Keep Photonics Under Control: How to Harness Programmable Photonic Circuits

Presented by:

OSA Optoelectronics Technical Group

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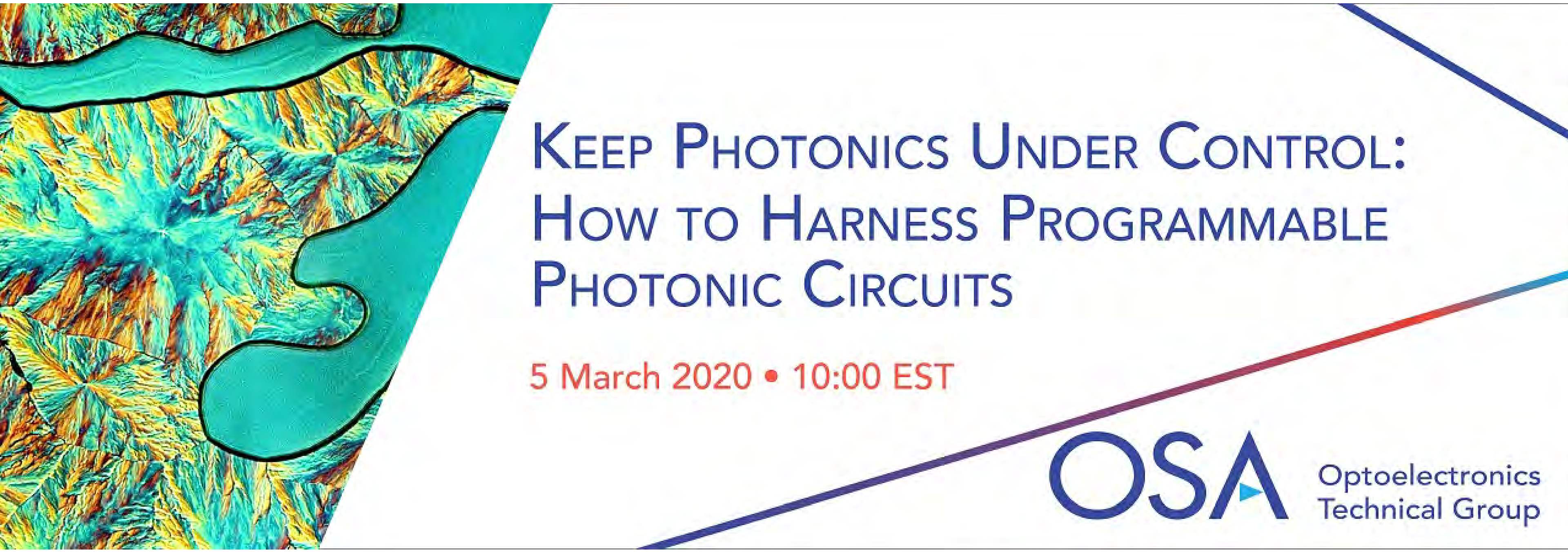

OSA Optoelectronics Technical Group

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Carleton University, Canada

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National Research Council Canada, Canada

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Jens H. Schmid
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OSA Optoelectronics Technical Group

Technical Group at a Glance

- Focus
  - The OP TG focuses in the field of semiconductor lasers, amplifiers, LEDs and super luminescent diodes, and other areas related to optoelectronics
  - Over 4,500 members within OSA
- Mission
  - To benefit ***YOU***
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact winnie.ye@carleton.ca
- Find us here
  - Website: www.osa.org/OptoelectronicsTG
  - LinkedIn: www.linkedin.com/groups/8297718/

OSA Optoelectronics Technical Group

Today's Webinar

Keep Photonics Under Control: How to Harness Programmable Photonic Circuits

Dr. Andrea Melloni, OSA Fellow, is Full Professor at Dipartimento di Elettronica, Informazione e Bioingegneria at Politecnico di Milano where he leads the group of Photonic Devices. With a background in microwaves, his field of research is in the analysis, design, characterization and exploitation of passive integrated optical devices for telecom and sensing. He is one of the pioneers of the slow light concept and its exploitation in the linear and nonlinear domains. In September 2008 he founded the company Filarete with the aim of developing and commercializing ASPIC (www.aspicdesign.com), the first circuit simulator for integrated optical circuits. He is active in characterization and testing techniques (from wafer to module testing), numerical methods in photonics (stochastic), development of high index contrast dielectric materials (SiliconOxyCarbide), design and analisys of photonic integrated circuits, biosensing (with exploitation of magnetic beads). Recently, he mainly focused on the control and stabilization of photonic circuits with a new technique of non invasive light monitors based on the natural surface state absorption phenomena occurring in waveguides. These activities are at the basis of the dynamic management and control of large and complex photonic integrated circuits for reconfigurable, programmable, locking and adaptive functionalities.

POLITECNICO
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Dipartimento di Elettronica, Informazione e Bioingegneria

polifab
POLITECNICO DI MILANO

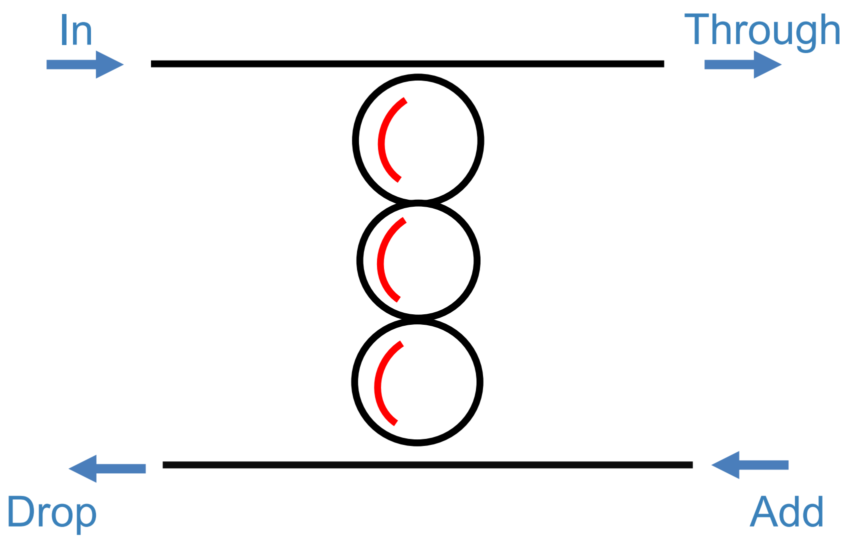
Keep Photonics Under Control: How to Harness Programmable Photonic Circuits

Andrea Melloni
Politecnico di Milano, Italy

Summary

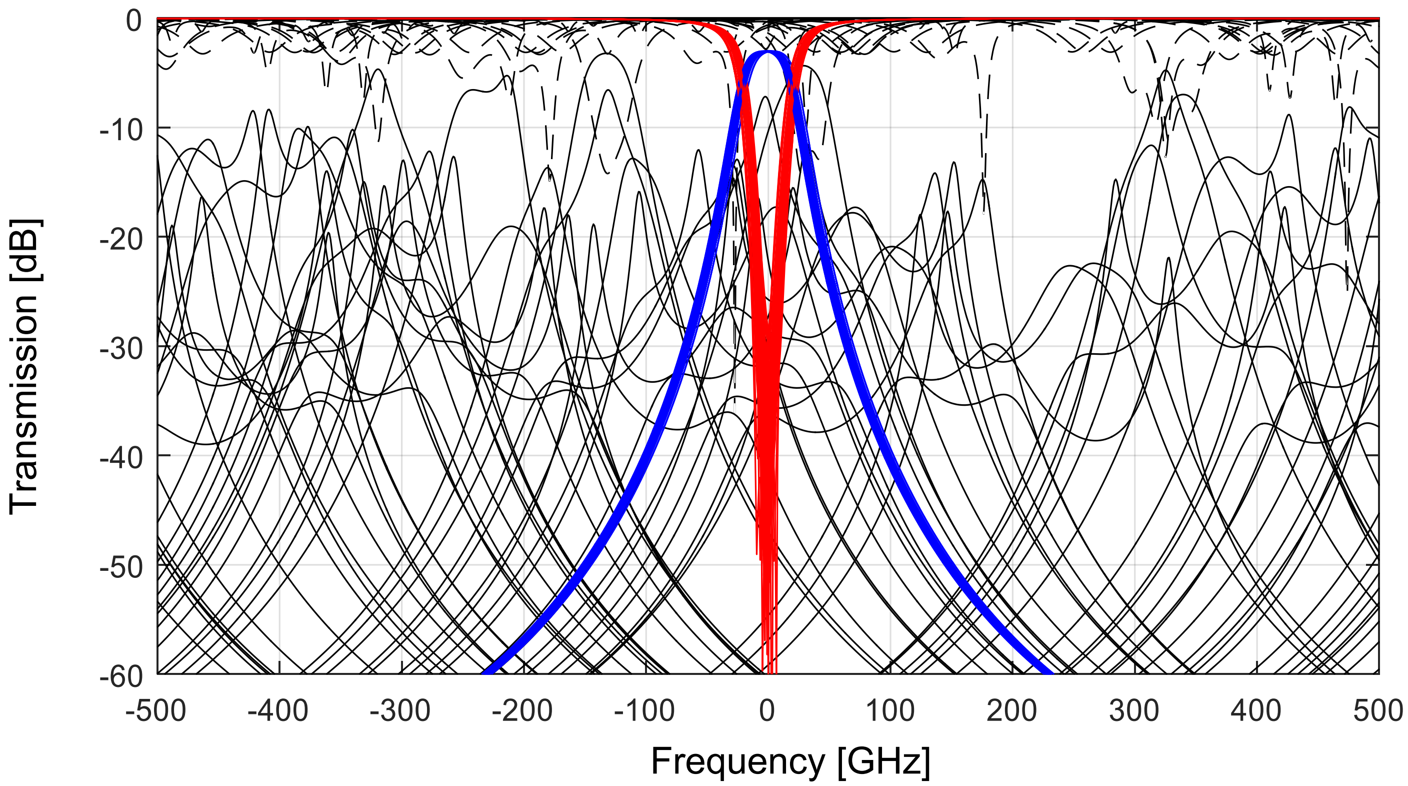
- Motivations and needs
- The ingredients:
  - monitors, actuators, electronics
  - techniques and algorithms:
    - Thermal management
    - Modulated signal for tuning
    - Pilot tones
- The recipes
- The dishes:
  - Filter tuning and operation
  - Look up table generation
  - Mode unscrambling
  - Dispersive media compensation

An Add-Drop Bandpass filter…



FSR = 8 nm (1000 GHz)

BW = 40 GHz

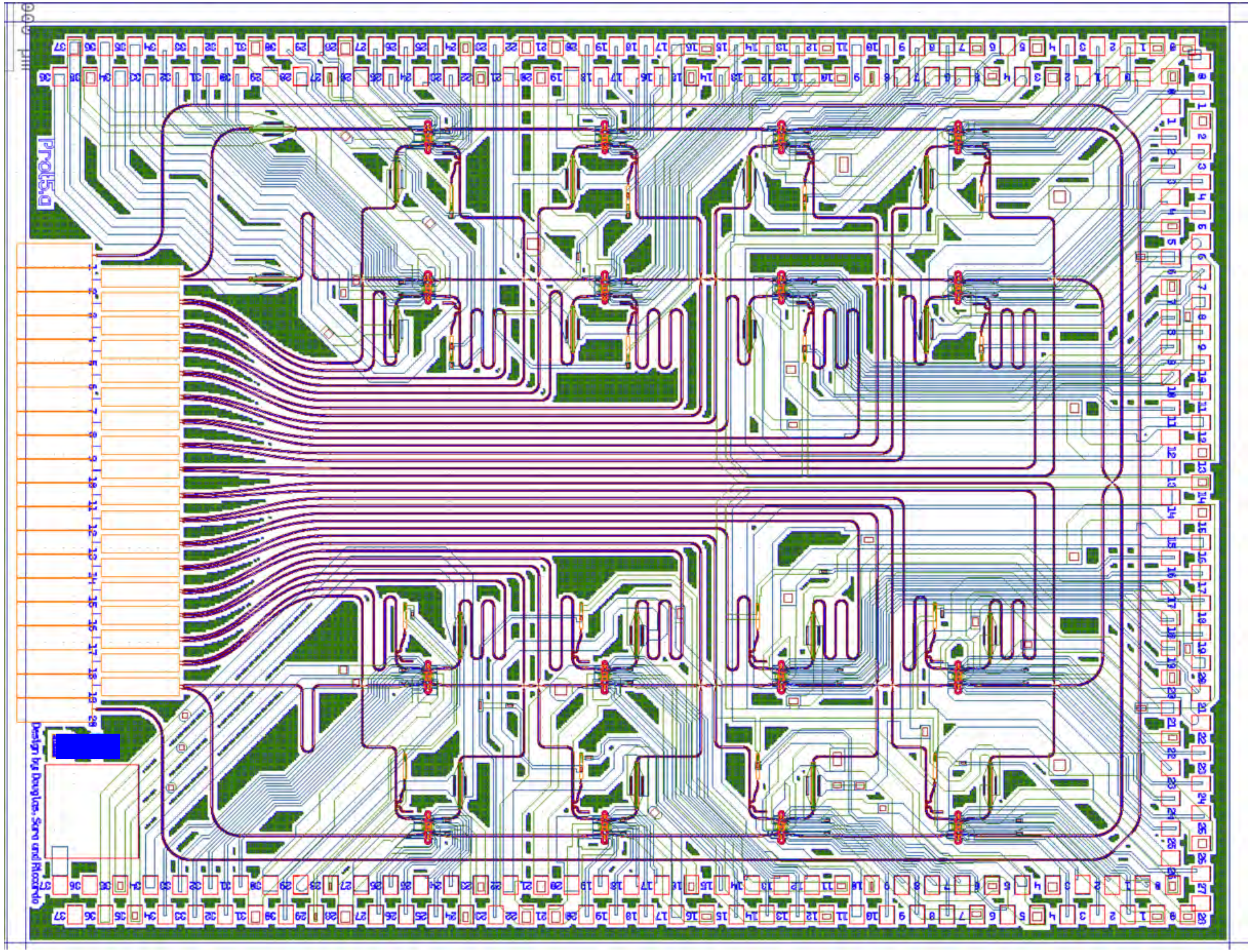


1 atom …. 1 BW shift

4 °C …. 1 BW shift

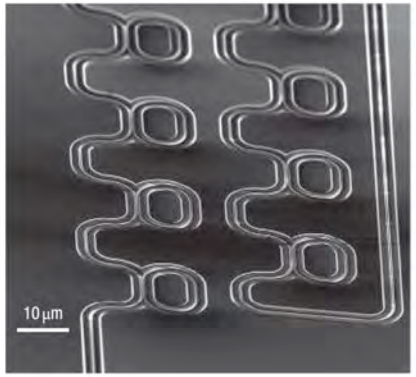
A complex device…

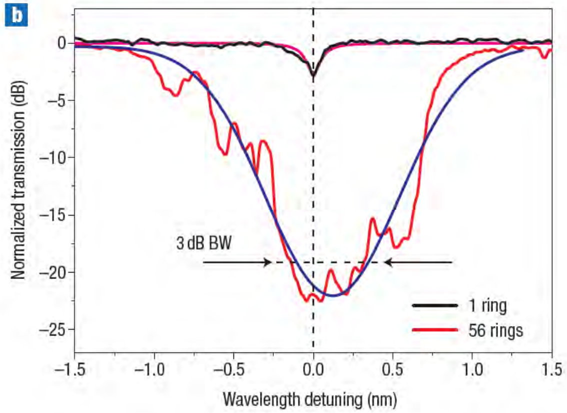
16 filters
64 rings
32 Mach-Zehnder
32 modulators
16 PD
….



PICs: uncertainties and variability

... fabrication tolerances





Courtesy of IBM, 2007

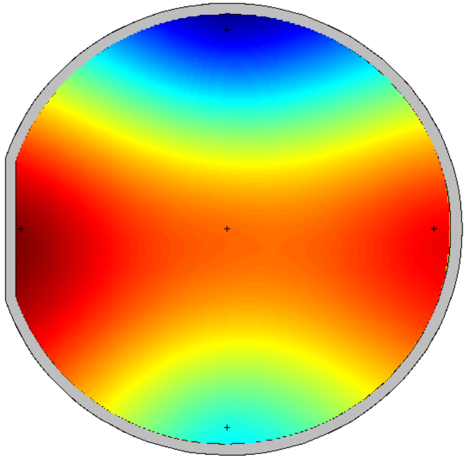
F. XIA, et al, Nat. Photonics, 2007

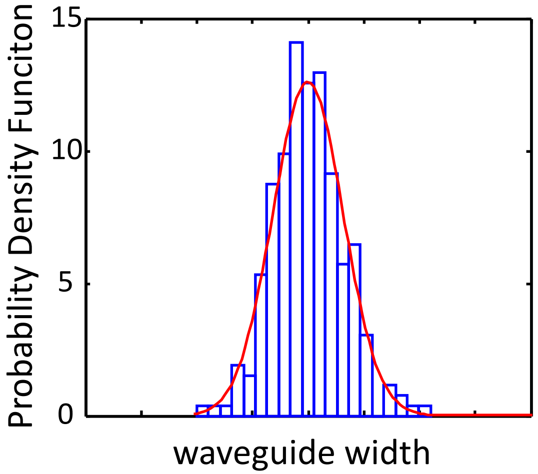
1nm tolerance in waveguide width, 100 GHz wavelength shift

... temperature dependence

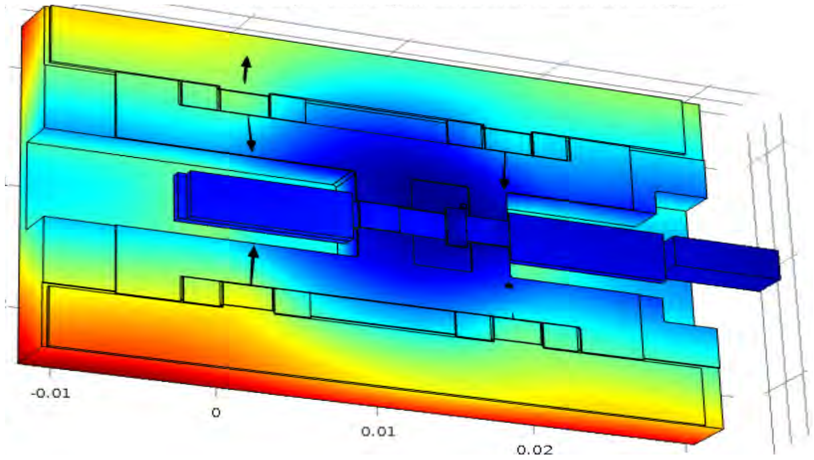
Material	K_{th} [K^{-1}]	$\Delta f/\Delta T$ [GHz K^{-1}]
SiO_2	10^{-5}	1.5
Si, InP,...	$2\ 10^{-4}$	10

... stochastic nature of parameters





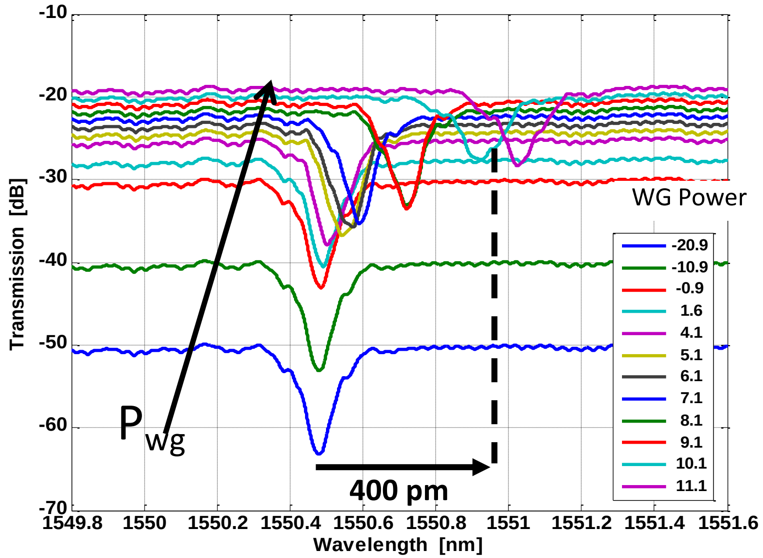
... operational conditions



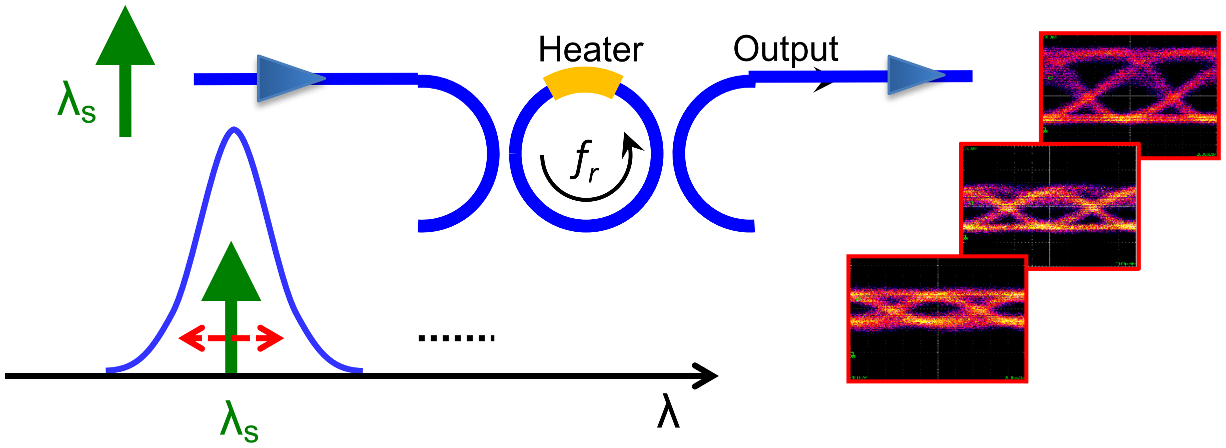
PICs: adaptivity and programming

... non linear effects

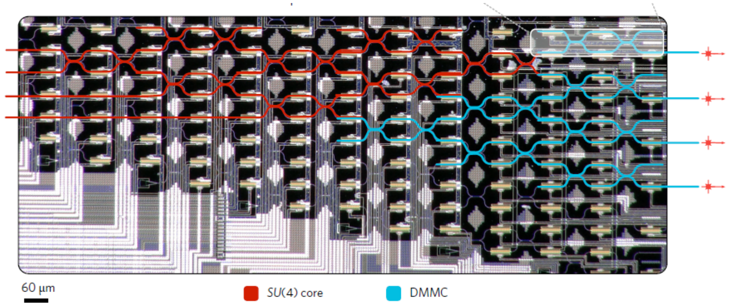
Nonlinear frequency shift, Two Photon Absorption



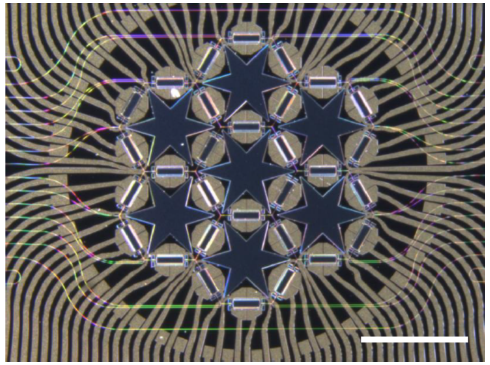
... adaptive tuning and locking to "external" drifts



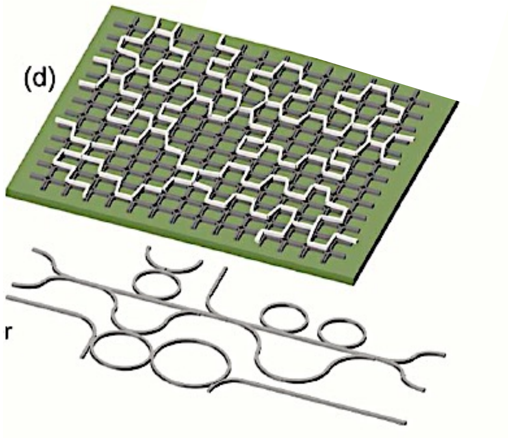
... programmable integrated photonics



Y. Shen et al, Nat Photonics **11** (2017)

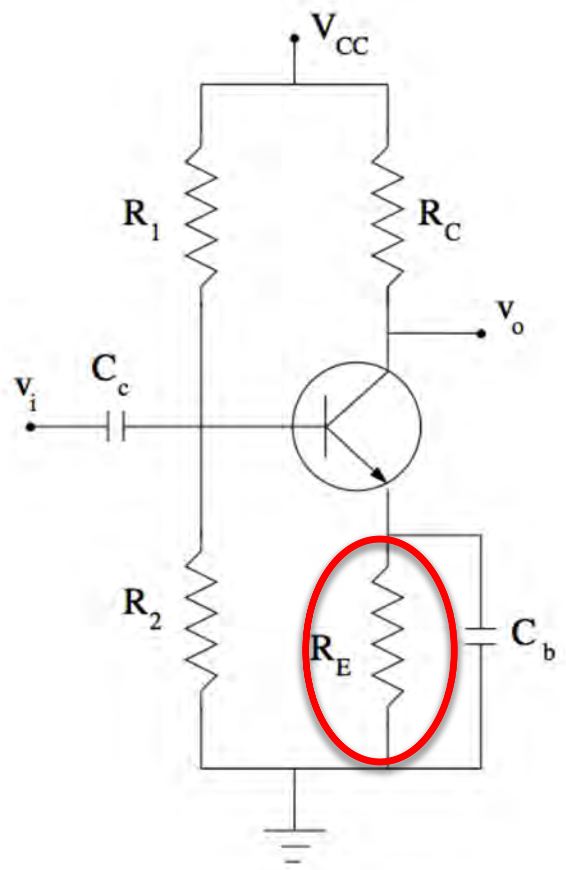


D. Perez et al., Nat Communications **8**:636 (2017)



L. Zhuang et al., Optica **2** (2015)

(Negative) Feedback for control …



- Human body temperature
- Production of human red blood cells vs oxygen
- Population of predators and prey
- The photosynthesis in plants vs CO_2 level
- Being reprimanded for coming to work late
- Economic: supply and demand law
- Several examples in mechanical …

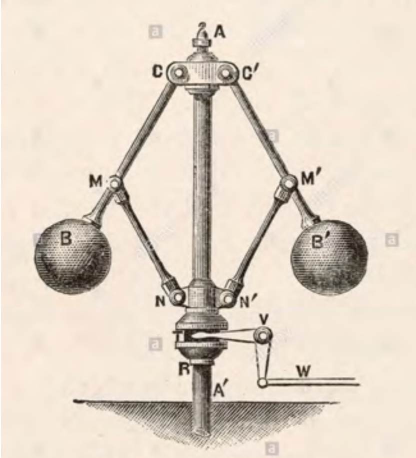
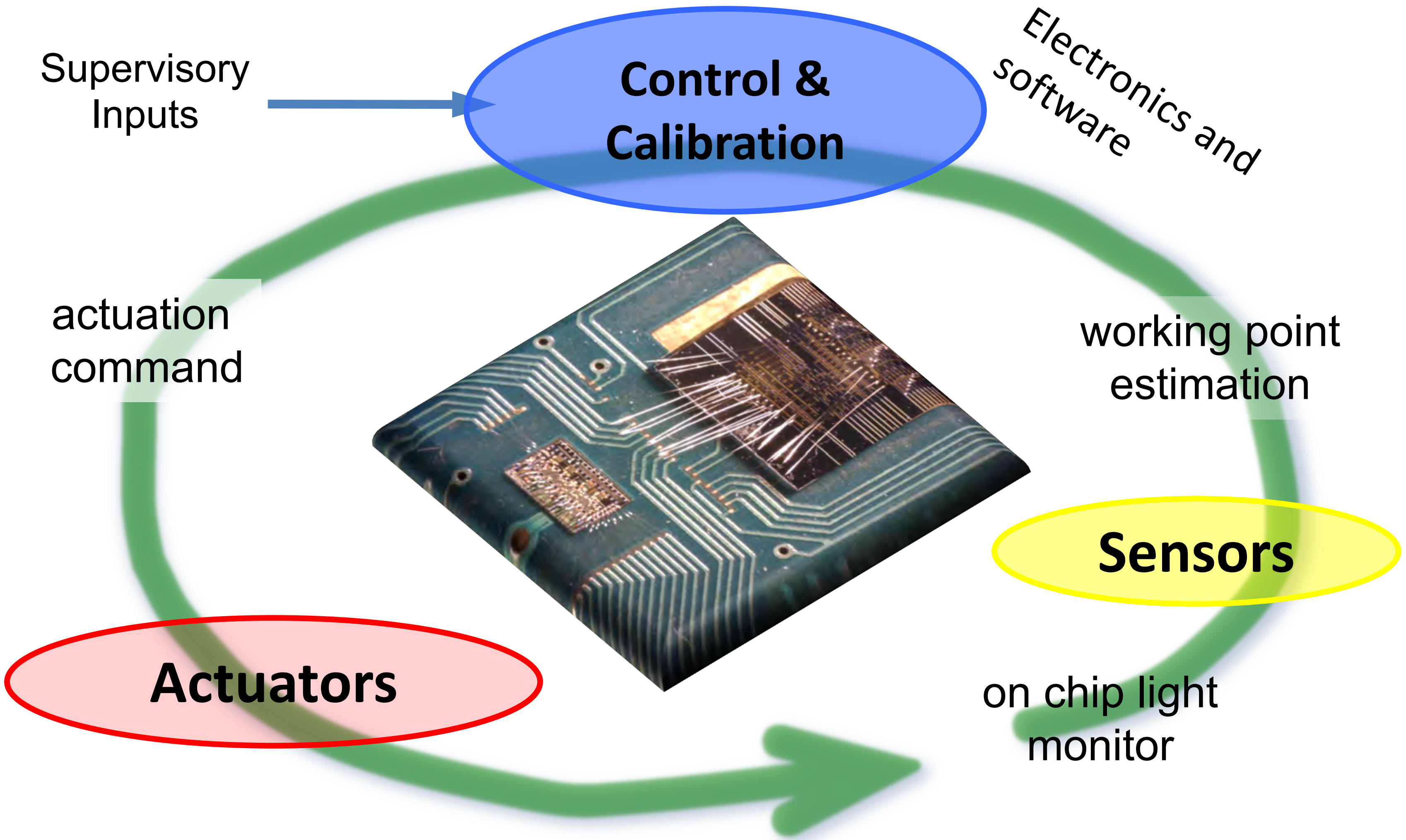


Fig. 29.—The Governor.

