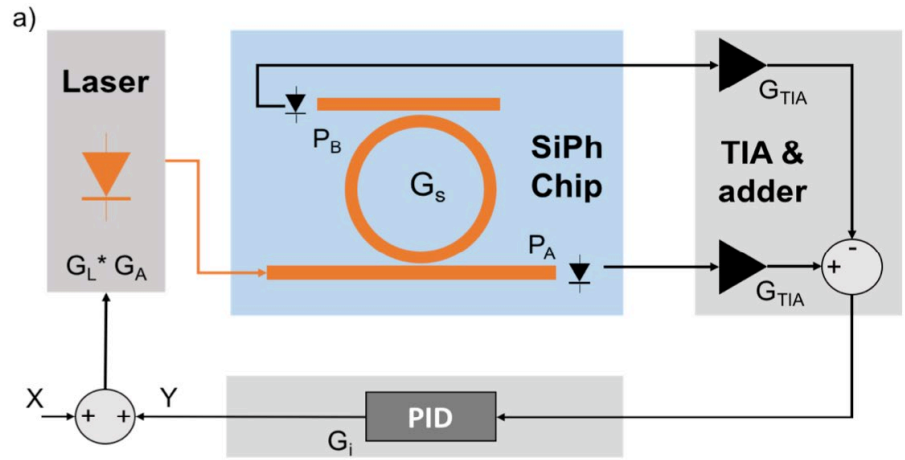


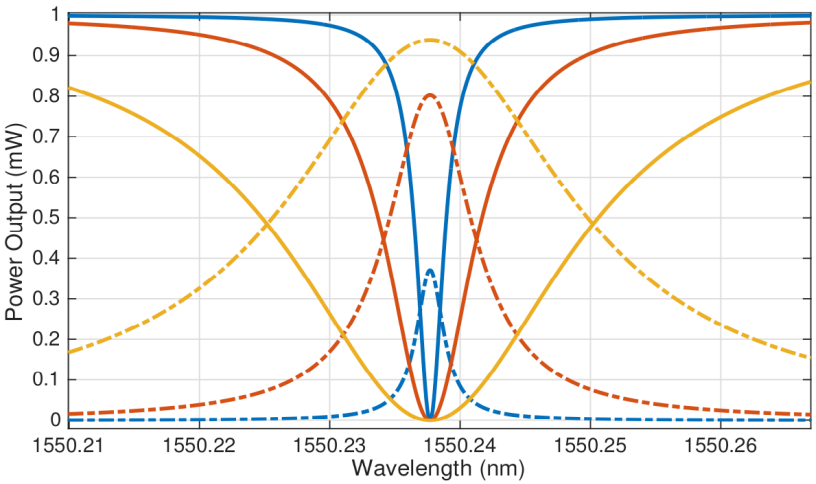


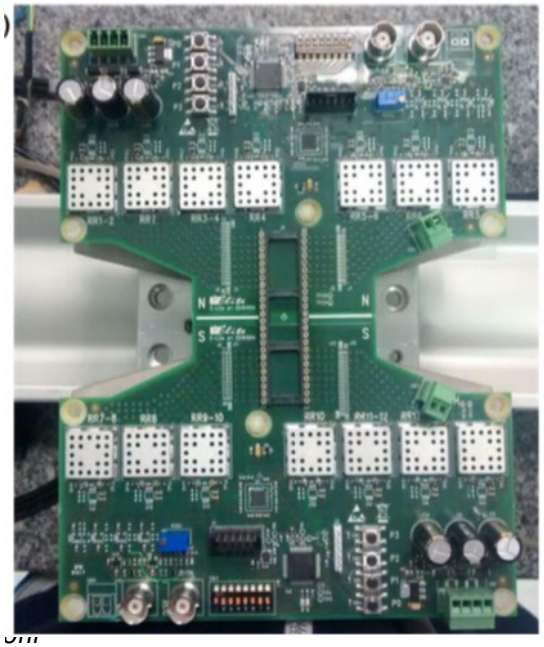


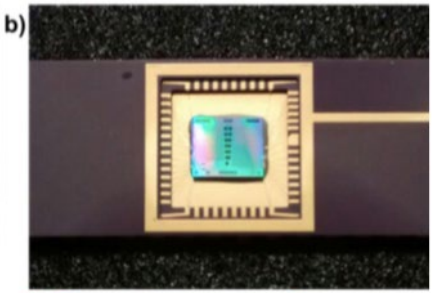
Biosensing and integrated photonics





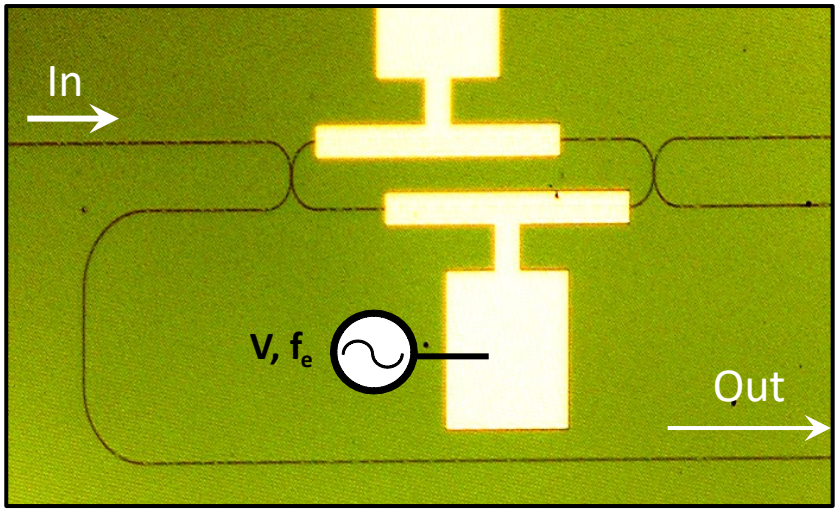


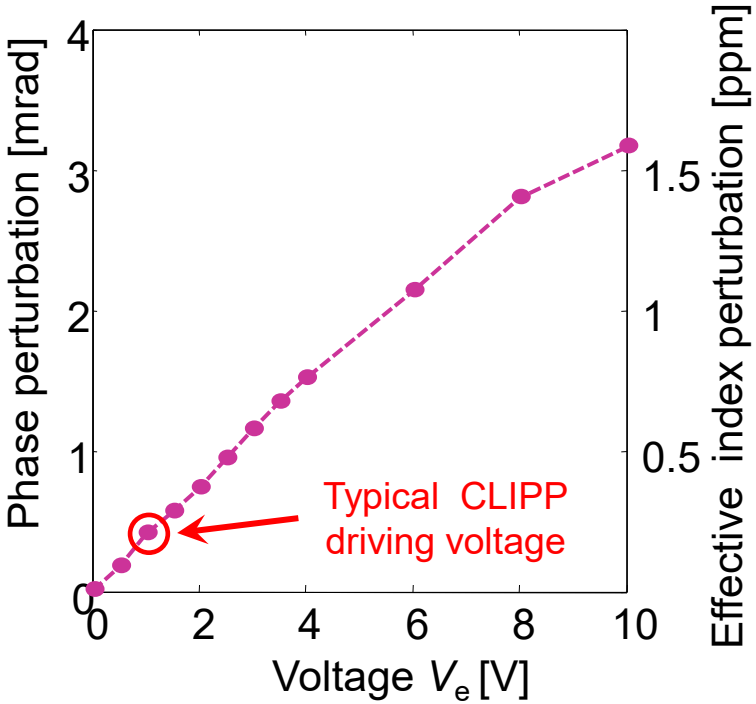




What does non-invasive mean?

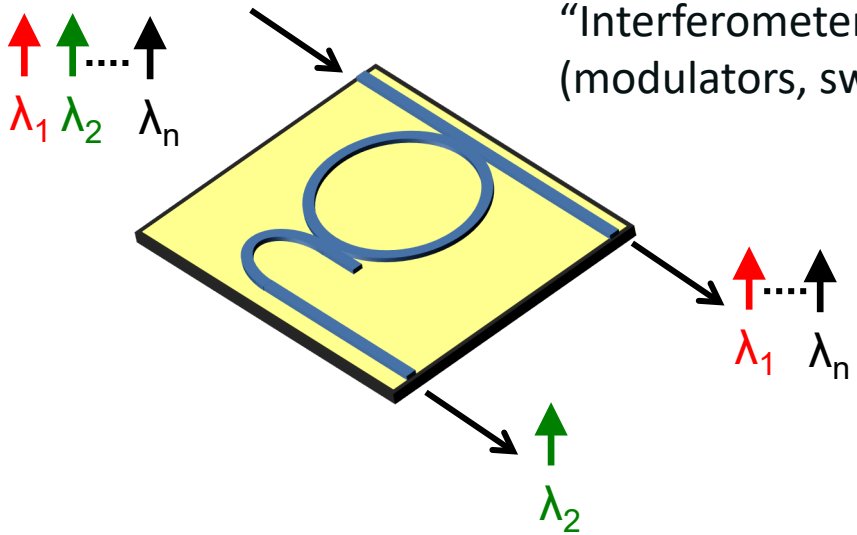
No amplitude perturbation, tiny phase modulation





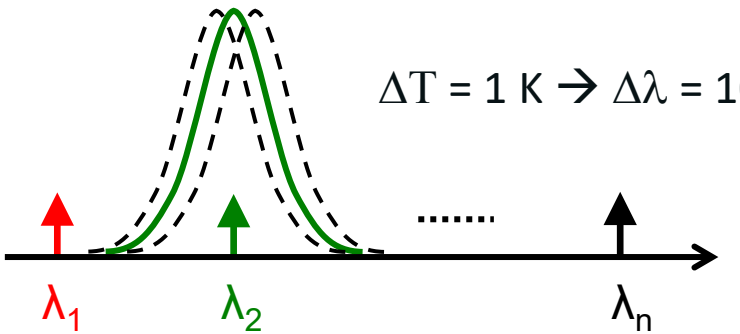
- ✓ tiny resonant wavelength shift (55 fm or 7 MHz @ 1V)
- ✓ effective index perturbation **< 0.5 ppm** (comparable to **3 mK** fluctuations)
- ✓ negligible for resonators with **Q** up to **10^6**
- ✓ perturbation due to the electro-optic coefficient of non-intentionally stressed SOI waveguides **$\chi(2)$~5 pm/V**

Feedback controlled photonics



"Interferometers" are key building blocks for optical links (modulators, switches, WDM filters…), however

suffer form strong temperature drifts and fabrication tolerances



$\Delta T = 1\ K \rightarrow \Delta\lambda = 10\ GHz$

$\Delta w = 1nm \rightarrow \Delta\lambda = 100\ GHz$

Photonics needs feedback control

- automated tuning process
- thermal stabilization & wavelength locking

Direction of the λ-shift?

Small **dither signal** applied to the ring
(Padmaraju et al., J. Lightw. Techn. 32(3), 2014)

Microring embedded in an interferometer (dither-free)
(Cox et al., CLEO: 2013)

Unambiguous location of the resonance shift, yet…

….**photon tapping** from the waveguide required