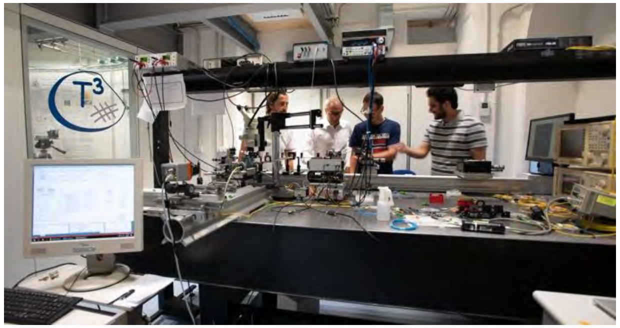
POLITECNICO DI MILANO

Integrated photonics

(The need to peep light)

Andrea Melloni

DEIB, Politecnico di Milano, Milano, Italy



Photonic Devices Lab

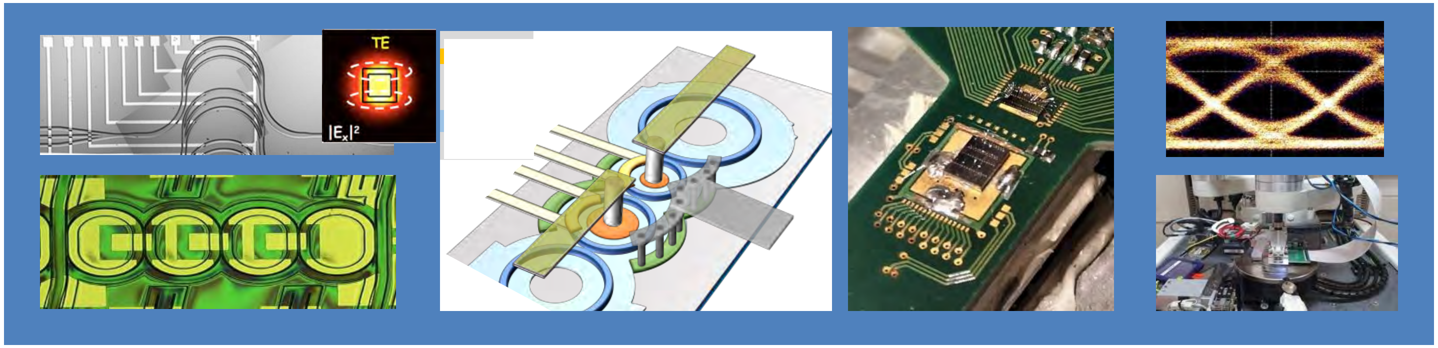
Andrea Melloni
Francesco Morichetti

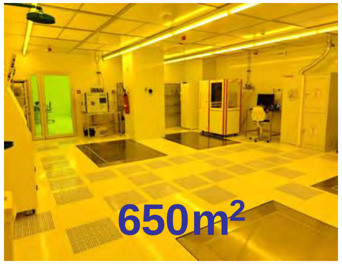
http://photonics.deib.polimi.it

POLITECNICO DI MILANO

polifab
POLITECNICO DI MILANO

PoliMi micro- nano- technology center





life.augmented

HUAWEI

AFR Advanced Fiber Resources

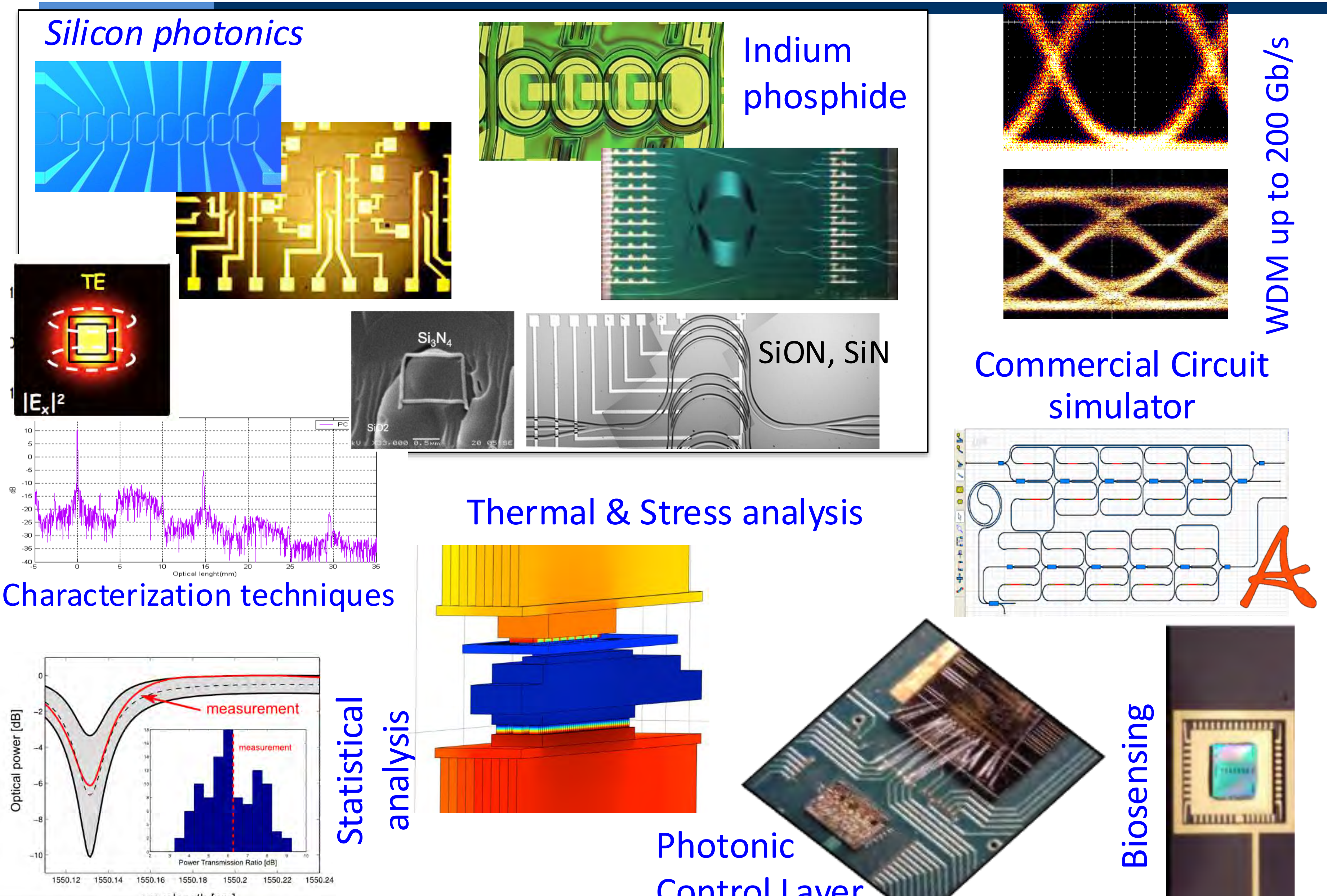
PiX·EUROPE

PHOTONPATH

LFOUNDRY Solutions for great visions

PHOTONICS21

>25 years of Multidisciplinary photonics@ PoliMi



PHOTONICS21

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.

Photonics21 – Photonics PPP

Annual Activity Report 2017

PHOTONICS21

PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Europe's age of light!

How photonics will power growth and innovation

2020-2030

Download from:

https://www.photonics21.org

PHOTONICS21

Photonics is pervasive

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Photonics

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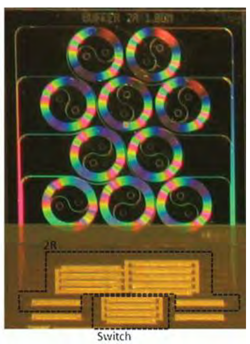
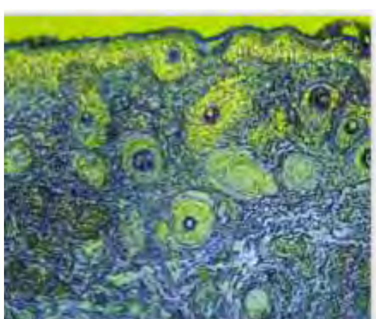
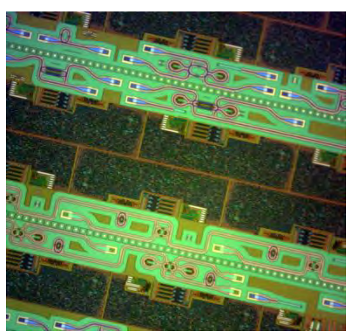
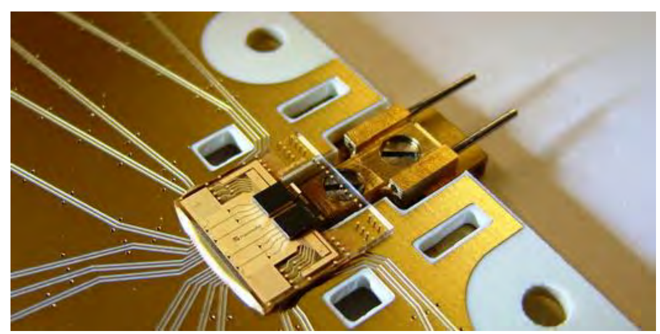
EPIC European Photonics Industry Consortium

PHOTONICS21



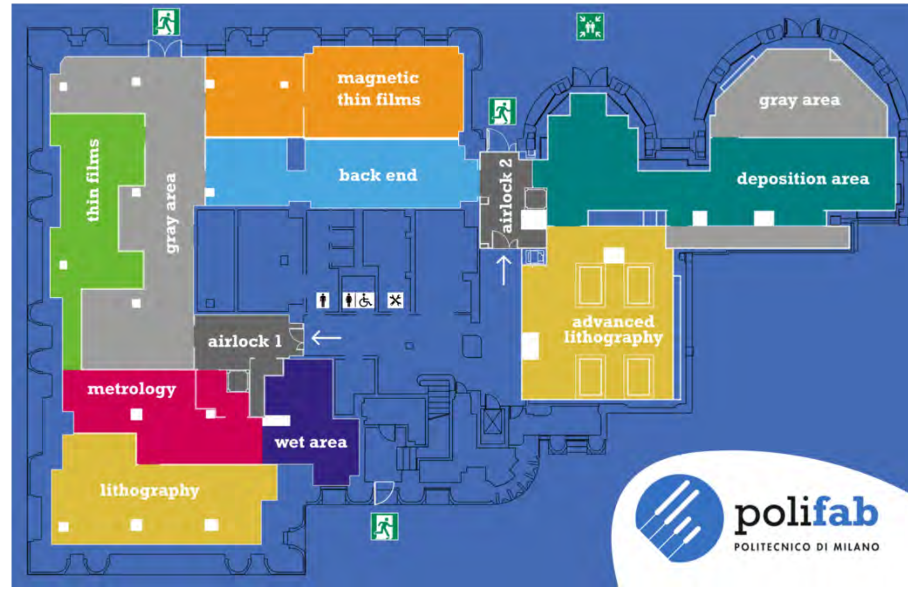


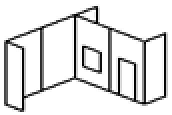




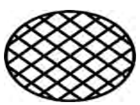
Polifab - the micro and nano fabrication facility of PoliMI

*Polifab provides **high technological standards** for a wide range of applications: photonics, micro and nanoelectronics, MEMS, biotechnologies, advanced materials and nanotechnology.*
*Polifab acts as an **aggregating** center for academic researchers, start-ups and companies*





+600 mq cleanroom, ISO 06

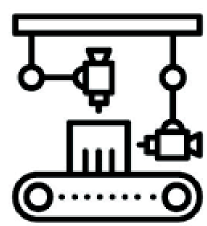


Up to 200 mm wafers

11 staff members

Open access

+160 researchers in 2024



~ 25 M€ tools installed

~ 40% from JRC with STm

Multidisciplinary approach, flexibility

Polifab facilities

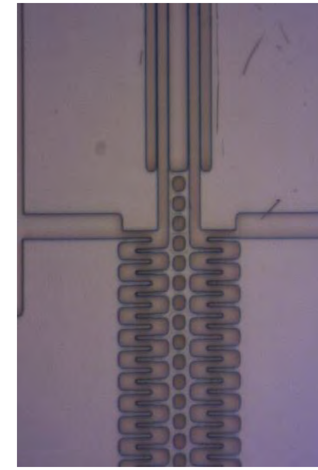
Lithography
- Photolithography
- 2 Maskless photolitho
- Electron beam lithography 50keV
- Thermal scanning lithography

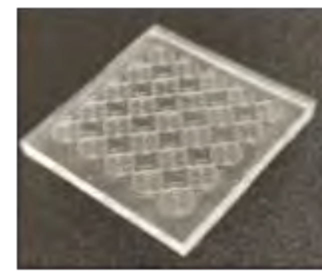
Deposition
- Electron beam evaporation
- Thermal evaporation
- Sputtering for metals and oxides
- Chemical vapor deposition
- Electrodeposition
- ALD

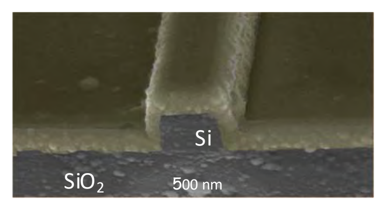
Etching
- Reactive ion etching
- Deep RIE
- Ion beam etching
- Plasma ashing
- Wet etching
- Lift-off

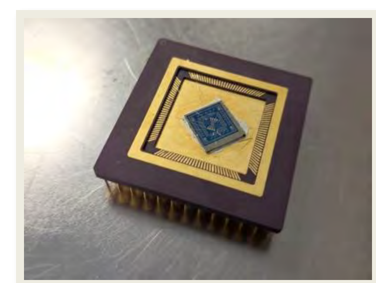
Characterization
- Optical microscopy
- Stylus profilometry
- Optical profilometry
- SEM, AFM
- Ellipsometry
- Electrical measurements
- X-ray diffraction
- EDX
- Micro-Raman spectroscopy

Backend
- Annealing ovens
- Rapid thermal annealing
- Wire bonding
- Dicing
- Pick & Place
- Alignements tools
- Two-photon polymerization tool









http://www.polifab.polimi.it

Contents

- (short) Overview on integrated photonics
- The photonic chip as system
    - Monitors
    - Actuators
    - (Feedback and Control)
- Applications: routing, tuning and computing

1969: 56 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

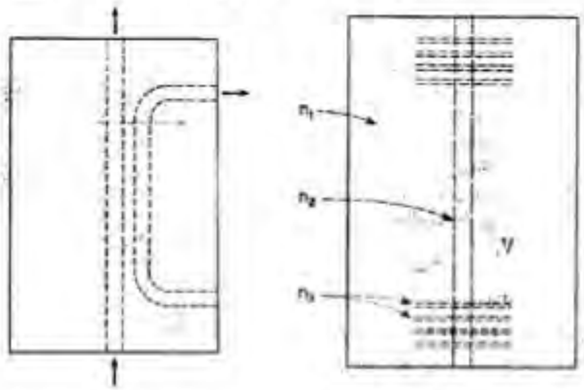


Fig. 6 — Directional coupler type hybrid. : 3 — Resonator using planar waveguide.

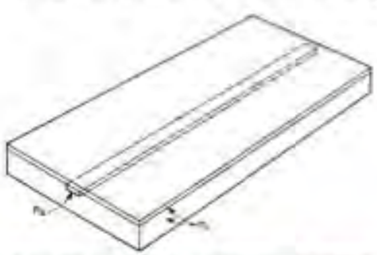


Fig. 1 — Planar waveguide formed using photolithographic techniques.

Bends in Optical Dielectric Guides

By E. A. J. MARCATILI

(Manuscript received March 3, 1969)

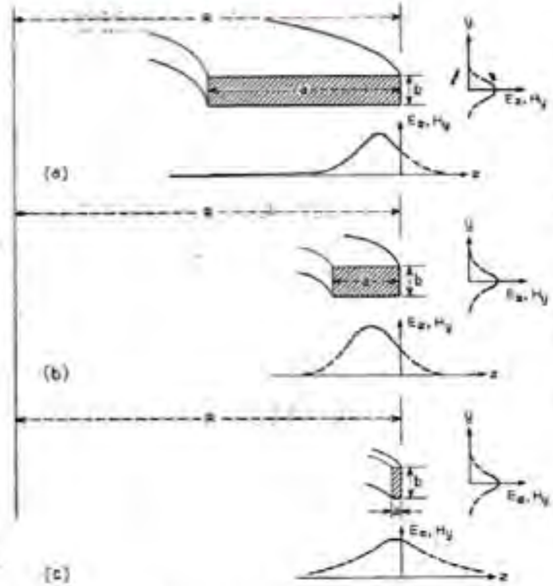


Fig. 6 — Field distribution as a function of guide width a with (a) $a/A \gg 1$, (b) $a/A \cong 1$, and (c) $a/A \ll 1$.

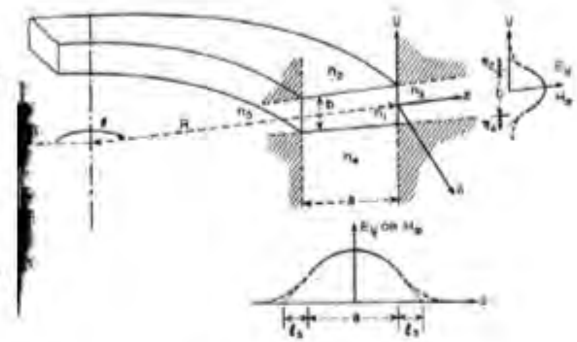


Fig. 2 — Curved dielectric guide.

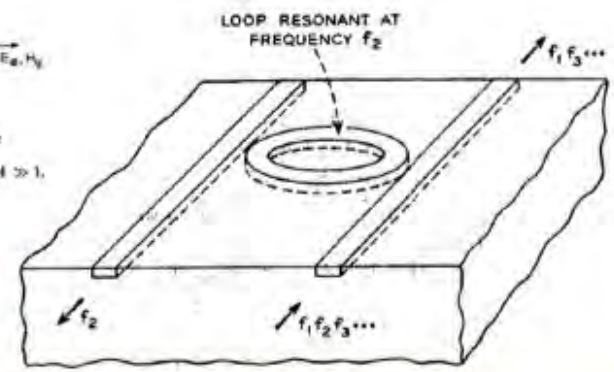
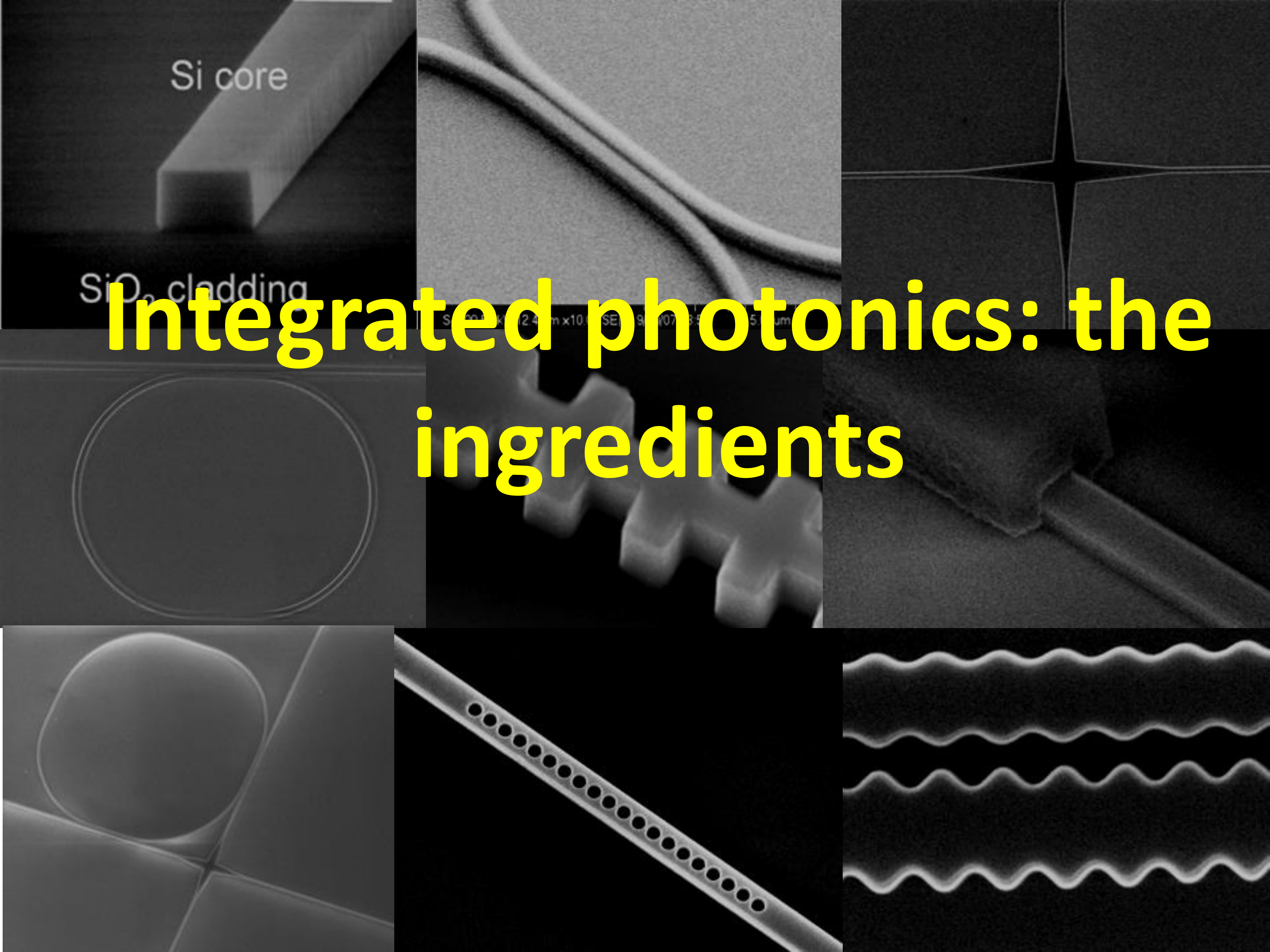
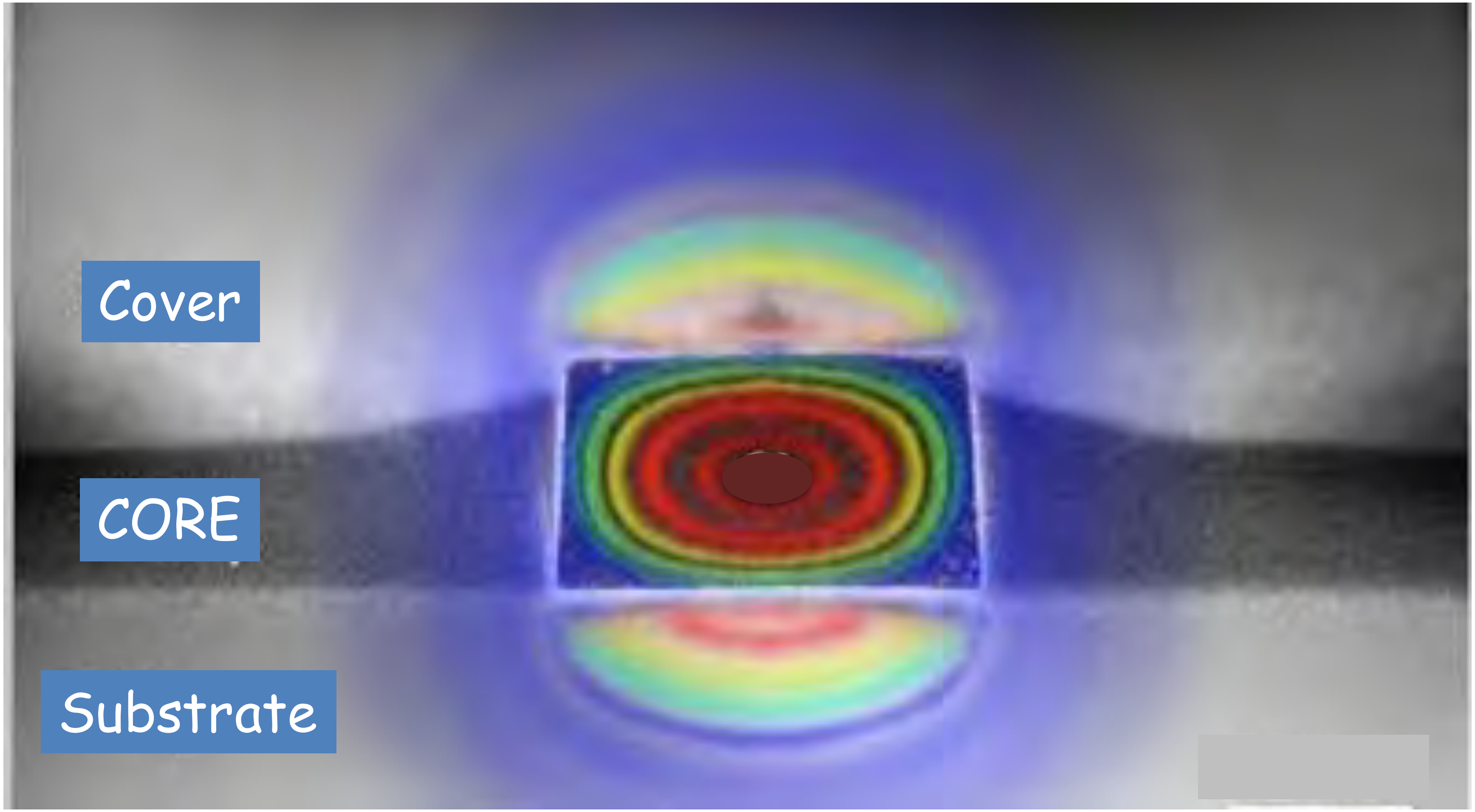


Fig. 1 — Channel dropping filter (ring type).