… also photonics needs feedback and control !!

The photonic chip as a system: **the control layer**



MOTIVATIONS

Fabrication tolerances

Uncertainties and variability

Stochastic nature of parameters

Temperature dependence

Operational conditions

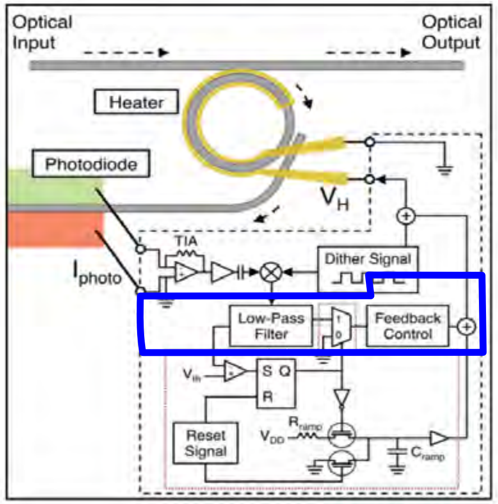
Nonlinearities

Programmable photonics

Adaptive photonics

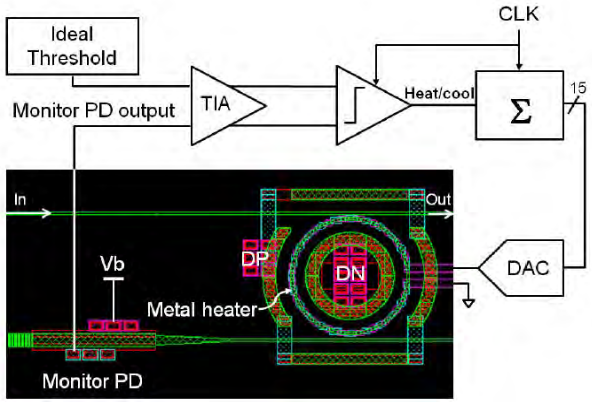
The control layer from literature (incomplete!)

Dithering, analog
Columbia Univ. 2014



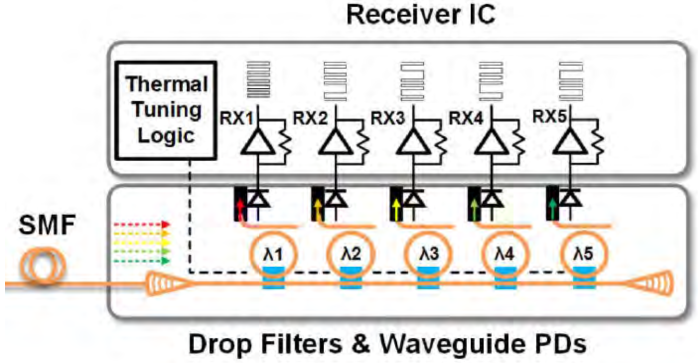
K. Padmaraju, et al, JLT 32(3), 2014

Bang-bang, digital 15 bits
Oracle 2014



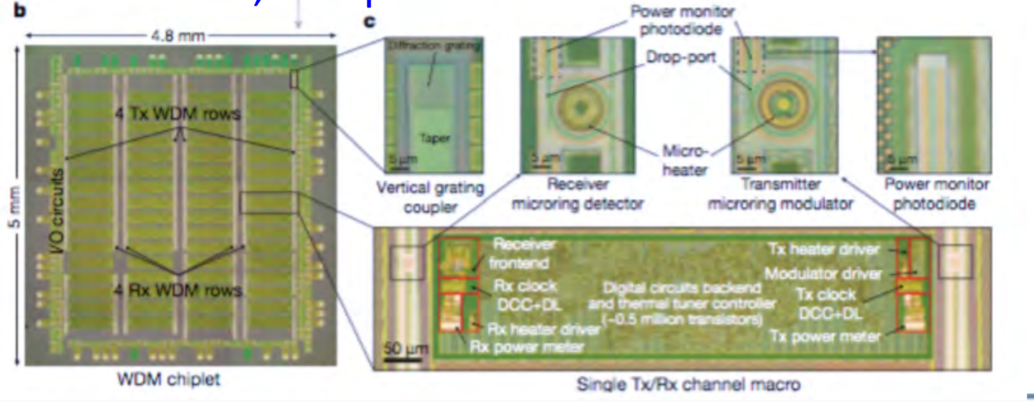
X. Zheng, Opt. Express, 22(10) 2014

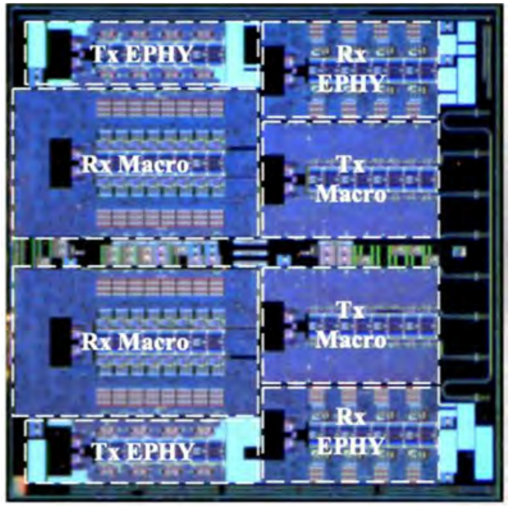
Tuning (peak search, analog) + locking (bang-bang, digital)
HP 2016



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

Integrating photonics with silicon nanoelectronics
Nature, 19 April 2018



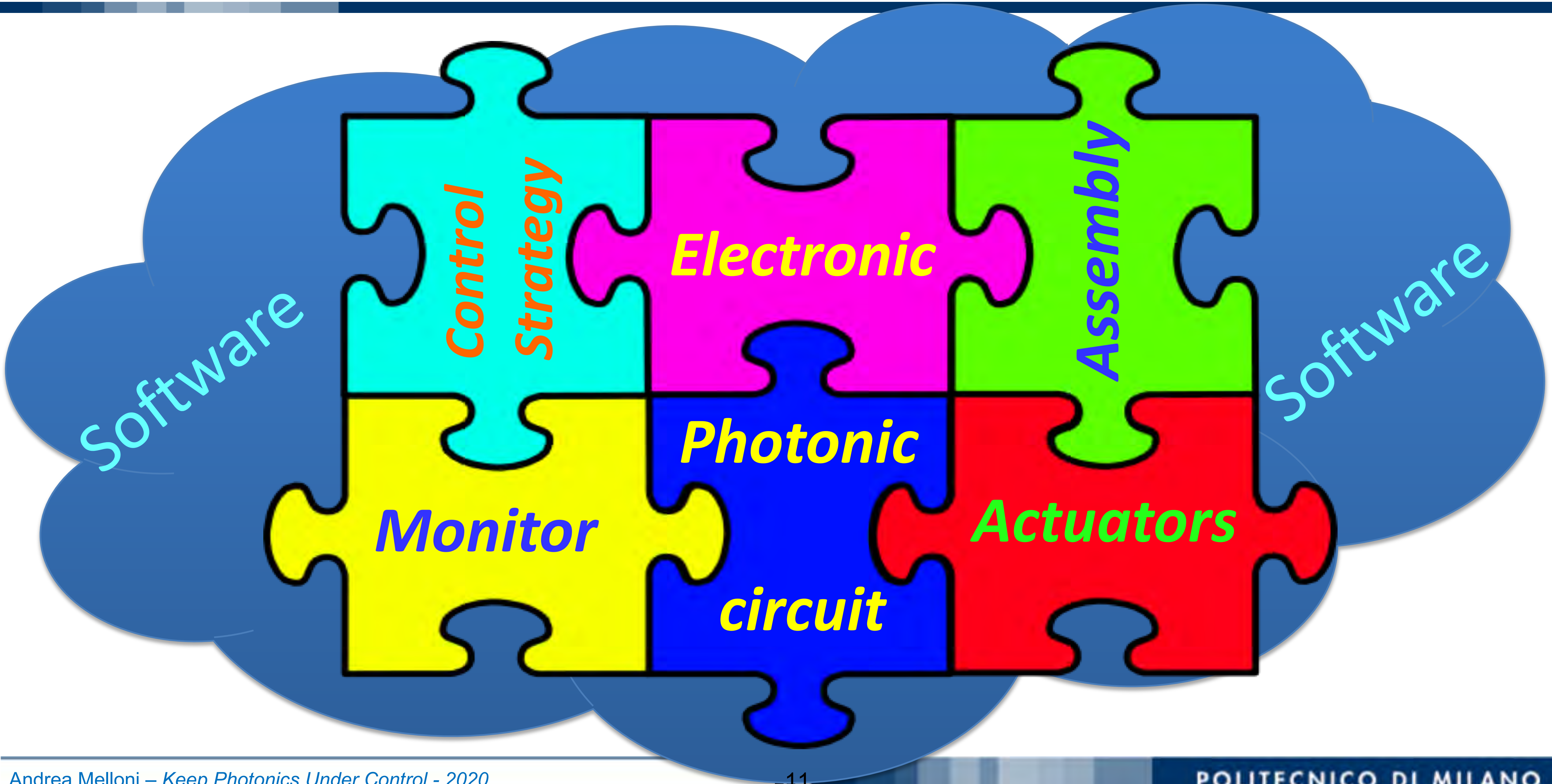


TeraPHY: A High-density Electronic-Photonic Chiplet, OFC 2019 - *Ayar Labs, Inc.*

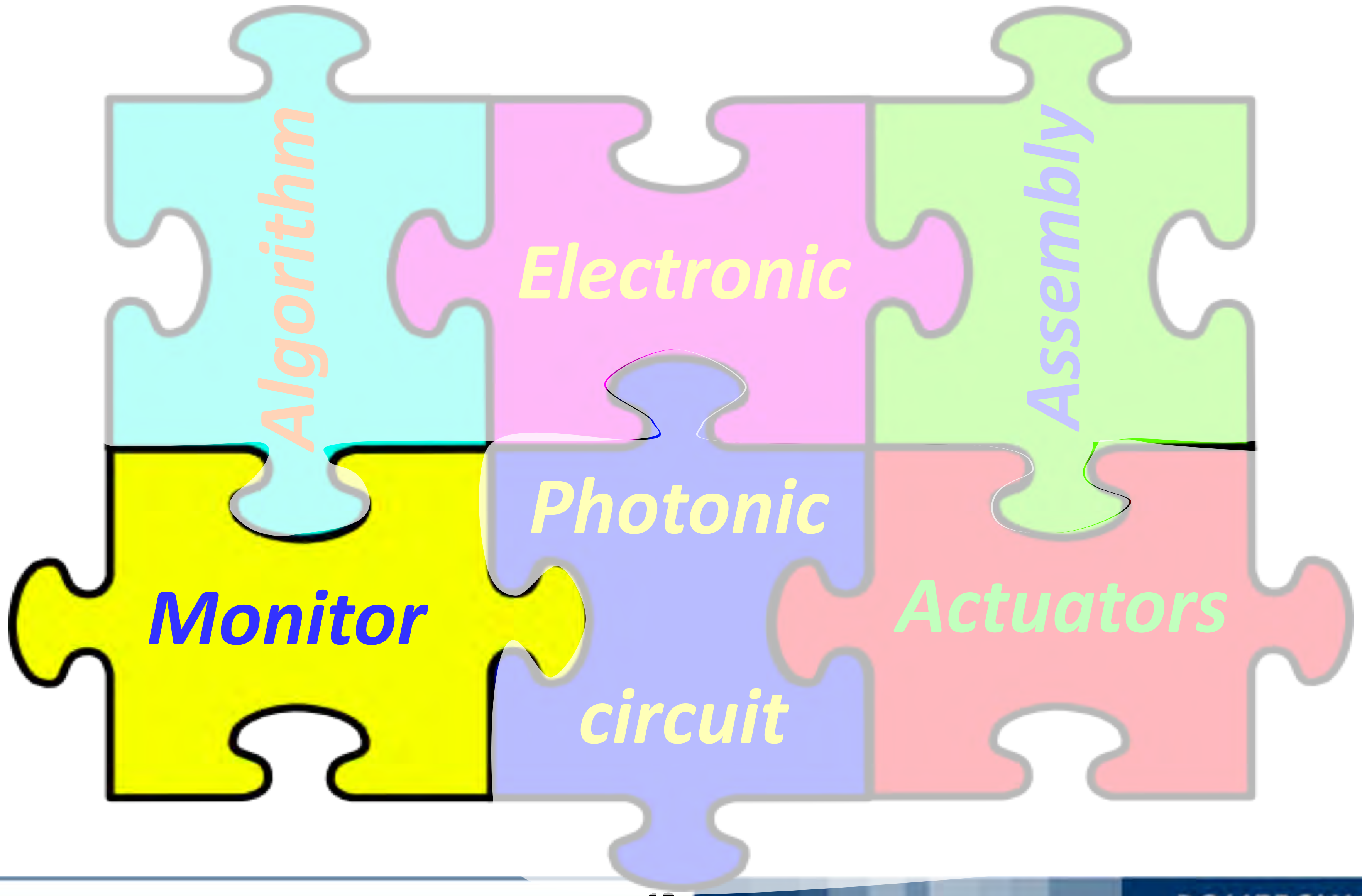
TeraPHY die

The ingredients

The control layer



The control layer: **monitor**



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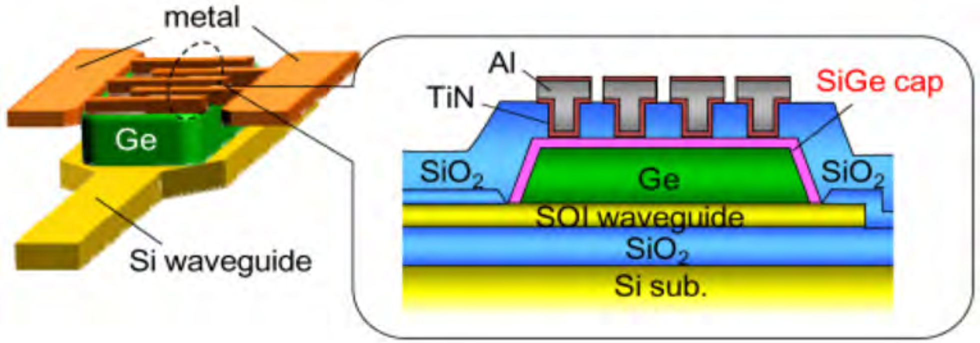
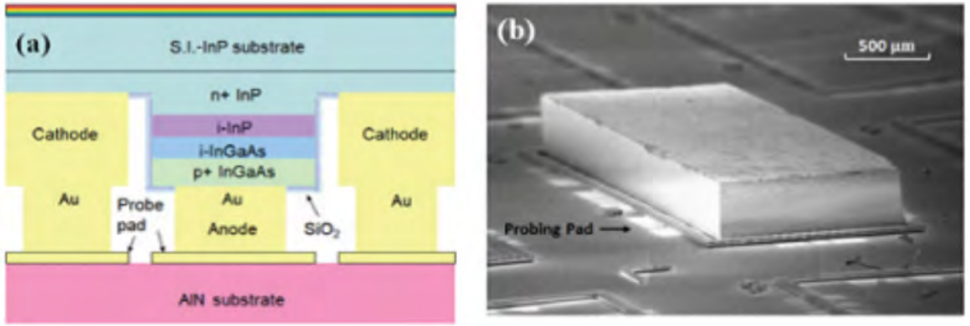
Light monitors: Ge, InP, hybrid, monolithic... CLIPP !

On-chip photodetection is a mature technology but... power hungry and photon hungry

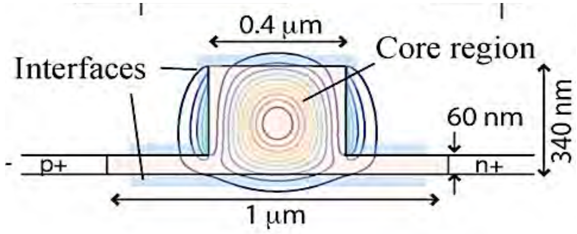
Ge on Silicon



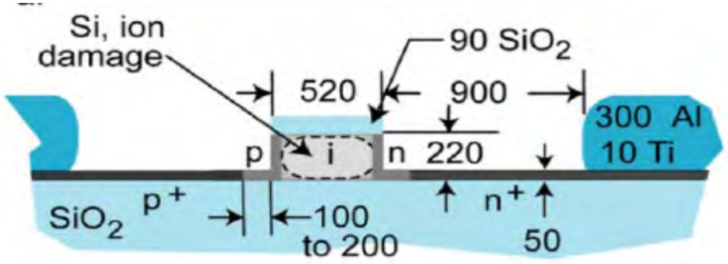
III-V compounds



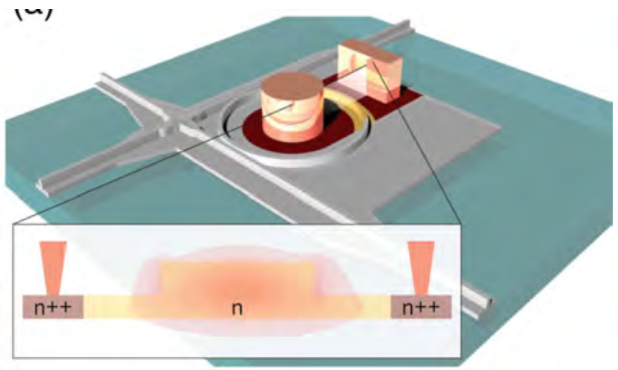
Silicon itself can be used for light detection in the near-IR



H. Chen et al., APL 95, 171111 (2009)



M.W. Geis et al., PTL 19(3), 2007



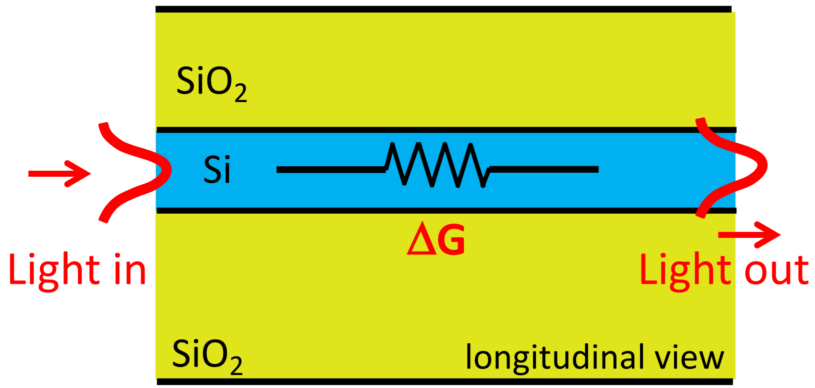
H. Jayatilleka et al., 6 (1) OPTICA, 2019

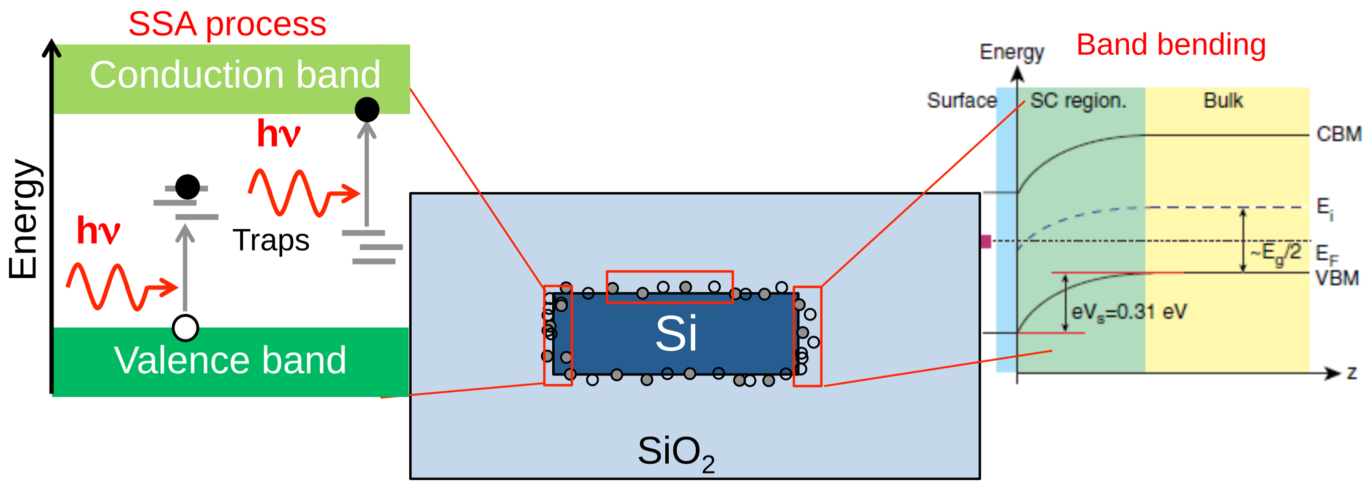
Surface and Defect state absorption PDs

Photogeneration due to natural and/or induced (ion implantation) defect states at the edges of the waveguide core (symmetry breaking & dangling bonds)

A transparent detector: the CLIPP concept

ContacLess Integrated Photonic Probe lockin detection of photoconductance





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

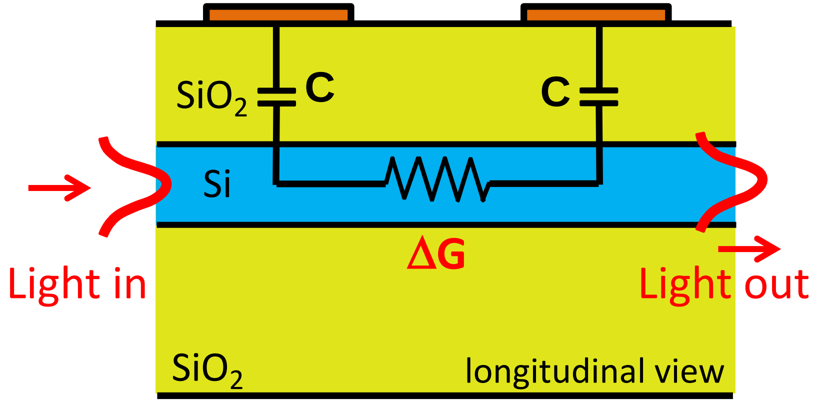
Si conductivity change induced by light

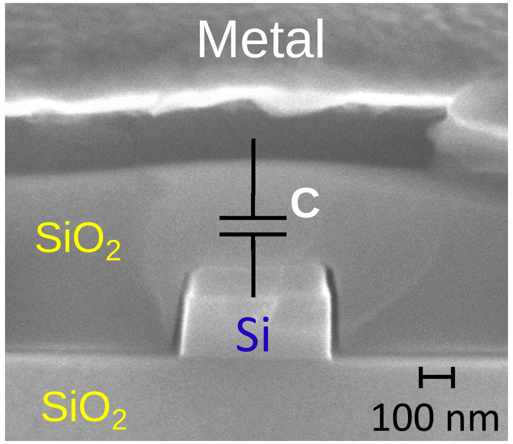
Carrier mobility is typically lower on the surface compared to the bulk

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

A transparent detector: the CLIPP concept

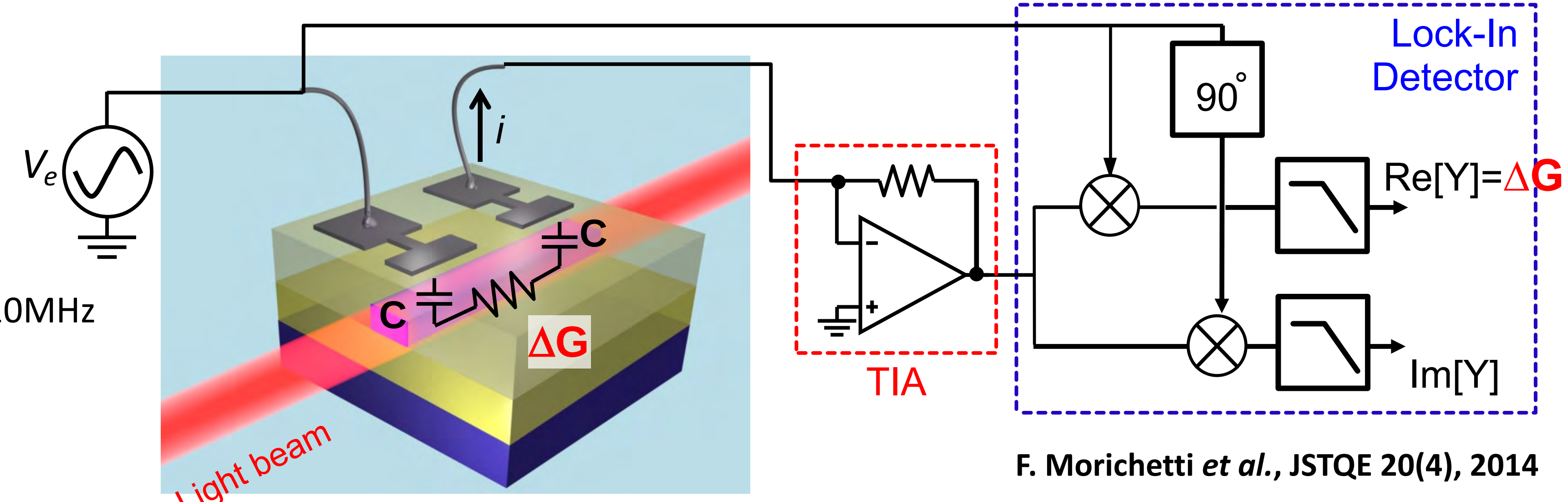
ContacLess Integrated Photonic Probe (CLIPP)





Contactless capacitive access to the waveguide

Measuring the SSA induced waveguide **conductance change ΔG** through a lock-in **detection circuit**



V_e = 1 V
f_e = 10kHz - 10MHz

nature COMMUNICATIONS

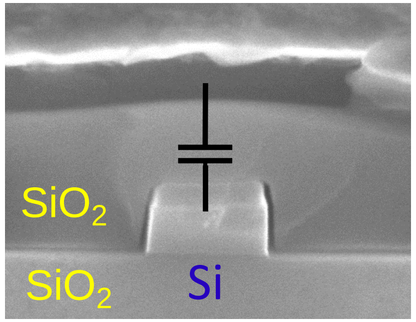
S. Grillanda, Nature Communications 6, 8182 (Sept. 2015)

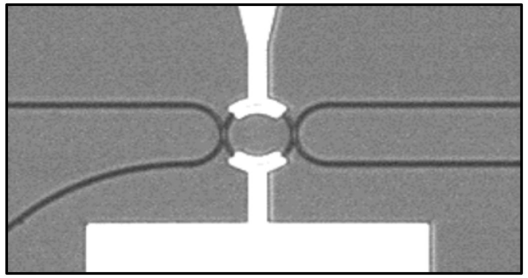
F. Morichetti *et al.*, JSTQE 20(4), 2014

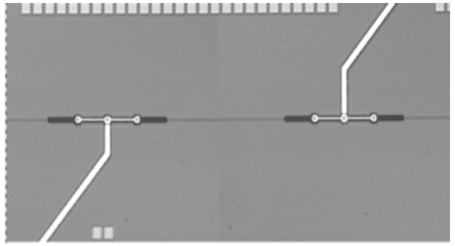
Stalking light, Nature Photonics Highlights 2014