Integrated photonics: the ingredients



WAVEGUIDE



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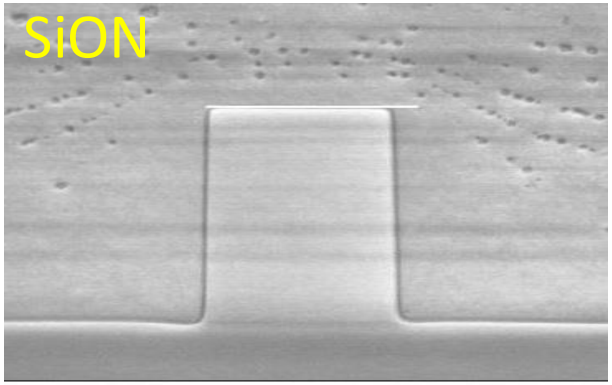
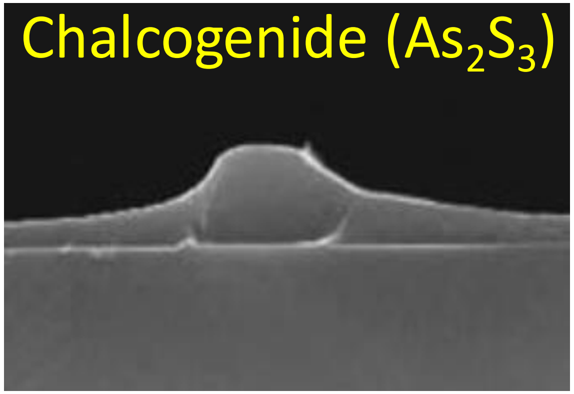
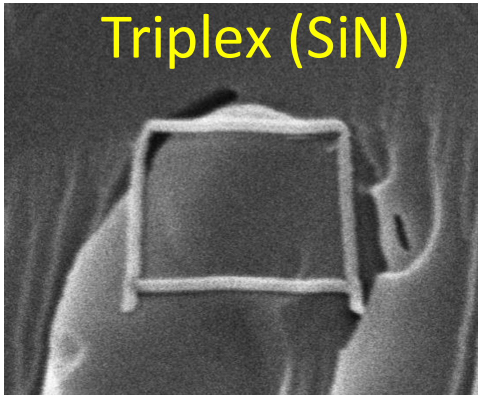
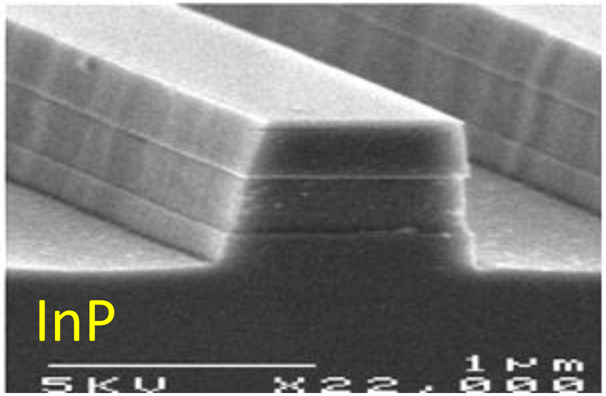
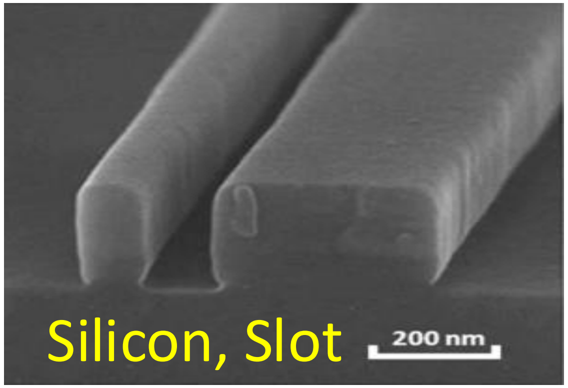
Waveguides...

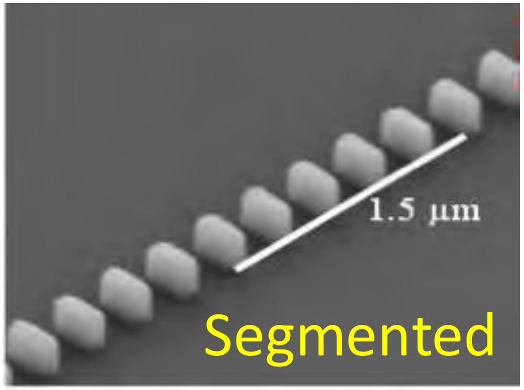

SiON

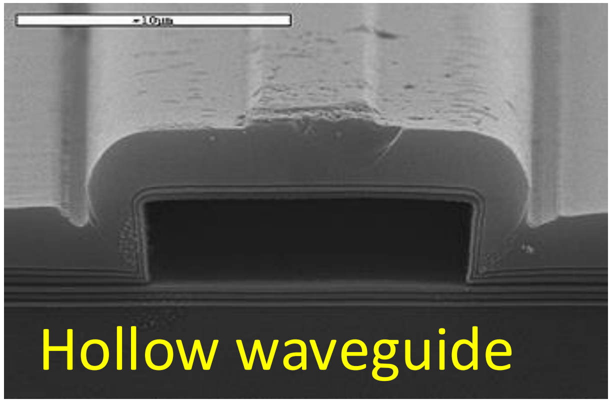

Chalcogenide (As_2S_3)

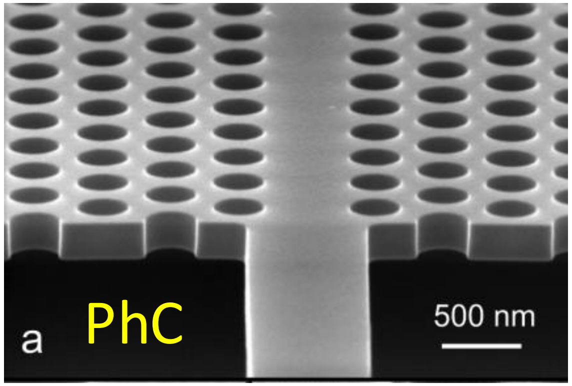

Triplex (SiN)

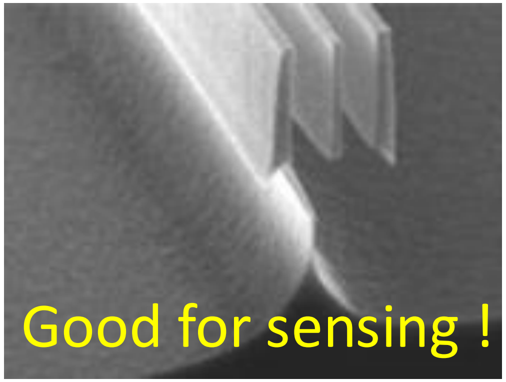

InP
1 μm
5KV X22,000


Silicon, Slot
200 nm

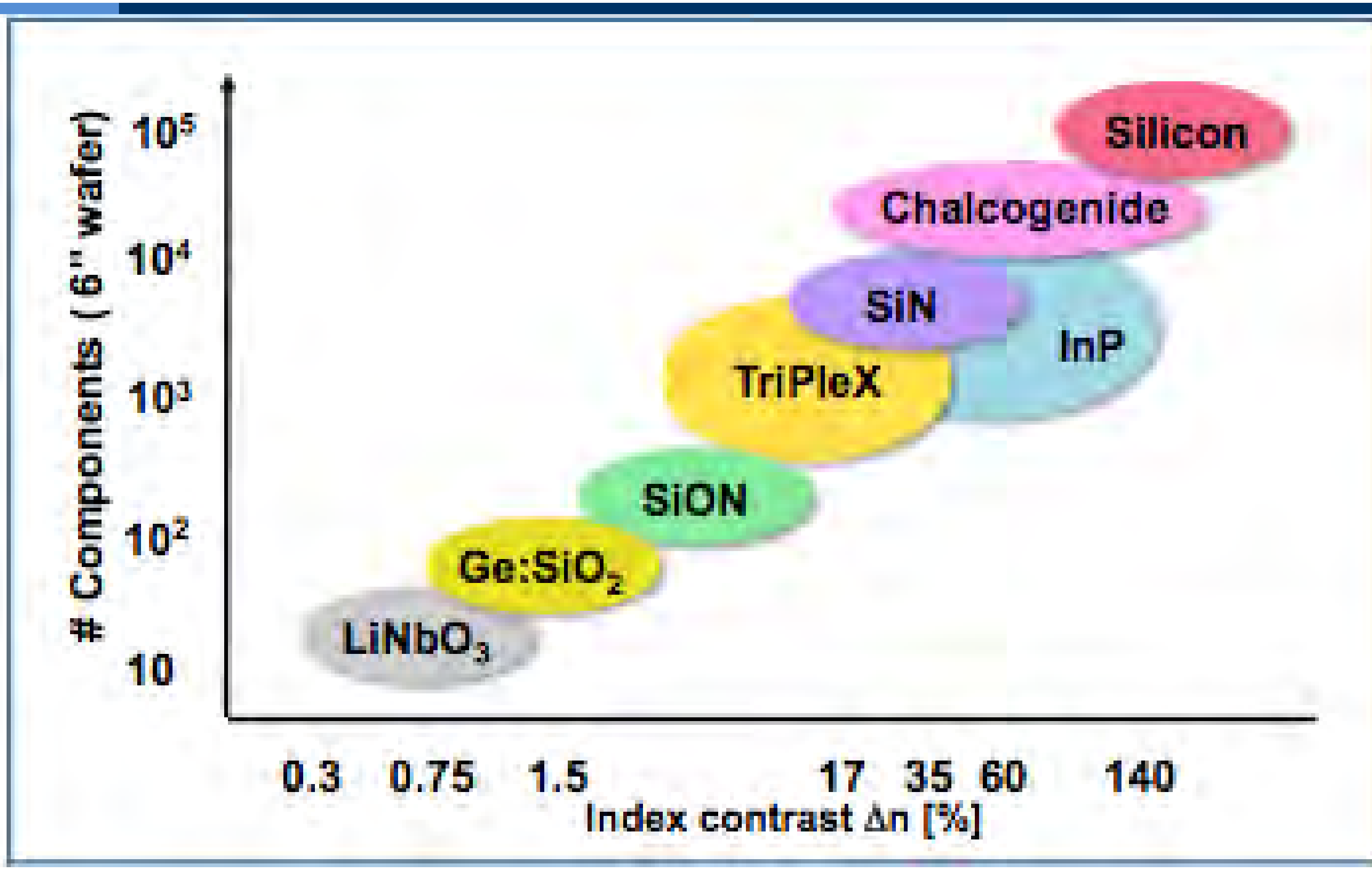

1.5 μm
Segmented

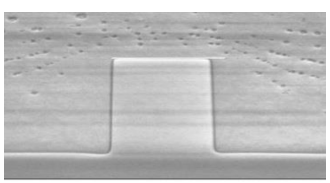

Hollow waveguide

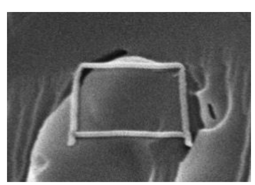

a
PhC
500 nm

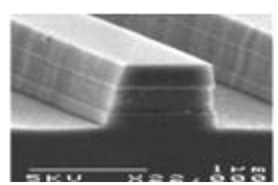

Good for sensing ! !

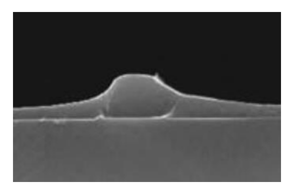
Materials for Photonic circuits

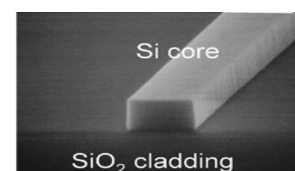












$Ge:SiO_2$ 0.5…3 %

SiON 2…8 %

Si_3N_4 38 %

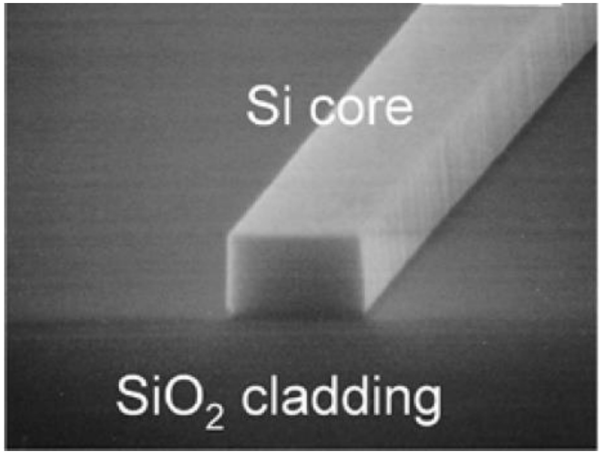
InP 3 / 70 %

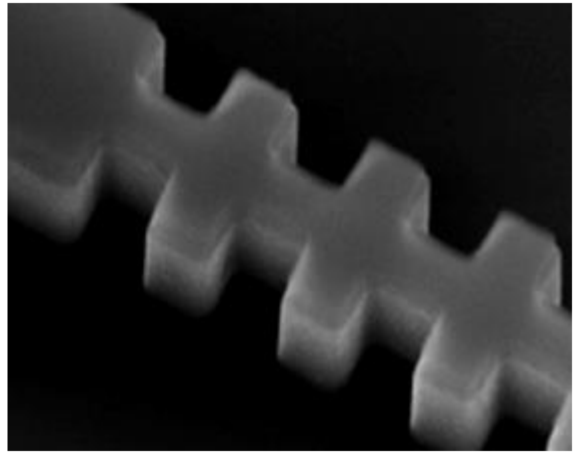
As_2S_3 60…100 %

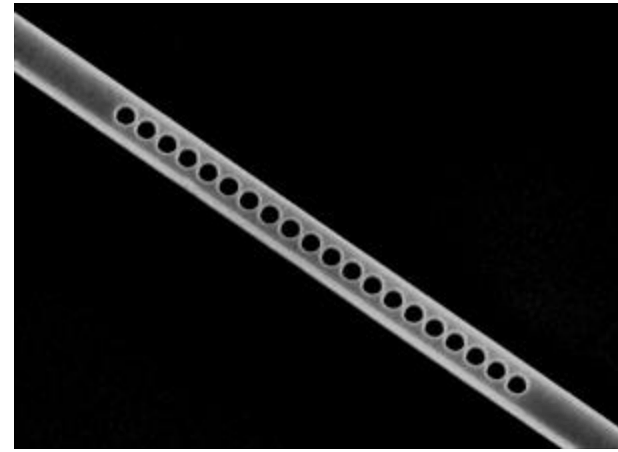
Silicon 140%

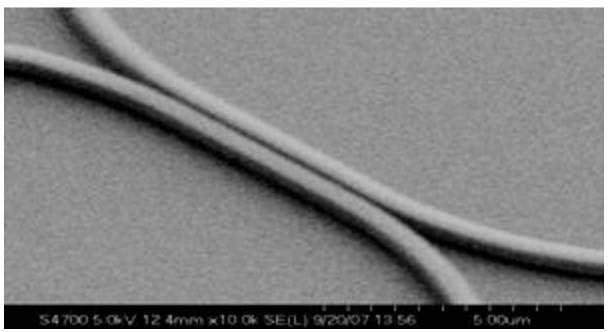
Δn

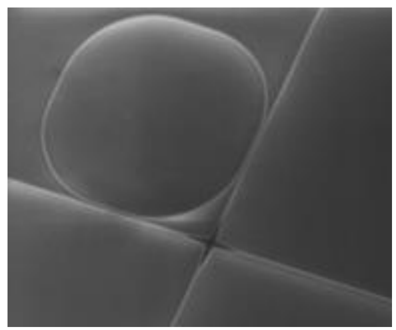
Integrated Photonics Building Blocks

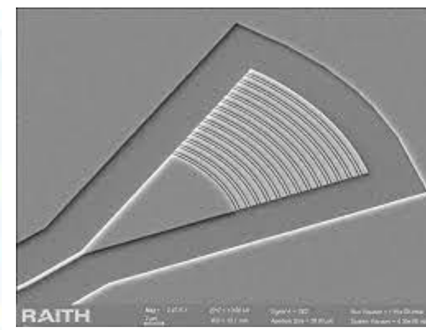


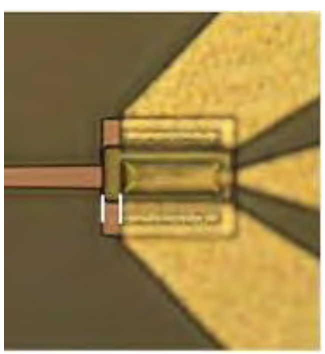


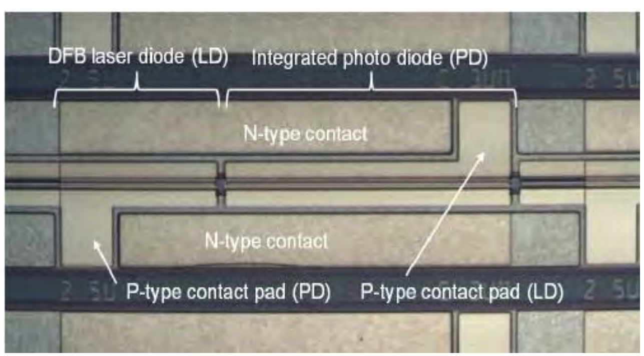


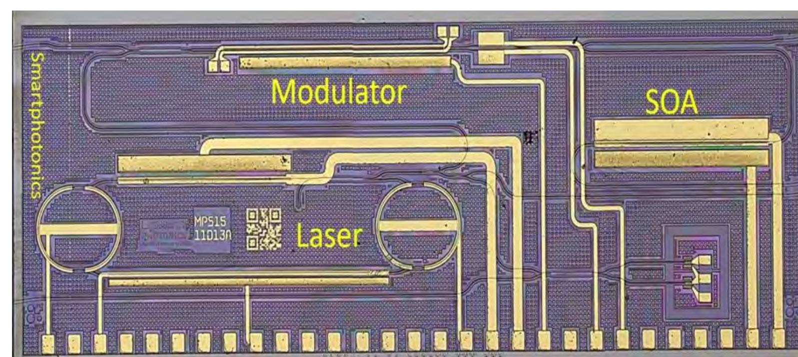




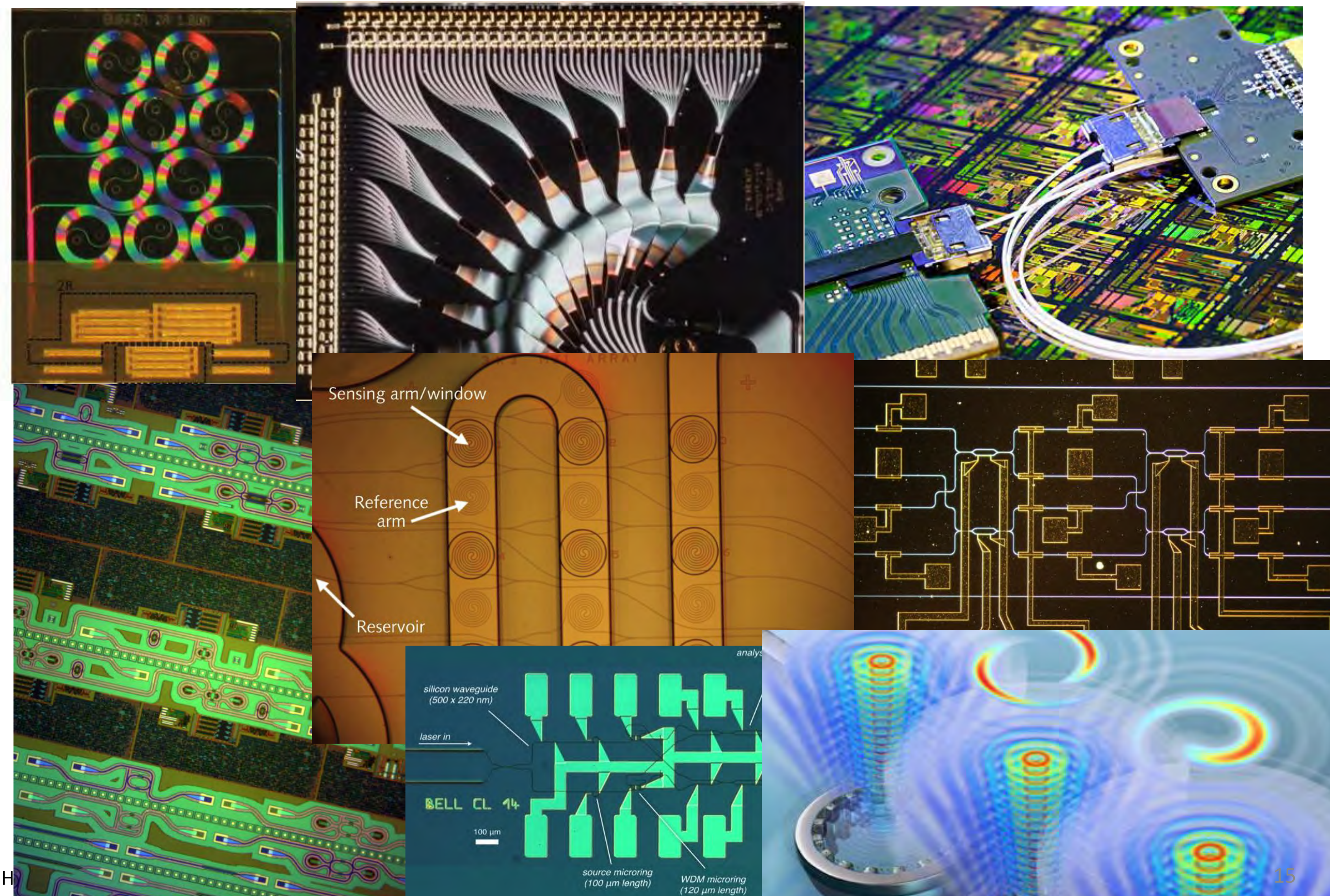




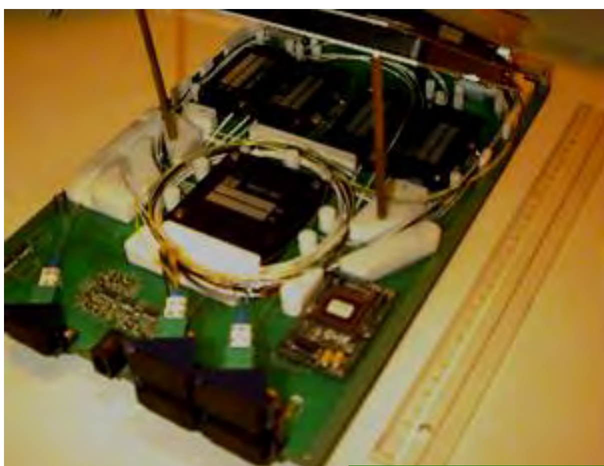




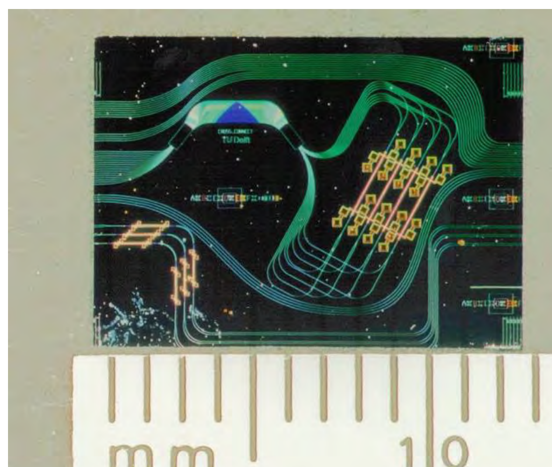
Integrated photonics: towards ubiquitousness



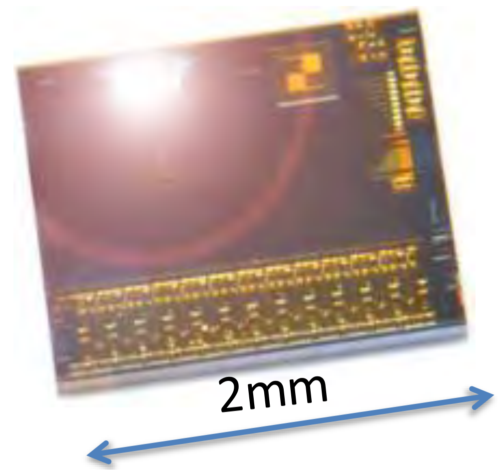
The need of Integrated Photonics



1994
4-λ 2x2 OXC



1998
4-λ 2x2 OXC



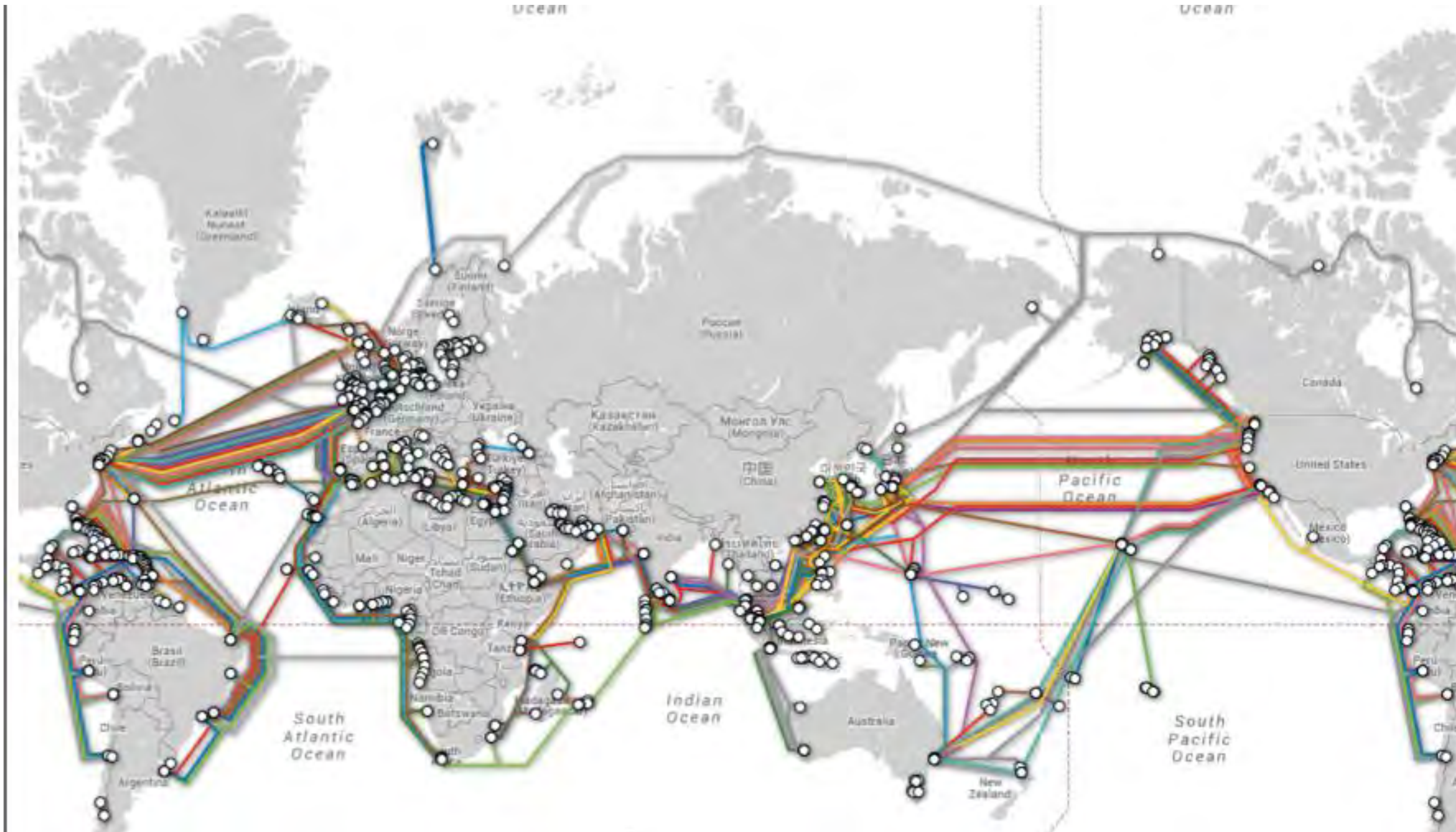
2018 Transceiver
2.4Tb/s, 12000km

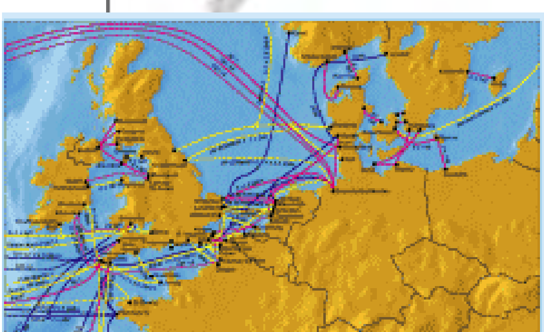
Photonic Integration: Motivation

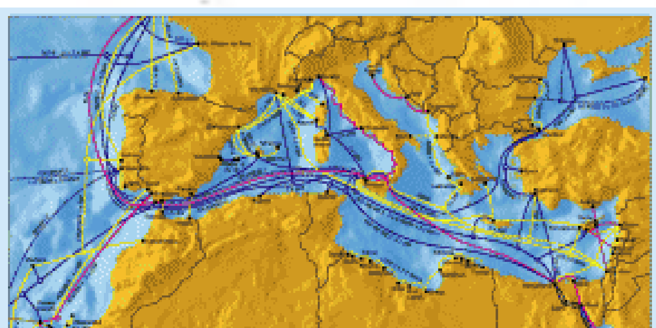
- Greatly reduced component cost
  - Monolithic interconnection of device elements
  - Simpler packaging and assembly, standard processes
- High reliability
  - Less interfaces
- High functionality
  - Many more functional elements per chip, higher creativity in design
- High phase stability, excellent 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

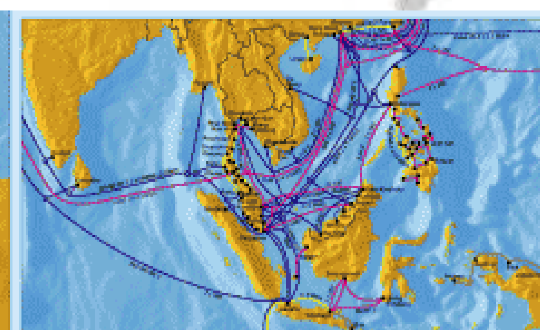
- Reduce packaging costs
- Co-integration with electronic, microfluidic, MEMS, microwave, ….
- Volume production

Submarine cables, optical fibers





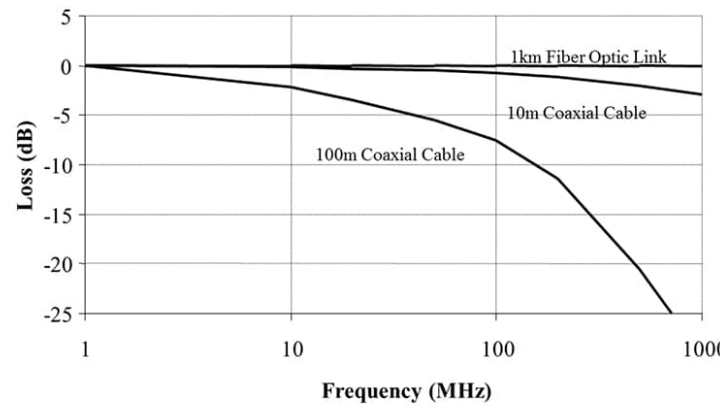




Why optical fibers?

- **Data Rate:** Optical fibers support **Tbps speeds**, copper cables are limited by high frequency metallic loss (**no skin effect**)
- **Longer Distance:** Optical fibers can transmit data over many km without significant signal loss.
- **Power Consumption:** Optical transceivers consume **less power per bit** than copper alternatives, making them **more energy-efficient**
  Optical fibers generate **less heat** than high-speed copper cables.
- **Latency:** Optical signals travel at **near the speed of light (both in fibers and copper cables !... See table)** – Hollow core fibers?
- **Electromagnetic Interference (EMI):** optical fibers are **not affected by EM noise**, ensuring **signal integrity** in high-density environments (like thousands of servers)
- **Space & Weight:** Optical fibers are **thinner and lighter** than copper cables, **better airflow and cooling**

Loss v Frequency Comparison for Fiber & Coaxial Cable



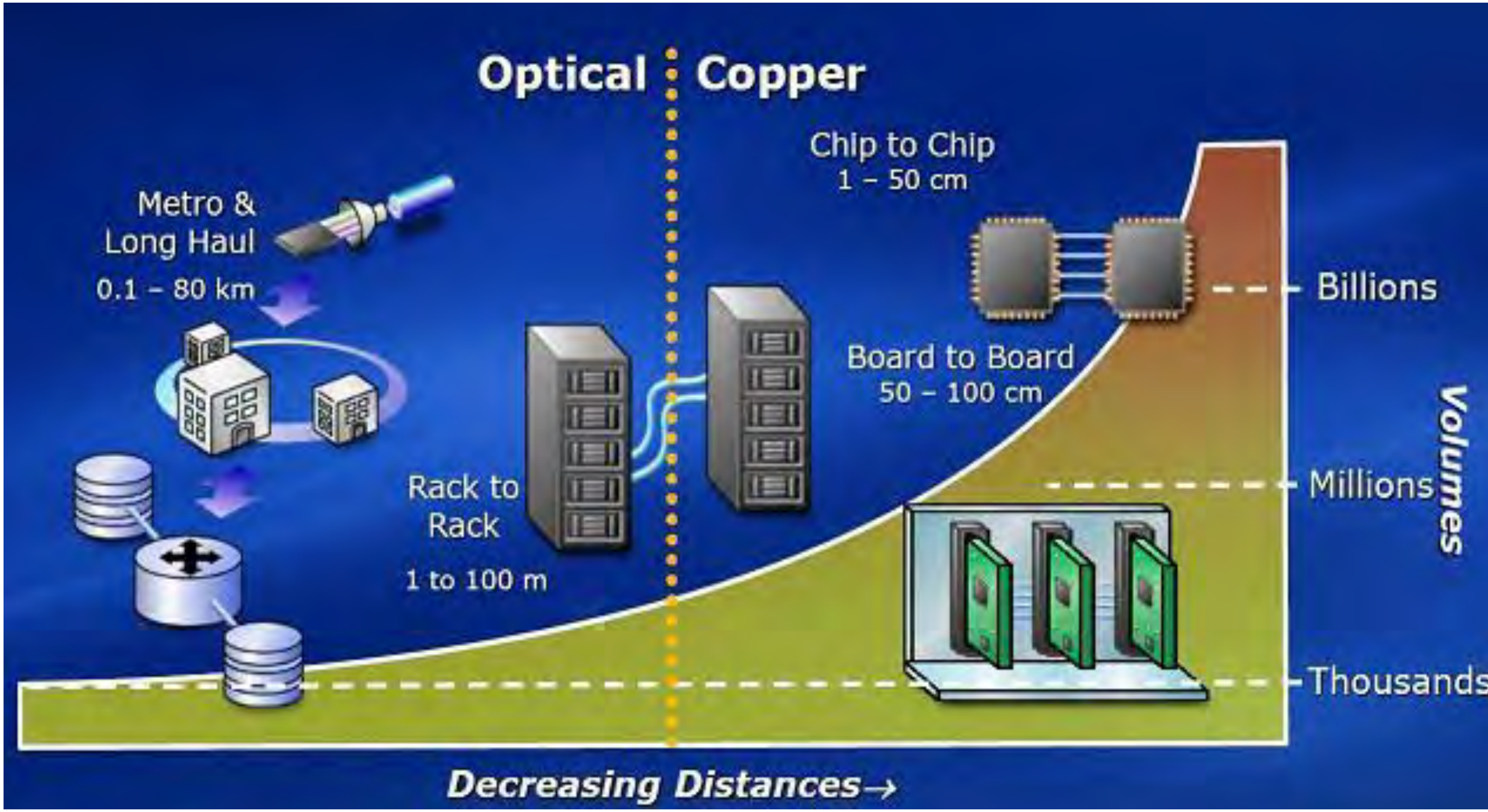
Material	Dielectric constant	VOP
TYPICAL INSULATION MATERIALS		
Cellular TFR	1.38	85%
FEP	2.1	69%
Silicone	3.6-2.1	53-69%
TFE	2.1	69%
Polyethlene	2.3	66%
PVC	8.2-3.0	35-58%
Nylon	4.5-3.6	47-53%
Optical fiber	**2.1**	**70%**

Velocity of propagation (VOP)

$$VOP[\%] = \frac{v}{c}$$

c speed of light (vacuum)

Photonics in datacenters & AI infrastructures…



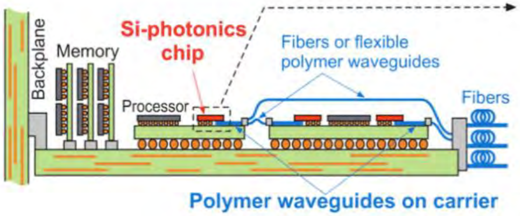
Photonics in datacenters & AI infrastructures…

Today

Optical Transceivers

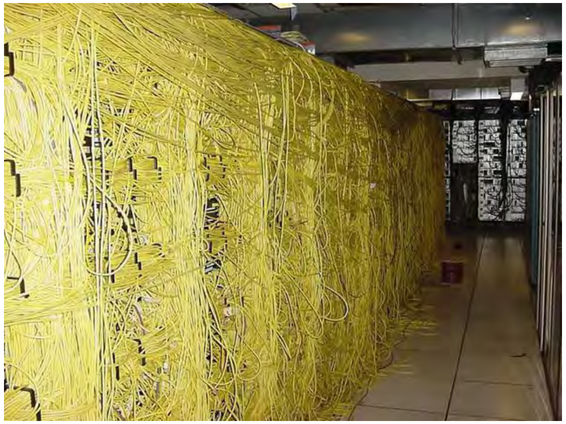
Convert electrical signals from GPUs, CPUs, and switches into optical signals for high-speed data transmission.

400G–800G today, moving toward **1.6T** optical links in near future.



Optical Fibers Today

Intra-Rack Communication (< 2 m) → **Multimode** fibers replacing copper cables
Inter-Rack Communication (< 50 m) → **Multimode** fibers
Inter-cluster Networking (100 m – 10 km) → **Single-mode** fibers
Inter Data Center Links (50 km – 1000+ km) → **Single-mode** fibers

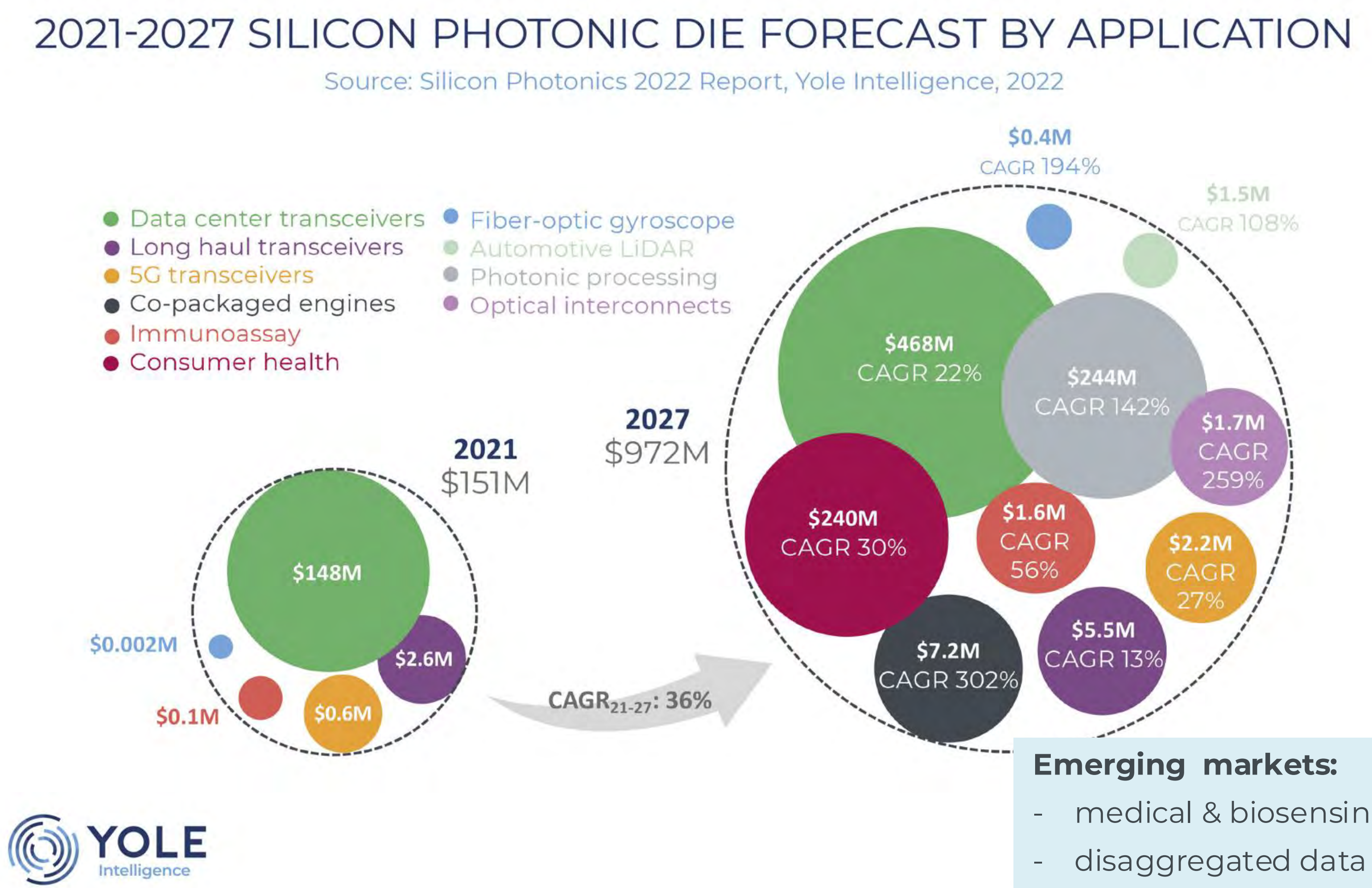


Optical Switches (Silicon Photonics & DWDM) Tomorrow (< 5 years)

Use **photonic switching** to manage massive AI workloads more efficiently than electrical packet switches

- <50ns switching time (faster than electrical packet switches).
- No electrical-to-optical conversion overhead (direct optical switching).

Silicon Photonics: roadmap and markets



Datacom is main market

(20% transceiver → 30% by 2027)

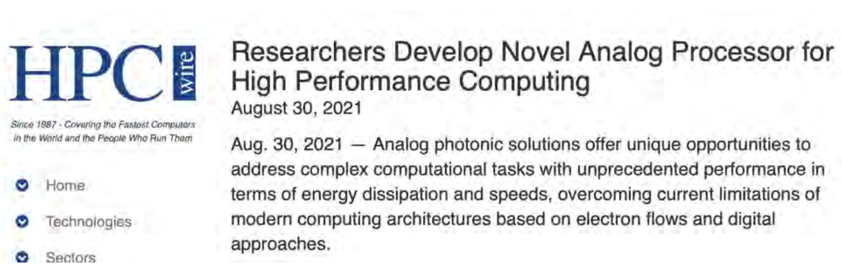
Emerging markets:

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

Photonics in datacenters & AI infrastructures…

Optical «processors» (photonic computing)

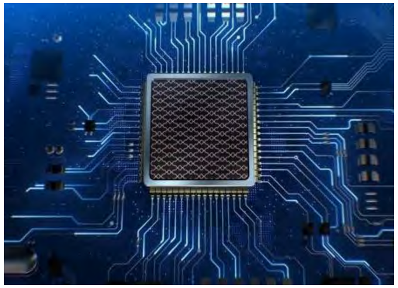
- Reduce latency, power consumption, and bandwidth bottlenecks
- Integration of optical components (lasers, waveguides, modulators, photodetectors) directly into GPUs, TPUs…
- Optical interconnects between GPUs and memory connections (inside servers)
- Use light for (some) AI computations (photonic accelerators) → Lower energy, faster speeds
- Quantum photonic processors



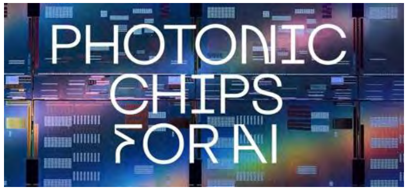
Researchers Develop Novel Analog Processor for High Performance Computing

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.