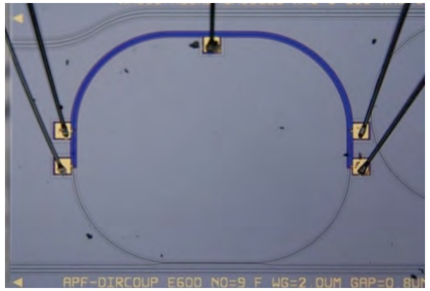
research highlights nature photonics

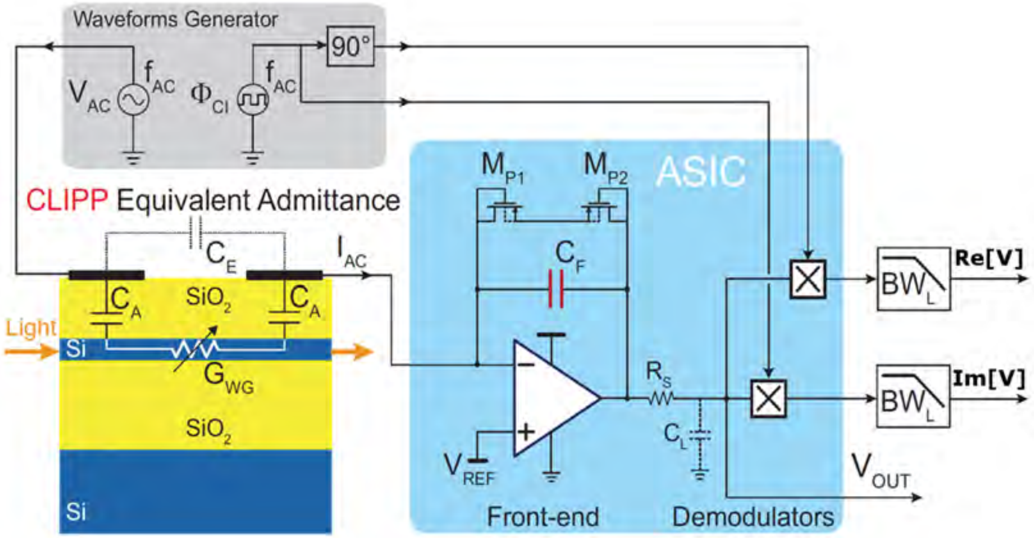
CLIPP performance

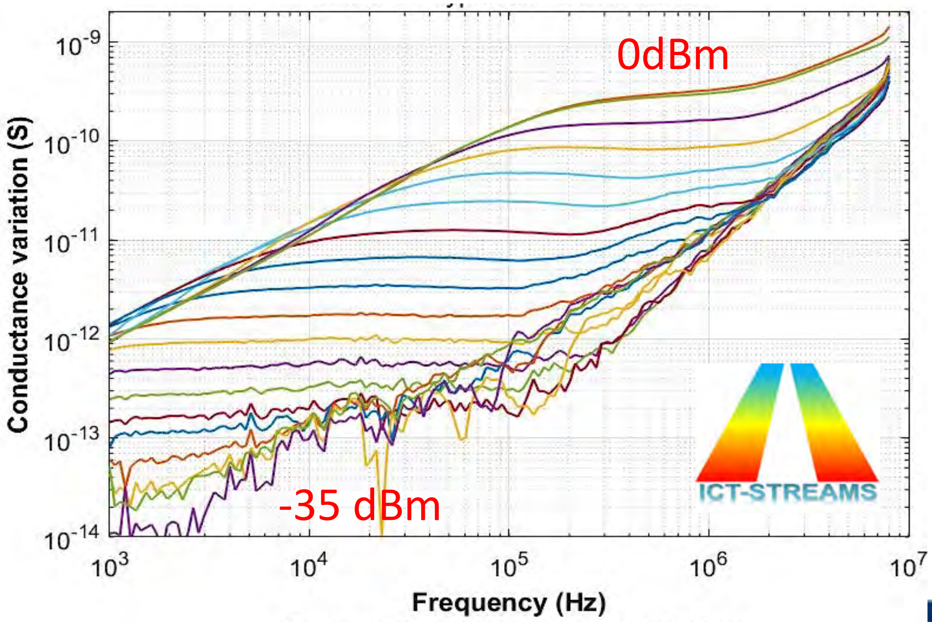








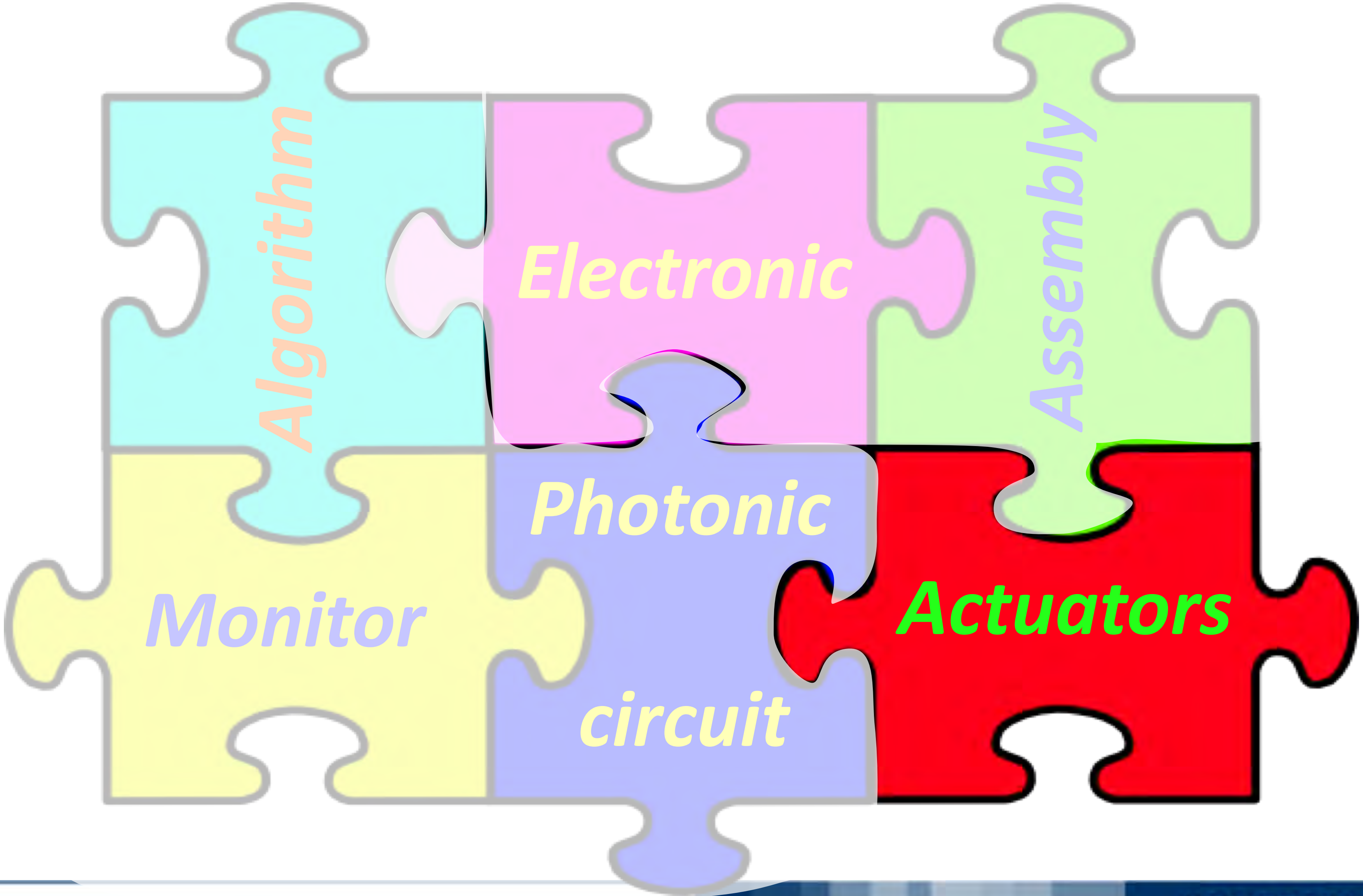




Performance match monitoring requirements:

- Compact size: *L* down to 25 µm
- Sensitivity down to -40 dBm
- 40 dB dynamic range
- Speed down to 20 µs
- Both TE/TM polarizations
- Arbitrary waveguide geometry (single-mode/multimode)
- No loss, no backreflection, no amplitude/phase perturbation, no need for doping

The control layer: **Actuators**



Integrated optical **actuators**

Phase / Amplitude

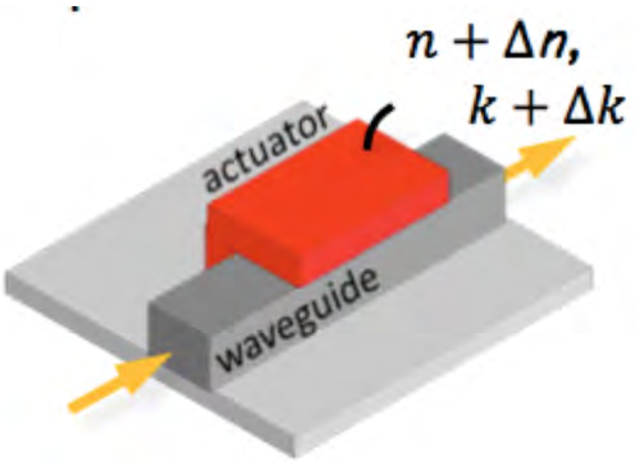
Analog / Digital

Reversible (tuning, switch) / **Permanent** (trimming, programming)

Fast (MHz for tuning/stabilization) / **Slow** (reconfiguration)

Compact (1-100 μm)

Low Power (< mW) **/ Energy consumption** (< pJ/bit)



S. Zanotto, Laser & Photonics Reviews 9 (6), 2015

Phase actuators

ON/OFF → $\Delta n = \pi$

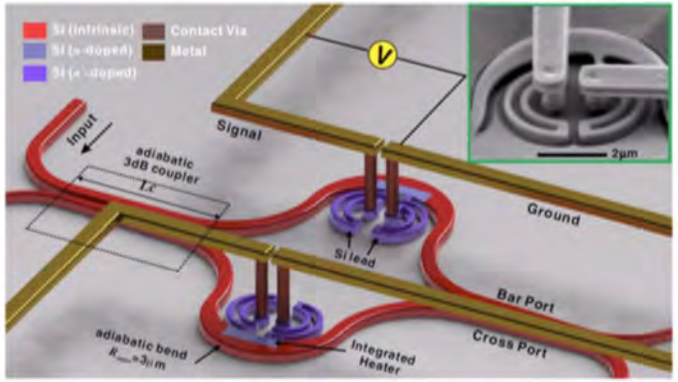
(large Δn, moderate Δk)

$$\Rightarrow \frac{\Delta n}{\Delta k} \geq 250$$

Integrated optical **actuators**

Thermal actuators

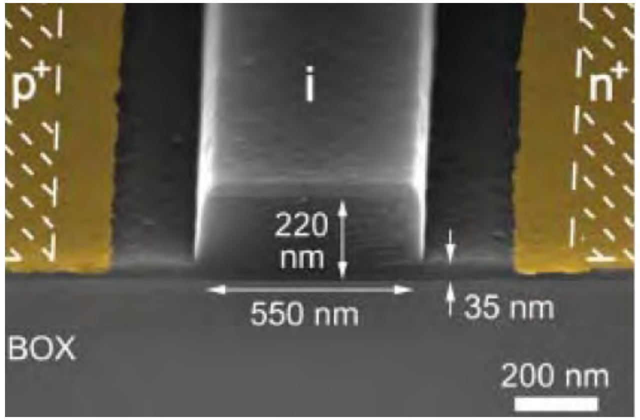
M. R. Watts, et al. Opt. Lett. 38, (2013)



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

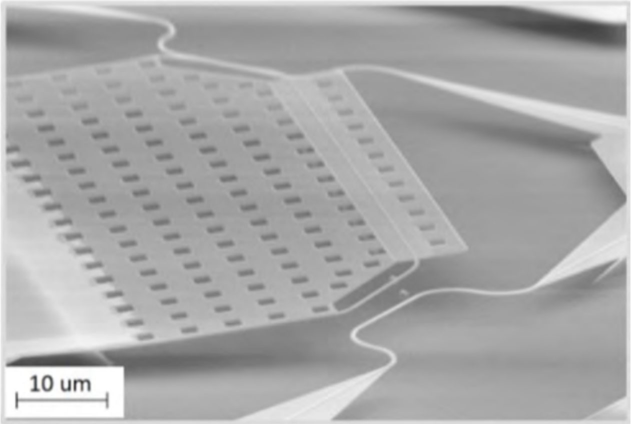
p-n junctions

Carrier injection/depletion



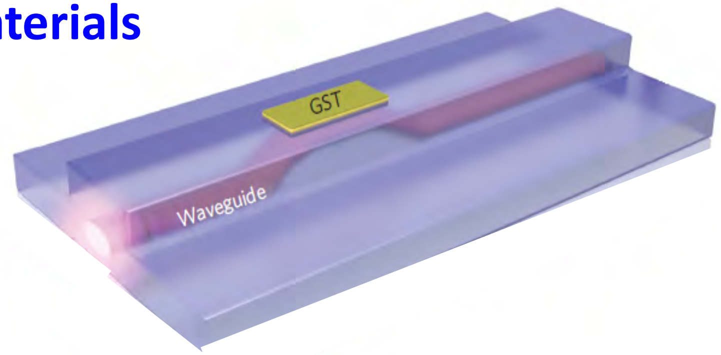
W.M. Green *et al.*, Opt. Express 15 (2007)

MEMS based switches



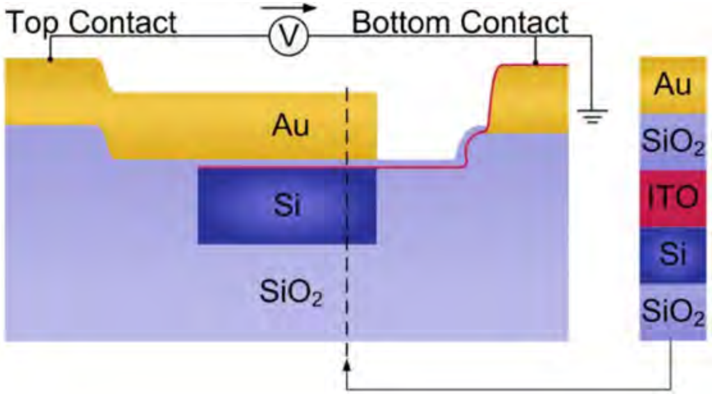
S. Han *et al.*, Berkeley, (2015)

Phase-change materials



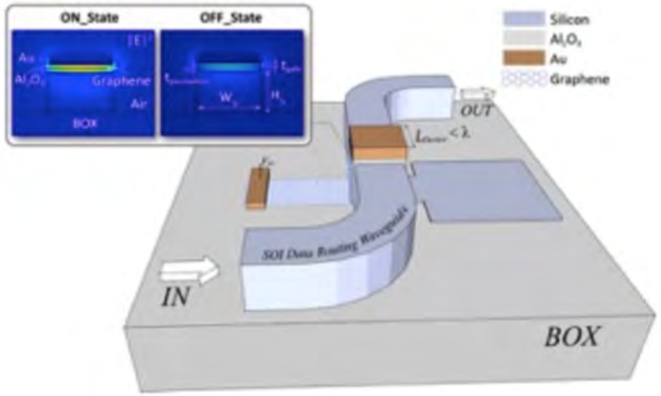
C. Rãos *et al*, Nature Photonics **6** (2015)
A. Joushaghani et al, APL, 102, 061101 (2013)

Plasmonic memristor



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

Graphene, $MoTe_2$, ITO modulators



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

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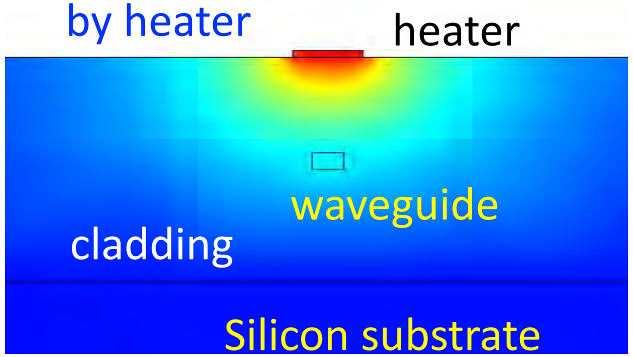
Integrated optical **actuators**

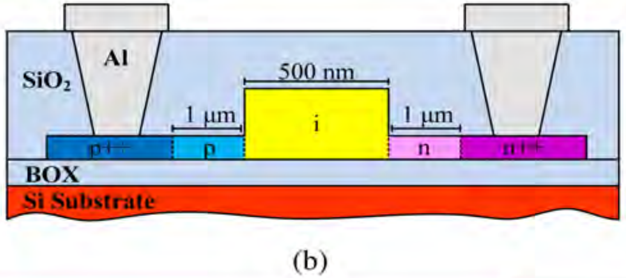
Thermal actuators

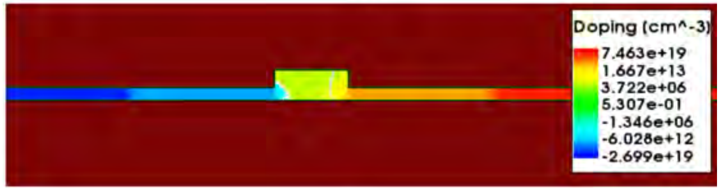
Thermal field induced by heater



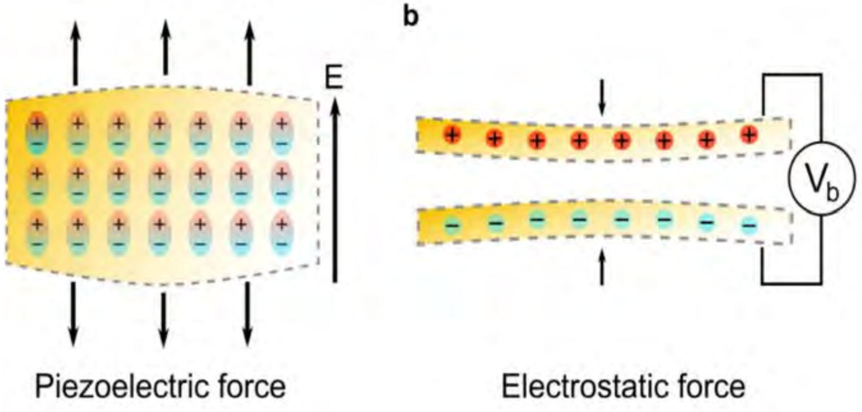
p-n junctions

Carrier injection/depletion





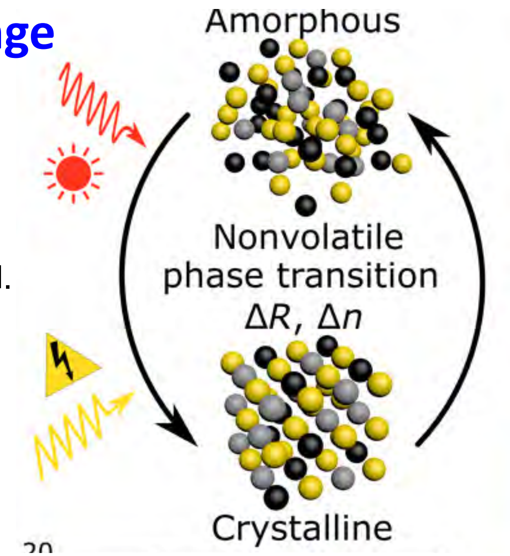
MEMS based switches



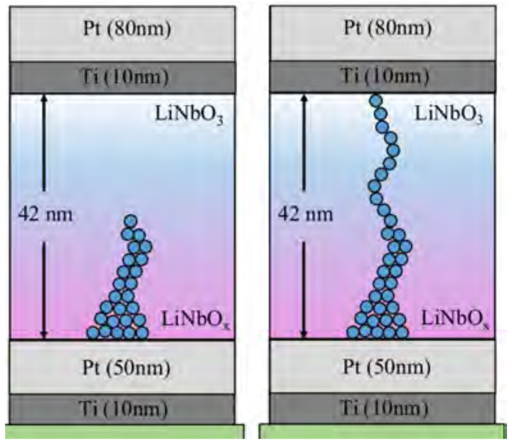
A. Fiore, TU/e

Phase-change materials

N. Farmakidis et al. Sci Adv 2019; 5

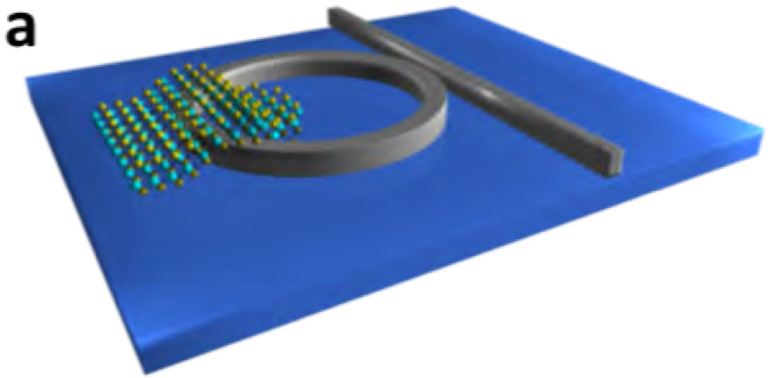


Plasmonic memristor



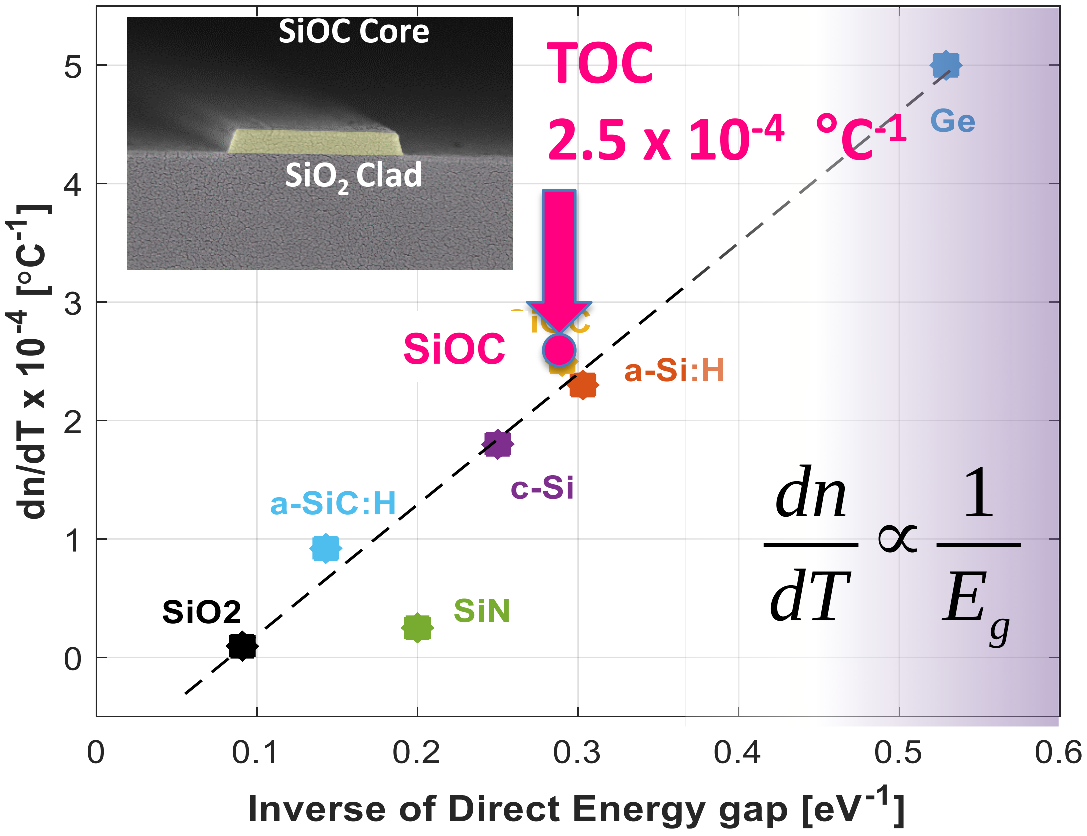
Yacopcic, 2017

Graphene, $MoTe_2$, ITO modulators

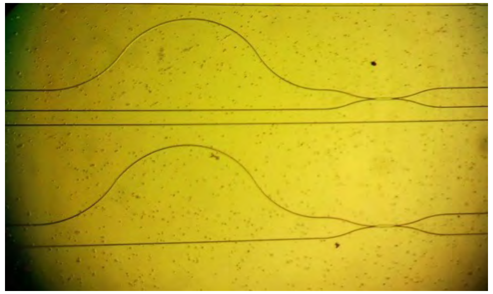


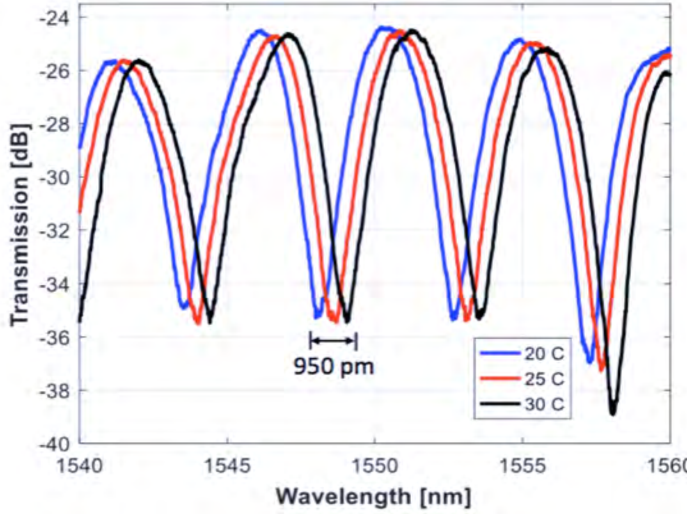
Silicon OxyCarbide with ultra high TOC

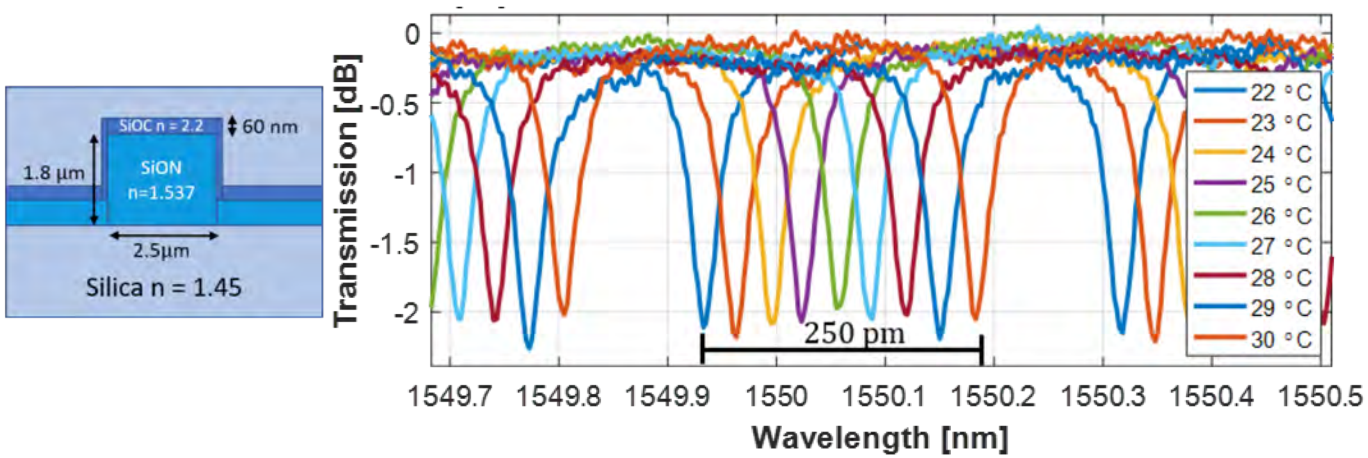
SiOC (n=2.2) is a material with low E_g
yet **transparent** in the near IR