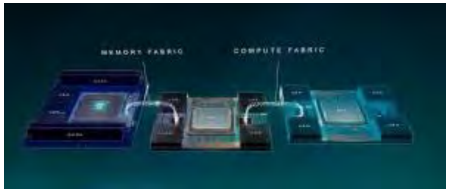


Billions of $ of investments…. (< 10 year old company)



https://lightmatter.co/

https://ayarlabs.com/



https://www.celestial.ai
/

https://www.psiquantum.com/

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

10^{23} FLOP/Day **GPT-4**

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

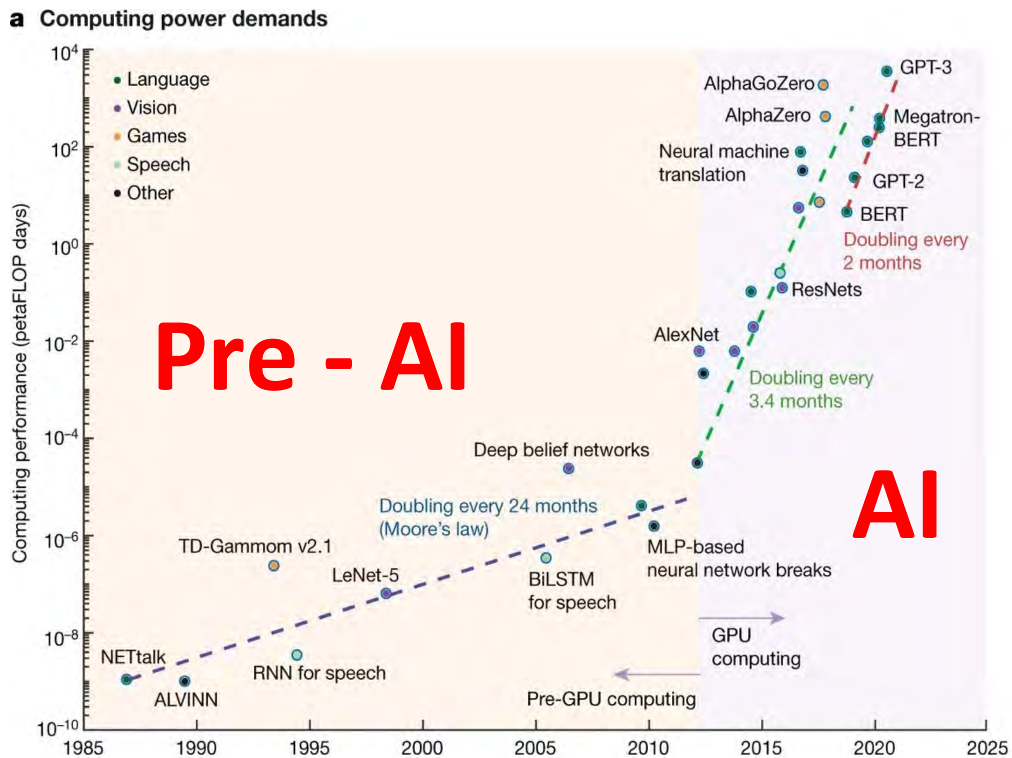
 # FLOP/s = 10^{18} FLOP/s **(# FLOP/day ≈ 10^{23})**

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

Total power consumption **>10 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
Communication		Free
Gain	Easy	Easy (but off-chip)
Nonlinearity	Easy (Transistor)	Hard
Memory	Easy (DRAM, SRAM)	Hard

$O(N^2)$

$O(N)$

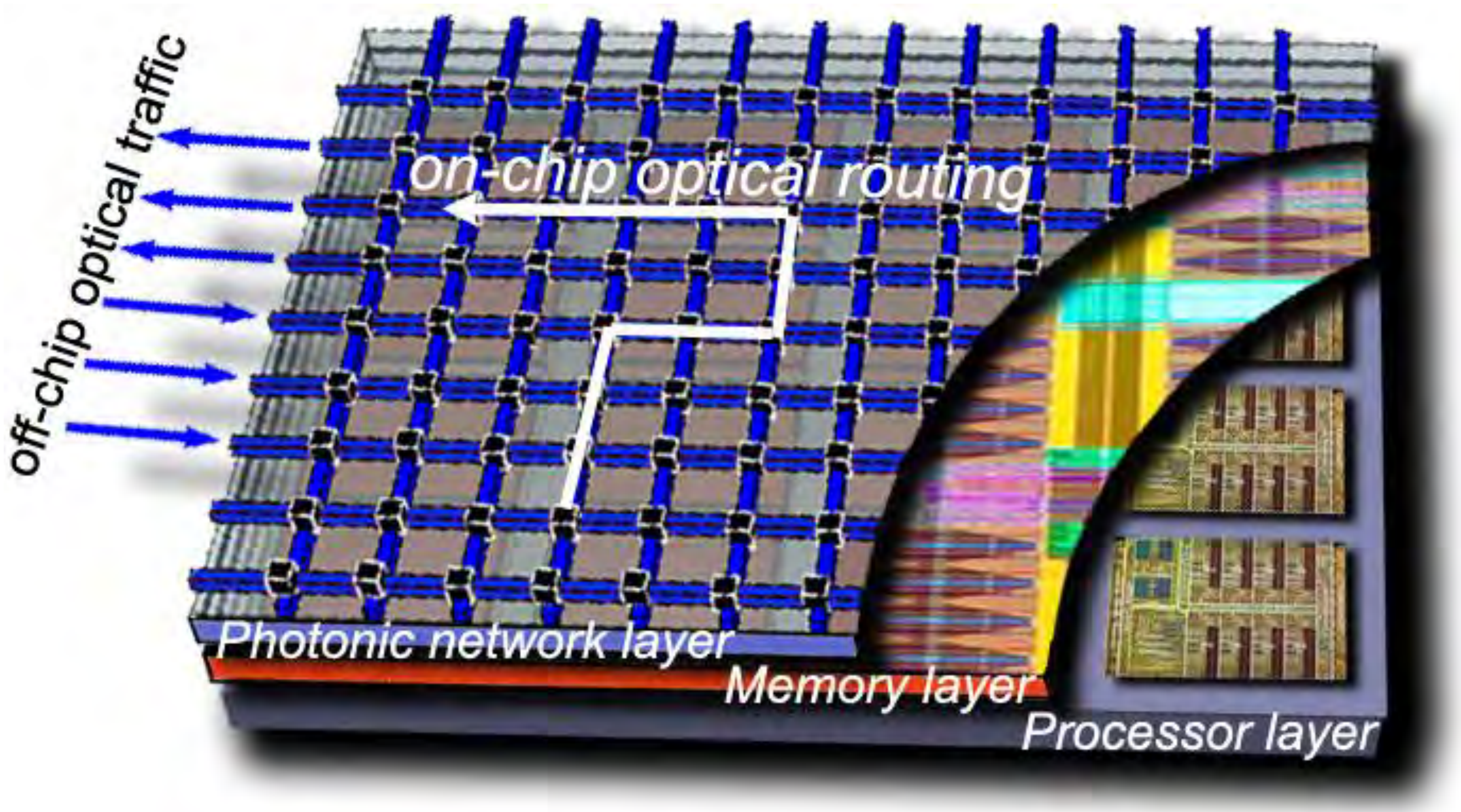
In neural networks, the convolutional part based on MVM occupies > 80% of the total processing time

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)*

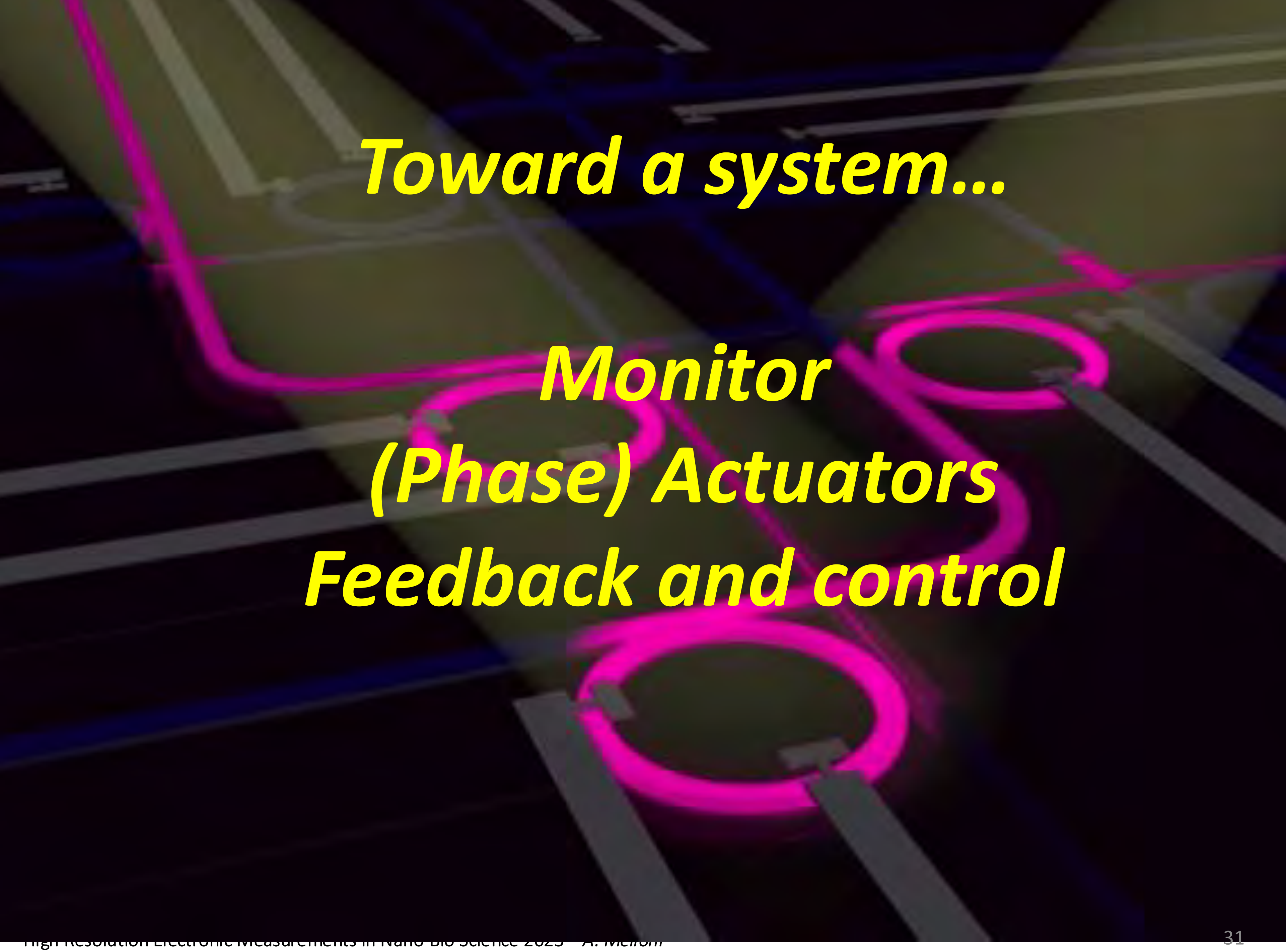
Advantages of photonic computing
- high <u>speed</u> (THz) & low <u>latency</u> (< ns) in solving linear mathematical operations
- low <u>energy/bit</u> consumption (<< pJ/bit)

→ 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



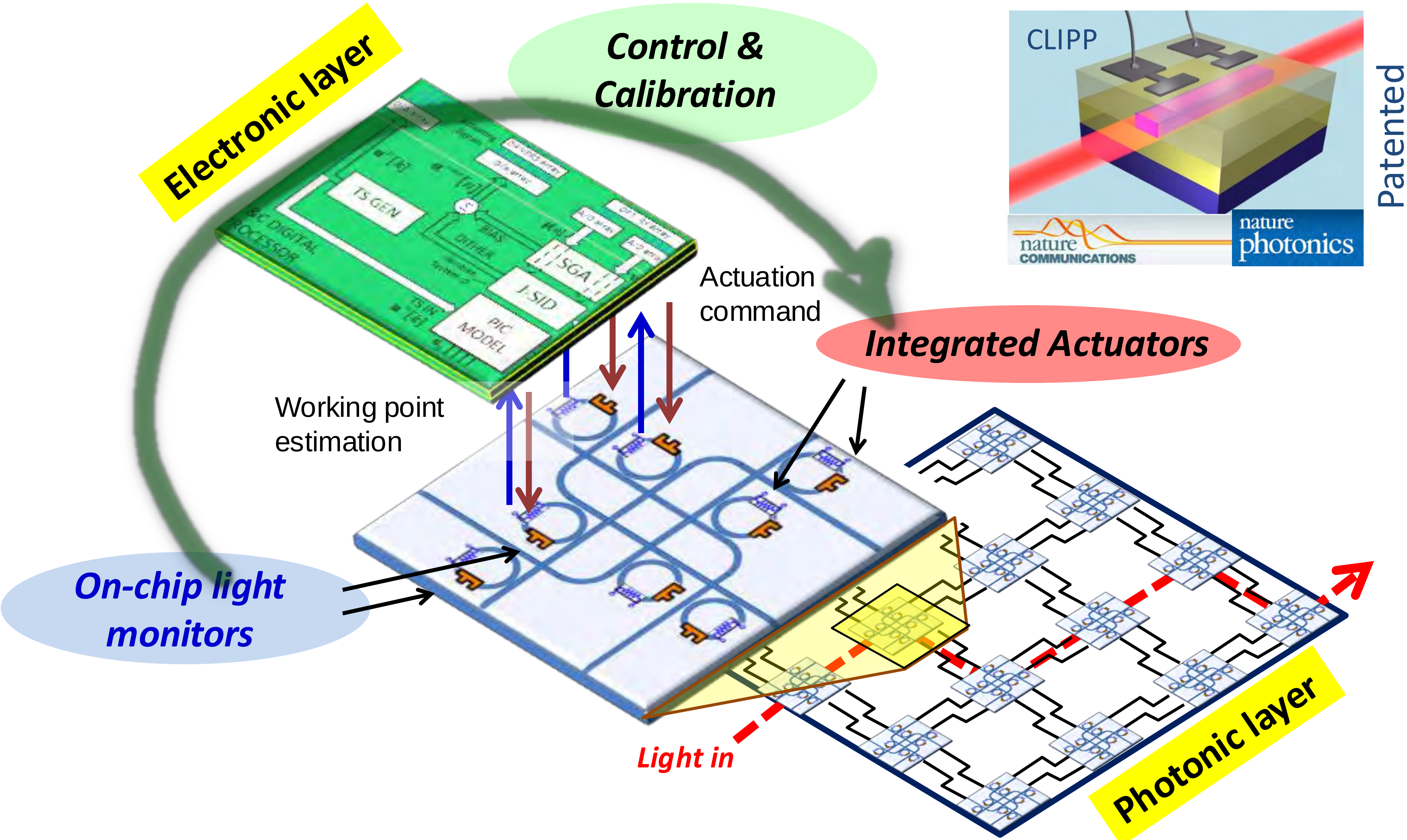
Toward a system…

Monitor

(Phase) Actuators

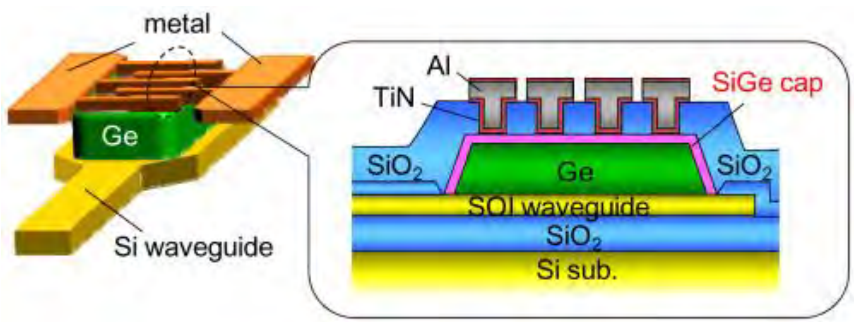
Feedback and control

Control layer for photonic integrated circuits

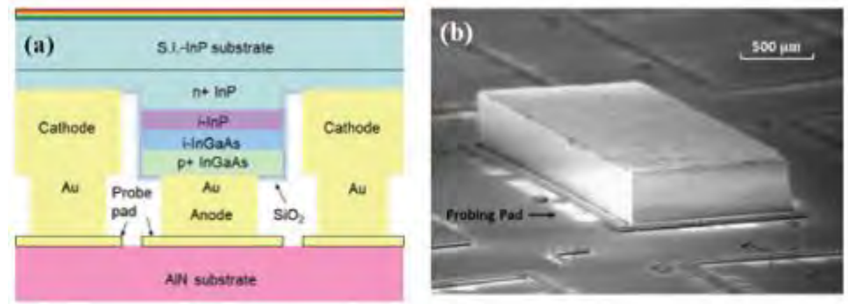


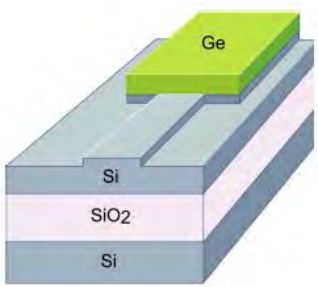
Light monitors: Ge, InP, hybrid, monolithic...

Ge on Silicon

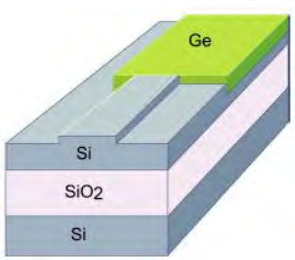


III-V compounds

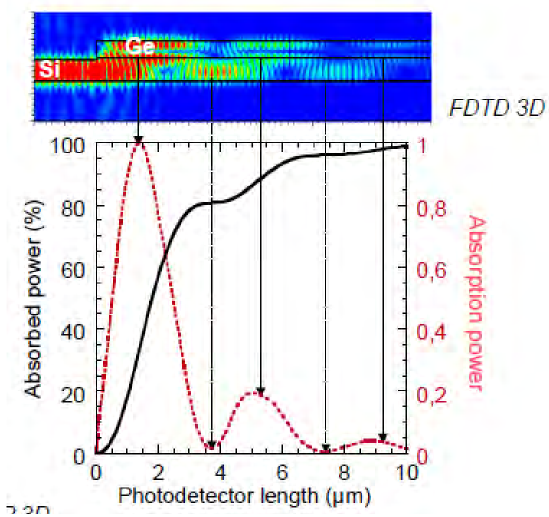


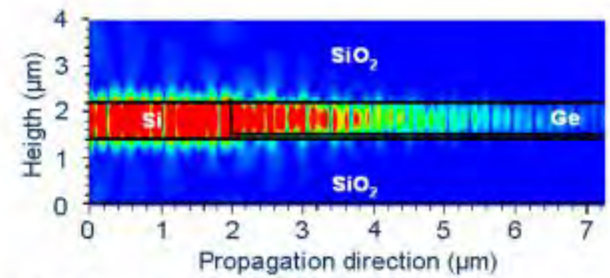


Vertical coupling



Butt coupling

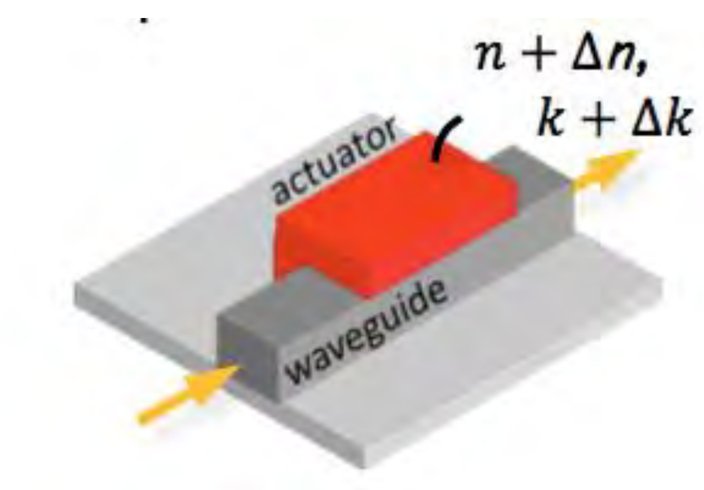




95% absorption length < 4µm

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

Actuators



Phase / Amplitude

Fast (MHz for tuning and reconfiguration)

Compact (10-100 μm)

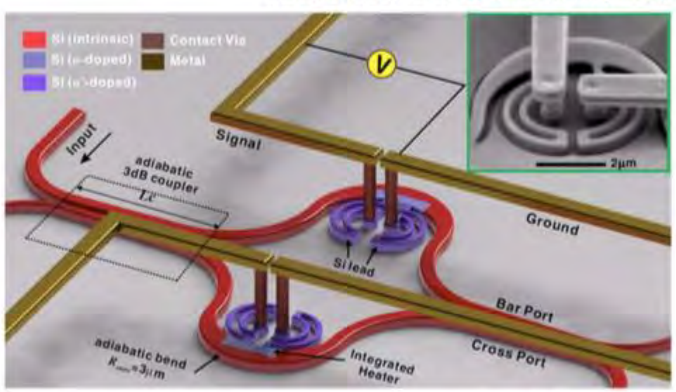
Low Power consumption (< mW)

Permanent, self holding to avoid to continuous feed

Analog / Digital

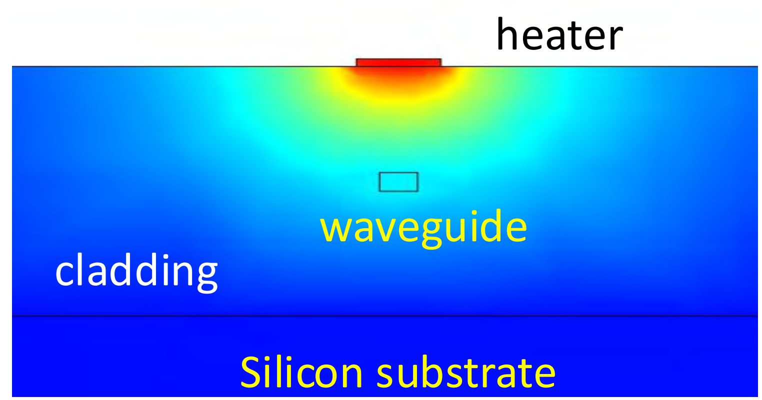
Thermal actuators, mature technology, power hungry

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



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

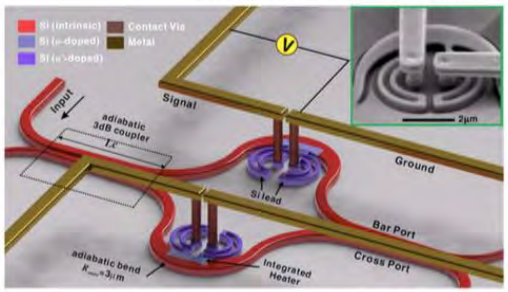
Thermal field induced by heater



Integrated optical actuators

Thermal actuators

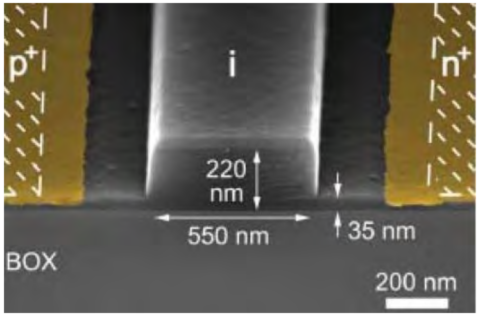
M. R. Watts, et al. Opt. Lett. 38, (2013)



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

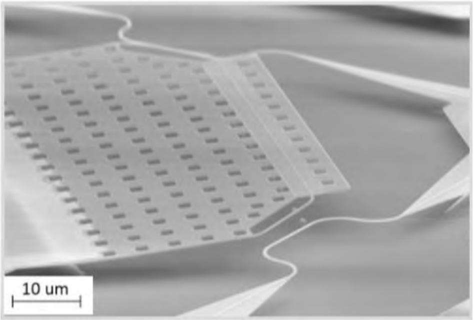
p-n junctions

Carrier injection/depletion



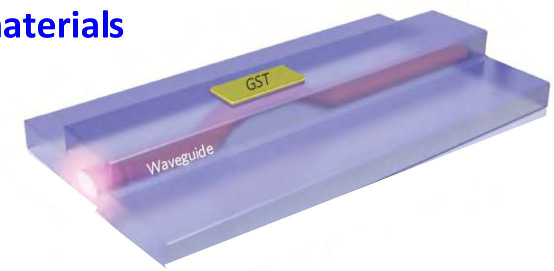
W.M. Green *et al.*, Opt. Express 15 (2007)

MEMS based switches



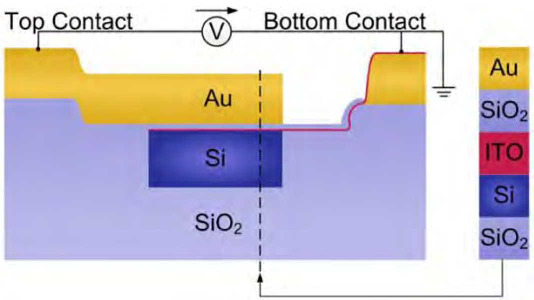
S. Han *et al.*, Berkeley, (2015)

Phase-change materials



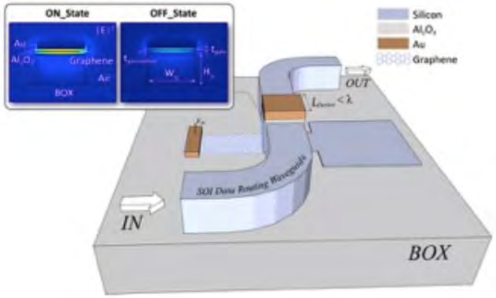
C. Rãos *et al*, Nature Photonics **6** (2015)
A. Joushaghani et al, APL, 102, 061101 (2013)

Plasmonic memristor



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

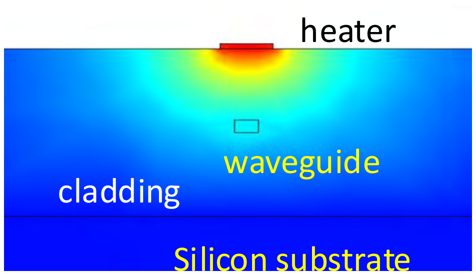
Graphene, $MoTe_2$, ITO modulators



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

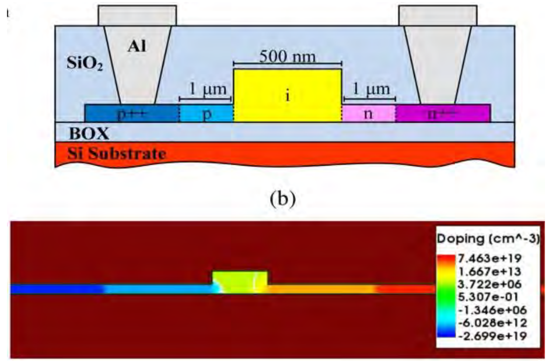
Integrated optical **actuators**

Thermal field induced by heater

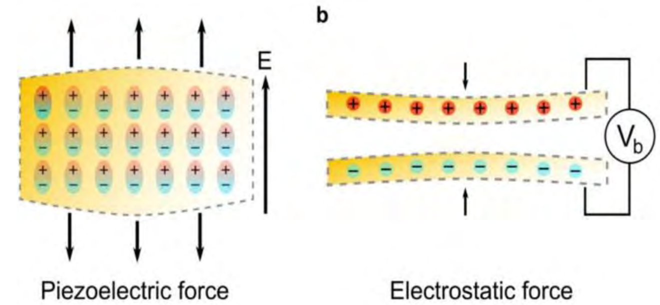


p-n junctions

Carrier injection/depletion



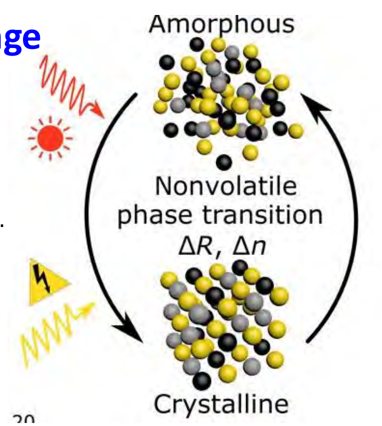
MEMS based switches



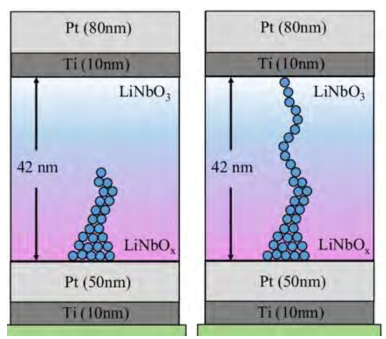
A. Fiore, TU/e

Phase-change materials

N. Farmakidis et al.
Sci Adv 2019; 5

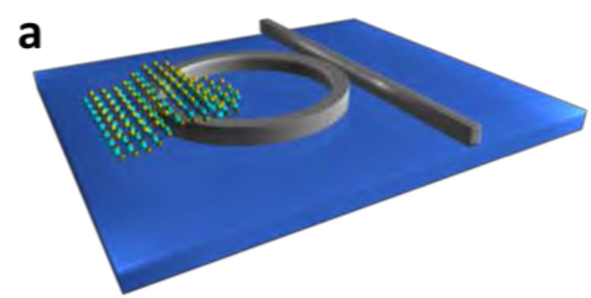


Plasmonic memristor



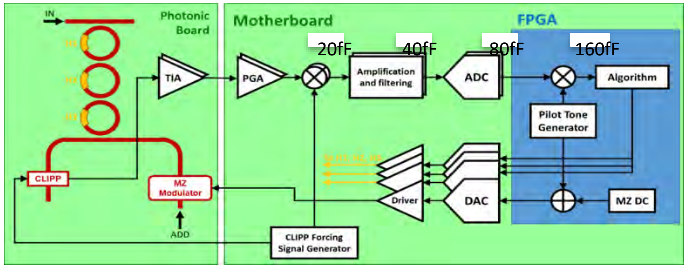
Yacopcic, 2017

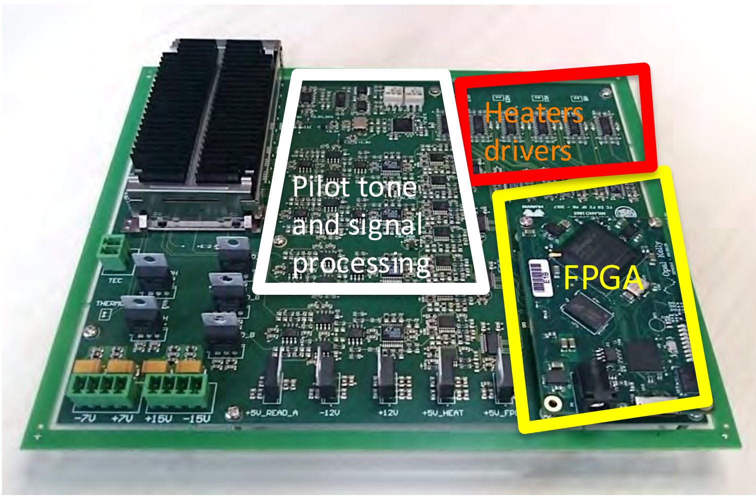
Graphene, $MoTe_2$, ITO modulators



Electronics at service of photonics

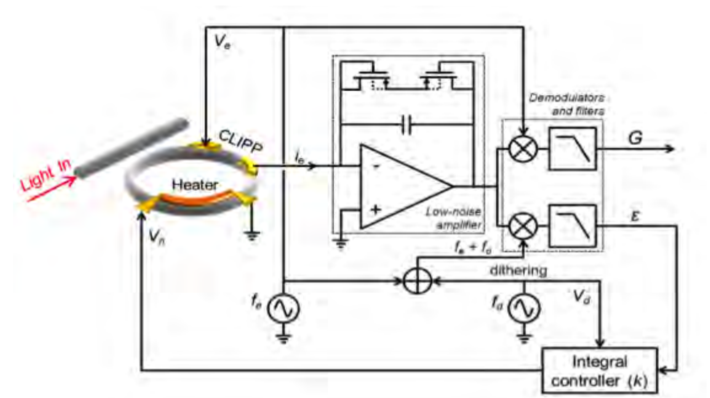
BRAIN – Central Control Unit

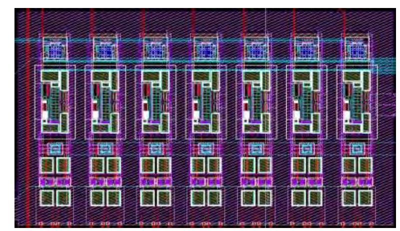




HUAWEI

REFLEX ARC– Local Analog Control

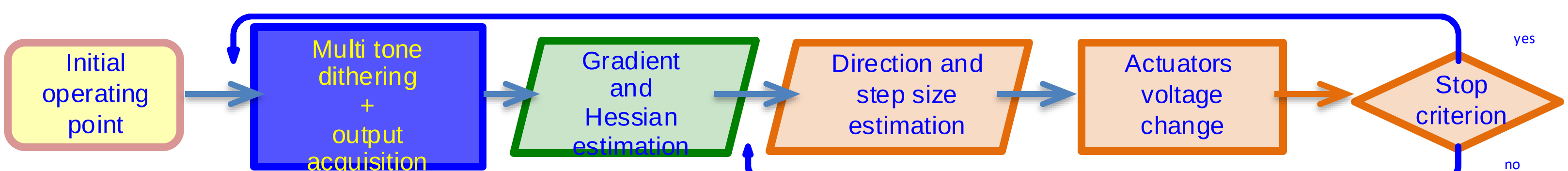




ICT-STREAMS

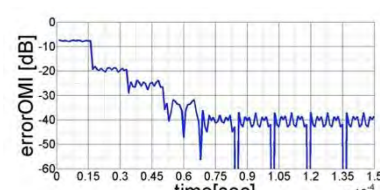
STm BCD8sp ASIC

M-DOF

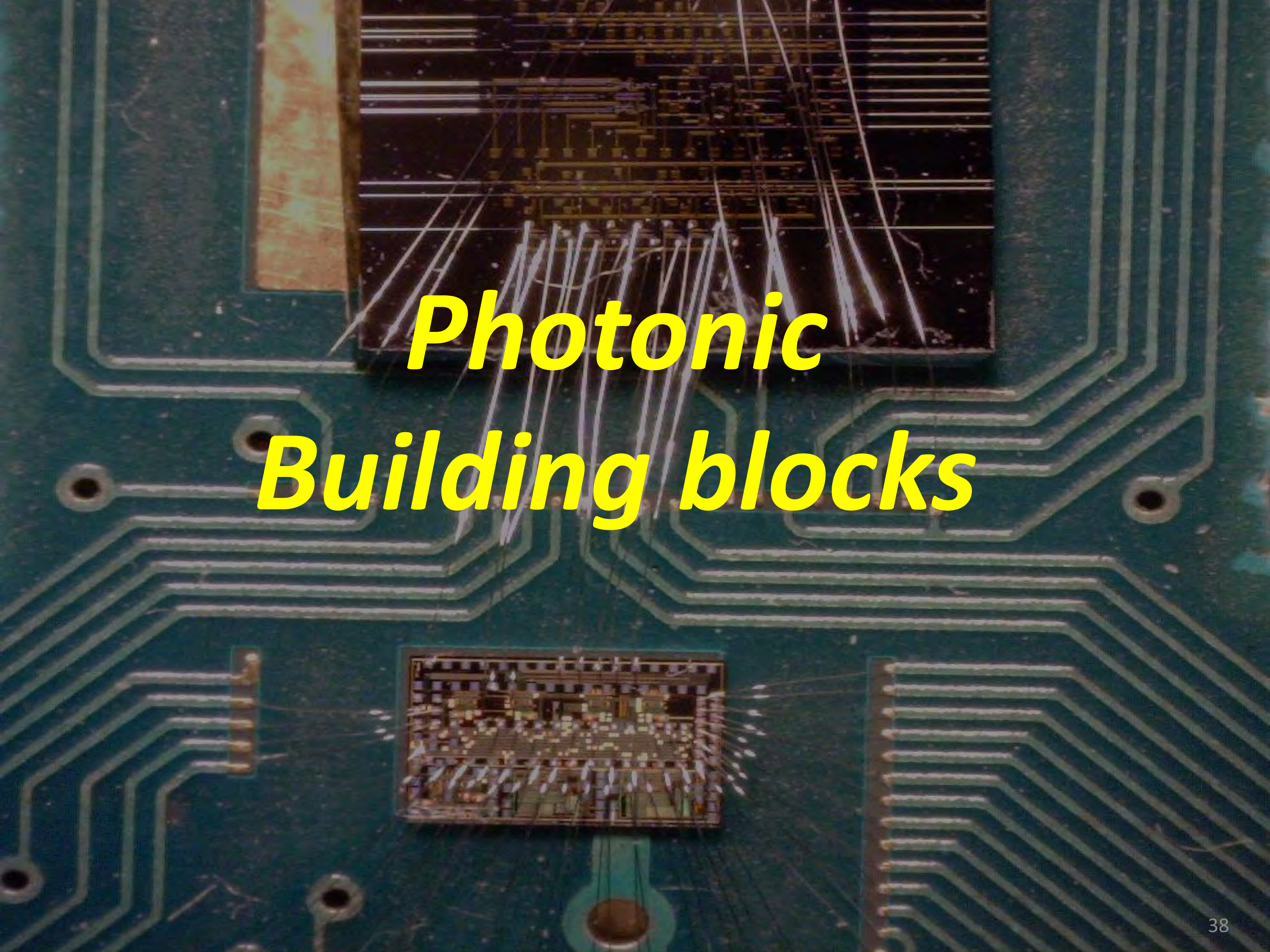


Control **many degrees-of-freedom** (DOFs) using a **single monitoring point**

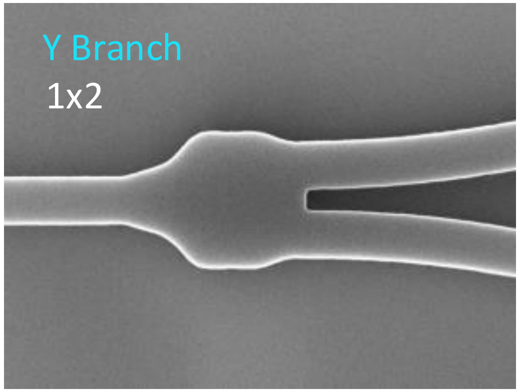
Several DOFs **simultaneously dithered at orthogonal frequencies** generated from a discrete-multi-tone generator

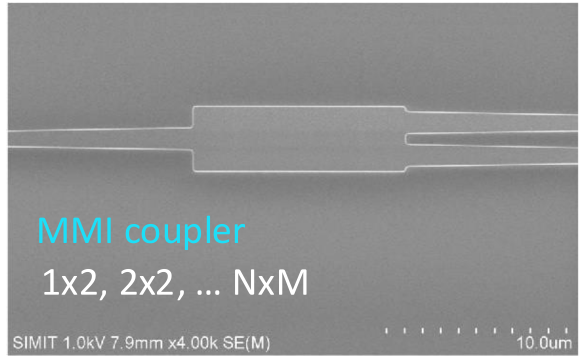


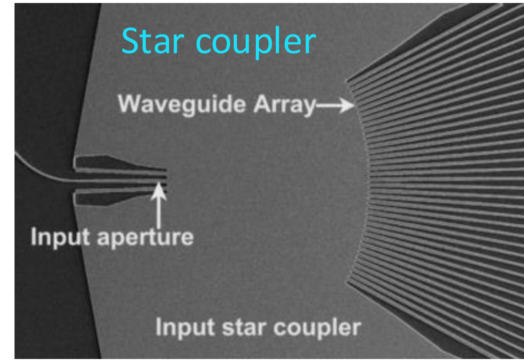
Photonic Building blocks

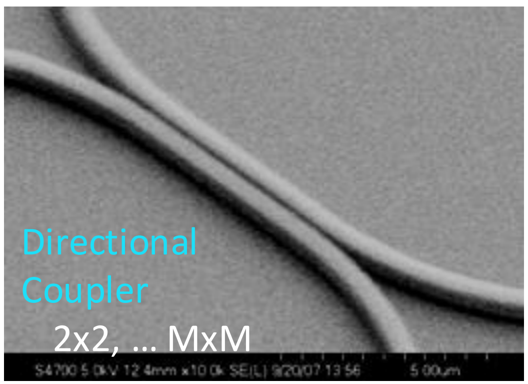


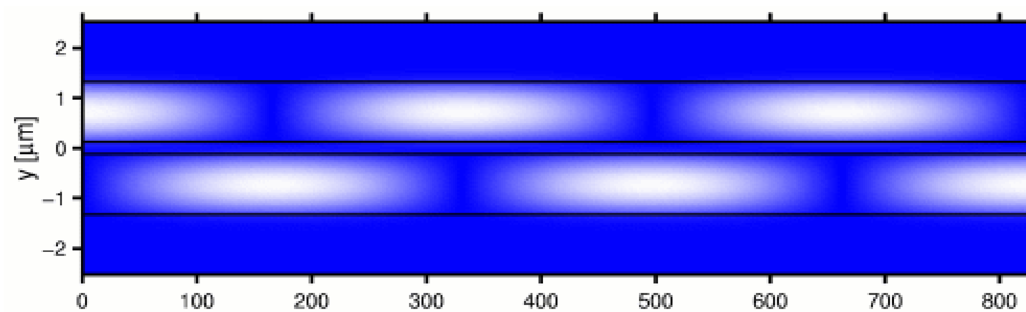
Integrated power splitters







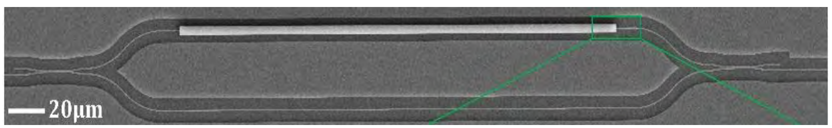




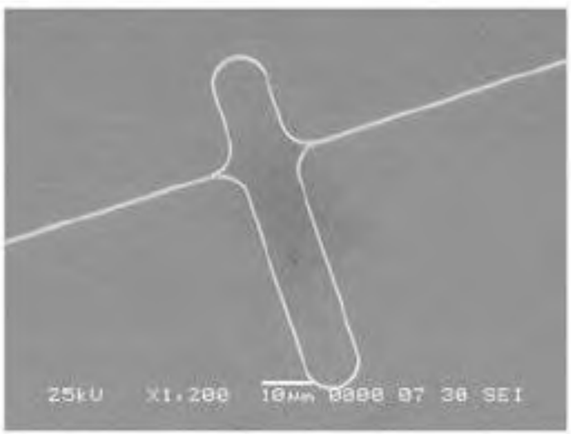
$$T_C = \begin{bmatrix} \cos(\kappa L) & -j\sin(\kappa L) \\ -j\sin(\kappa L) & \cos(\kappa L) \end{bmatrix} = \begin{bmatrix} r & -it \\ -jt & r \end{bmatrix}$$

Key building blocks

Mach Zehender interferometer (MZI)

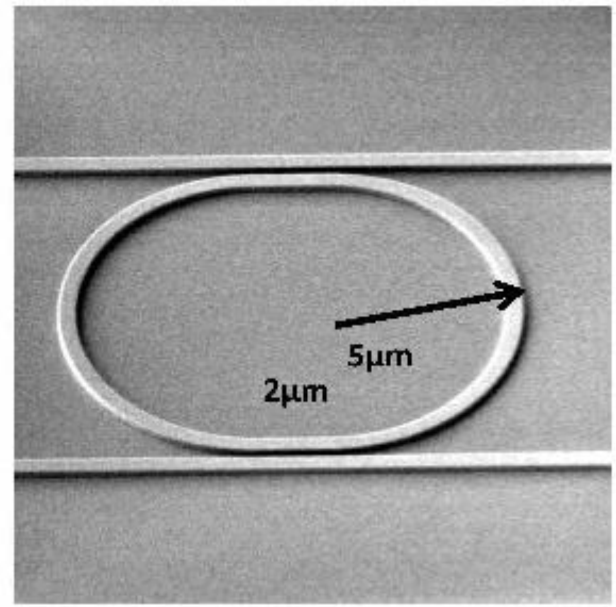


balanced



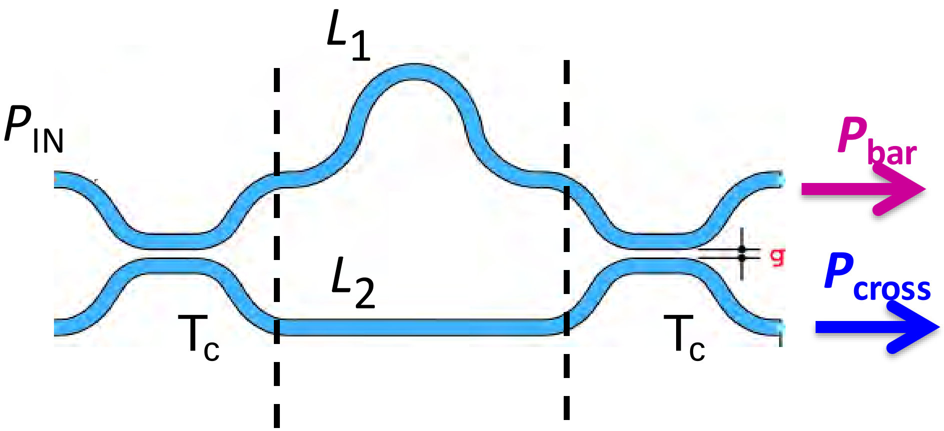
unbalanced

Microring resonator (MRR)



Mach-Zehnder interferometer (unbalanced)

feed-forward interferometer



MZI with 3 dB power splitter

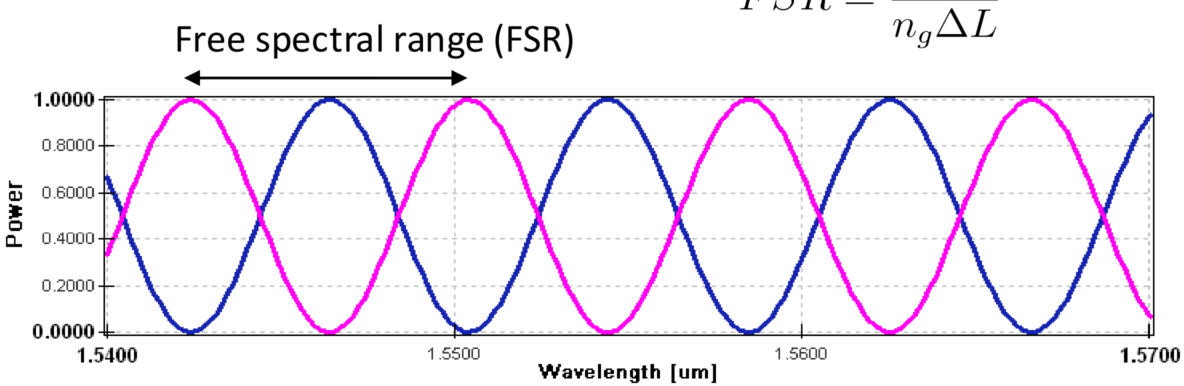
$$\Delta L = L_1 - L_2$$ Geometric unbalance

$$\Delta\varphi_L = \frac{2\pi}{\lambda} n_{eff} \Delta L$$ Phase unbalance

$$P_{bar} = \sin^2\left(\frac{\Delta\varphi_L}{2}\right) P_{IN}$$

$$P_{cross} = \cos^2\left(\frac{\Delta\varphi_L}{2}\right) P_{IN}$$

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

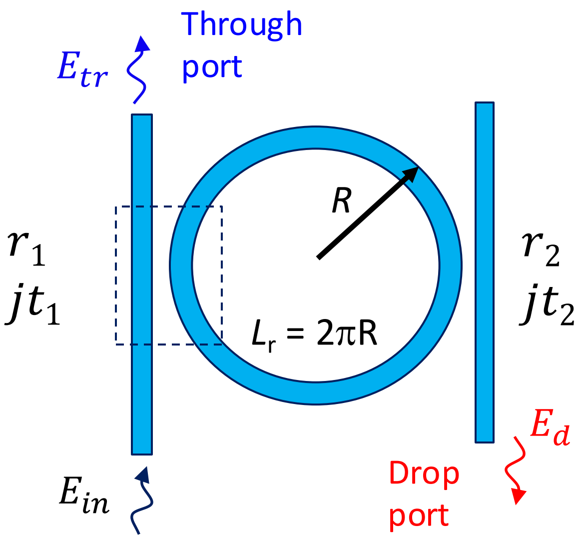


n_g group index
(takes into account chromatic dispersion)

$$n_g = \frac{c}{v_g} = \frac{c}{d\omega/d\beta} = n_{eff}(\omega) + \omega \frac{dn_{eff}}{d\omega}$$

Ring Resonator Filter

feed-back interferometer

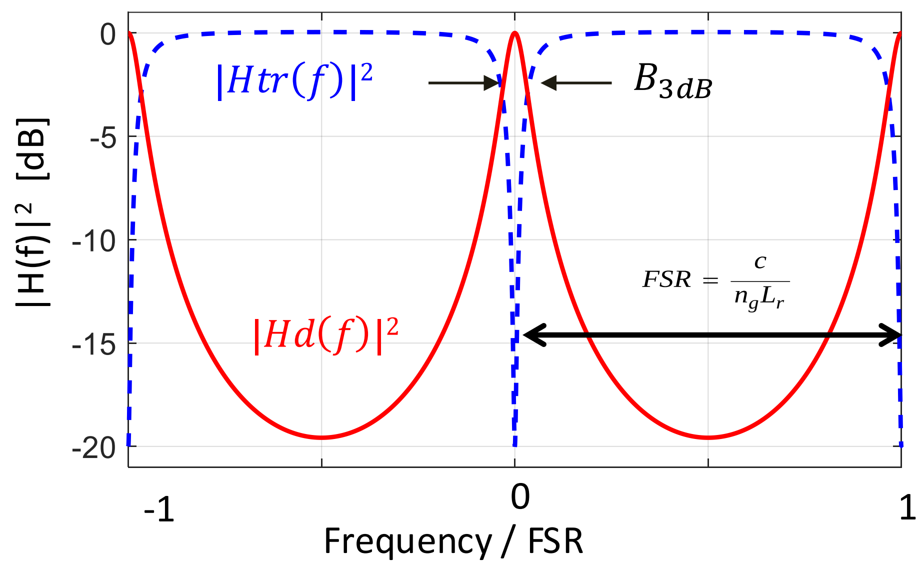


$$H_{tr}(f) = \frac{\boldsymbol{E_{tr}}}{\boldsymbol{E_{in}}} = \frac{r_1 - r_2 e^{-\gamma L_r/2}}{1 - r_1 r_2 e^{-\gamma Lr}}$$

$$H_d(f) = \frac{\boldsymbol{E_d}}{\boldsymbol{E_{in}}} = \frac{t_1 t_2 e^{-\gamma Lr/2}}{1 - r_1 r_2 e^{-\gamma Lr}}$$