SiOC Mach-Zehnder



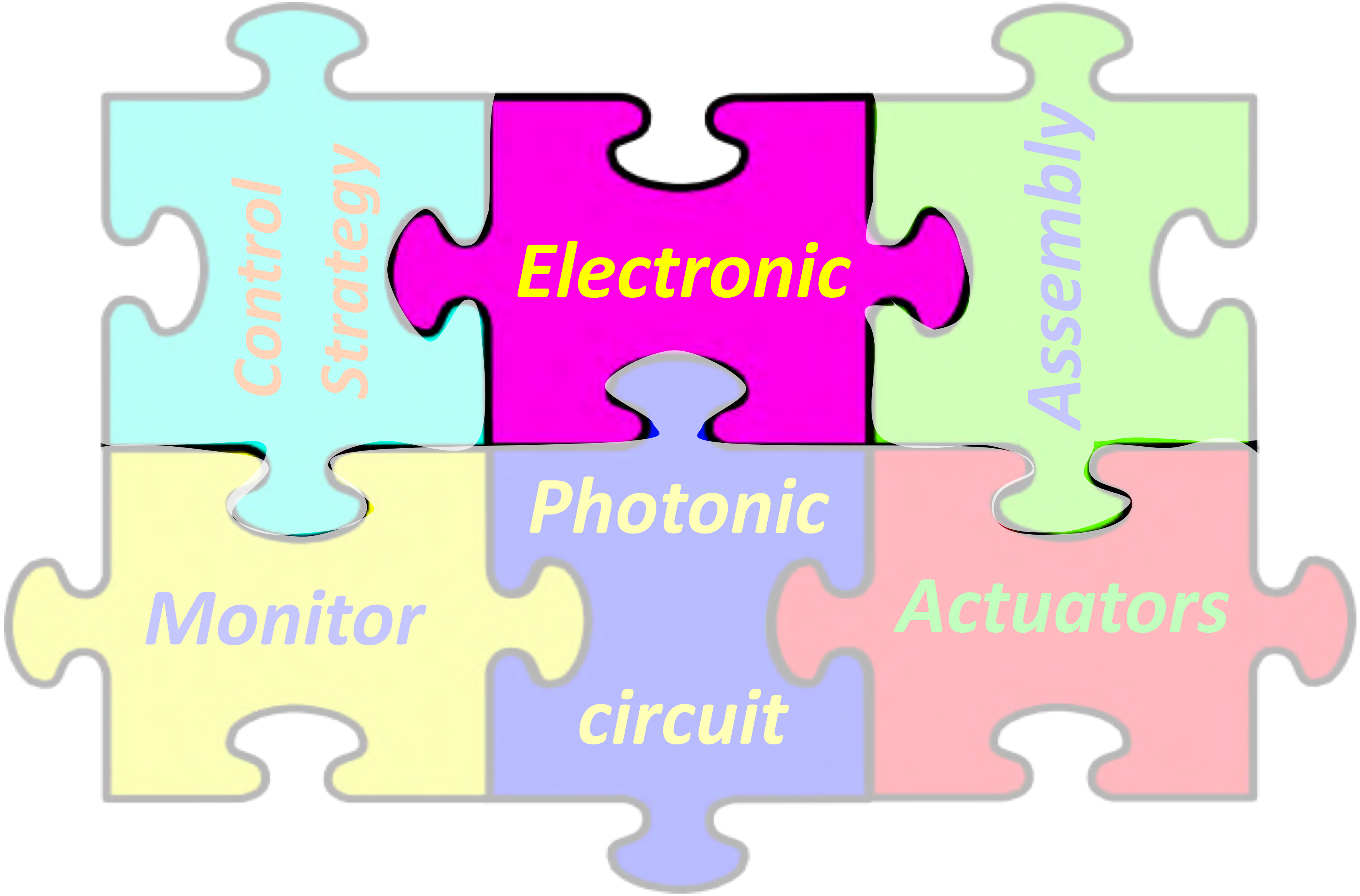




F. A. Memon et al., ACS Photonics, 2018

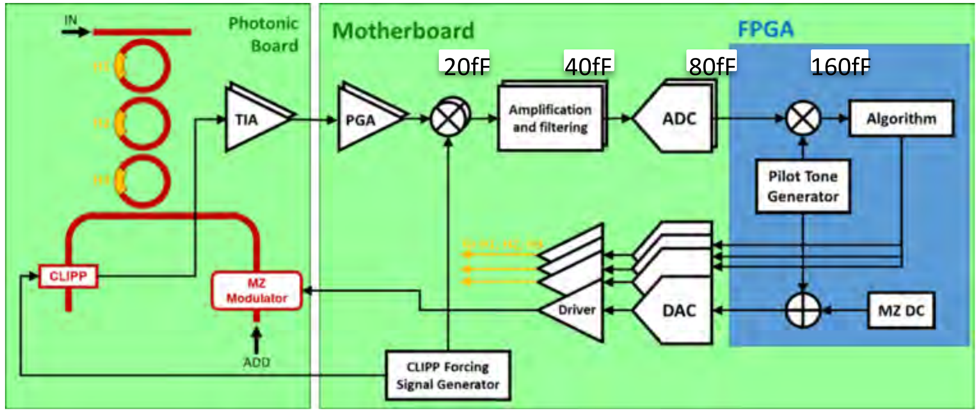
SiOC as enabling material for efficient heaters
... **10X higher than TOC of SiO_2 and Si_3N_4**

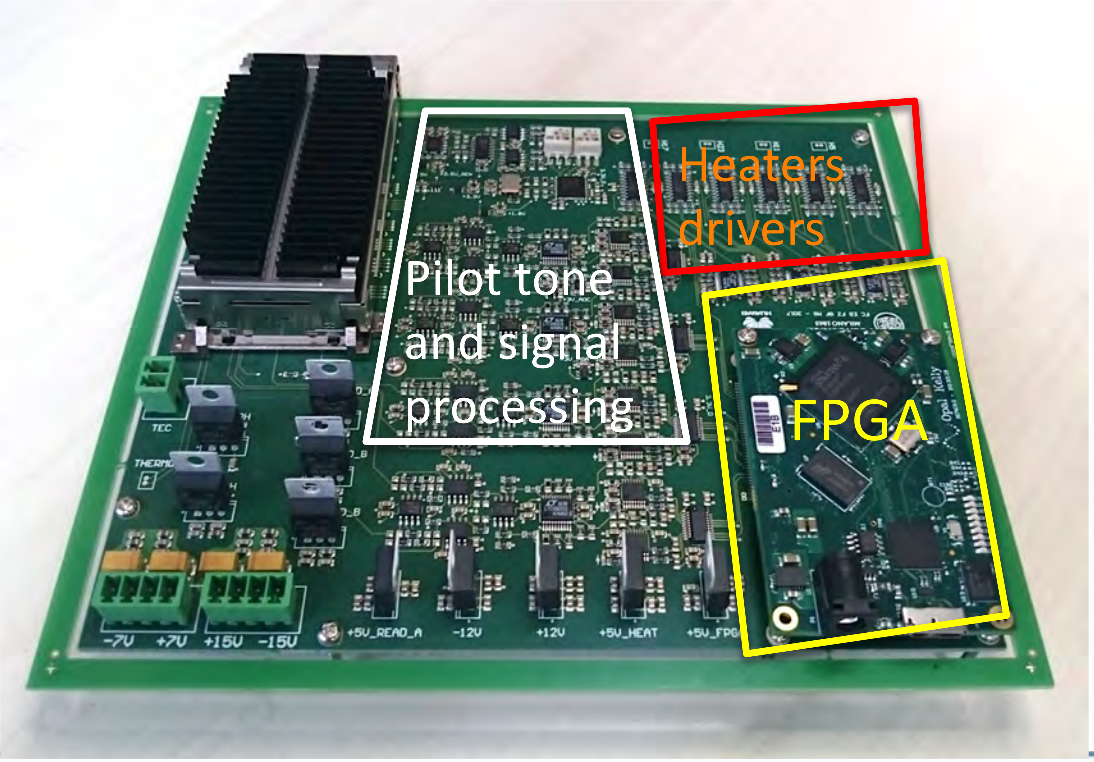
The control layer: **electronic**



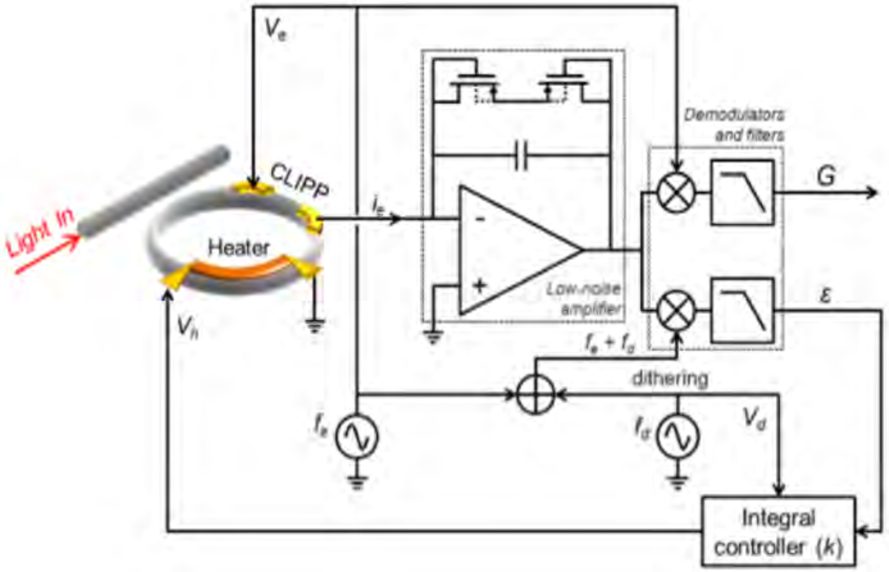
Electronics at service of photonics

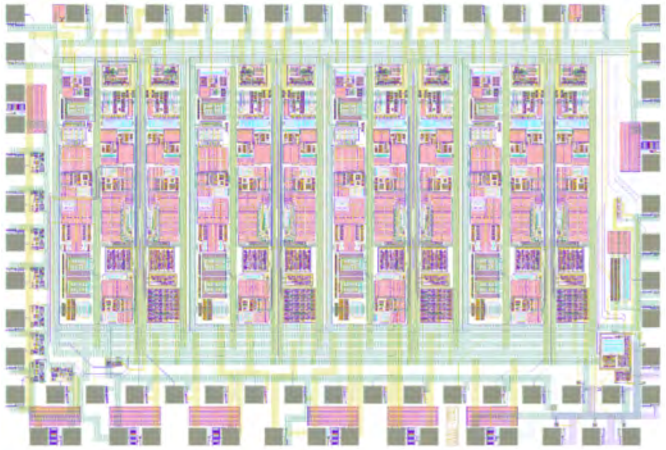
BRAIN – Central Control Unit





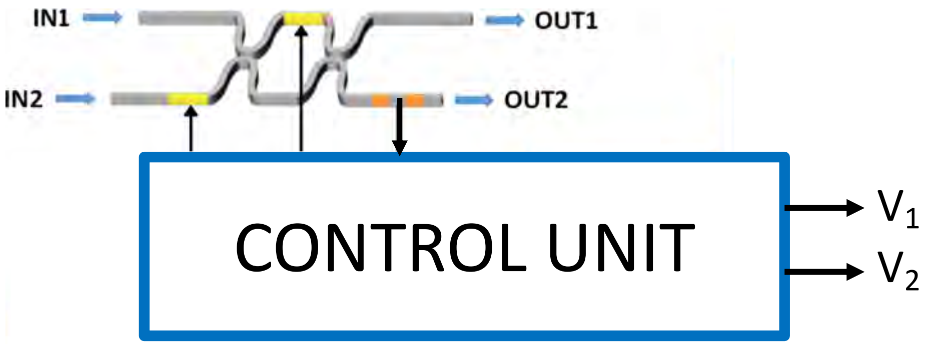
REFLEX ARC– Local Analog Control



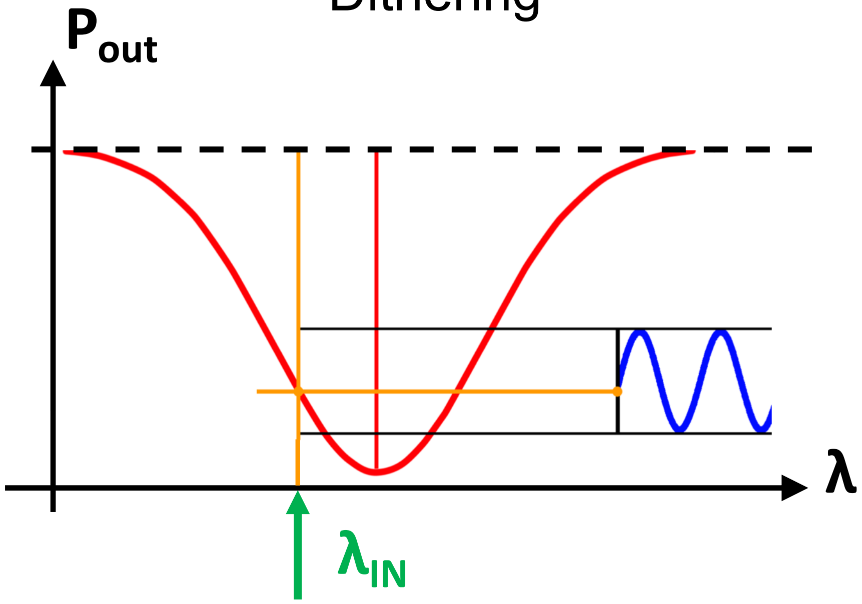


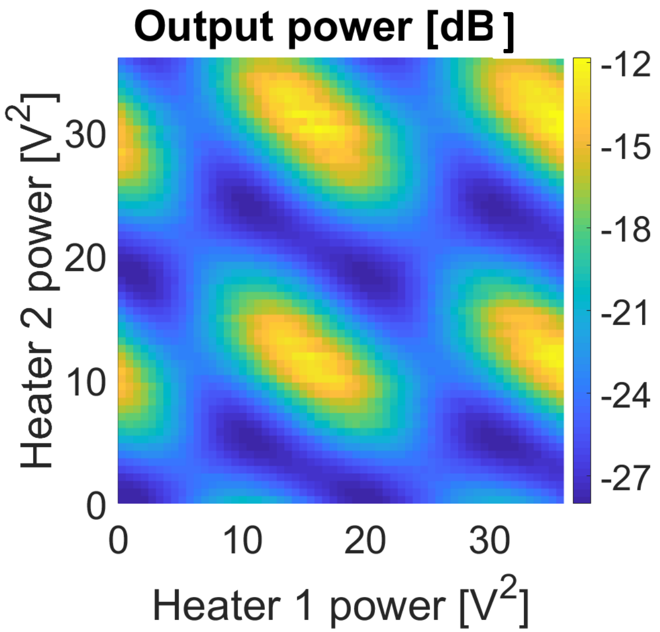
CMOS 0.35µm

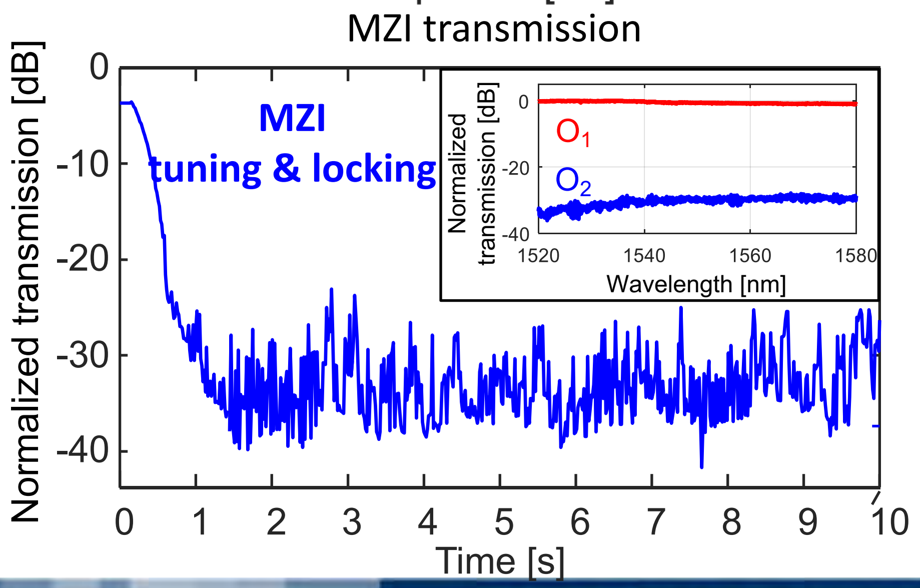
Feedback and control – Reflex Arc



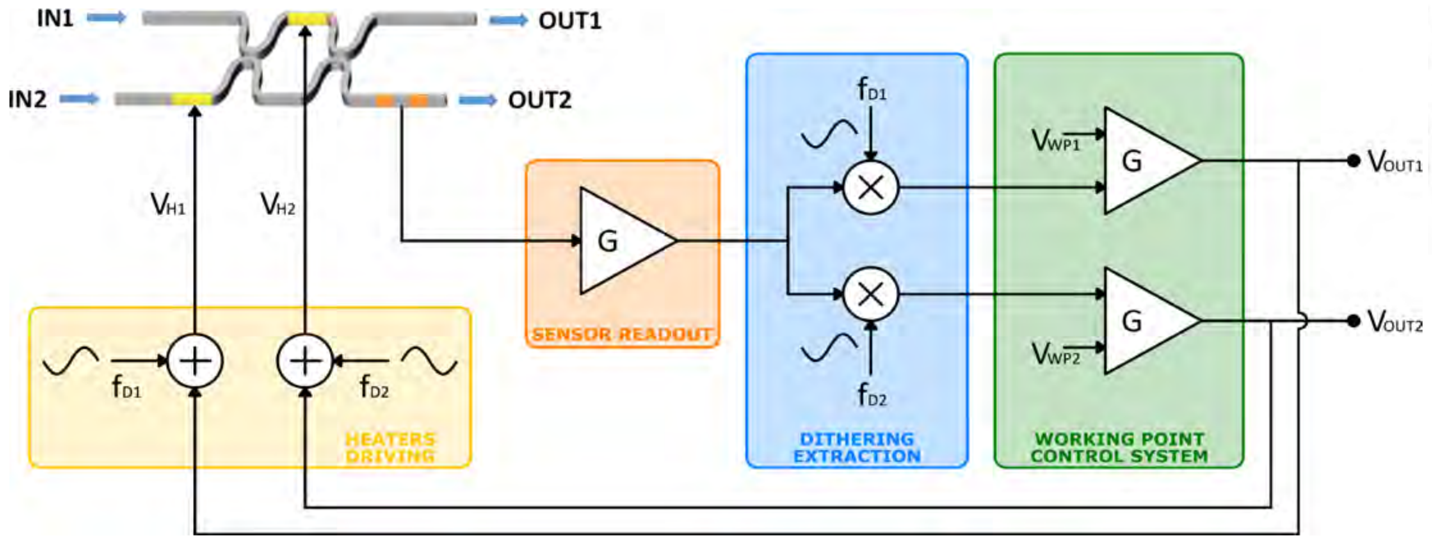
- Local feedback loop
- Automatic tuning and locking of MZI
- Dithering

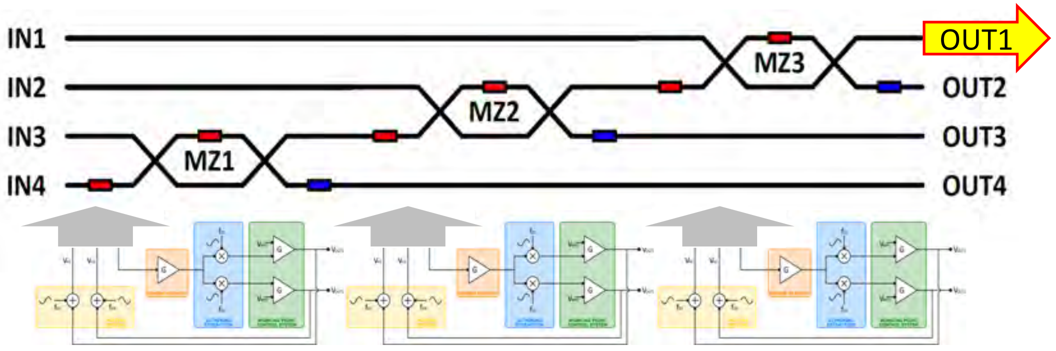


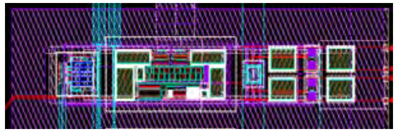




Feedback and control by dithering – Reflex Arc

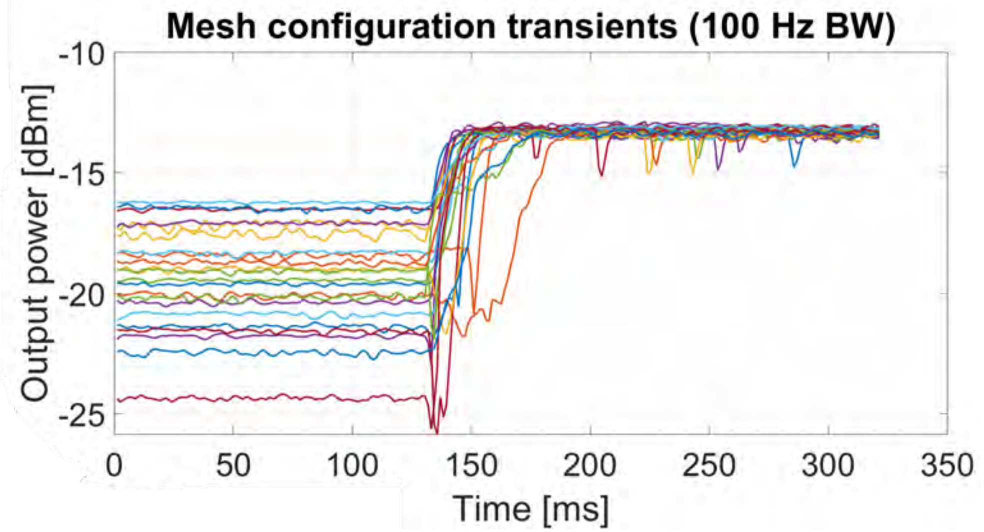






STmicroelectronics BCD8sp MPW

- **Dithering tecnique to** extract **partial derivatives** (2 frequencies)
- **Integral controller** locking heaters to the desired working point
- Control loop **bandwidth** affects **speed** and **accuracy** of locking

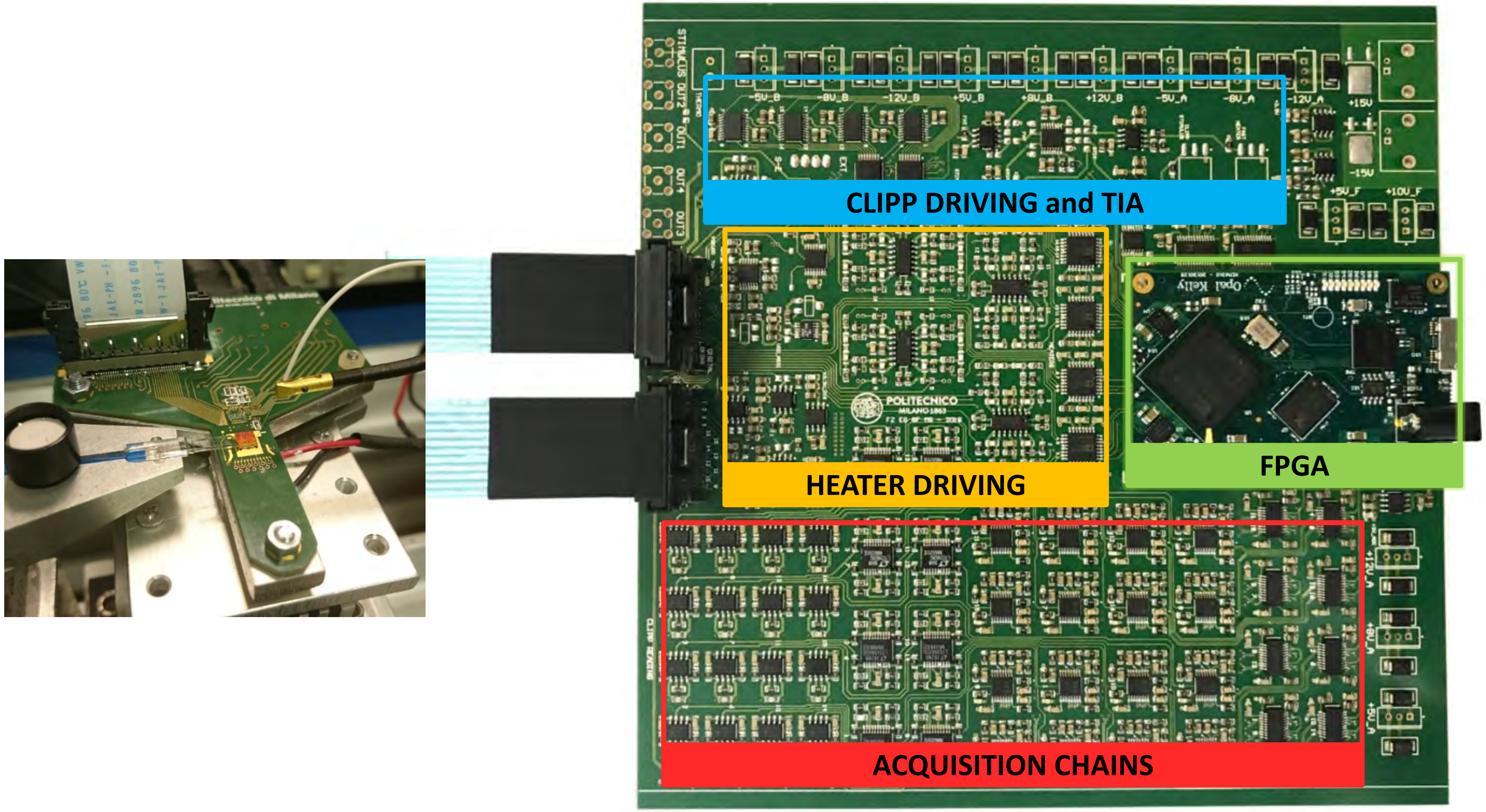


Courtesy of Prof. M. Sampietro (PoliMi)

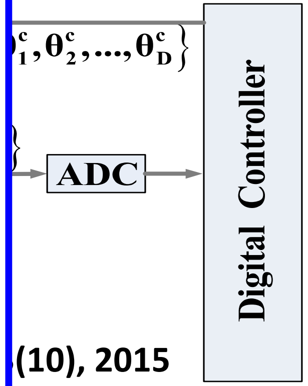
Handling multiple degrees of freedom

Contr
single

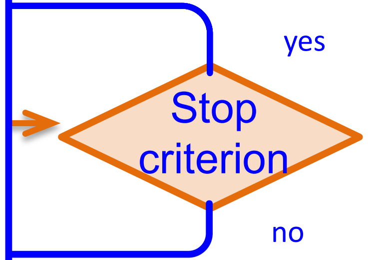
Severa
frequ
(DMT



Courtesy of Prof. M. Sampietro (PoliMi)