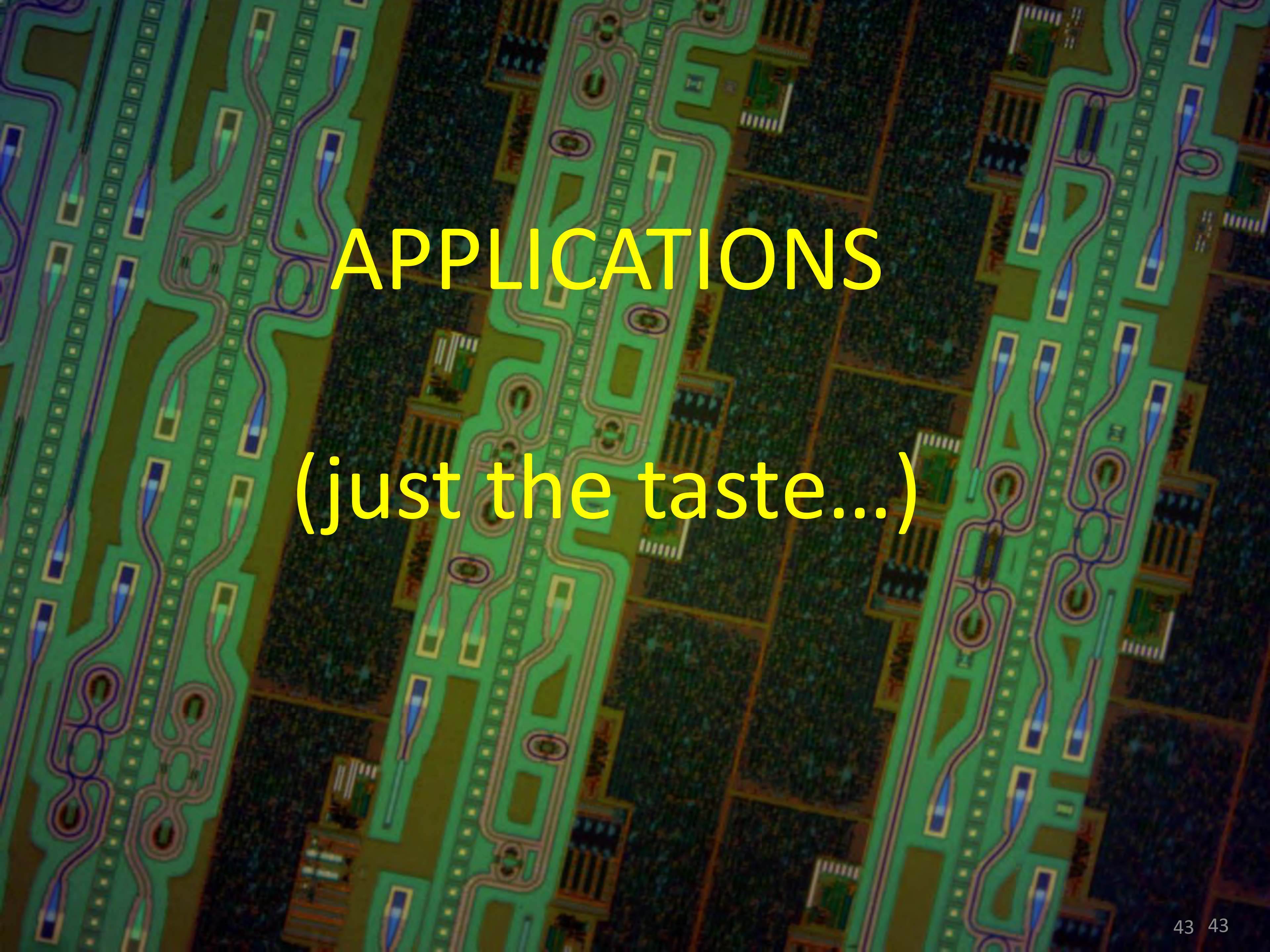
$\gamma = \alpha + j\beta$	Propagation constant
$\beta = \frac{\omega}{c} n_{eff}$	Phase constant
α	Attenuation constant

- Same frequency resonse as a Fabry-Pérot cavity
- Lossless case ($\alpha = 0$), $|H_{tr}(f_0)|^2 = 0$ if $r_1 = r_2$
- Lossless ($\alpha = 0$) & symmetric ($r_1 = r_2 = r$) $B_{3dB} \cong FSR \frac{t^2}{\pi}$



$$\beta L_r = M 2\pi \quad \rightarrow \quad f_{0,M} = \frac{c}{L_r n_{eff}} M$$

resonance frequencies



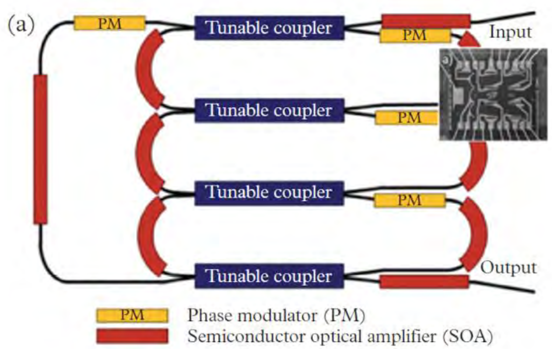
APPLICATIONS

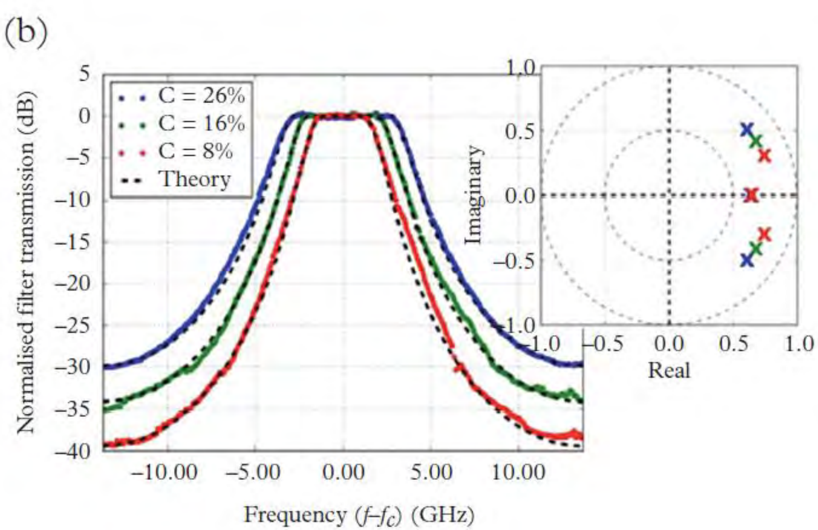
(just the taste…)

 43

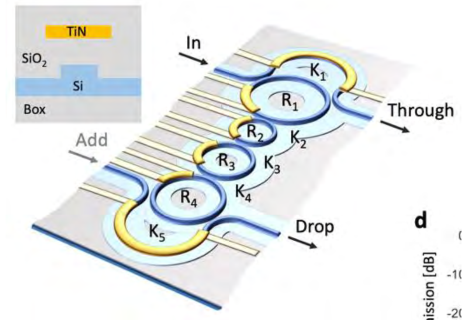
Reconfigurable filters

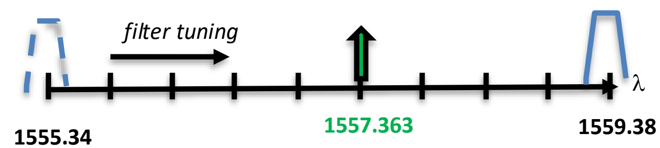
Tuneable bandwidth filter

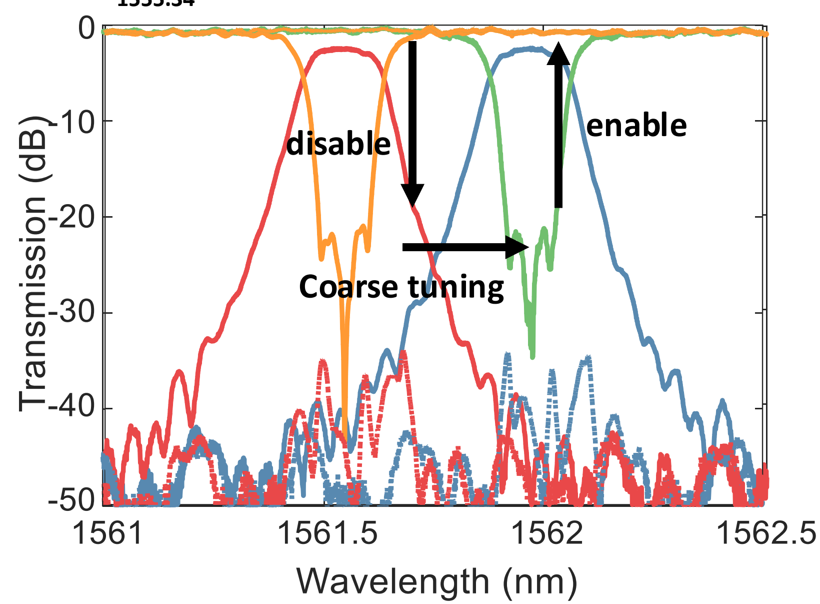




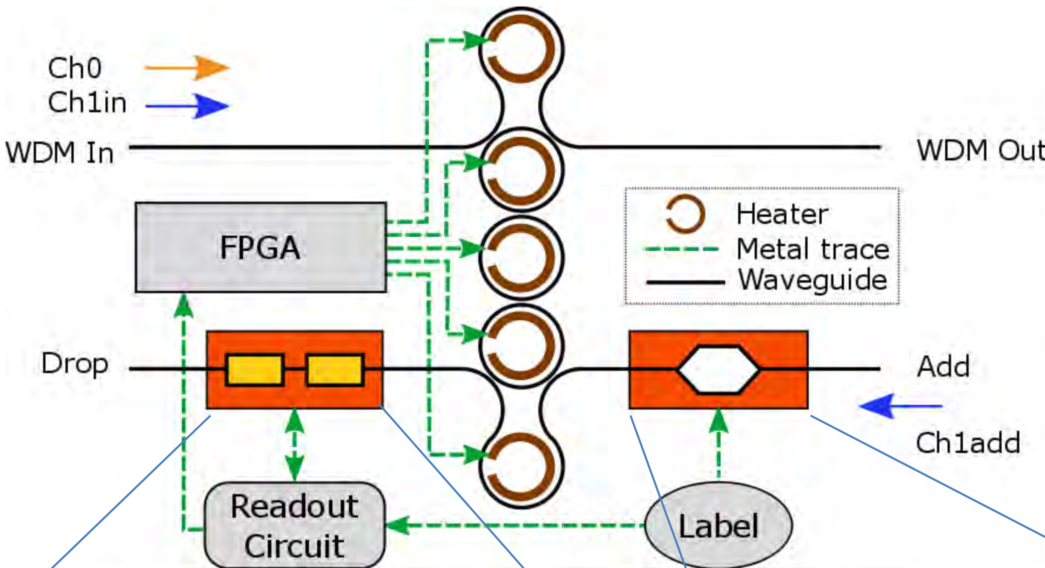
Reconfigurable hitless filters







Reconfigurable hitless filter

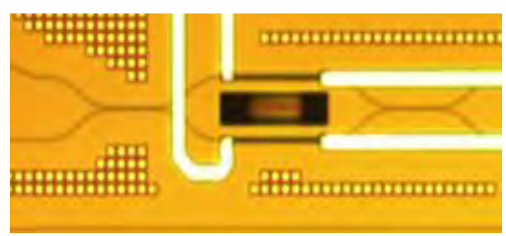


Filter characteristics:

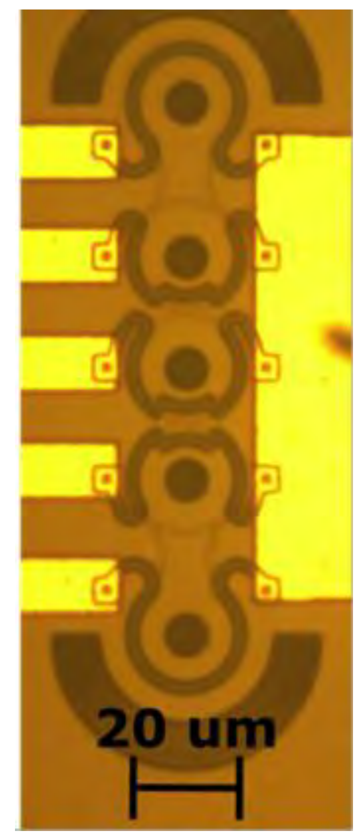
- Hitless tuning
- 1 THz (8 nm) of Free Spectral Range (FSR)
- 40 GHz of 3 dB bandwidth
- 20 dB in band isolation

HUAWEI

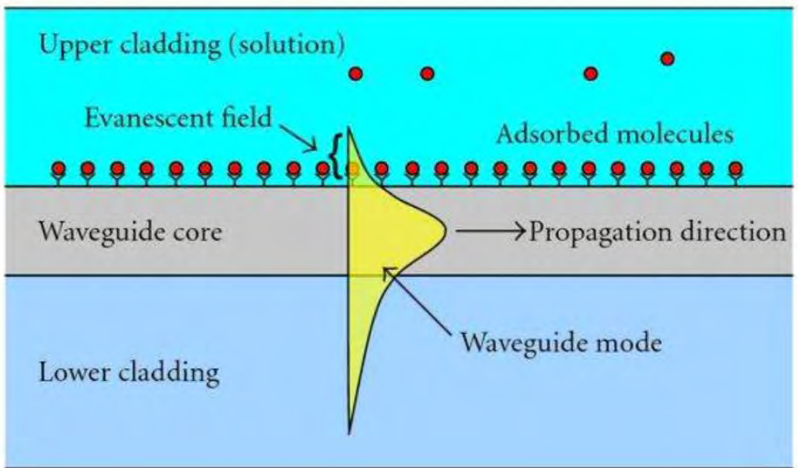
CLIPP at the Drop port to read optical label



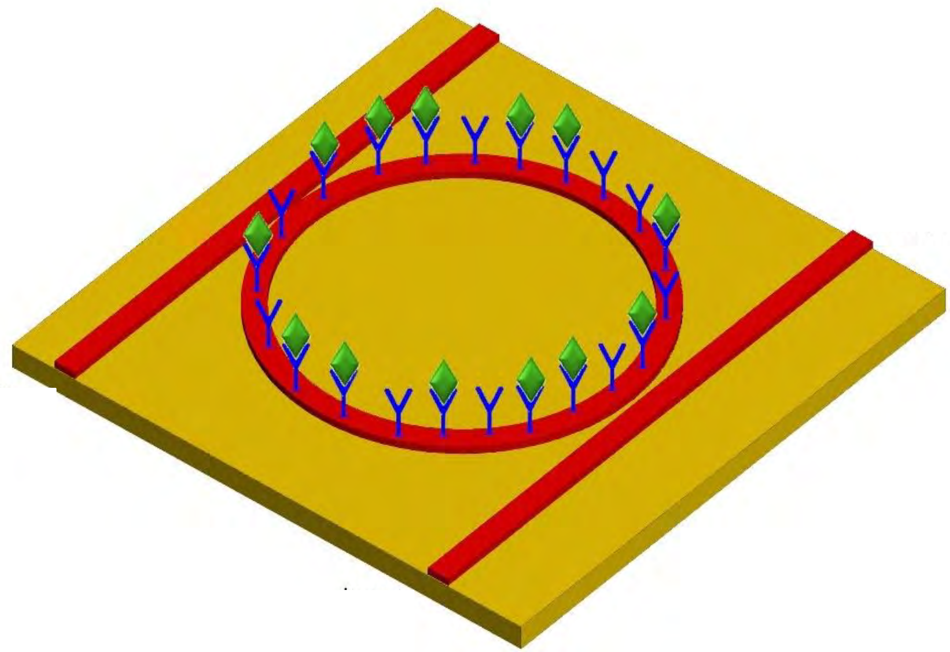
Mach-Zehnder Modulators (MZM) in the add port to apply optical label



Biosensing and integrated photonics

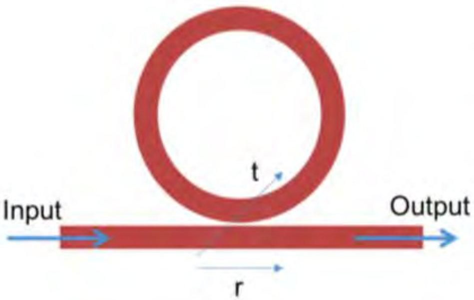


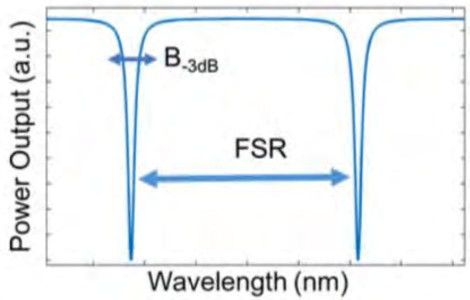
Evanescent field detection
Negligible absorbtion
Phase change of the light

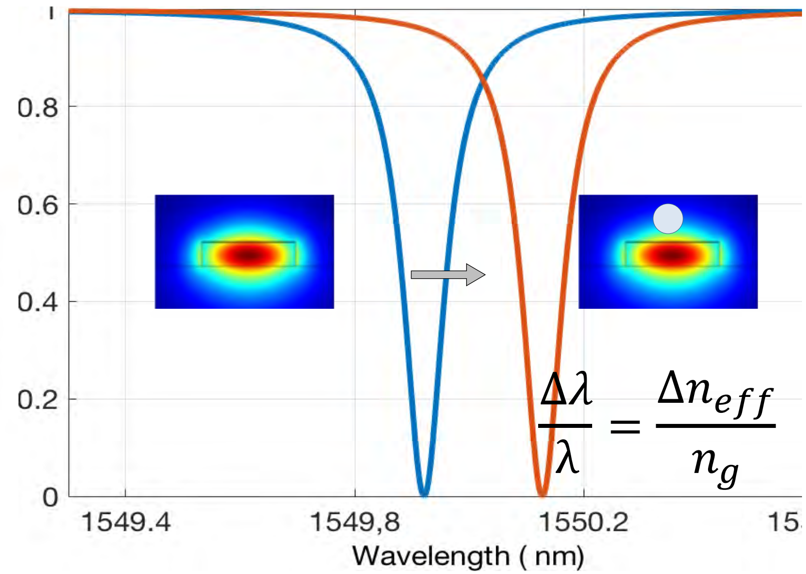


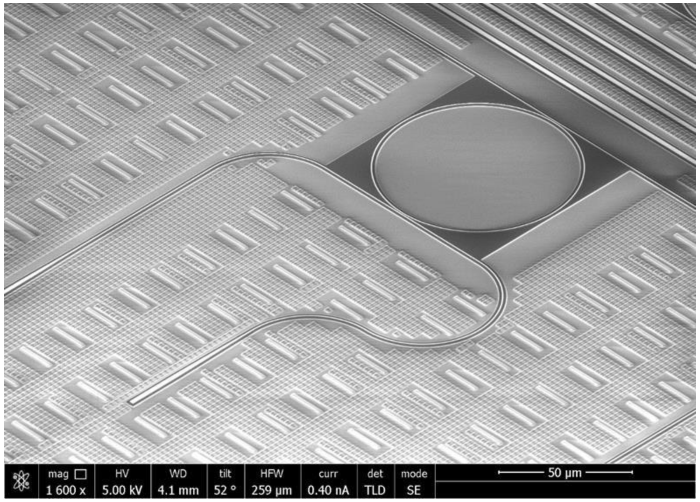
Phase-intensity conversion with an
“interferometer” (ring resonator)

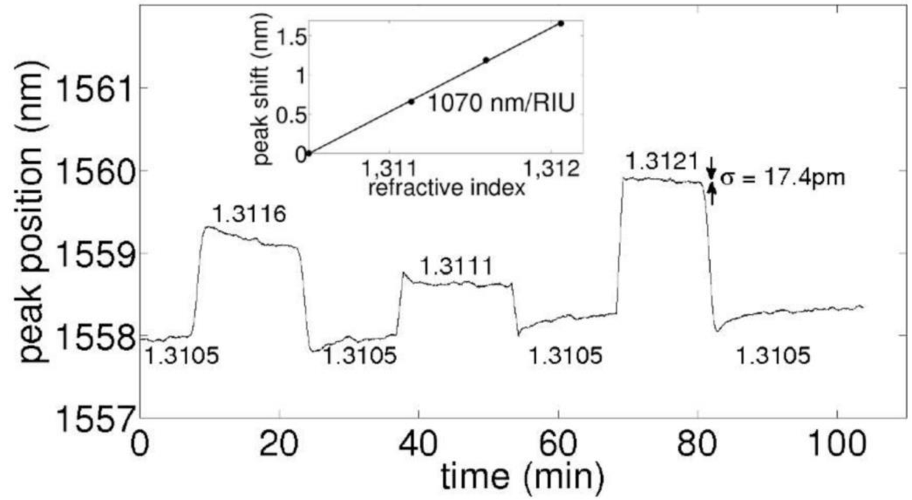
Biosensing and integrated photonics



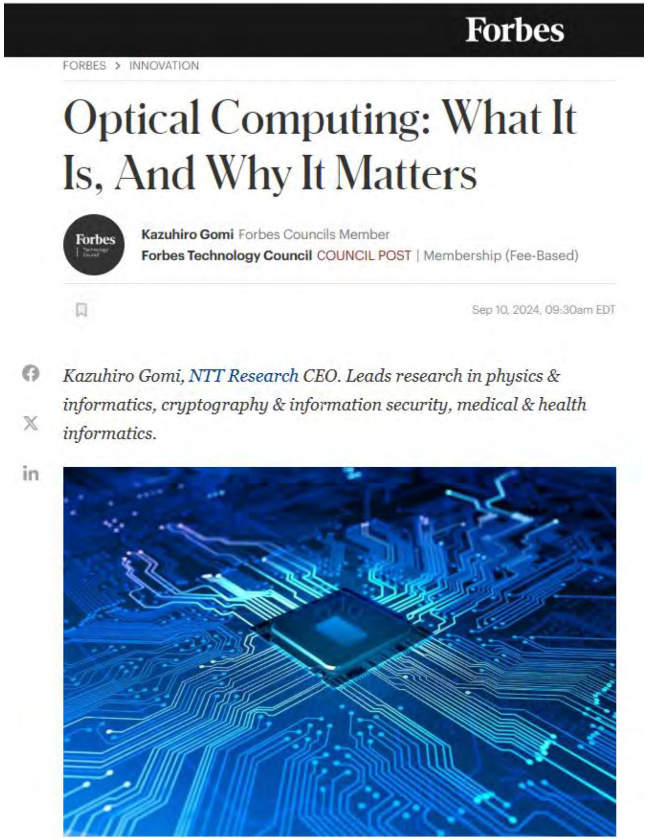








Photonic Computing


Forbes

FORBES > INNOVATION

Optical Computing: What It Is, And Why It Matters

Kazuhiro Gomi Forbes Councils Member
Forbes Technology Council COUNCIL POST | Membership (Fee-Based)

Sep 10, 2024, 09:30am EDT

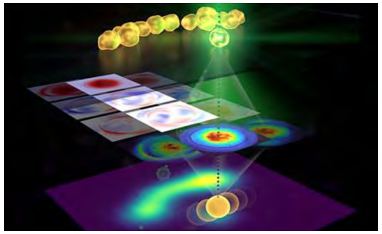
Kazuhiro Gomi, NTT Research CEO. Leads research in physics & informatics, cryptography & information security, medical & health informatics.

https://www.forbes.com/councils/forbestechcouncil/2024/09/10/optical-computing-what-it-is-and-why-it-matters/

- **Electronic computing…** two decades ago, GPUs were starting to supplant CPUs
- **Moore's law** is fading
- The **von Neumann** computing model (memory separated from processing since the 1940s) has inherent limits
- To address big computing challenges, it helps to think big and in new ways…
- Use photons instead of electrons… (somewhere)
- A general-purpose **optical neural network** may be years out… but could end up being **1,000 times as efficient as its electronic counterparts**

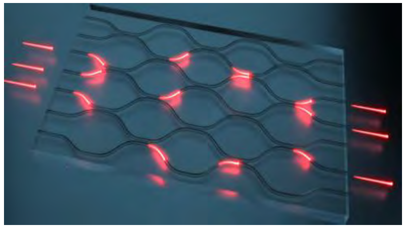
Positioning & Ranging (LIDAR)

Beam forming, imaging & microscopy

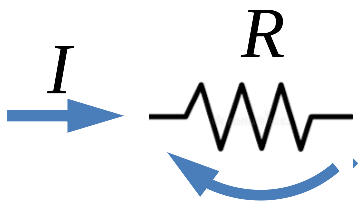


Micro-projectors & augmented reality

Quantum photonics (communication, computing & sensing)

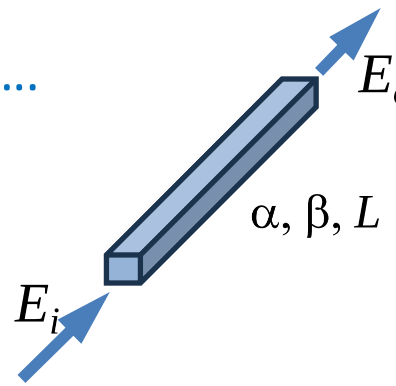


Any circuit is a mathematical solver



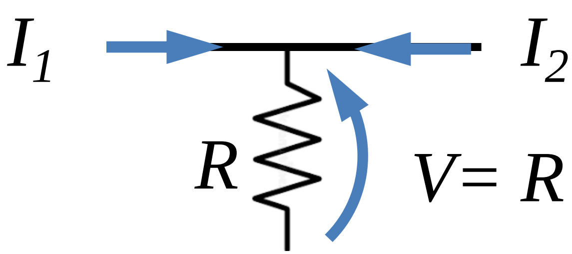
$$V=R\,I$$

Multiplication ....