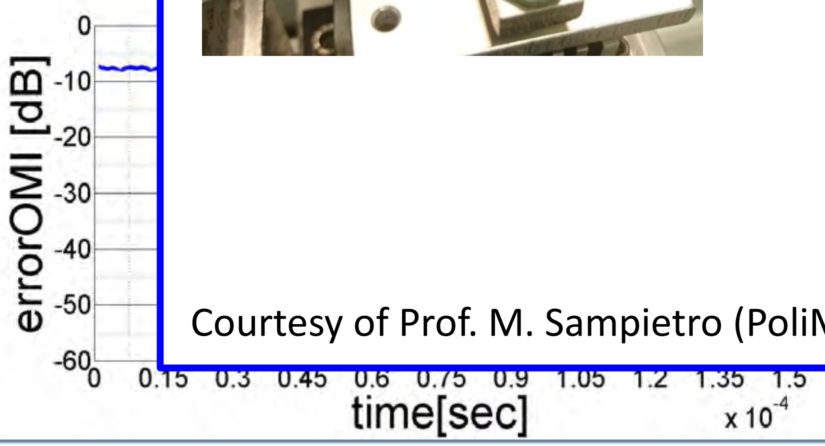
(10), 2015

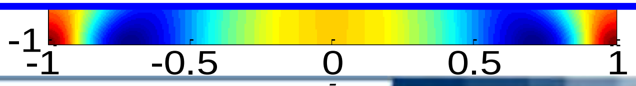


dithering tones (**gradient,**

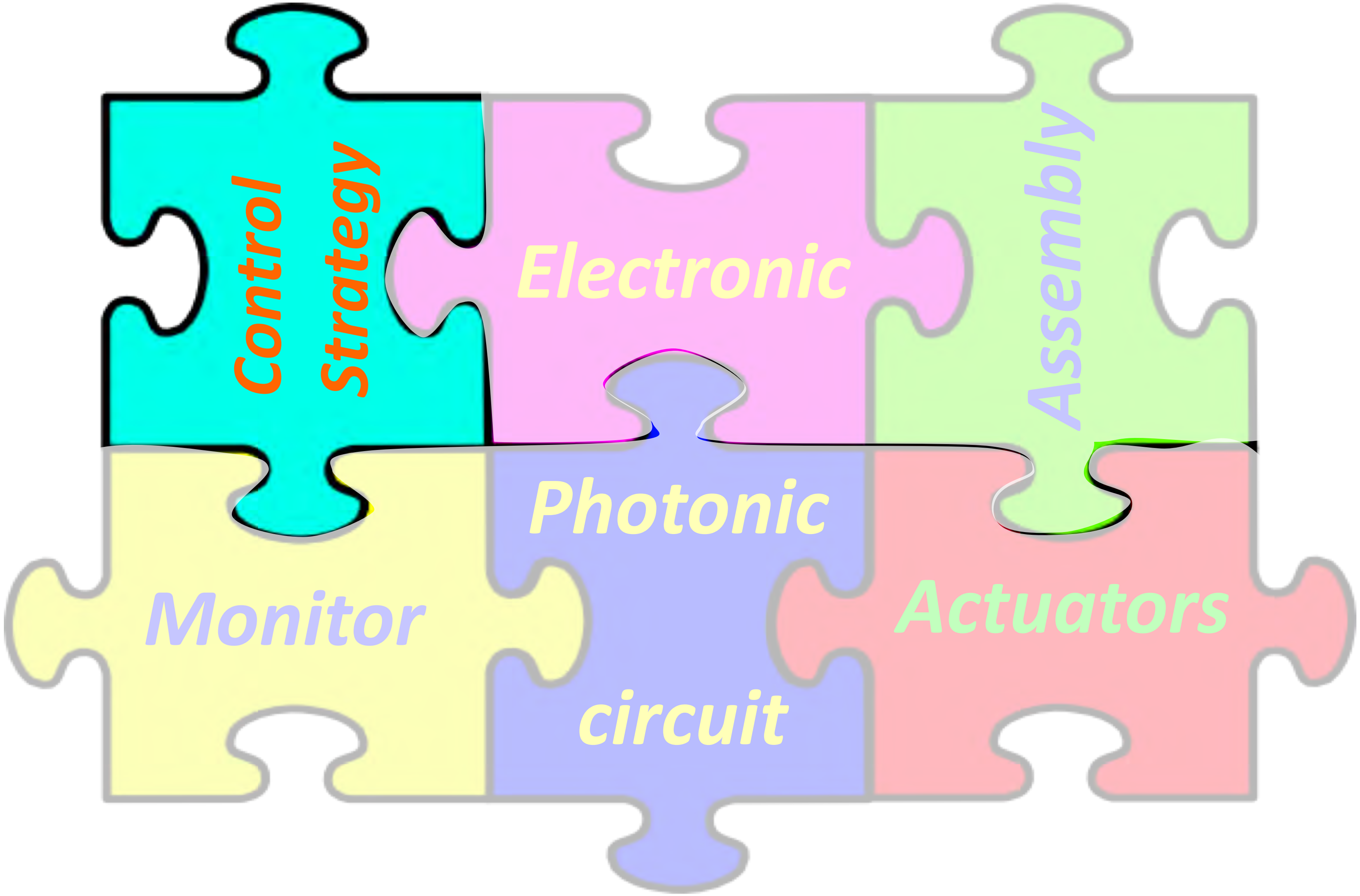
direction & step size
ethod)
e.g. Back-Trace-Line-Search)

- **Bang-Bang** techniques



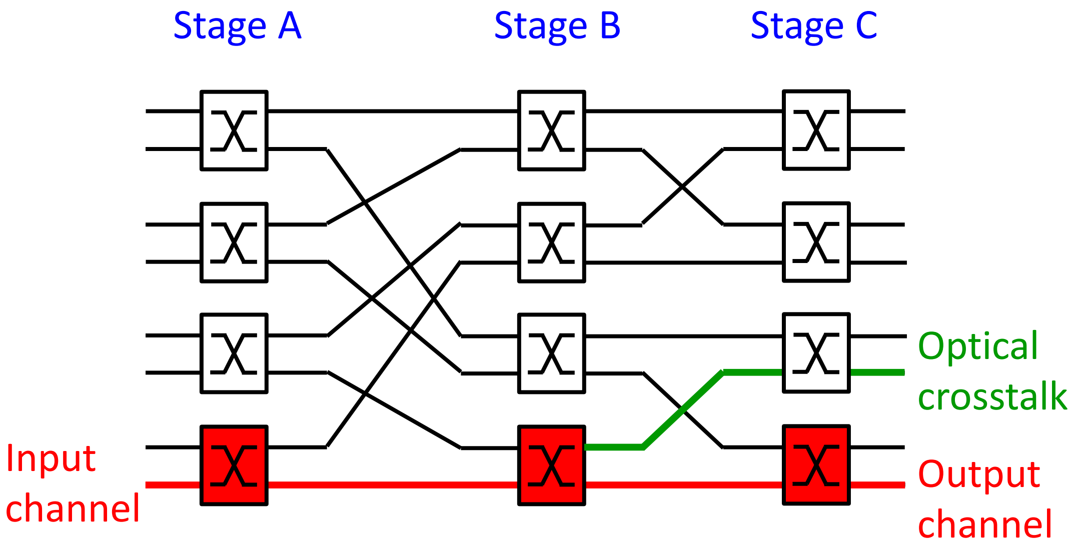


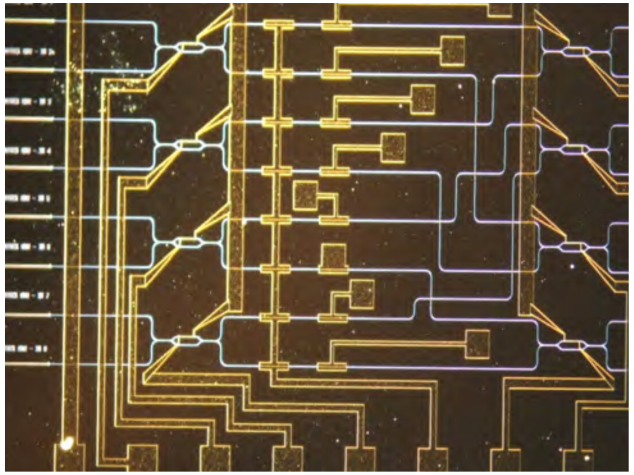
The control layer: **algorithms and techniques**

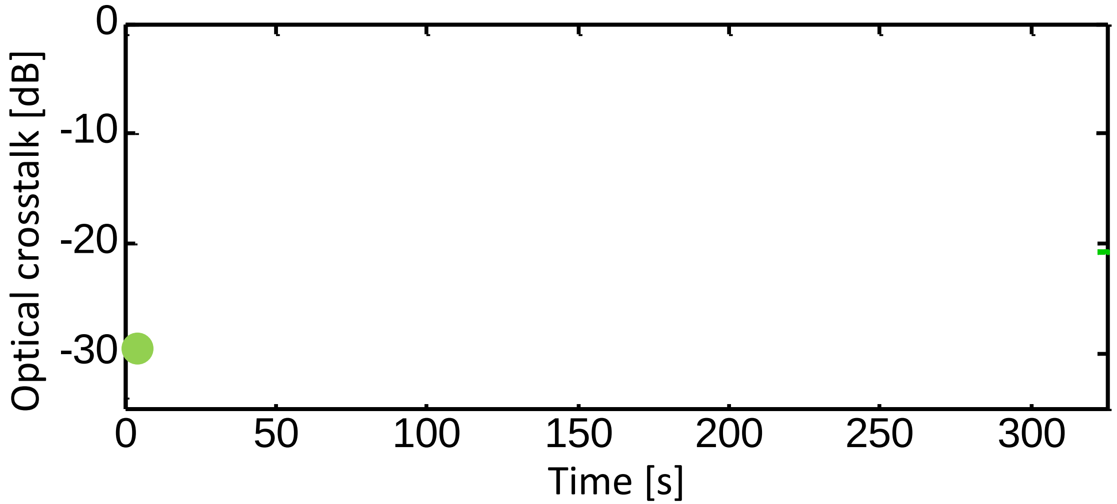


Feedback control of thermal xtalk

8x8 Si photonic switch matrix

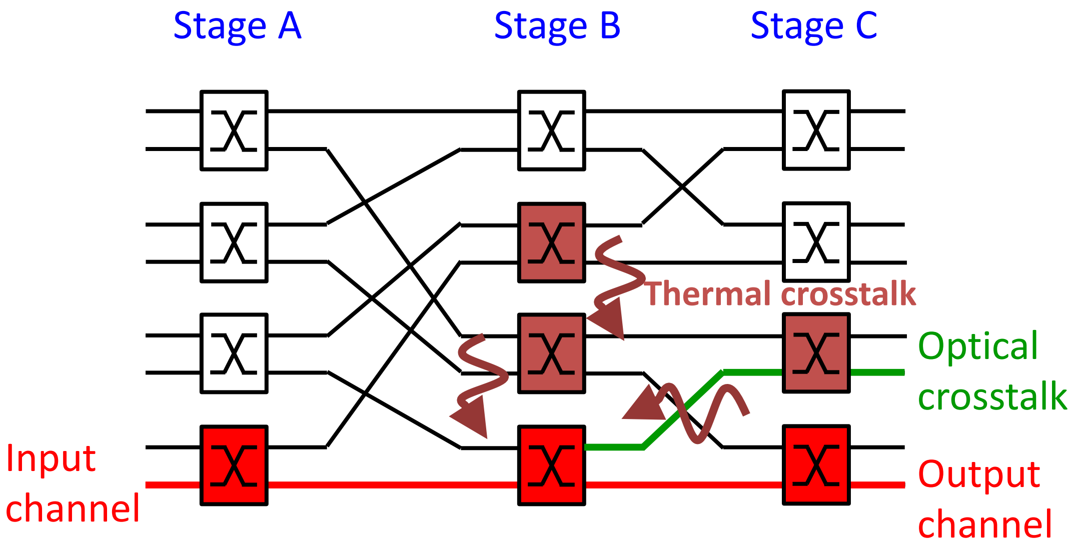


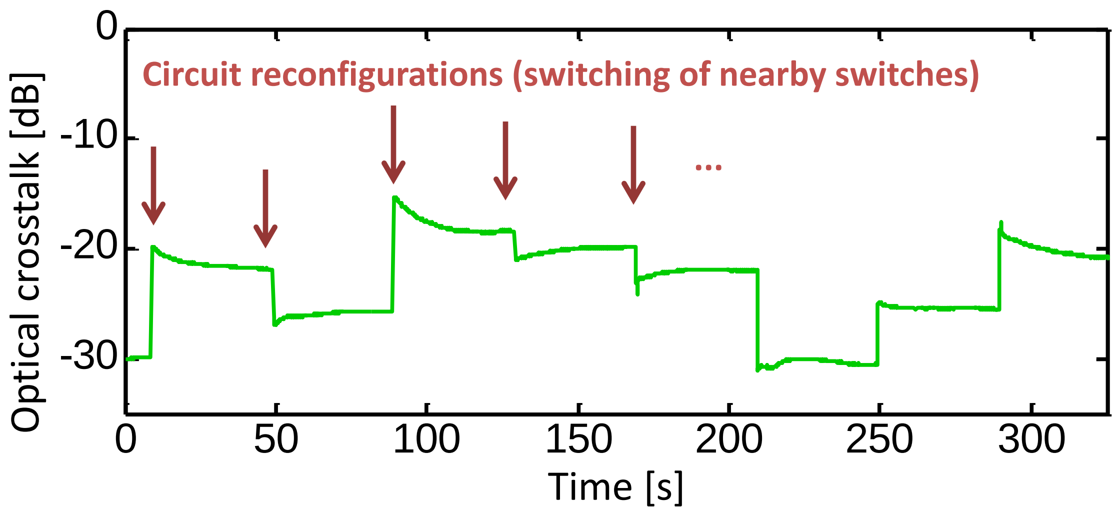


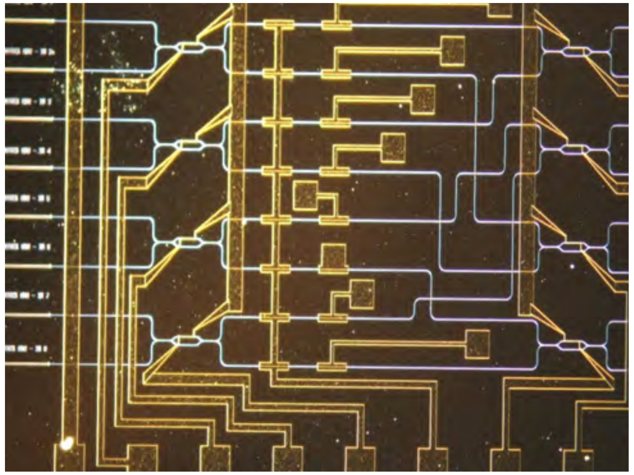


Feedback control of thermal xtalk

8x8 Si photonic switch matrix

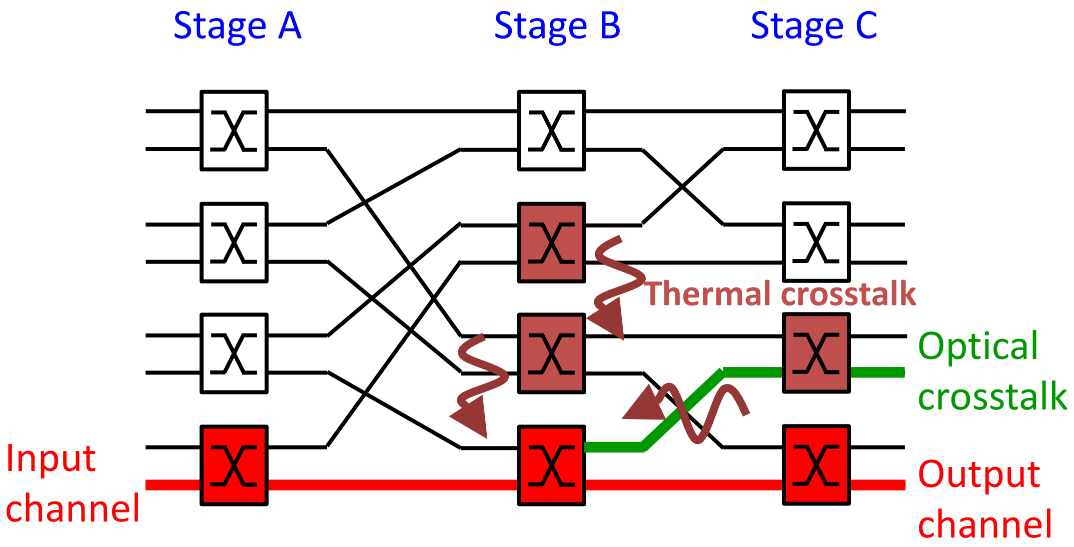


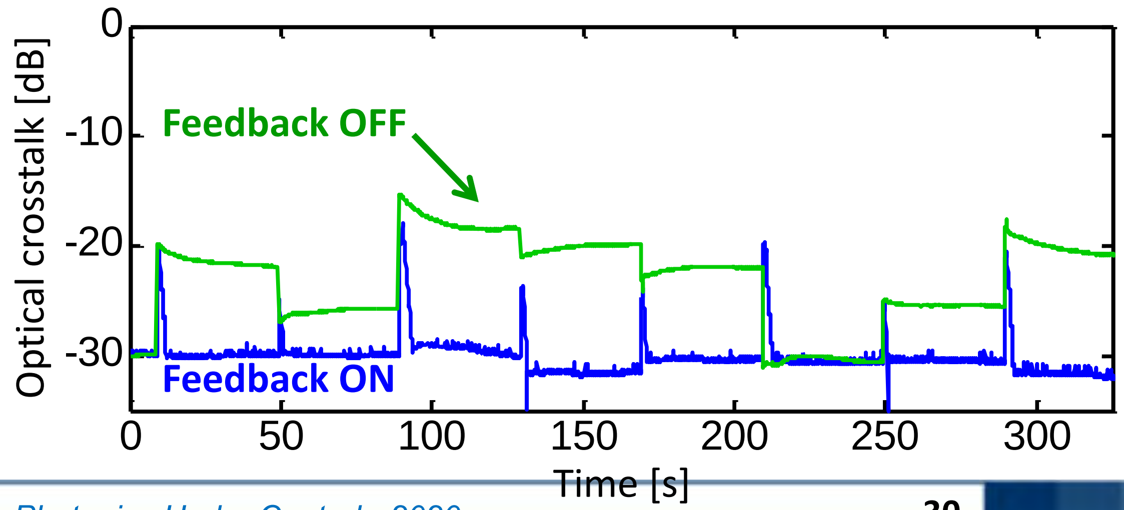


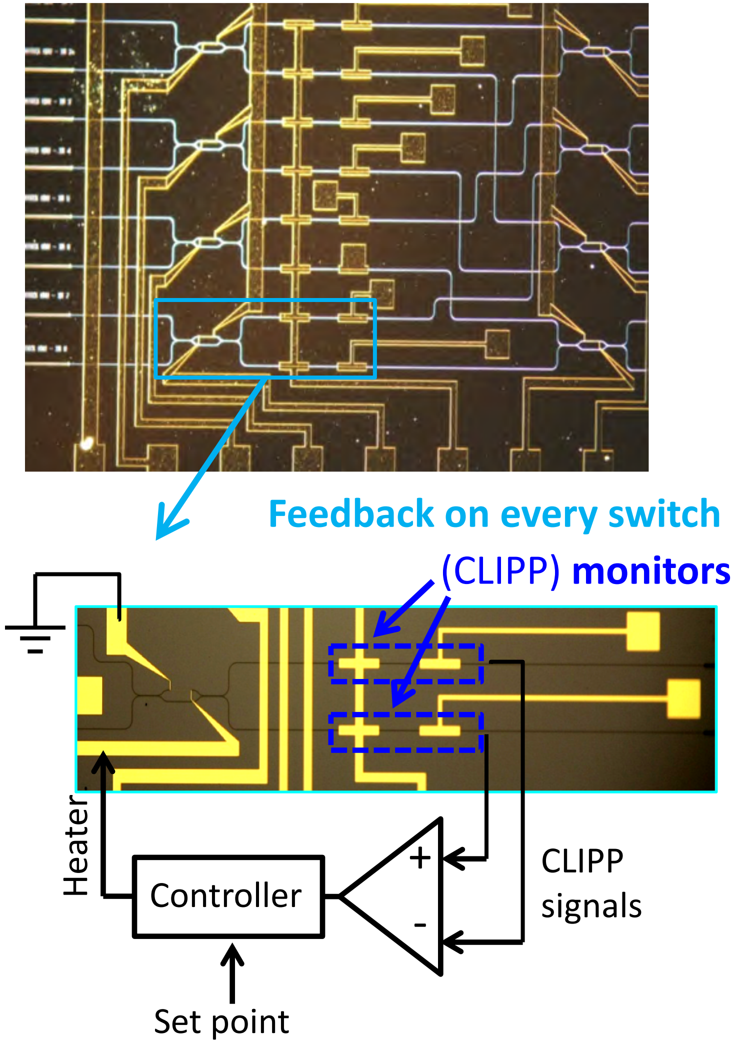


Feedback control of thermal xtalk

8x8 Si photonic switch matrix



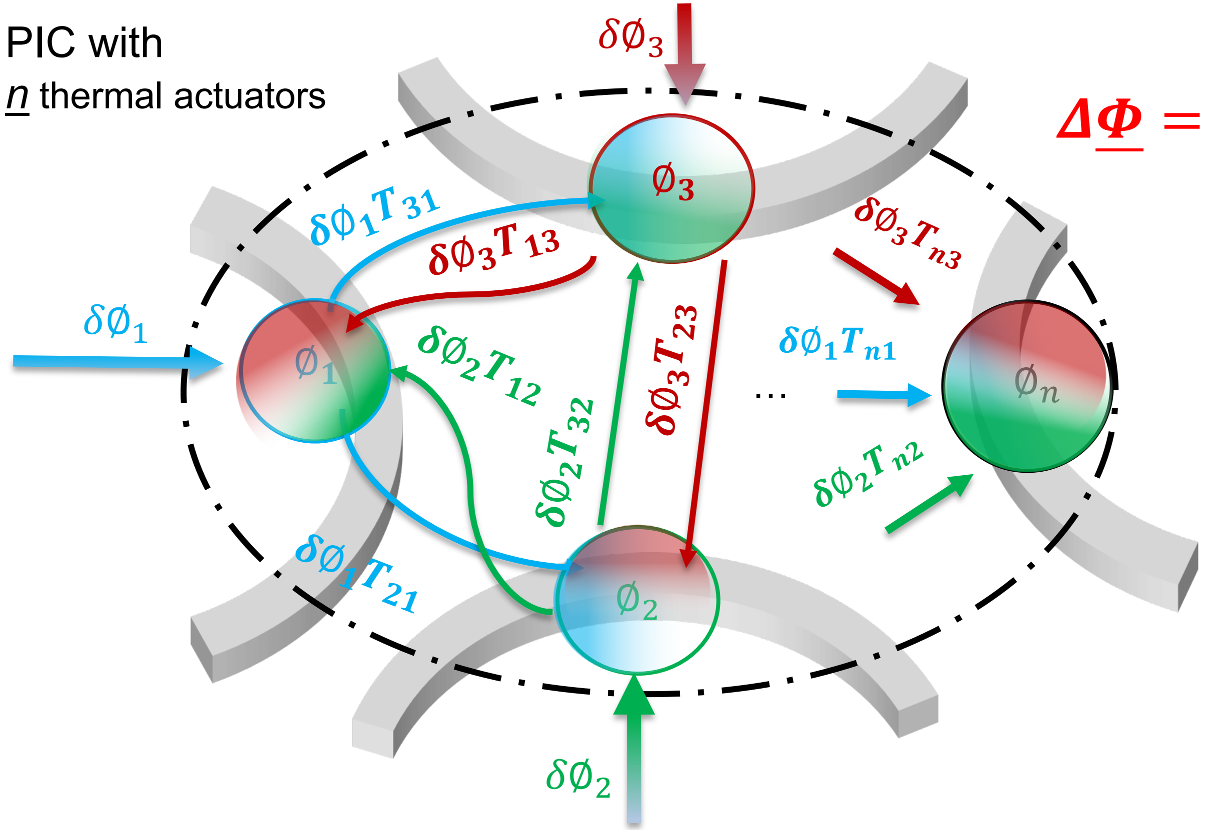




A. Annoni *et al.*, JSTQE 2016

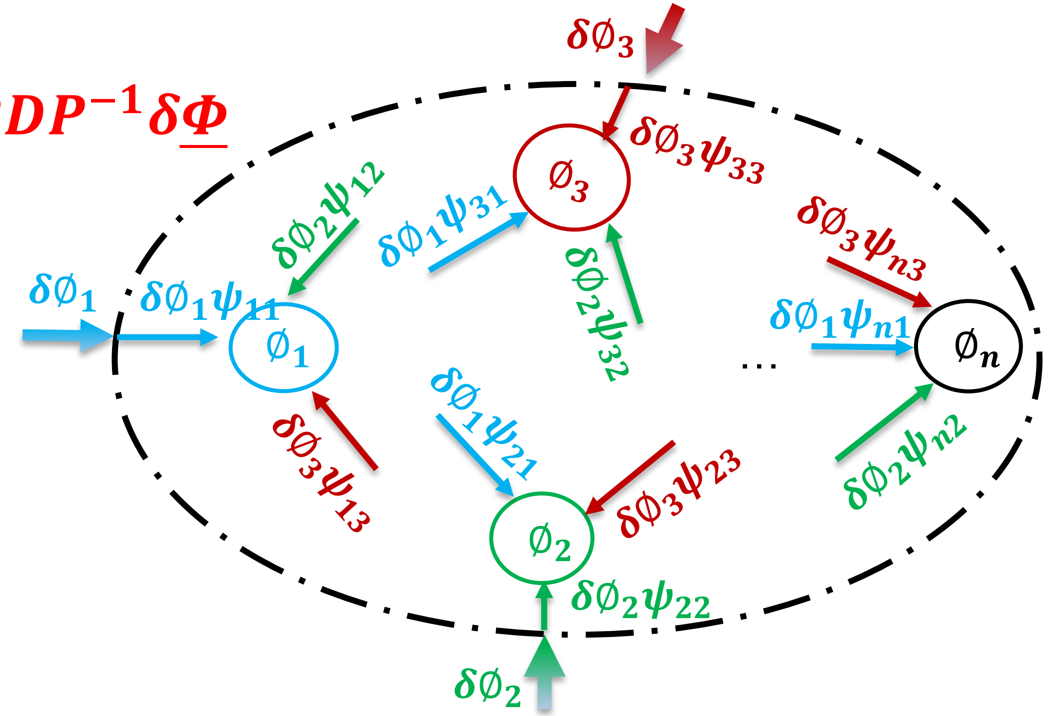
Handling thermal cross talk

PIC with
$\underline{n}$ thermal actuators



TED

$$\underline{\Delta\Phi} = T\underline{\delta\Phi} = PDP^{-1}\underline{\delta\Phi}$$



Actual phase changes
$$\underline{\Delta\Phi} = \begin{pmatrix} T_{11} & T_{12} & T_{13} & \cdots & T_{1n} \\ T_{21} & T_{22} & T_{23} & \cdots & T_{2n} \\ T_{31} & T_{32} & T_{33} & \cdots & T_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ T_{n1} & T_{n2} & T_{n3} & \cdots & T_{nn} \end{pmatrix} . \underline{\delta\Phi}$$
Desired phase changes

Phase coupling matrix ***T***

Coordinate transformation $\delta\underline{\Psi_i} = P_i^{-1}\delta\Phi$ according to the **eigensolutions of the thermally-coupled system**

A thermal-xtalk free system is achieved (orthogonal coordinates):

$$\underline{\Delta\Psi} = \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{pmatrix} . \underline{\delta\Psi}$$

F. Morichetti et al., JLT 1/2019

Use of the TED technique

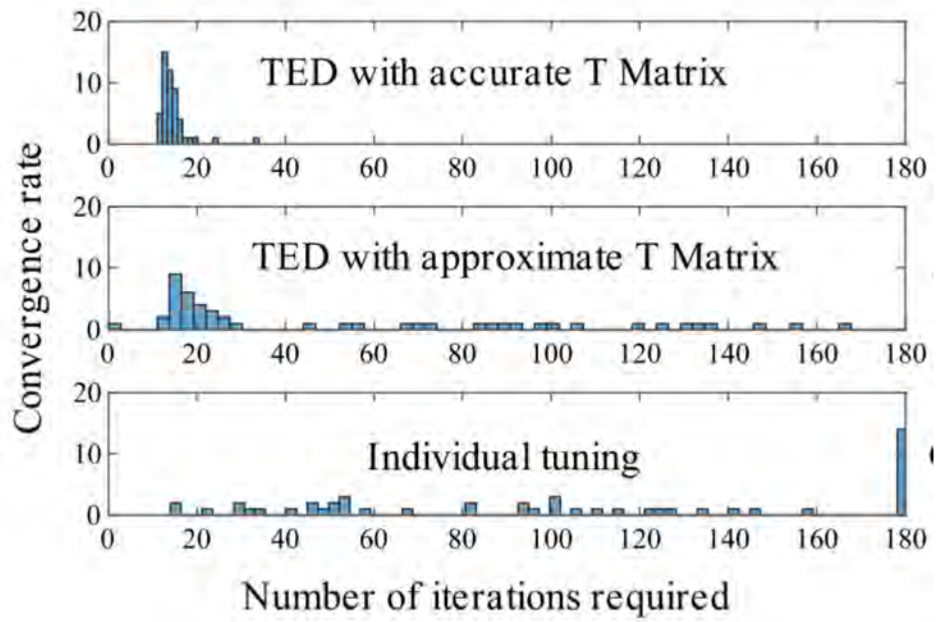
- TED technique can be adopted to **cancel phase coupling** in *arbitrary* PICs and *arbitrary* algorithms for tuning, locking, optimizing, switching…
- Circuit modifications are achieved in direction of $\boldsymbol{\delta\psi_i}$ to minimize the error function
- (At each iteration) desired phase changes in each phase shifters are calculated by $\delta\underline{\Phi} = P\delta\underline{\Psi}$ and applied via thermal actuators
- ***T*** is the phase coupling matrix

Canceling thermal cross-talk effects in photonic integrated circuits
M. Milanizadeh et al., JLT 37 (4), 2019

Estimation of Cross talk matrix T

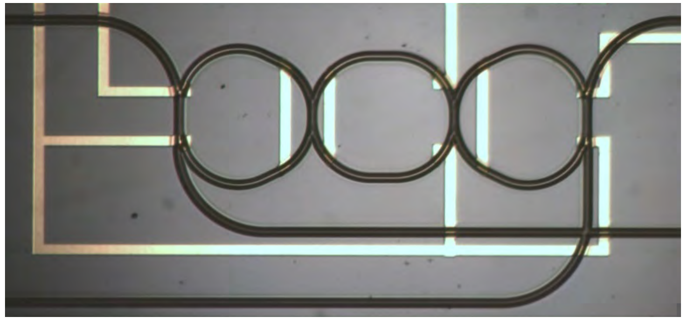
$$T = \begin{pmatrix} 1 & \alpha & \beta & \gamma \\ \delta & 1 & \varepsilon & \eta \\ \mu & \xi & 1 & \theta \\ \varphi & \omega & \tau & 1 \end{pmatrix}$$