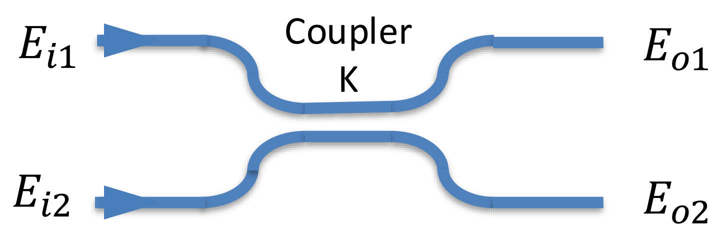


$$E_o=E_i\, e^{-\alpha L}\, e^{-j\beta L}$$

Sum ....



$$V= R\,(I_1+I_2)$$



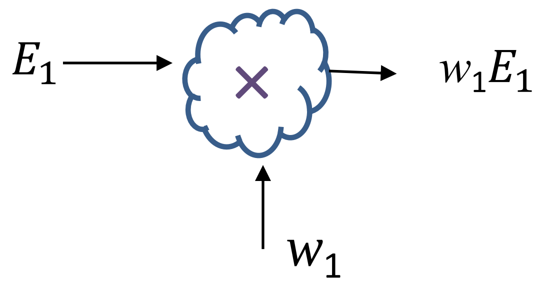
$$E_{o1} = \sqrt{1-K}\,E_1 + j\sqrt{K}\,E_2$$

... è una **interferenza (→ sommatore coerente)**

Multiplication by a complex weight

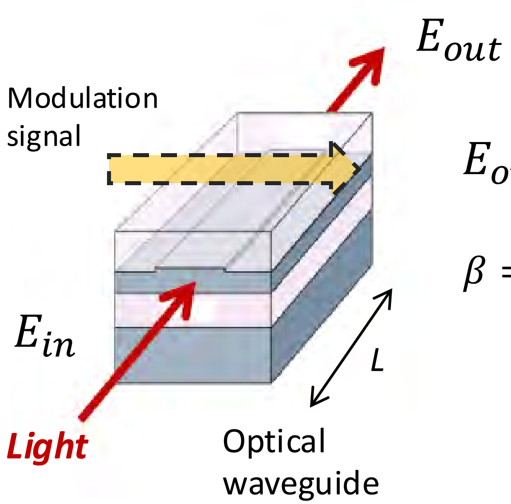
Let's consider an optical signals (frequency, polarization and spatial mode here is not much relevant) with power P_1

$$P_1 \propto |E_1|^2$$



... basically it is an **amplitude & phase** modulation

$$w_1 = e^{-\alpha L} e^{-j\beta L}$$



$$E_{out} = E_{in} e^{-\alpha L} e^{-j\beta L}$$

$$\beta = \frac{2\pi f_0}{c} n_{eff}$$

Electro-absorption

Change of the attenuation constant (α) by an external applied signal

Intensity modulation

$$|w_1| = e^{-\alpha L}$$

Electro-refraction & Thermal

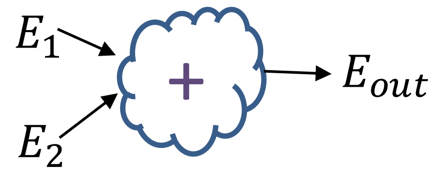
Change of the refractive index (phase constant β) by an external applied signal

Phase modulation

$$\angle w_1 = -\beta L$$

Summing... amplitude or power?

Let's consider 2 optical signals (same frequency, polarization and spatial mode) with power P_1 and P_2 respectively



Is it possible to get the signal "sum" with field amplitude $E_{out} = E_1 + E_2$?

Can we implement a field «amplitude adder»? NO !!!

A simple justification

$P_1 \propto |E_1|^2$

$P_2 \propto |E_2|^2$

$E_1 = 1 \qquad P_1 = 1$

$E_2 = 1 \qquad P_2 = 1$

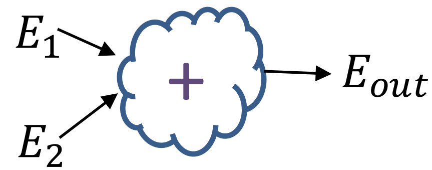
There is no way to make an «electric field adder» (... power conservation !)

$E_{out} = E_1 + E_2 = 1 + 1 = 2 \; P_{out} = 4$

$instead \ldots P_{in} = P_1 + P_2 = 2$

A fundamental issue… the photonic power adder

Let’s consider 2 optical signals (same frequency, polarization and spatial mode) with power P_1 and P_2 respectively

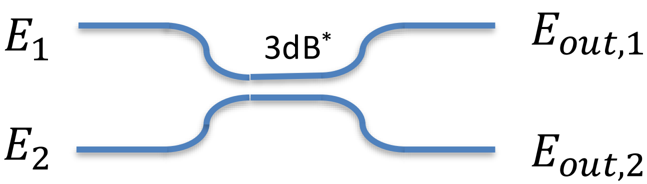


How to get the signal “sum” with power $P_{out} = P_1 + P_2$?

$$P_1 \propto |E_1|^2$$

$$P_2 \propto |E_2|^2$$

Can we use a «power combiner»… like a directional coupler ?



$$T_c = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}$$

$$E_{out,1} = \frac{1}{\sqrt{2}} E_1 - j \frac{1}{\sqrt{2}} E_2$$

$$E_{out,2} = -j \frac{1}{\sqrt{2}} E_1 + \frac{1}{\sqrt{2}} E_2$$

$$P_{out,1} = P_1 + P_2$$

$$P_{out2} = 0$$

… only if

$$|E_1| = |E_2| \longrightarrow P_1 = P_2$$

$$\angle E_1 - \angle E_2 = -\frac{\pi}{2}$$

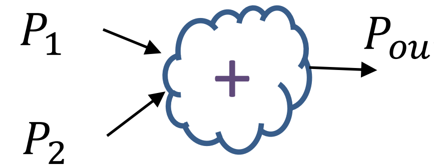
The output power depends on the amplitude and the phase of the input signals !(*)

… that’s **interference (→ coherent adder)**

(*) using non-3dB couplers, phase dependence will remain anyway !

Non-coherent adder (= summing orthogonal signals)

If we want the output power NOT depend on the **amplitude** and the **phase** of the input signals…
… we need to avoid **interference**

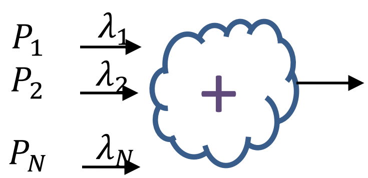


Interference may happen only if signals share frequency, polarization and spatial mode)

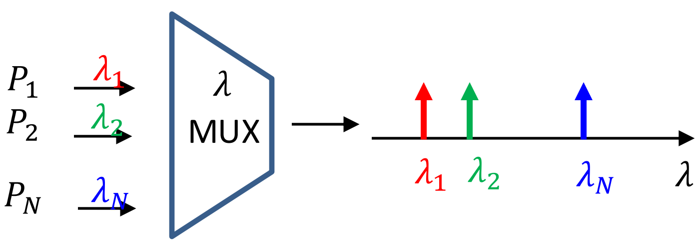
$$P_1 \propto |E_1|^2$$

$$P_2 \propto |E_2|^2$$

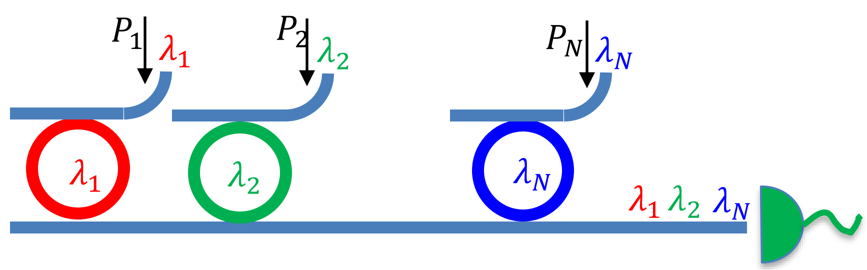
Use different **frequencies/wavelengths** (non-coherent adder)



$$P_{out} = \sum_{1}^{N} P_i$$



An example of implementation



Different frequencies mean that the signals are **orthogonal** in the frequency domain

$$I_{out} \sim P_{out} = |E_1\cos(\omega_1 t) + E_2\cos(\omega_2 t)|^2 = |E_1|^2 + |E_2|^2 + \ldots\cos(\omega_1 - \omega_2) + \ldots\cos(\omega_1 + \omega_2)$$

Programmable photonic circuits for computing

$$Y = WX = \begin{bmatrix} w_{11} & w_{12} & \dots & w_{1N} \\ w_{21} & w_{22} & \dots & w_{2N} \\ \dots & \dots & \dots & \dots \\ w_{N1} & w_{N2} & \dots & w_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_N \end{bmatrix}$$

$$y_n = \sum_{m=1}^{M} w_{n,m} x_m$$

It basically translates in doing **multiplications** of optical signals (x_i) with weigths (w_{ij}) and **sums** them up

The photonic circuit implement a NxM linear transformations **W** (matrix)

Matrix–vector multiplication (MVM) is one of the fundamental mathematical operations widely used in data "processing":

- convolution, factorization, linear equalization, filtering
- Fourier transform (and other linear transforms e.g., Hadamard, Gram-Schmidt, etc.)
- Neural networks (weighted interconnections between adjacent neurons)

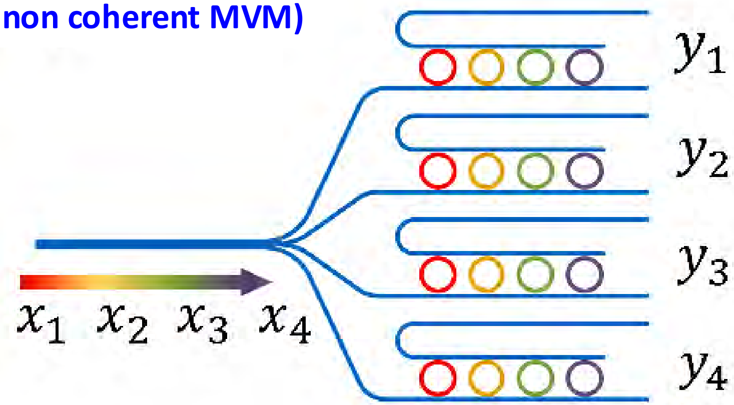
How to implement it optically?

Photonic Matrix Vector Multiplication (MVM)...

$$Y = WX = \begin{bmatrix} w_{11} & w_{12} & \dots & w_{1N} \\ w_{21} & w_{22} & \dots & w_{2N} \\ \dots & \dots & \dots & \dots \\ w_{N1} & w_{N2} & \dots & w_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_N \end{bmatrix}$$

$$y_n = \sum_{m=1}^{M} w_{n,m} x_m$$

Integrated optics (non coherent MVM)



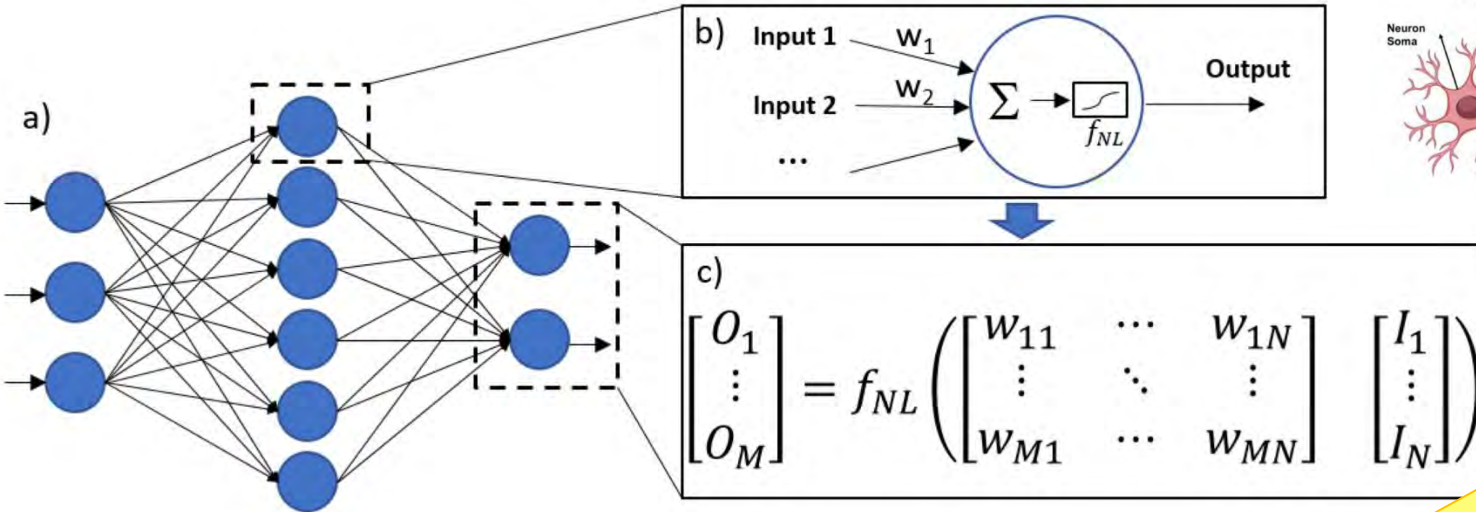
A filter bank is used to scale the various elements (**multipliers**)

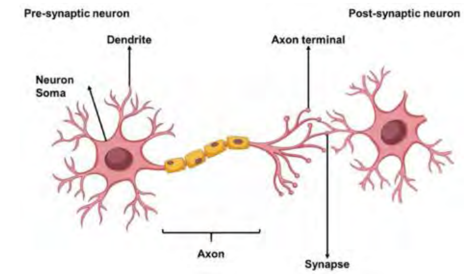
PDs detetect only the optical power (not the complex amplitude)

In non coherent MVM weigths are **real numbers**

J. Cheng et al., «Photonic Matrix Computing: From Fundamentals to Applications», Nanomaterials, 11, 1683 (2021)

Neural Network Architectures

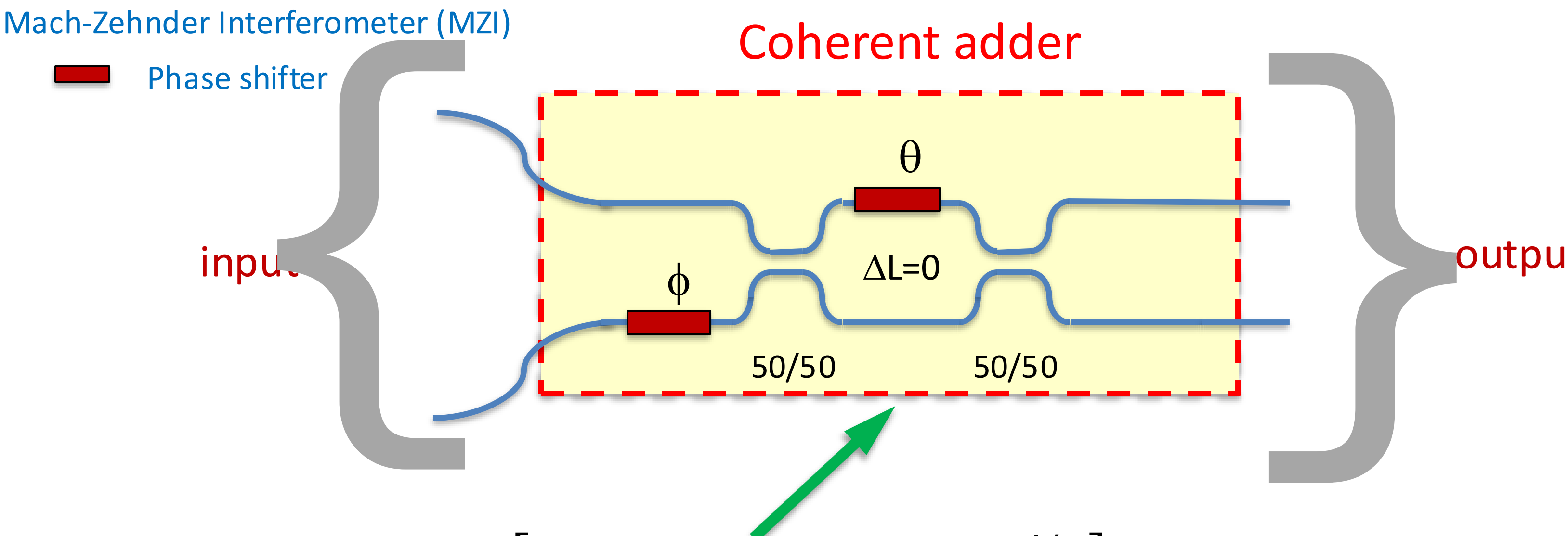




In neural networks, the convolutional part based on MVM occupies > 80% of the total processing time

- A network with a large number of **interconnections** relative to logical nodes (e.g., the brain has 10^{11} neurons and 10^{15} synapses)
- **Distributed processing** based on weighted interconnections & localized nodes having **simple logic**
- **Nonlinearity** required to implemented decision making and model complex systems

Coherent MVM: MZI is the simplest coherent combiner



$\theta = 2\cos^{-1} r$

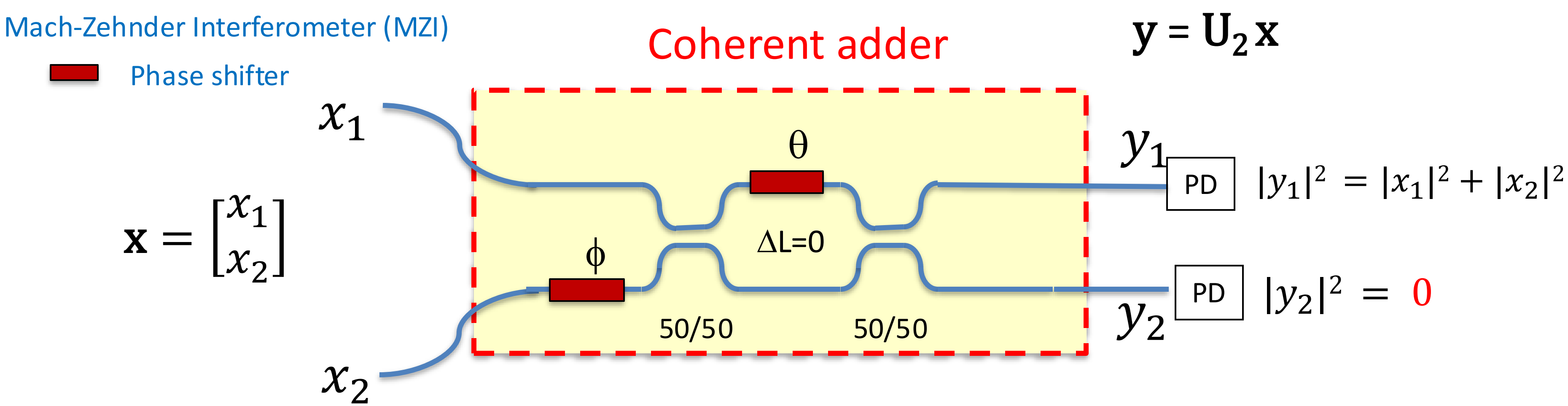
$t = \sqrt{1 - r^2}$

$$\mathbf{U}_2 = -je^{j\theta/2}\begin{bmatrix} \sin(\theta/2) & \cos(\theta/2)\, e^{j\phi} \\ \cos(\theta/2) & -\sin(\theta/2)\, e^{j\phi} \end{bmatrix} = -je^{j\theta/2}\begin{bmatrix} t & re^{j\phi} \\ r & -te^{j\phi} \end{bmatrix}$$

2x2 Unitary Transformation

- $\mathrm{U}^{\dagger}\mathrm{U}=\mathrm{U}\mathrm{U}^{\dagger}=\mathrm{I}$, $\mathrm{U}^{-1} = \mathrm{U}^{\dagger}$, $\det(\mathrm{U}) = 1$
- preserves inner product $\langle \mathrm{Ux},\mathrm{Uy}\rangle = \langle \mathrm{x},\mathrm{y}\rangle$, i.e.,
- preserves “length” & “angle” (only a “rotation”) ⇒ power conservation
- eigenvalues on unit circle, orthogonal eigenvectors

2x1 coherent adder



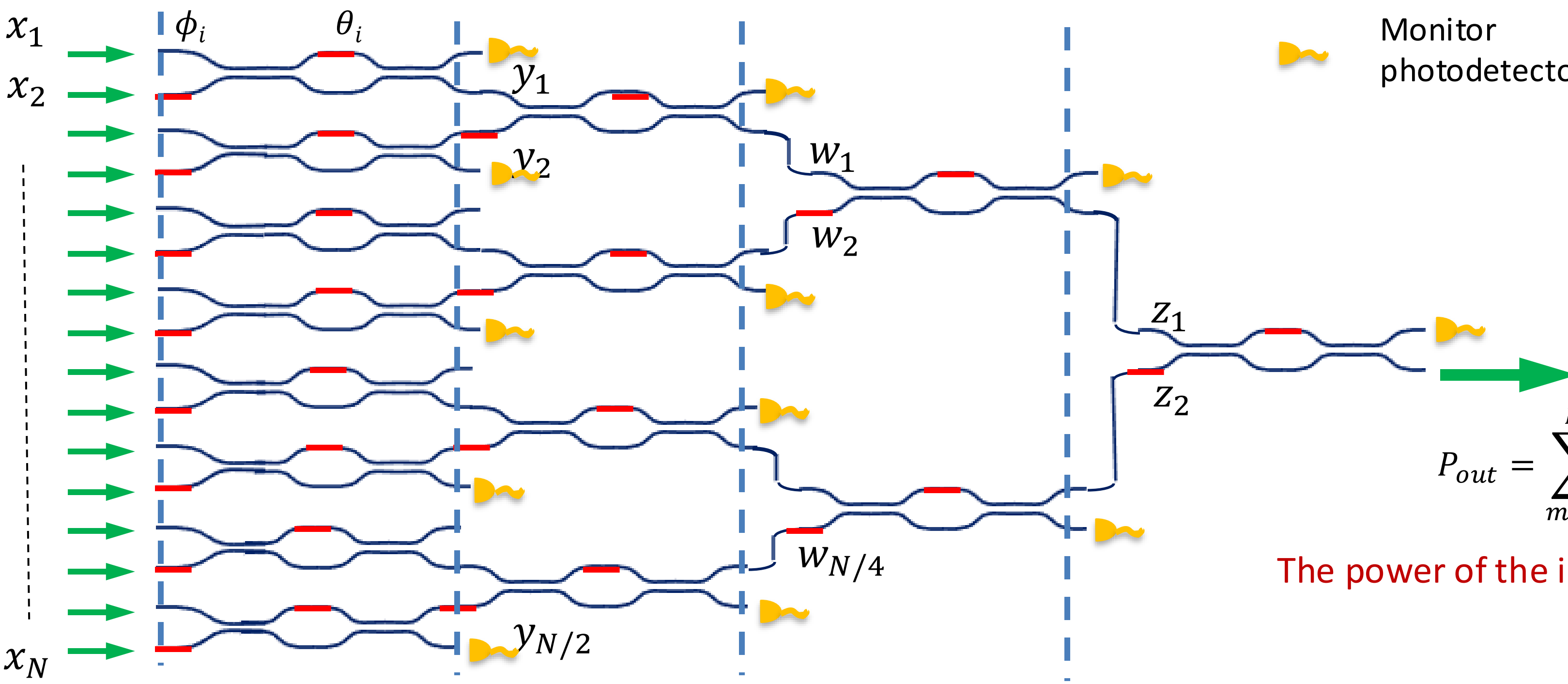
Condition to null the output power at port 2

$$y_2 = -je^{j\theta/2}\left[\cos\left(\frac{\theta}{2}\right)x_1 - e^{j\phi}\sin\left(\frac{\theta}{2}\right)x_2\right] = 0$$

$$\Rightarrow \cos\left(\frac{\theta}{2}\right)x_1 = e^{j\phi}\sin\left(\frac{\theta}{2}\right)x_2$$

$$\Rightarrow \begin{cases} \theta = 2\tan^{-1}\left|\frac{x_1}{x_2}\right|, \quad \theta \in [0,\pi] \\ \phi = (\angle x_1 - \angle x_2) + 2N\pi \end{cases}$$

Nx1 coherent adder - Binay tree MZI mesh



Monitor photodetectors (PDs)

$$P_{out} = \sum_{m=1}^{N} |x_m|^2$$

The power of the input signal !