- Optically measured (exact)
- Electrical measured (symmetrical)
- Estimated (simulations)



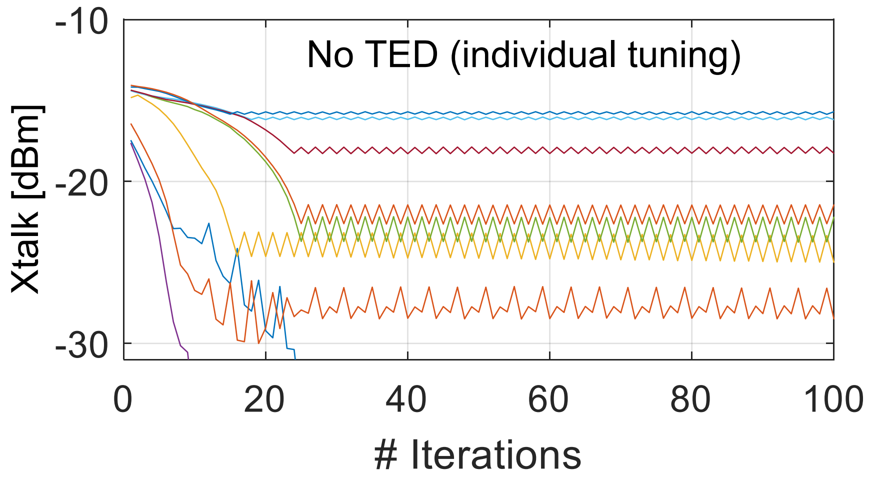
TED demo on tuning of coupled MRR in SiON

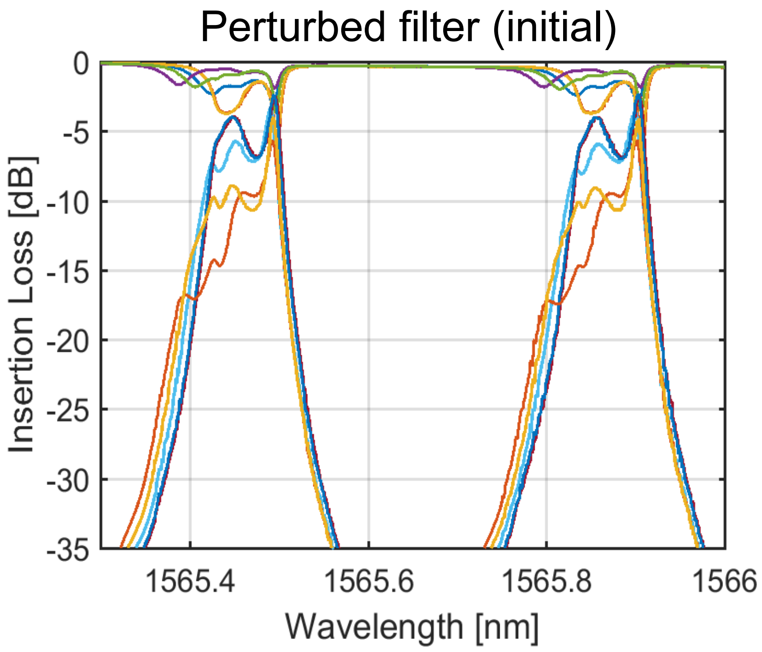
3rd order coupled MRR based filter (SiON platform)



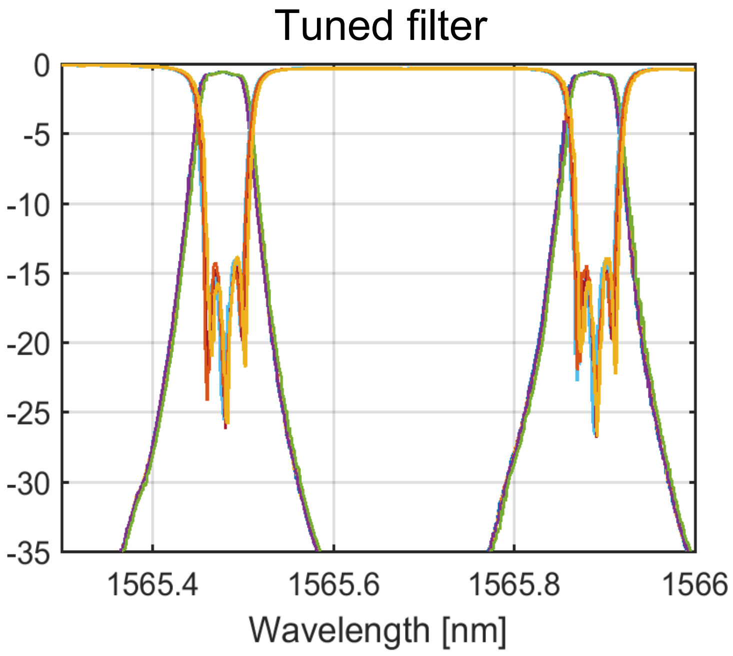
Bandwidth 6.5 GHz
FSR 50GHz

Input signal
5 Gbit/s OOK channel

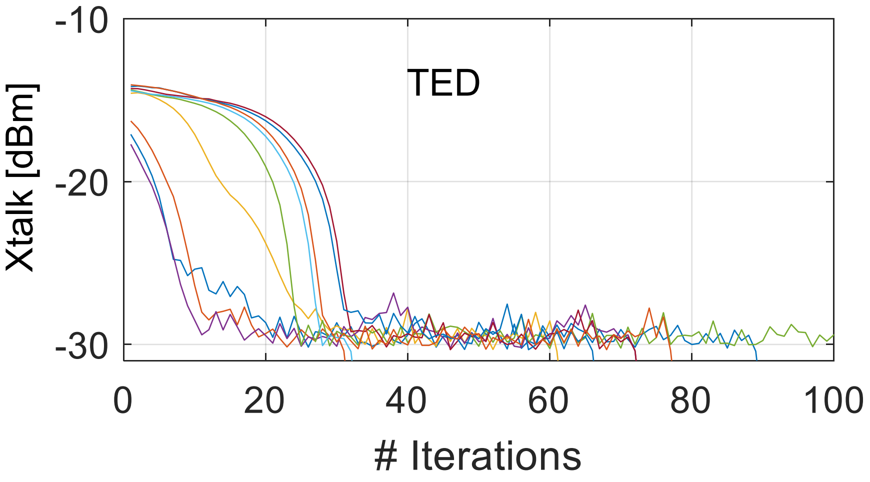




±6.5 GHz random perturbation

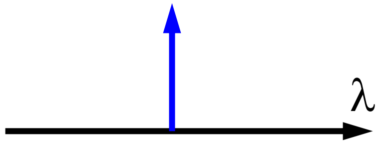


TED-assisted automated tuning



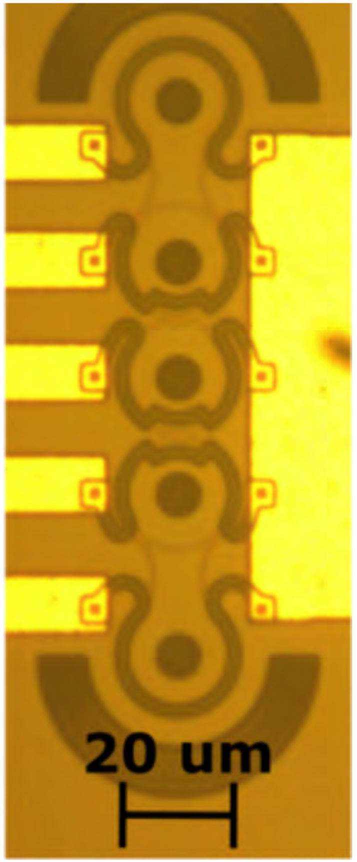
TED always guarantees convergence of the tuning algorithm

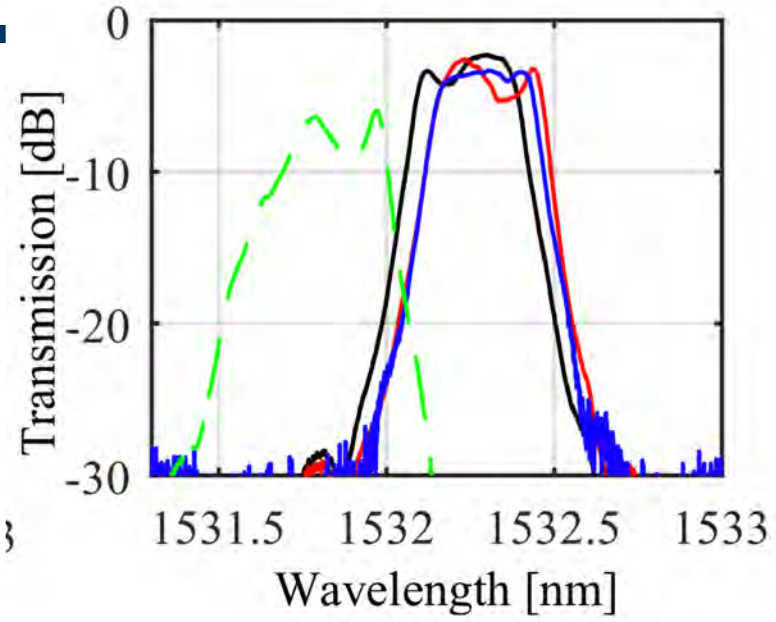
Signal assisted tuning



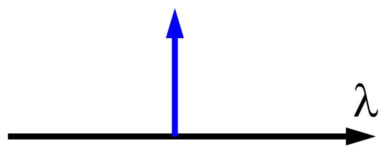
CW

Filter

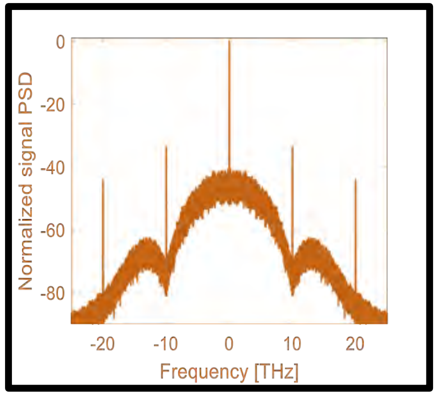




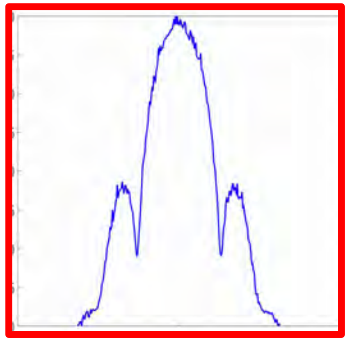
Signal assisted tuning



CW

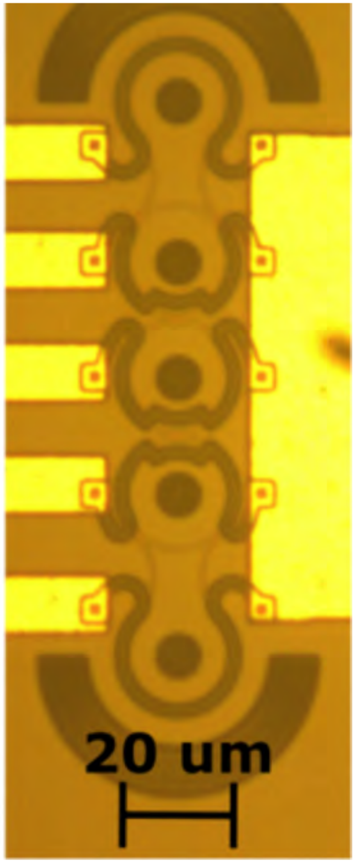


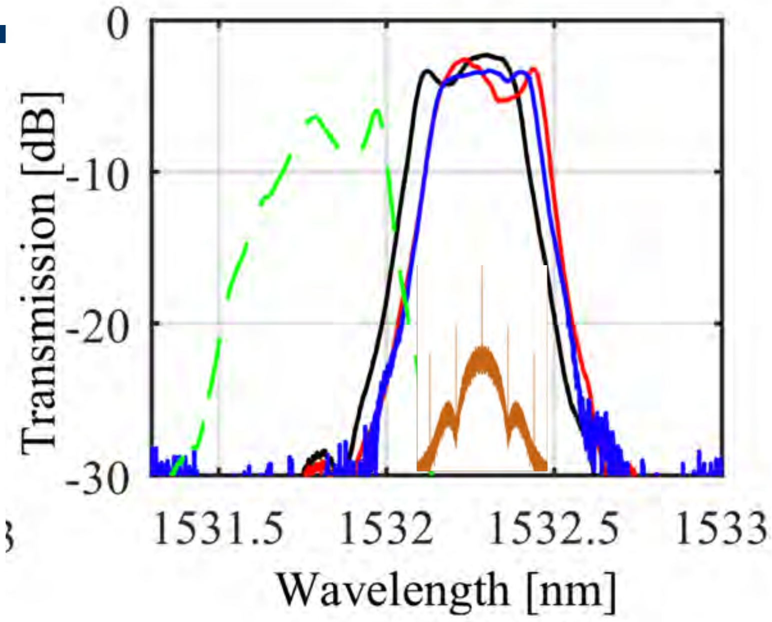
10 Gbit/s
OOK Module

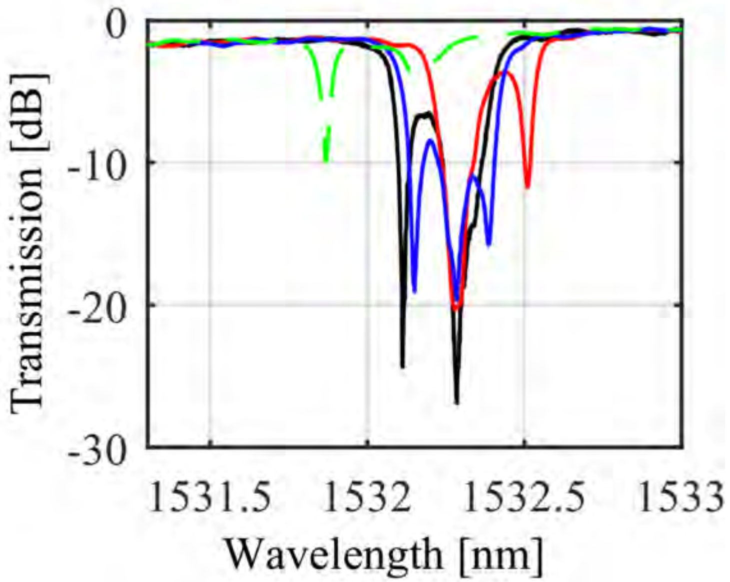


100 Gbit/s
QPSK Module

Filter





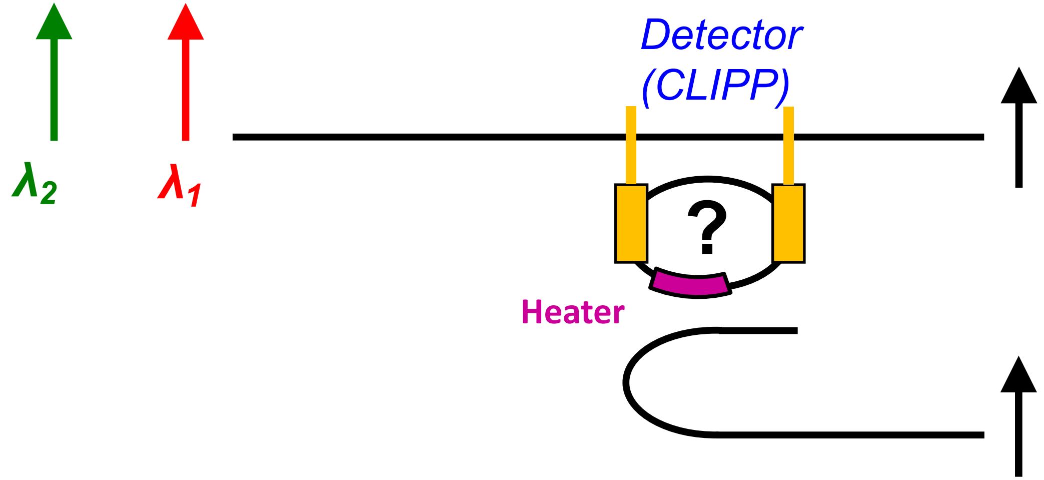


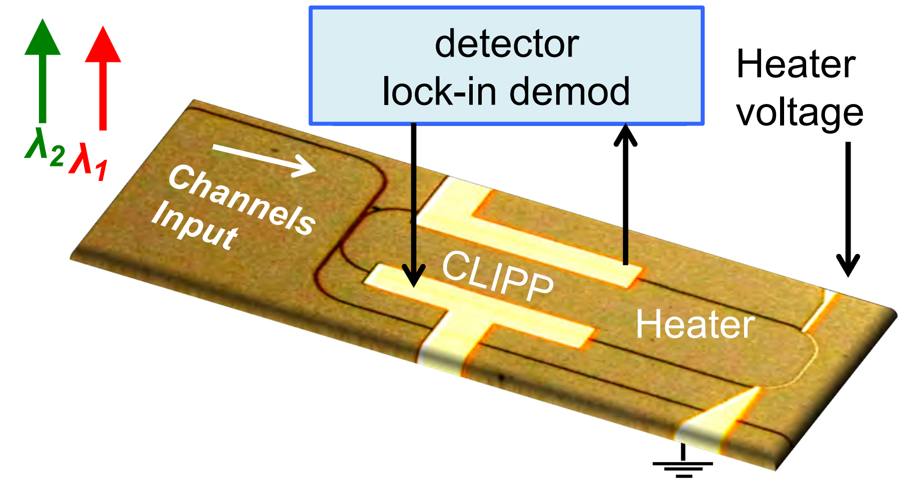
Pilot tones for device control (WDM regime)

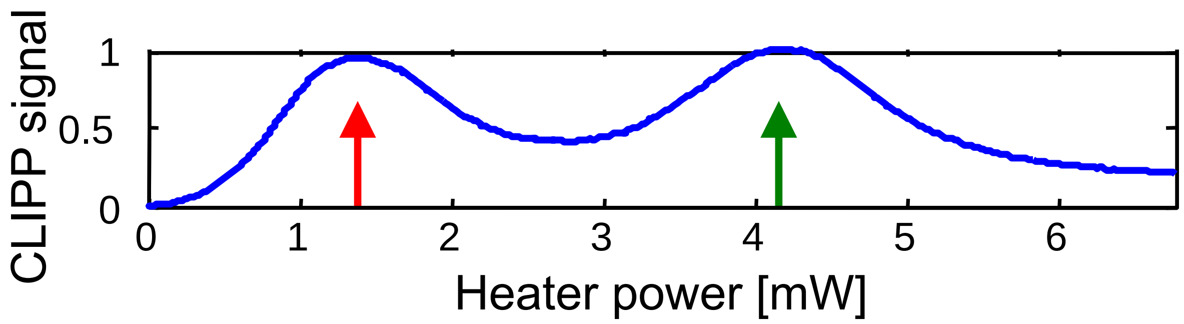
Two input channels at different wavelengths

λ_1 = 1549.59 nm

$\lambda_2 = \lambda_1$ + 120 pm





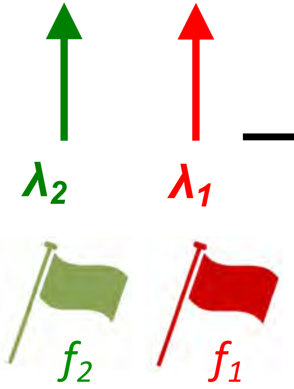


Pilot tones for device control (WDM regime)

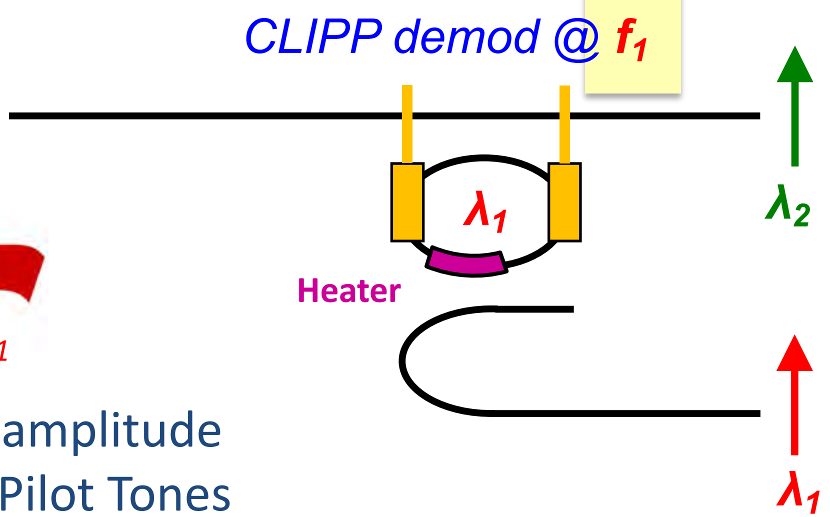
Two input channels at different wavelengths

λ_1 = 1549.59 nm + label 2% @ **f_1 = 10 kHz**

$\lambda_2 = \lambda_1$ + 120 pm + label 2% @ **f_2 = 11 kHz**

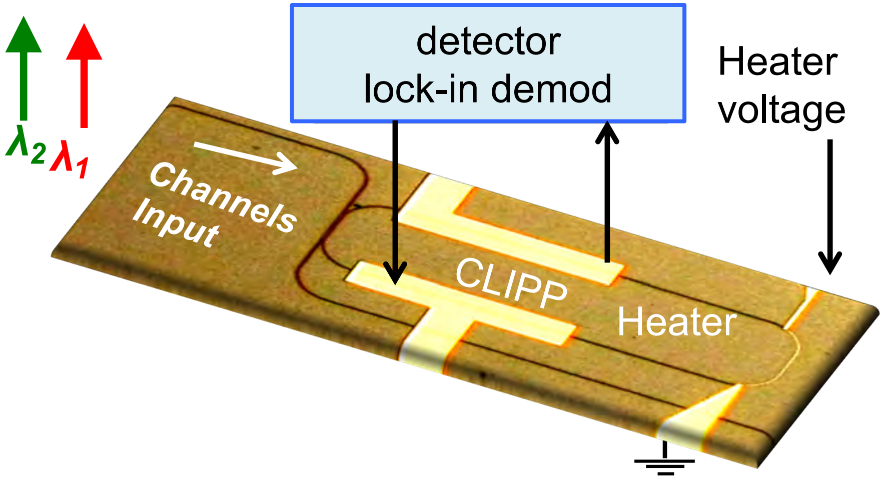


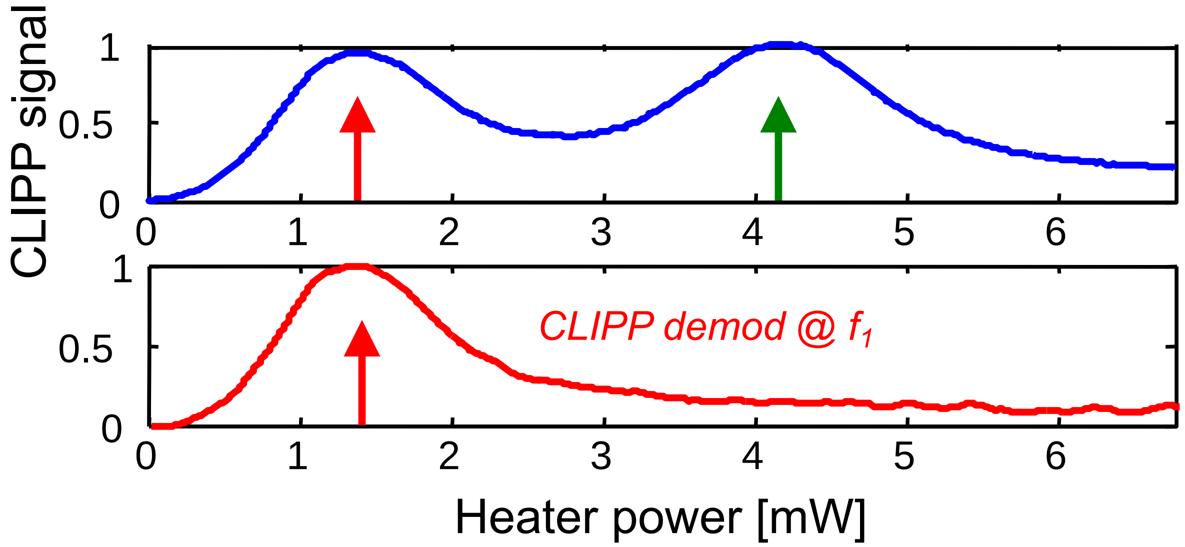
Weak (2%) amplitude modulated Pilot Tones (kHz)



λ_1 identified

Automatic tuning and *locking at* λ_1



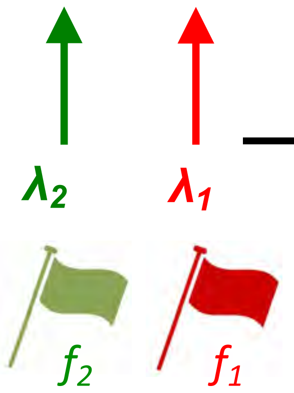


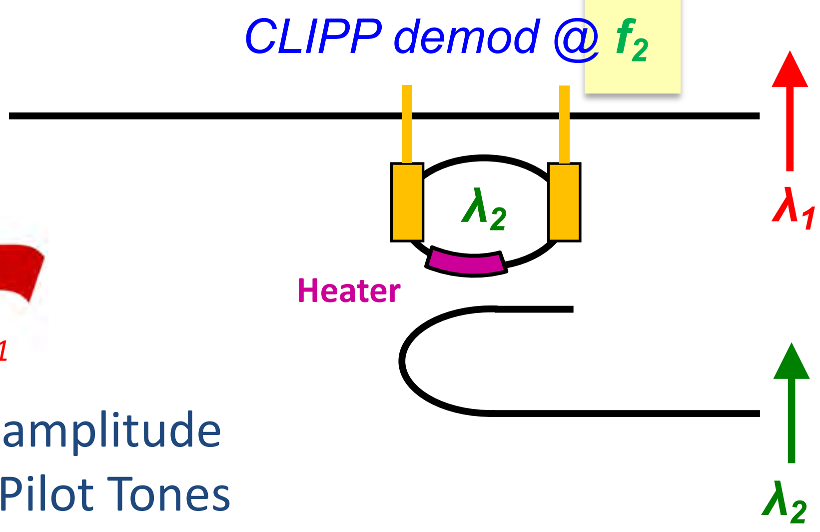
Pilot tones for device control (WDM regime)