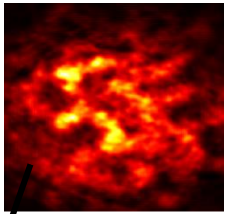
$$\phi_i = \angle x_{i+1} - \angle x_i$$

$$\theta_i = 2\tan^{-1}\left|\frac{x_i}{x_{i+1}}\right|$$

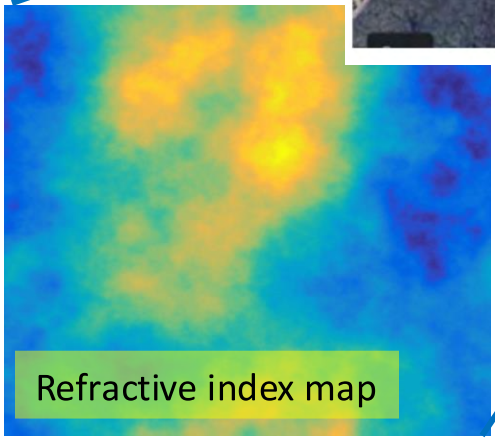
- Combining 2x1 coherent adders, an arbitrary number of inputs signals can be coherently summed
- Calibration strategy: zeroring the power at monitor ports

Free Space Optical (FSO) Link

Transmitter - TX



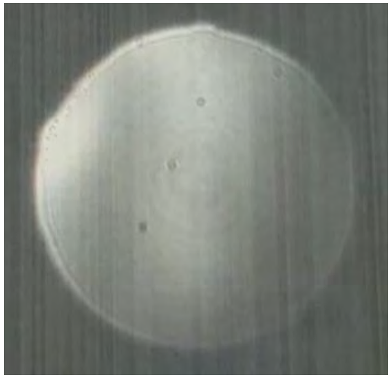
Receiver - RX



Free Space Channel

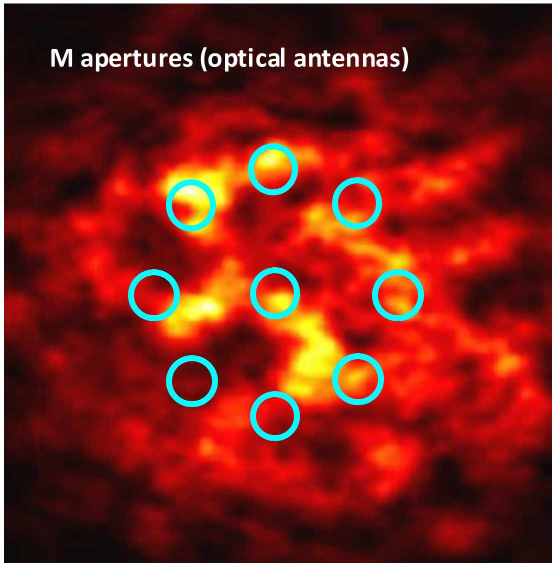
- Attenuation
- Multipath
- Time varying channel
- **Turbulence** (scintillation & wander)
- Polarization

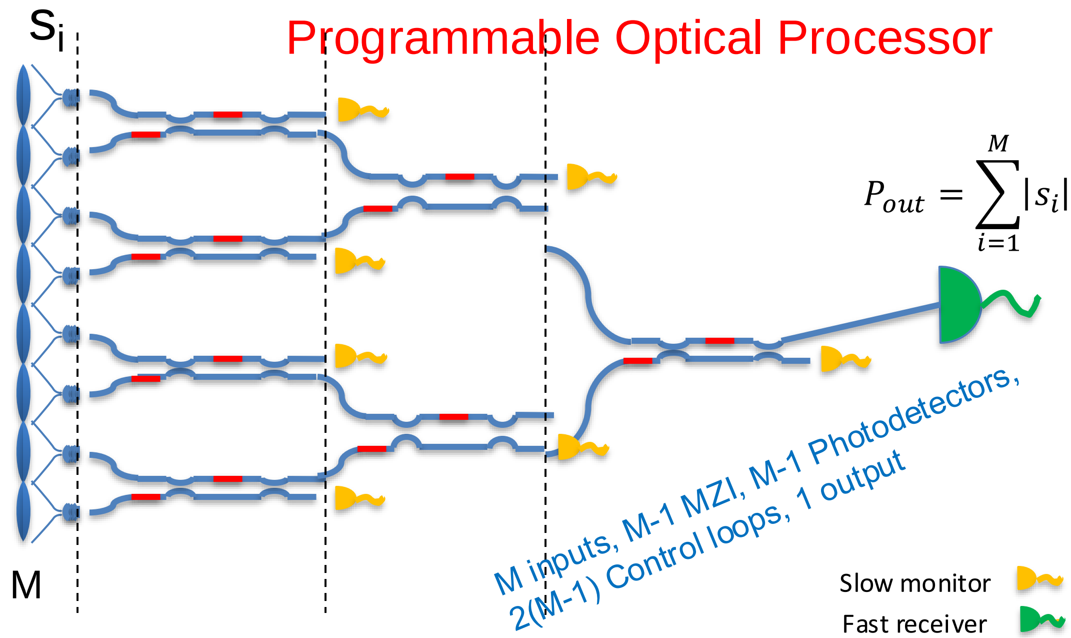
320 m FSO link
100 fps



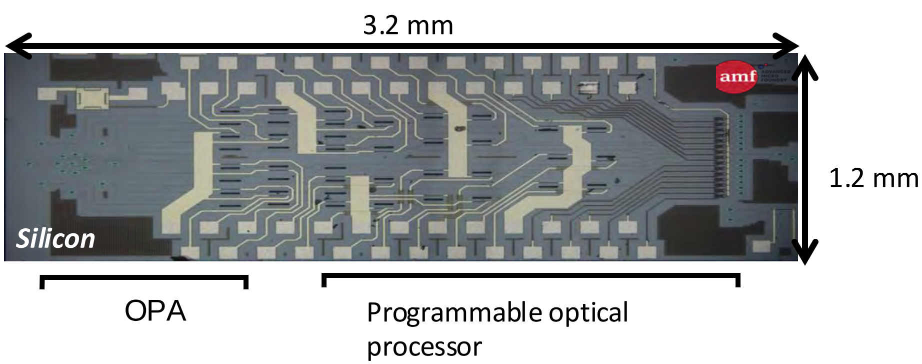
A. Trichili et al., **Roadmap to Free Space Optics,** JOSA B, July 2020

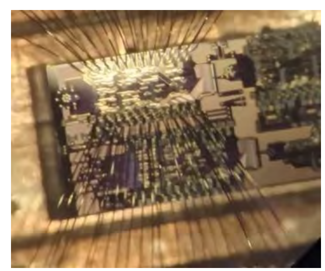
The Optical Analog Processor based receiver





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)

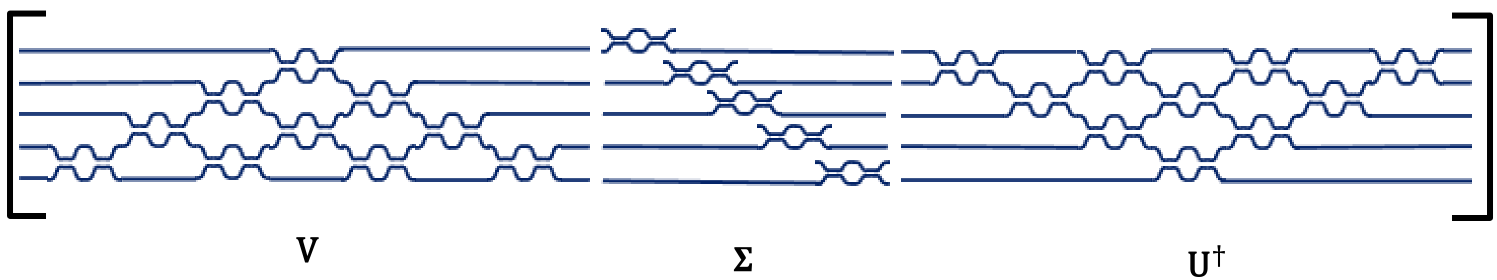
Singular Value Decomposition

Any matrix can be factorized as the product of two unitary matrices $\mathbf{V}$ and $\boldsymbol{U}$, and a diagonal matrix $\boldsymbol{\Sigma}$ (singular values)

$$\mathbf{W} = \mathbf{V}\boldsymbol{\Sigma}\mathbf{U}^{\dagger}$$

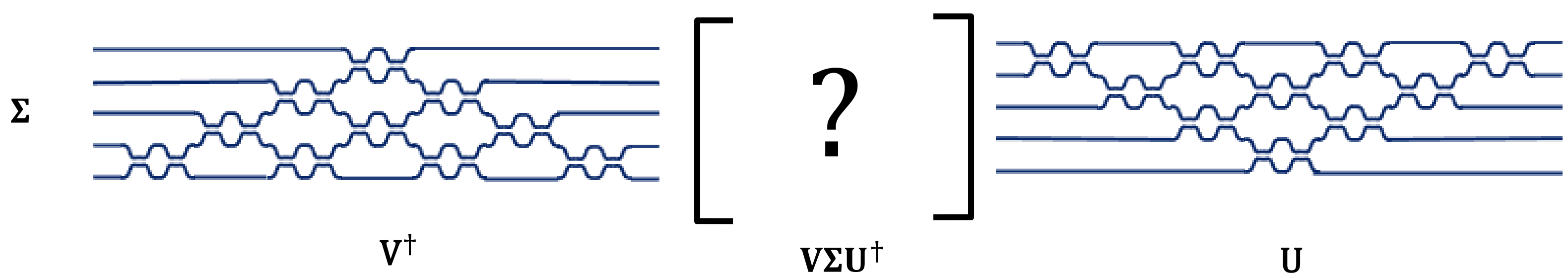
A system of MZI meshes can be used to implement any arbitrary matrix $\mathbf{W}$

Synthesis:



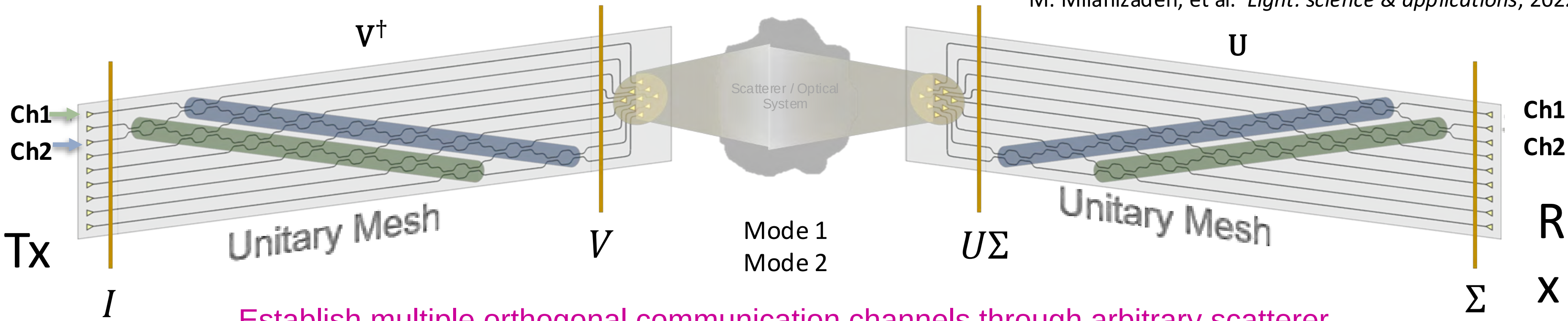
… but also to calculate the SVD of an arbitrary optical sistem (SVD factorization)

Analysis:



Application: Chip to chip communication

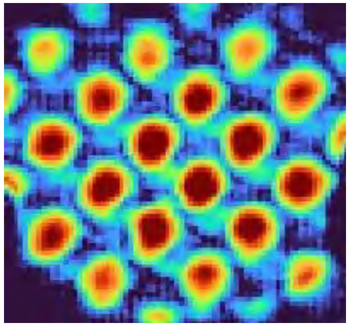
M. Milanizadeh, et al. *Light: science & applications*, 2022



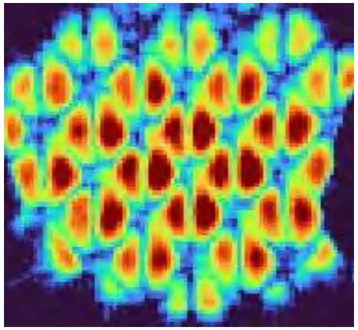
Establish multiple orthogonal communication channels through arbitrary scatterer

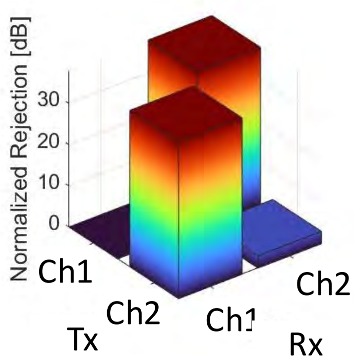
N antennas… up to N spatial **orthogonal** modes → Towards free-space optical MIMO

$Mode_1$



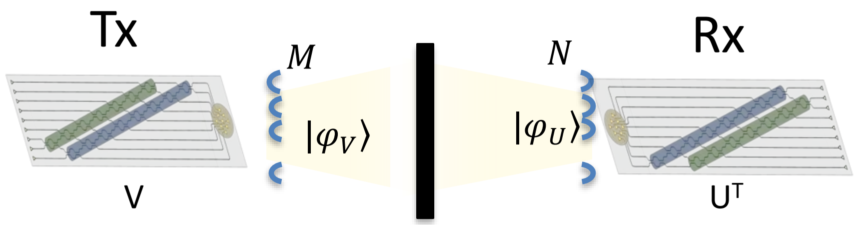
$Mode_2$

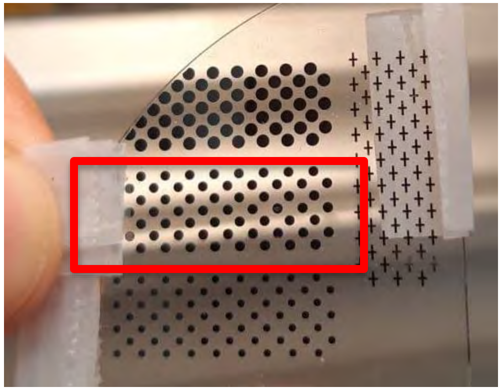




The best FSO orthogonal modes (channels) can be found automatically…

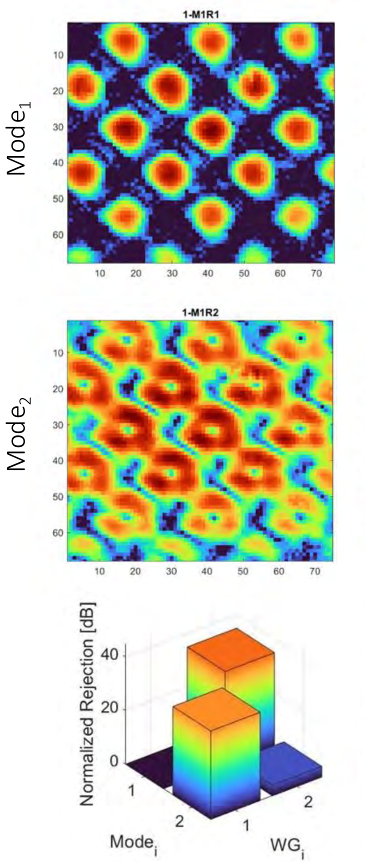
Obstacle in the free-space path





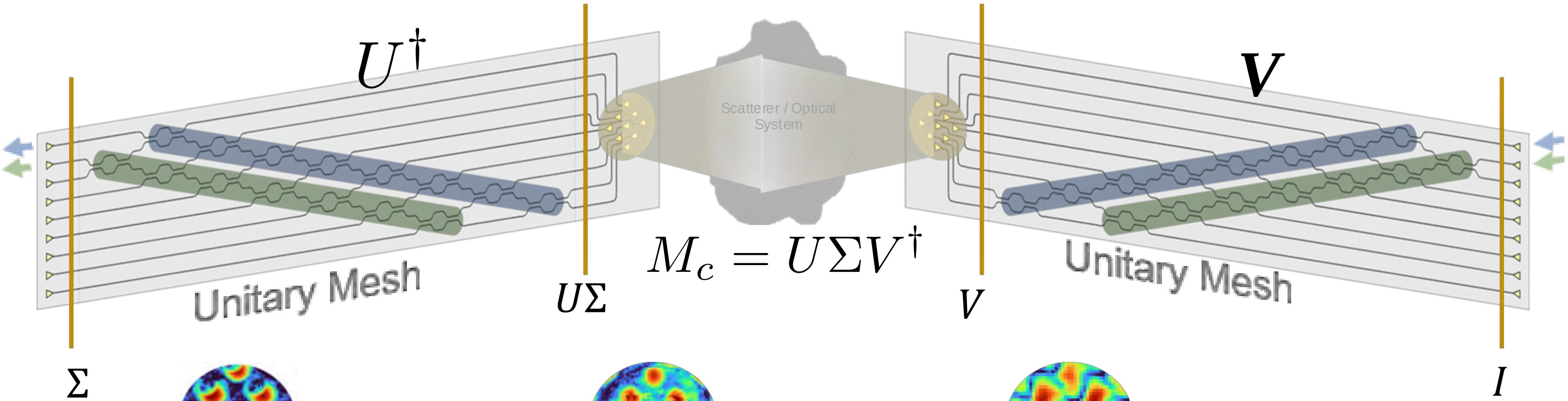
Beam shapes not belonging to any standard family of modes, yet mutually orthogonal

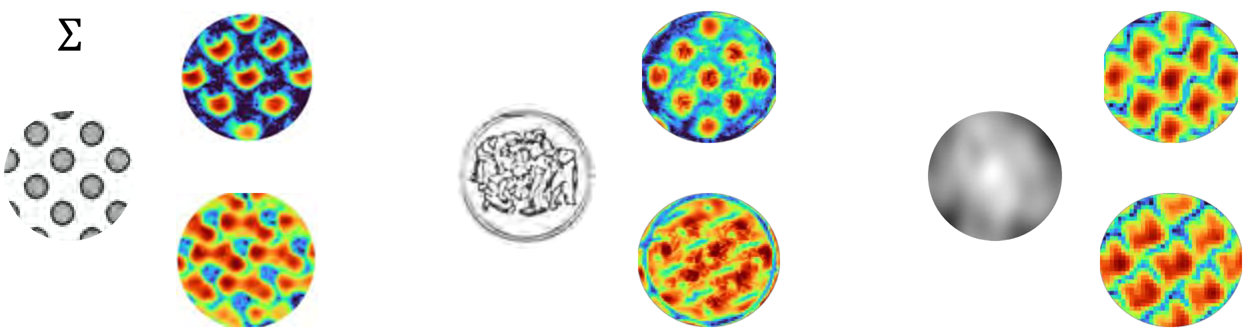
NO obstacle



Singular value decomposition

This is a physical implementation of **singular value decomposition (SVD)** of the channel transmission matrix



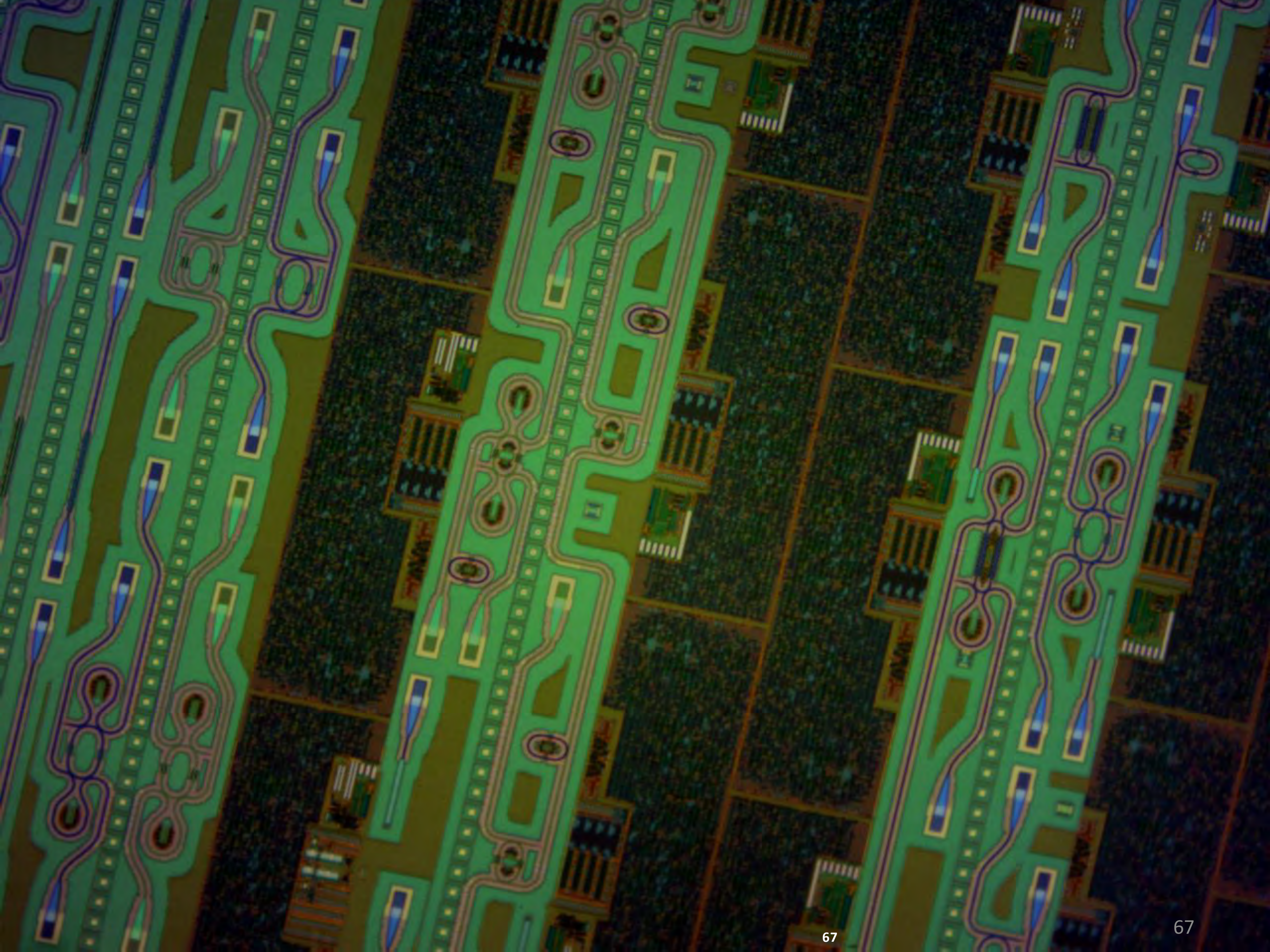


nature
Light Sci Appl **11**, 197 (2022)

S. SeyedinNavadeh et al., **Nat. Photonics,** 2024

A. Melloni et al, 2023
Science
AAAS
380, 398–404, Apr 2023

Applications: general purpose, Matrix Algebra, mathematical accelerators, convolutional NN, tensor cores,…



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