Two input channels at different wavelengths

λ_1 = 1549.59 nm + label 2% @ **f_1 = 10 kHz**

$\lambda_2 = \lambda_1$ + 120 pm + label 2% @ **f_2 = 11 kHz**

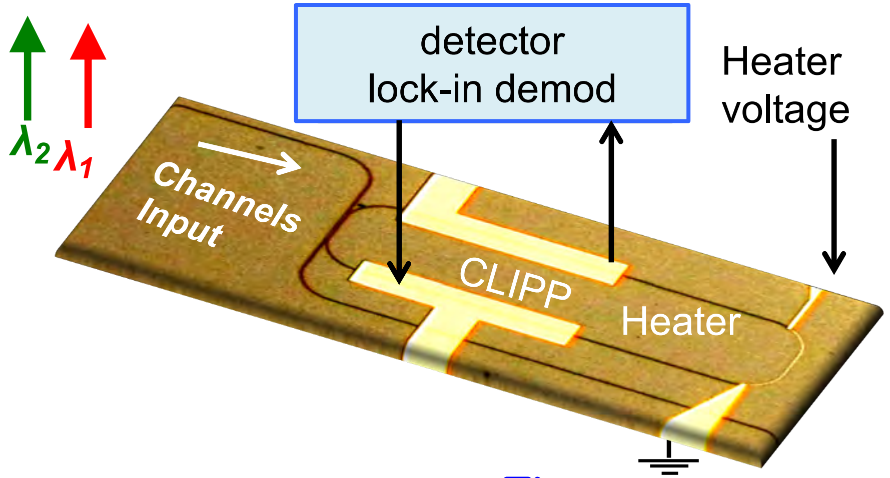


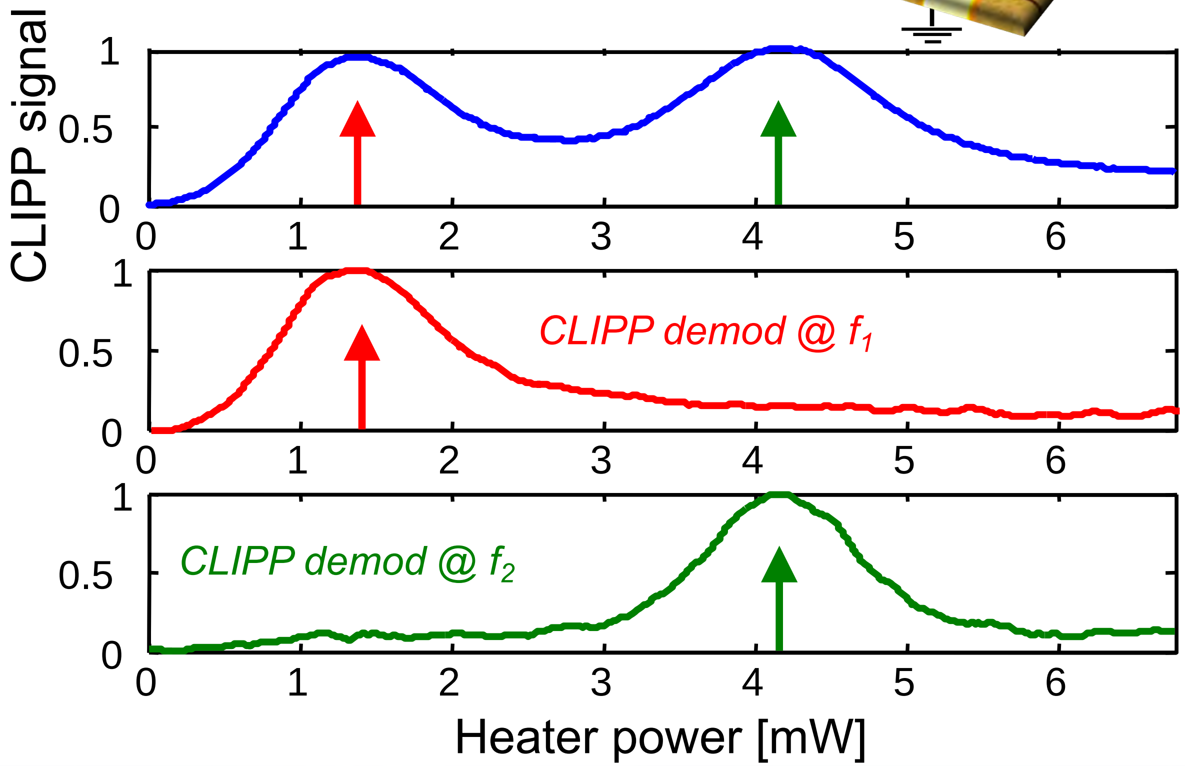


Weak (2%) amplitude modulated Pilot Tones (kHz)

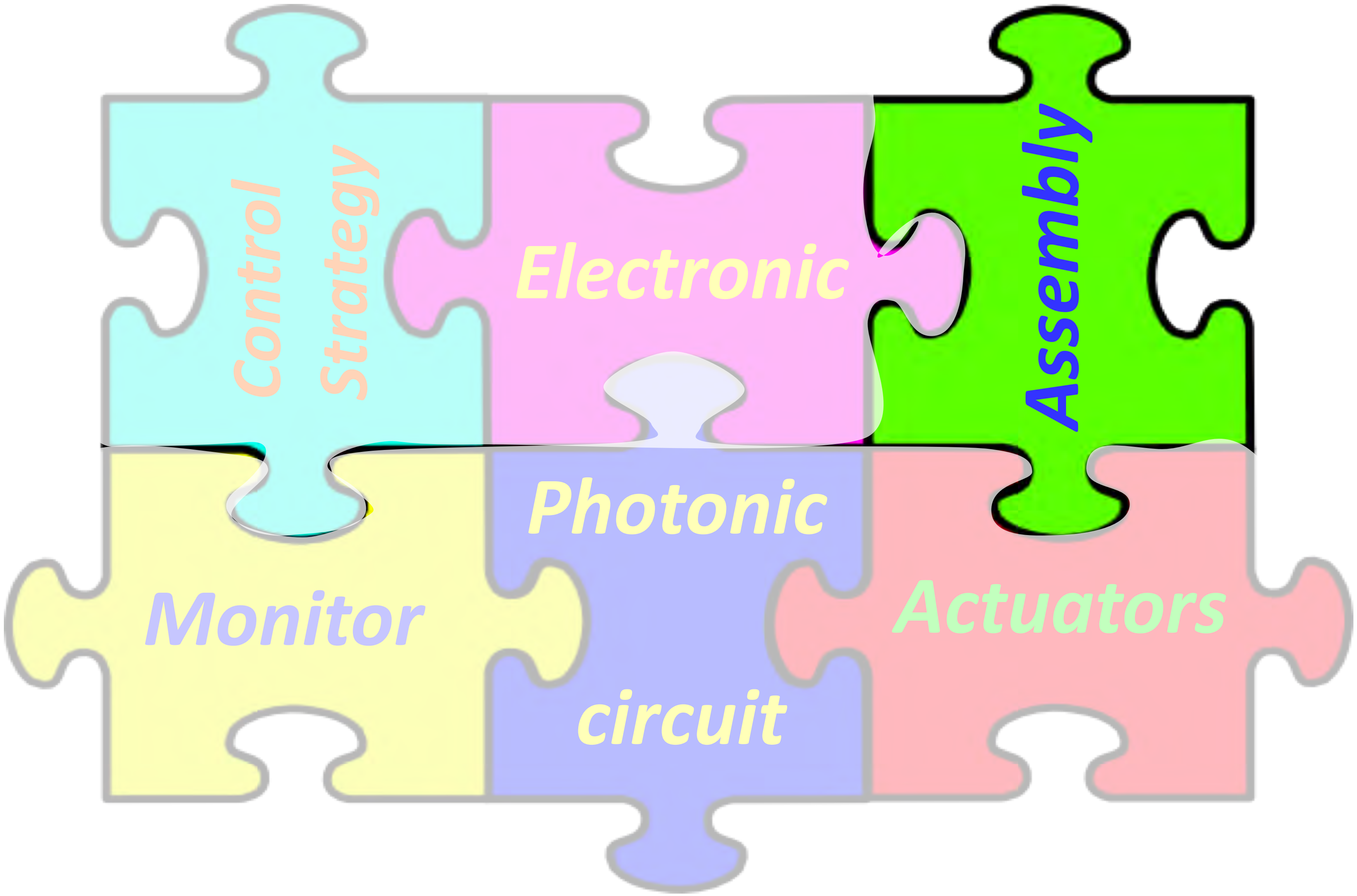
λ_2 identified

Automatic tuning and *locking at* λ_2

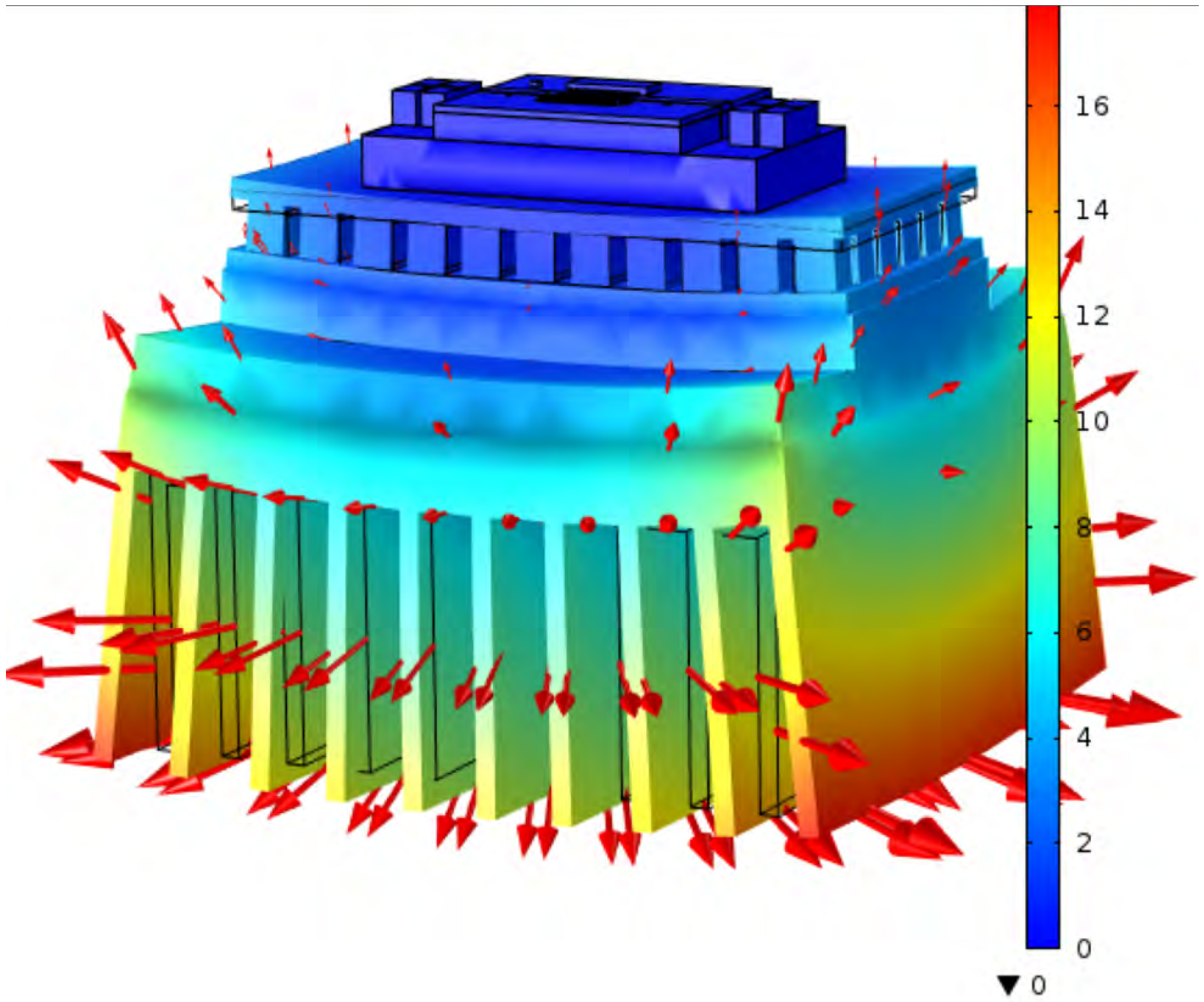


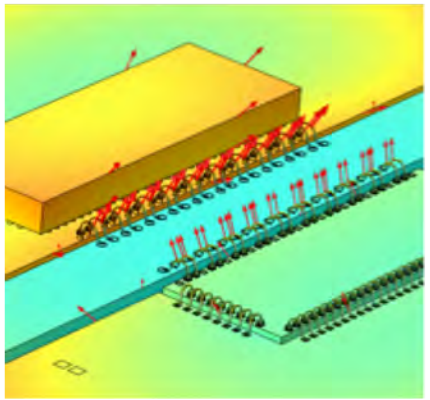


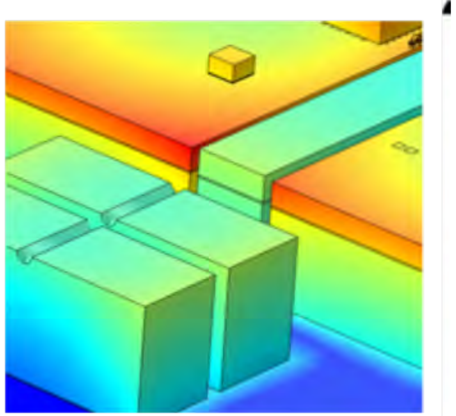
The control layer: **assembly**



A multiphysics world !!







RF connections, reflections and crosstalk

Thermal management

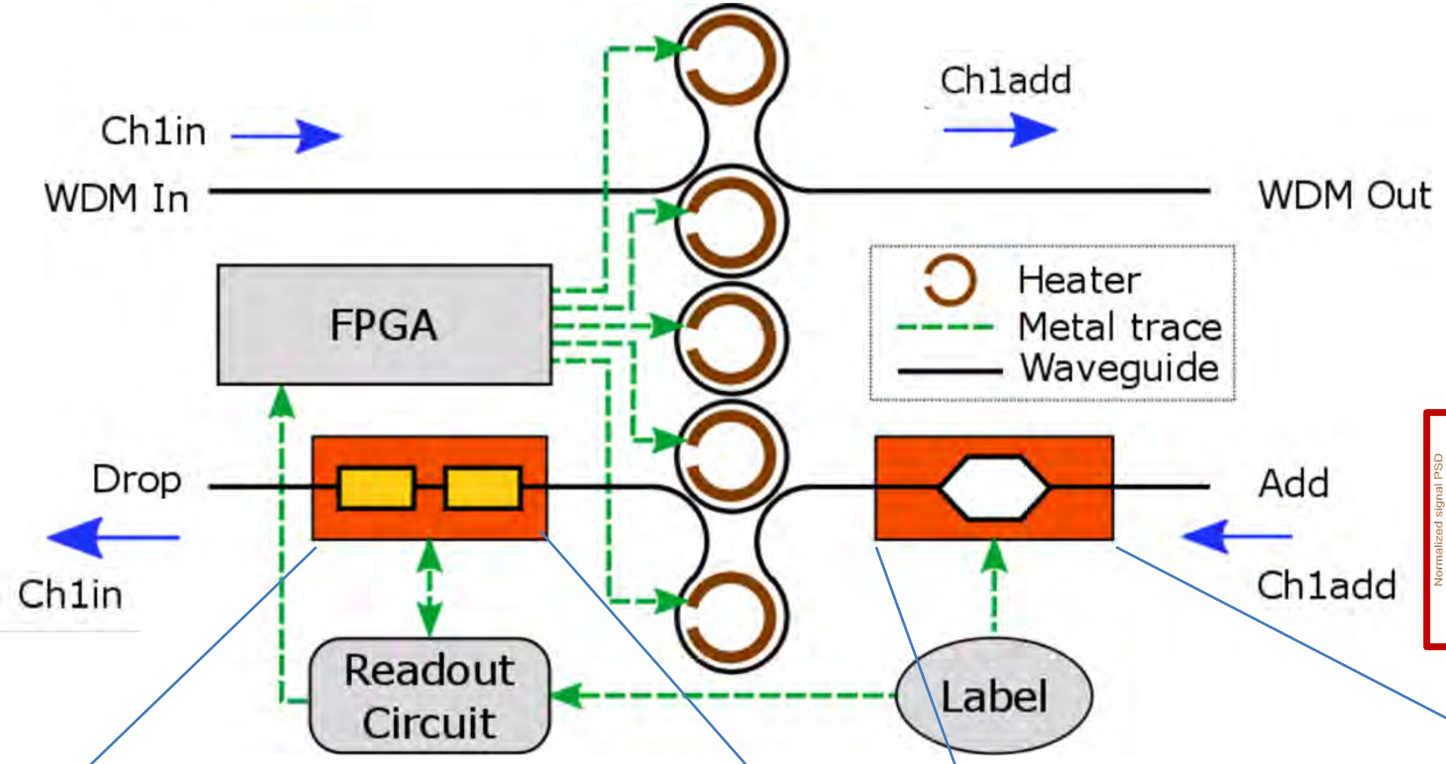
Stress and strain

Time varying phenomena

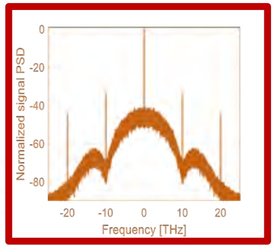
.....

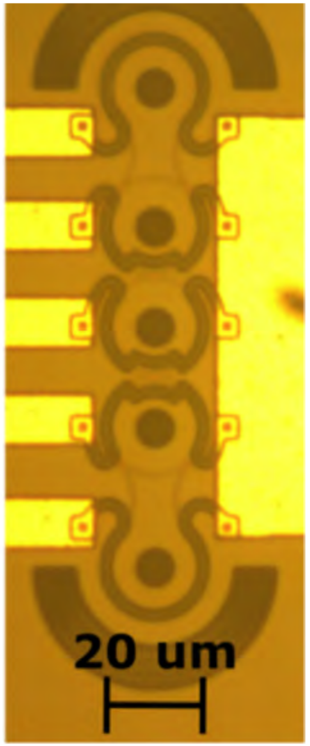
Let's use the ingredients !

Reconfigurable hitless filters

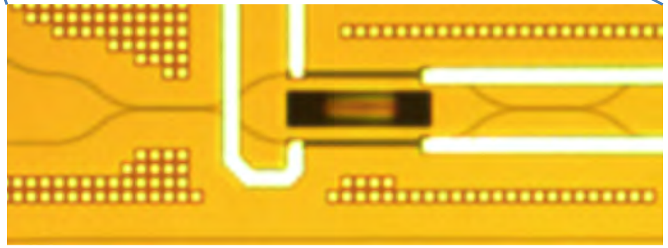


Filter design nominal values:
- 1 THz (8 nm) of Free Spectral Range (FSR)
- 40 GHz of 3 dB bandwidth
- 20 dB in band isolation





CLIPP detector at the Drop port

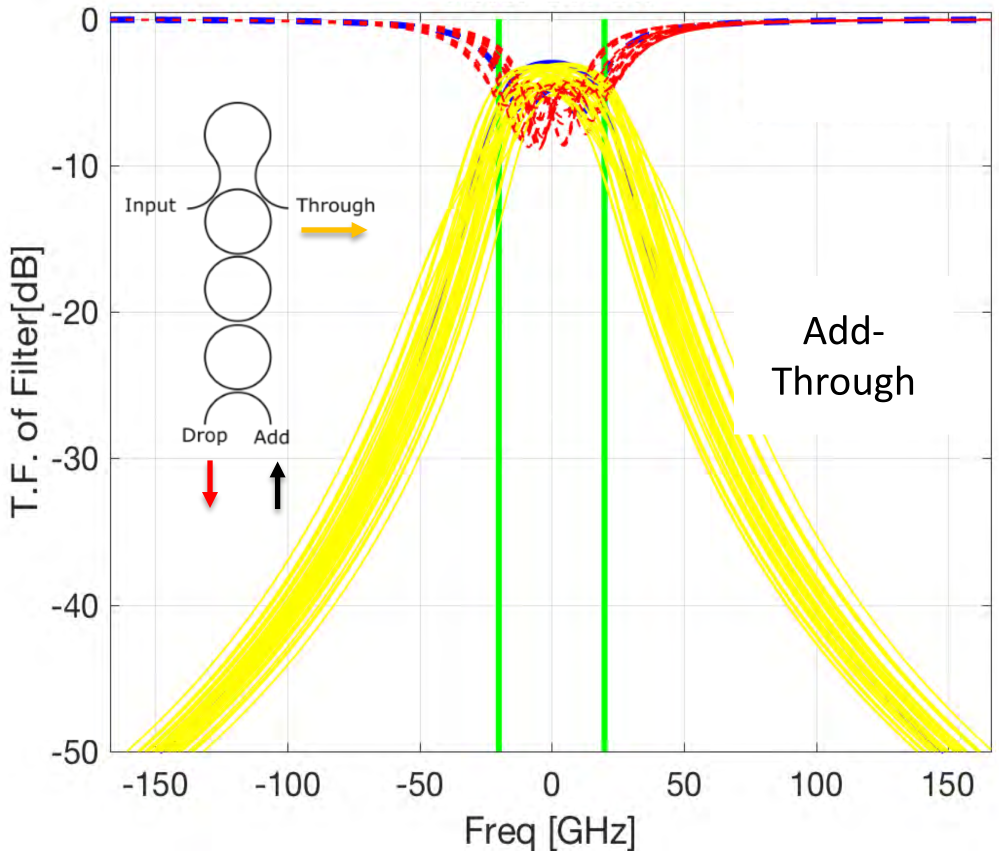


Mach-Zehnder Modulators (MZM)
in the add port to apply optical label

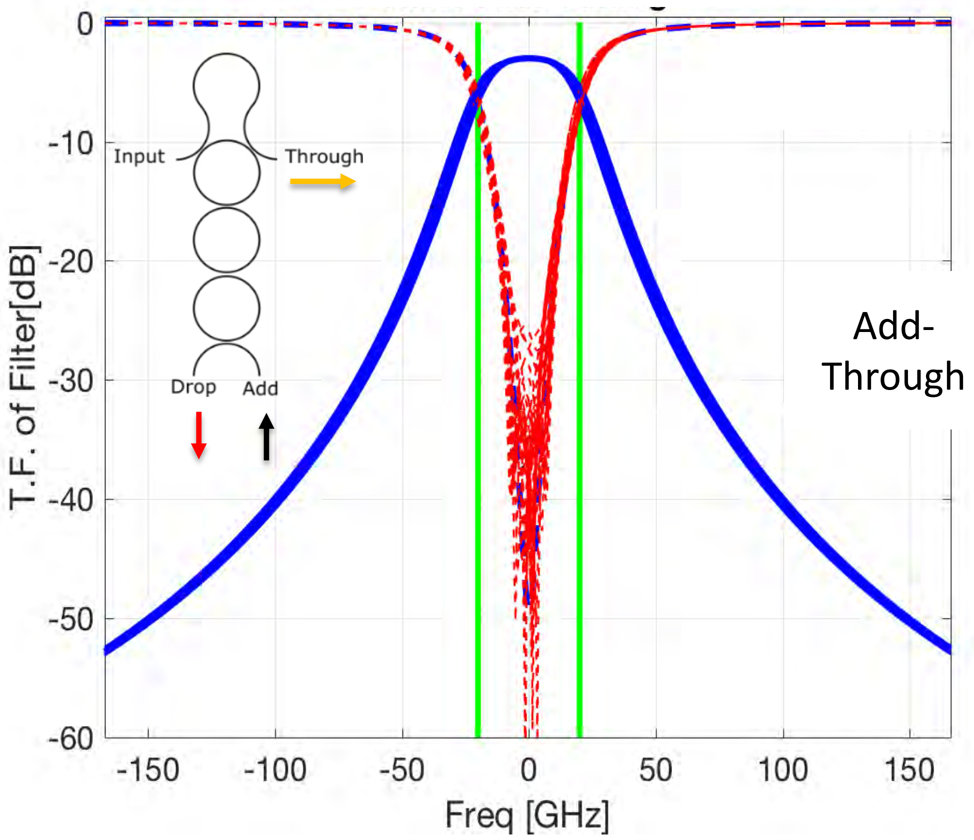
Reconfigurable hitless filters

- Exploit **TED** to actuate MRRs
- Light monitor at the **Drop port (CLIPP)**
- Marking the added channel with a **label**
- Added channel is **modulated**

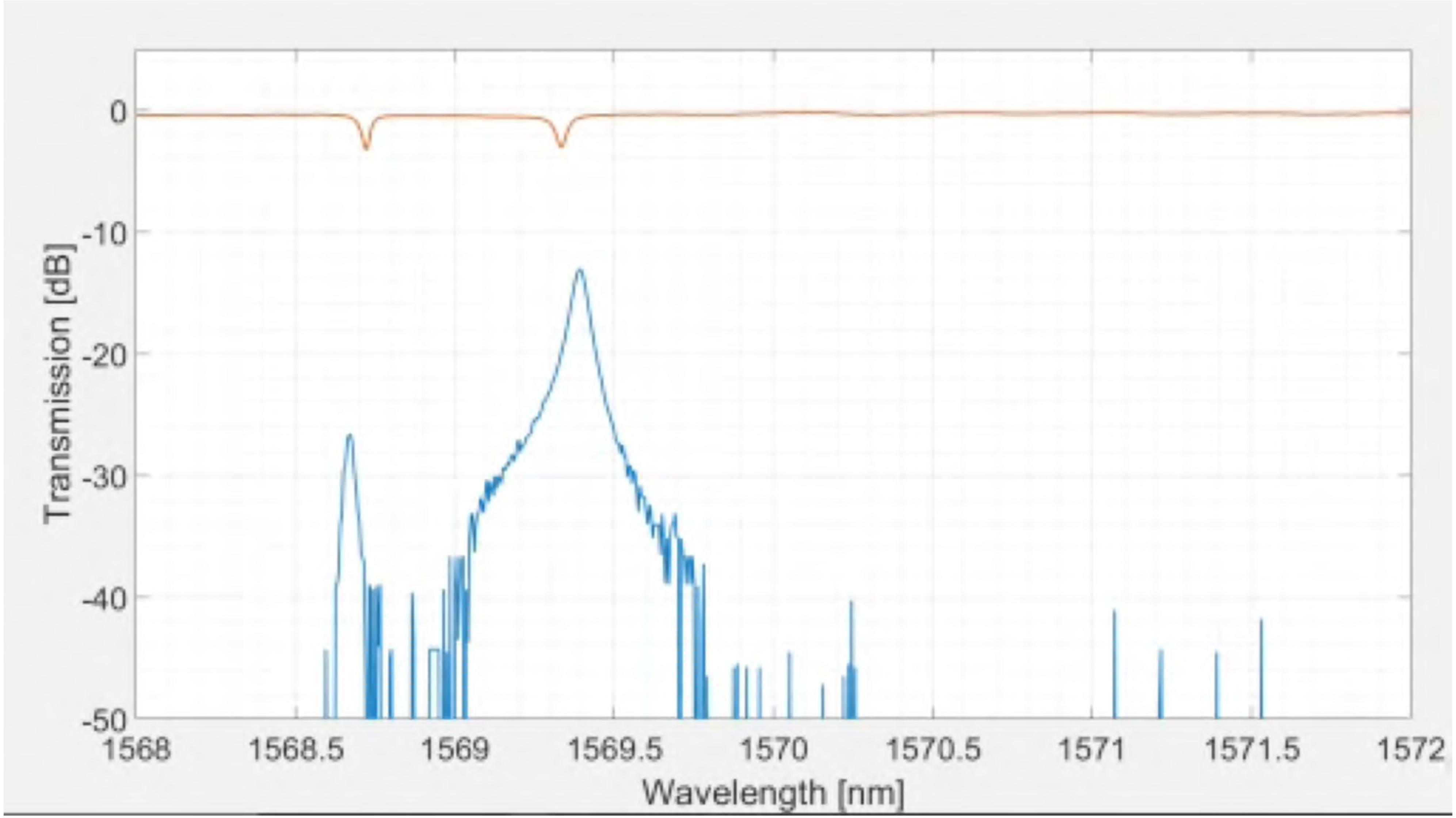
Look-up Table



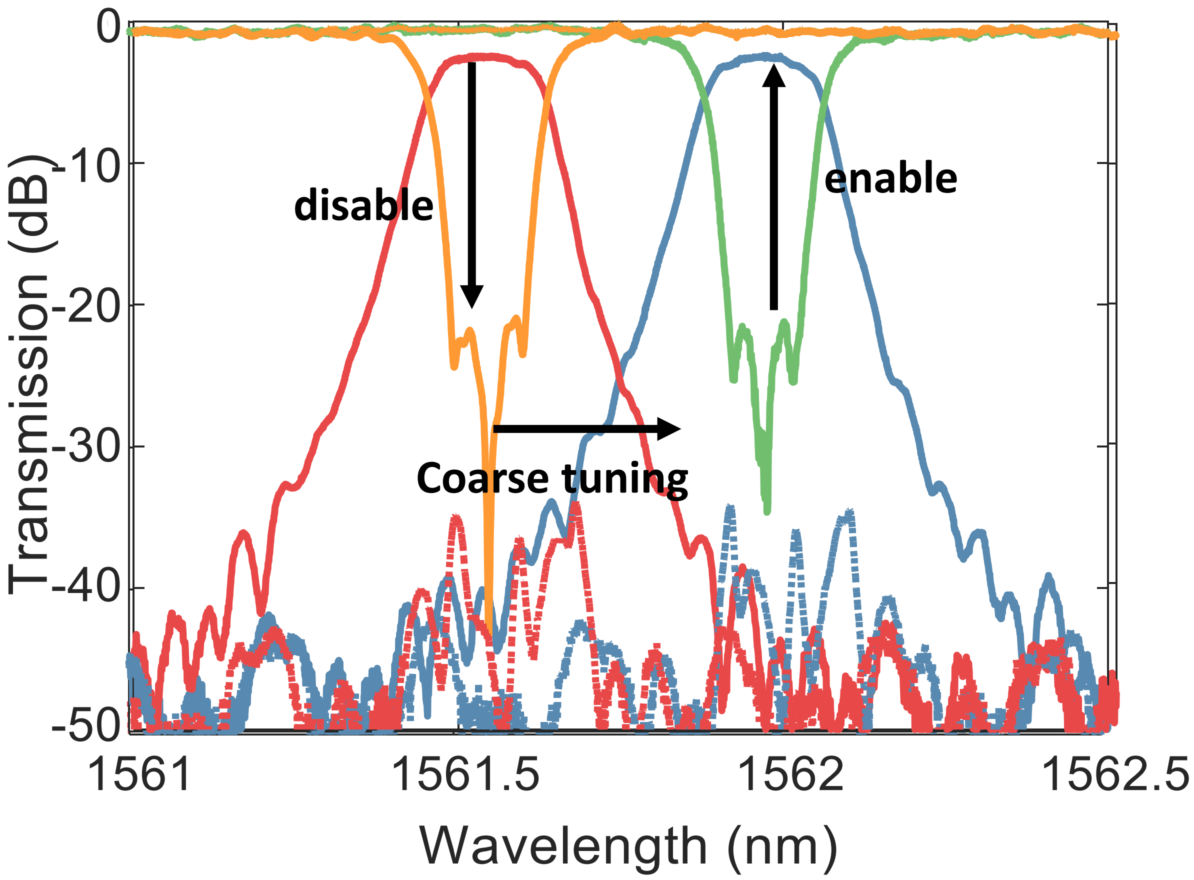
Fine tuning

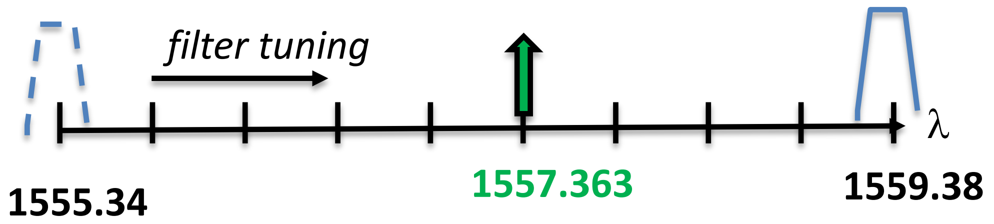


Automatic tuning of the transfer function



Reconfigurable hitless filters



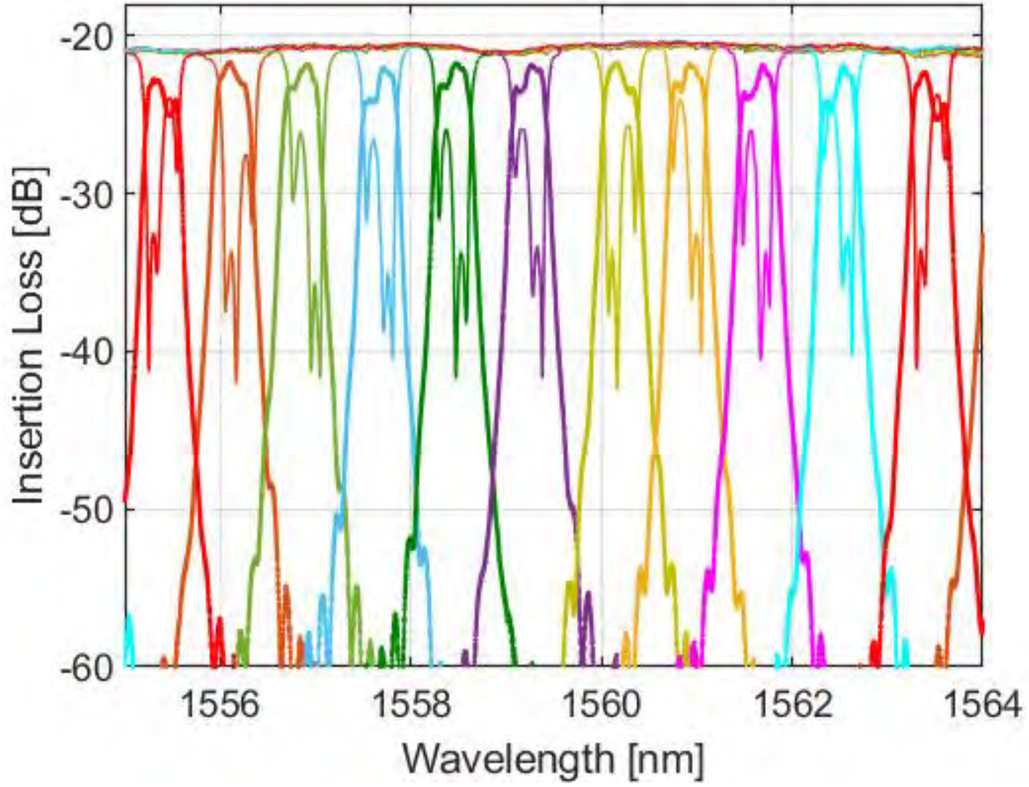


Automatic tuning and locking algorithm:

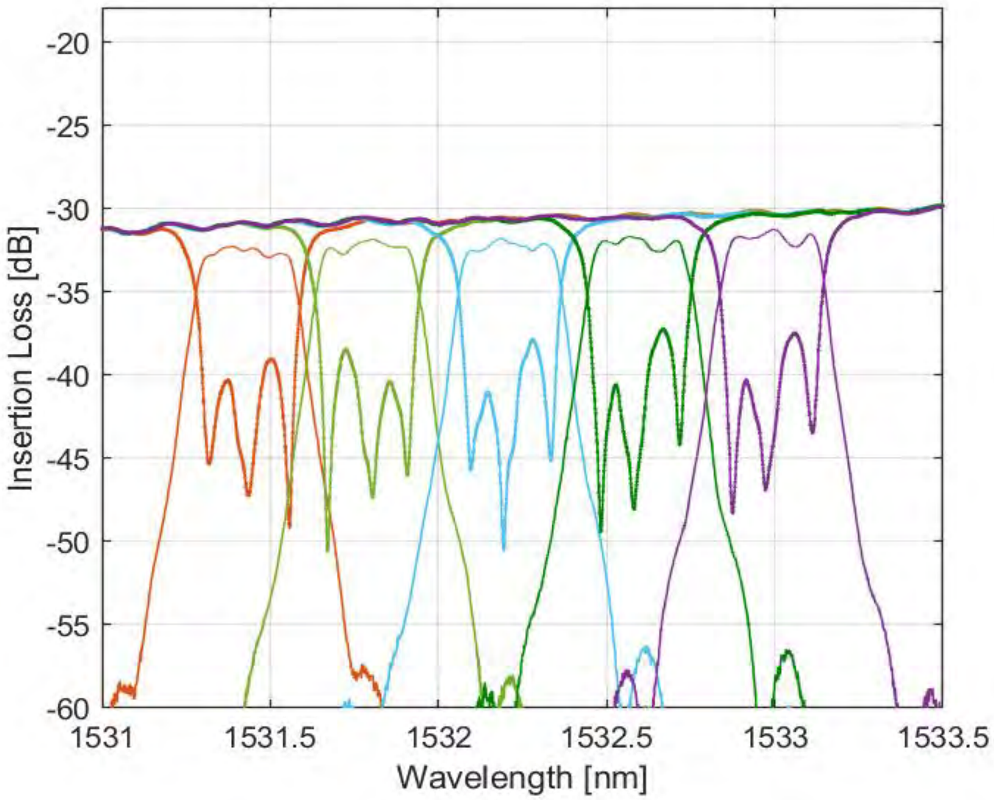
1. Disconnect filter from the bus and add/drop
2. Coarse tune of rings with a **Look Up Table**
3. Connect filter to bus and add/drop
4. **Fine tuning and automatic locking of the filter**

Look Up Table automatic generation

Drop & Through ports, 10 Gb/s, 100 GHz spaced



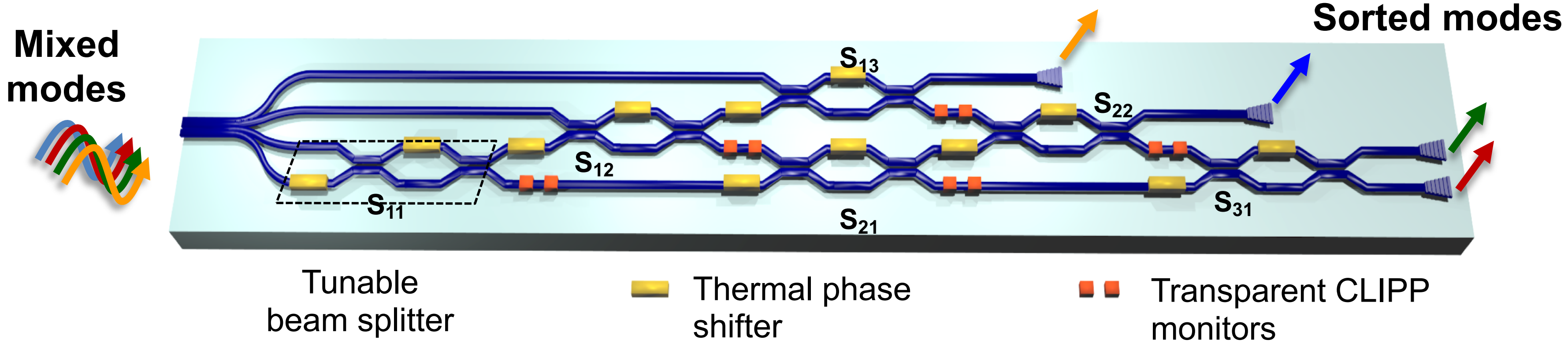
Drop & Through ports, 50 Gb/s QPSK, 50 GHz spaced

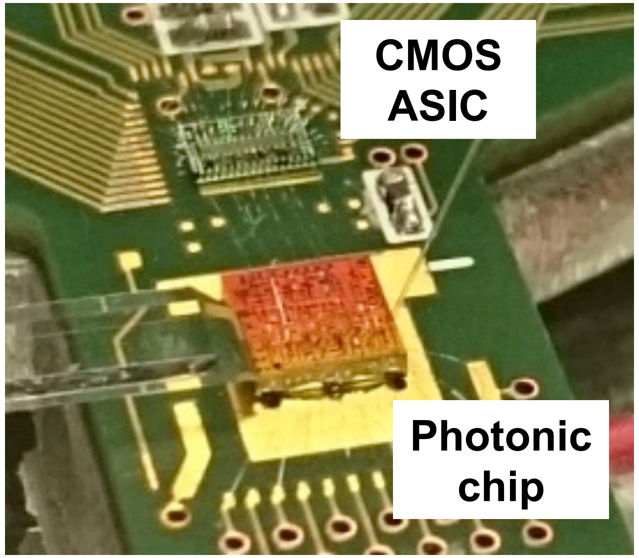


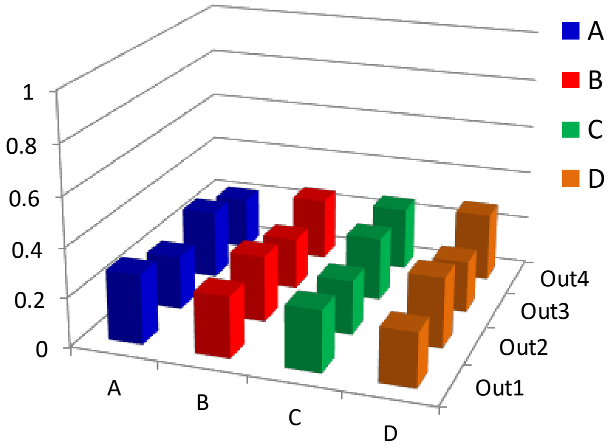
Voltages of heaters for one channel of LUT

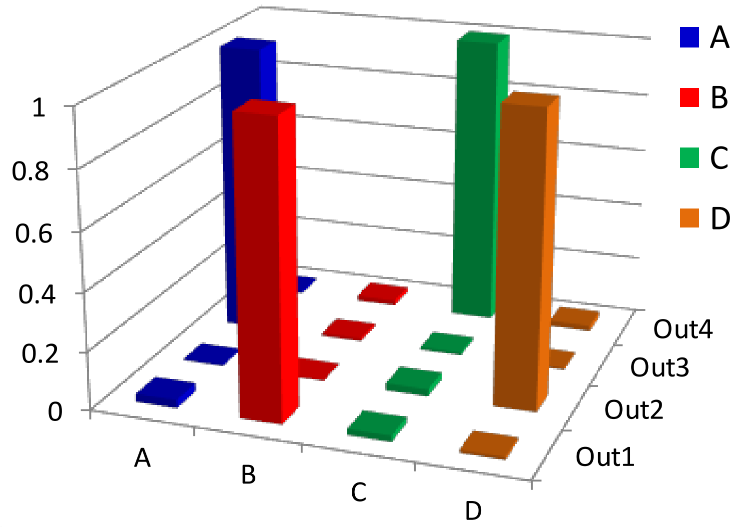
Wavelength [nm]	Ring Top [V]	Ring Middle [V]	Ring Bottom [V]	MZ Connected [V]	MZ Disconnected [V]
1559,25	3,071	2,986	2,752	3,245	1,436

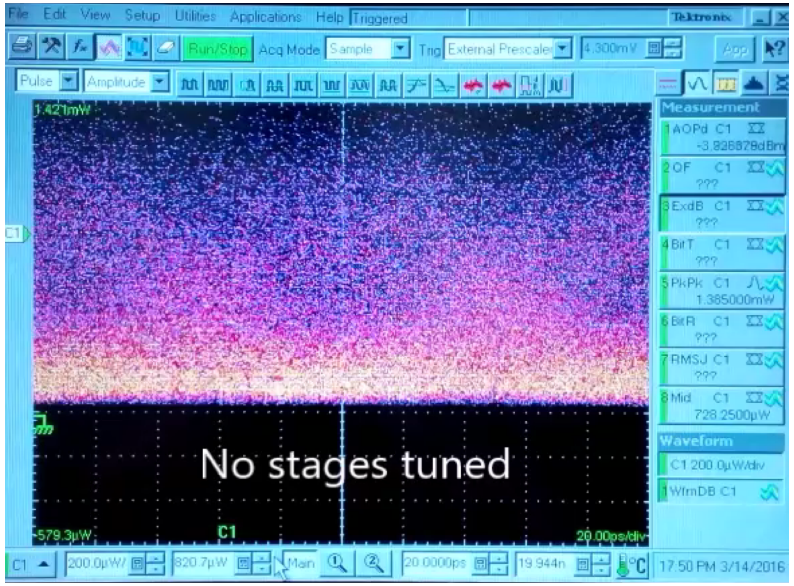
Unscrambling light (with reflex arc control and pilot tones)





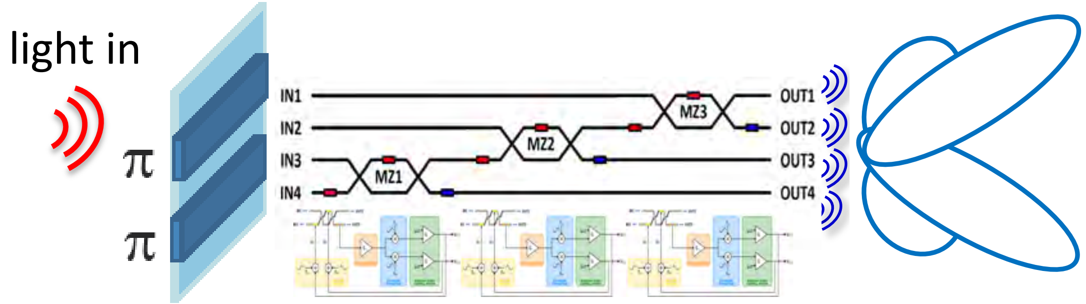




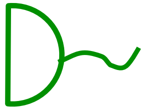


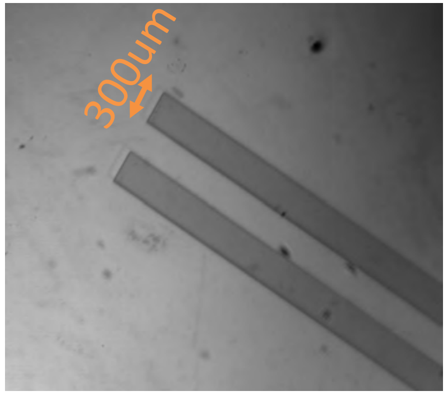
A. Annoni et al., Light: S&A 6, e17110 (2017)

Phase front reconstruction



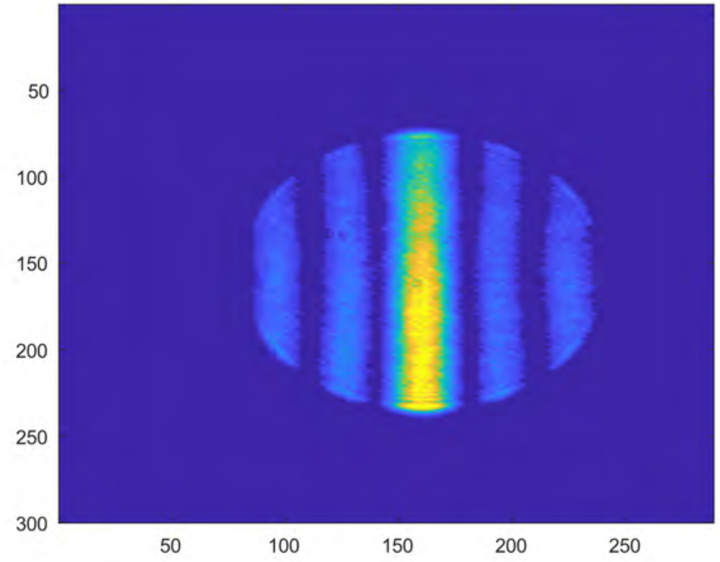
Mesh configured to maximize power at detector



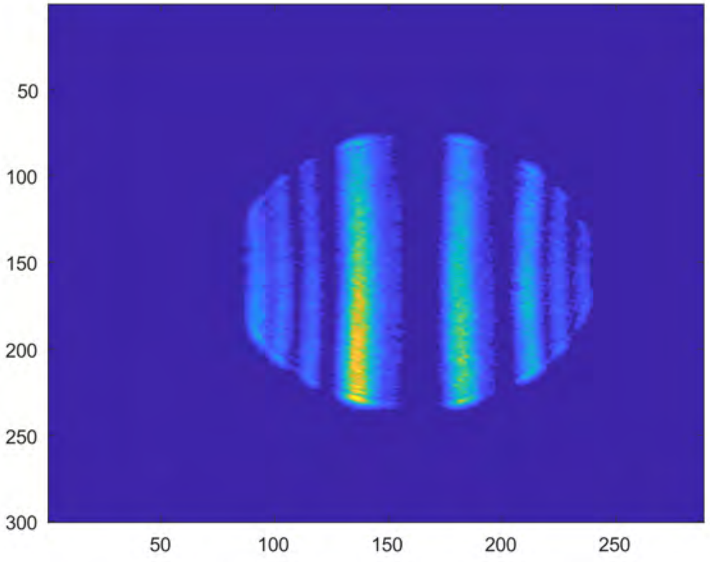


Beam size at the phase mask 1.4 mm

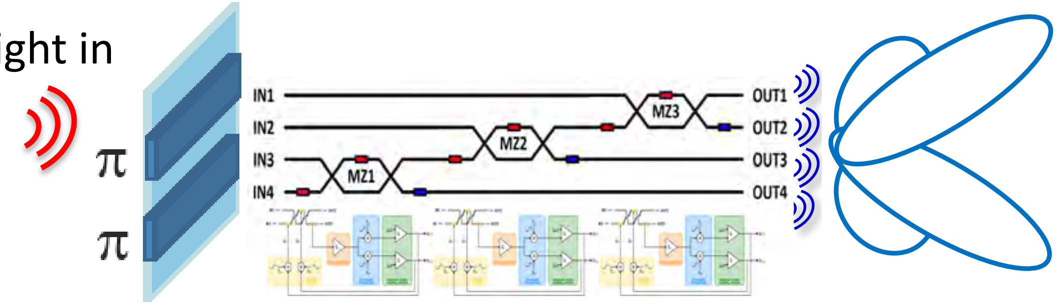
Initial Pattern



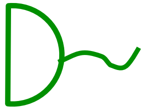
Perturbed Pattern



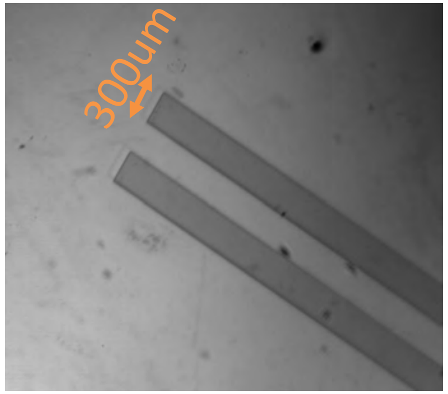
Phase front reconstruction



Mesh configured to maximize power at detector



Camera

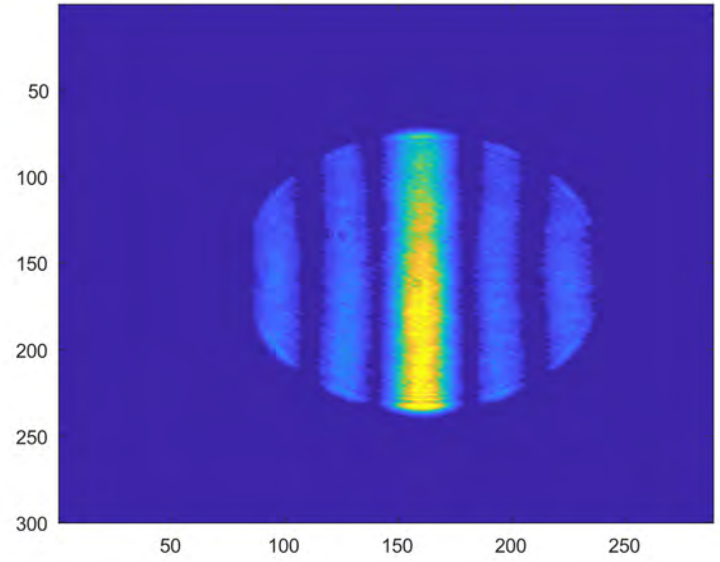


Beam size at the phase mask 1.4 mm

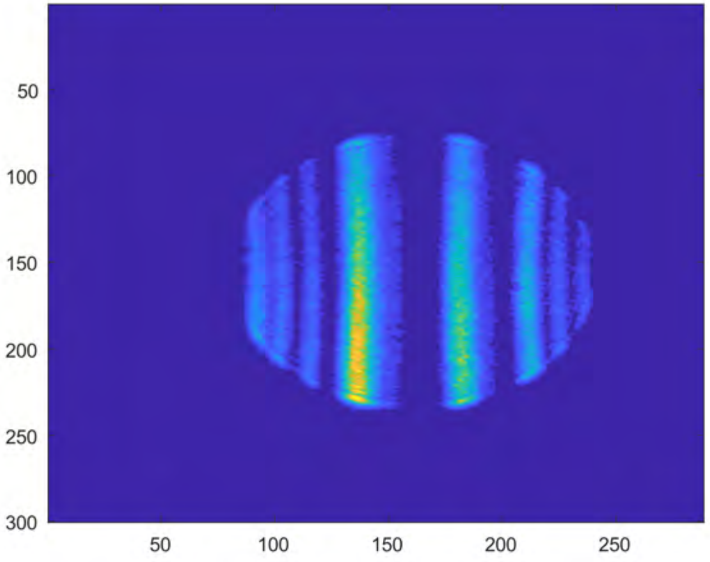
Mesh realigns compensating for phase-front perturbation

Now Mesh is reconfigured compensating for phase mask effects...

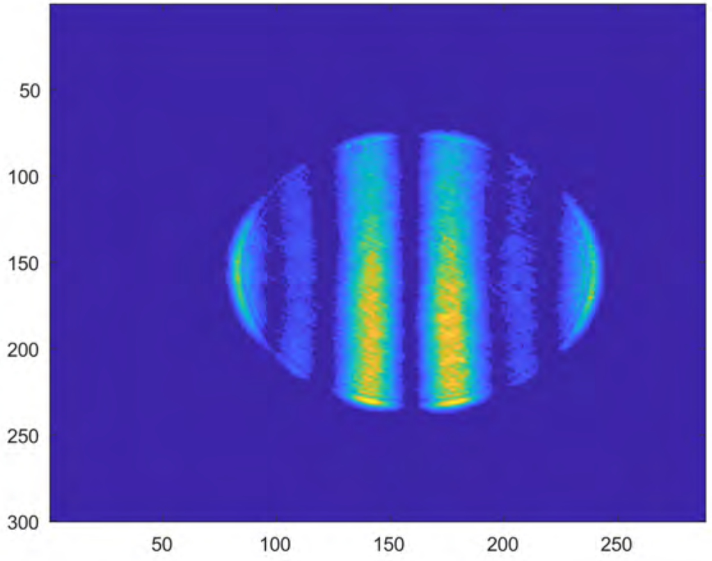
Initial Pattern



Perturbed Pattern



Compensated Pattern



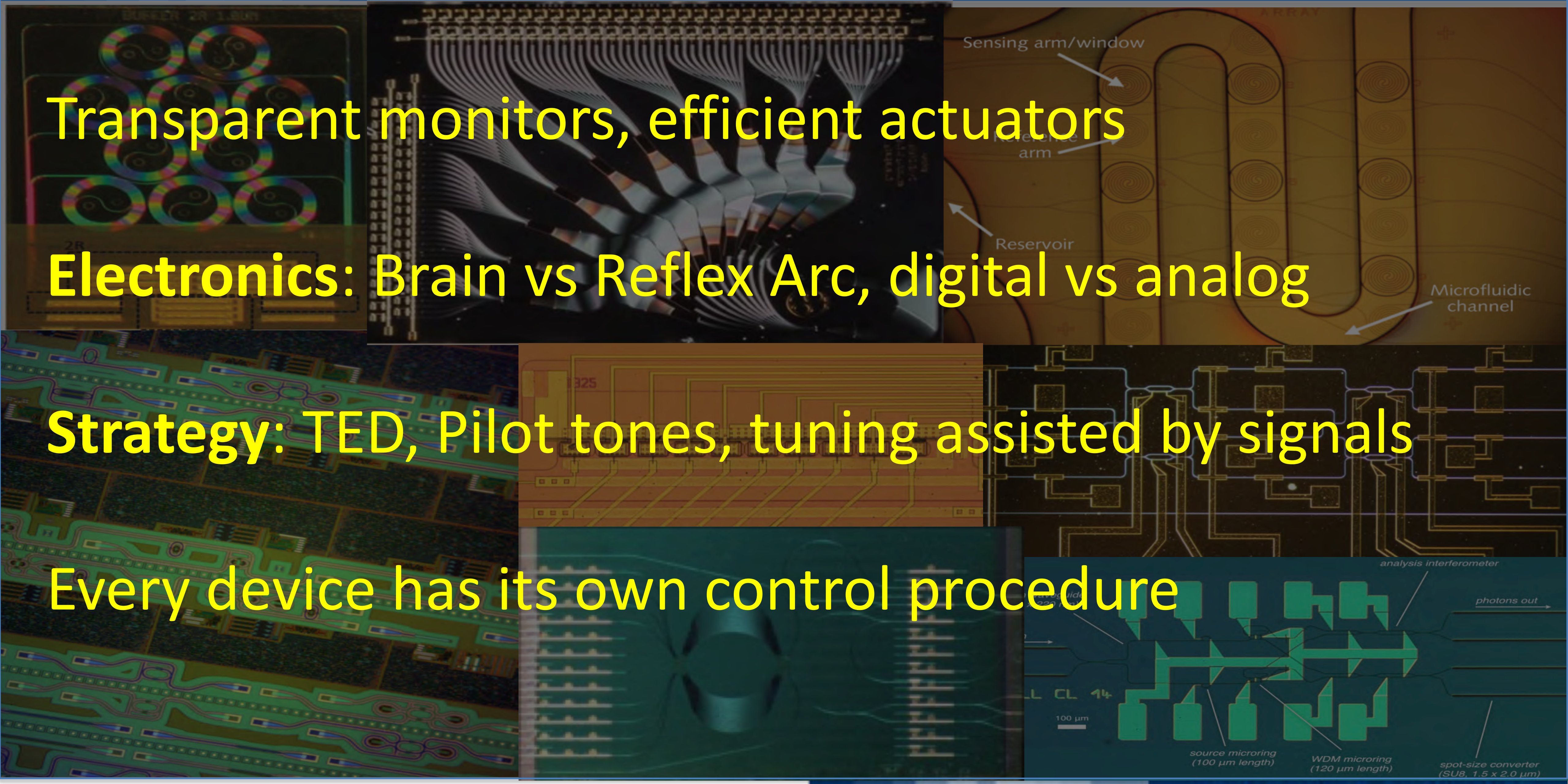
Take home messages

Transparent monitors, efficient actuators

Electronics: Brain vs Reflex Arc, digital vs analog

Strategy: TED, Pilot tones, tuning assisted by signals

Every device has its own control procedure



Acknowledgments to the many people behind !

Photonics Devices Group
F. Morichetti, M. Milanizadeh, D. Melati, D. Aguiar, M. Petrini, A. Melloni

Innovative Integrated Instrumentation for the Nanoscience (I3N)
M. Carminati, P. Ciccarella, F. Zanetto, E. Guglielmi, F. TosoG. Ferrari, M. Sampietro

Polifab, Micro & Nanofabrication Center (Politecnico di Milano)

M. Sorel, B. Holmes, C. Klitis,
University of Glasgow, Glasgow, UK

James Watt Nanofabrication Center (University of Glasgow)

H2020 ICT-Streams Project.
http://www.ict-streams.eu/

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

A. Vannucci, A. Annoni
Photonics42, Italy

H2020 FET -https://www.superpixels.org/

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)

David Miller
Stanford University, US