Harnessing Photonic Integrated Circuits

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Photonic Devices

1969: 46 years of integrated optics …

THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48 September 1969 Number 7

Integrated Optics: An Introduction

By STEWART E. MILLER

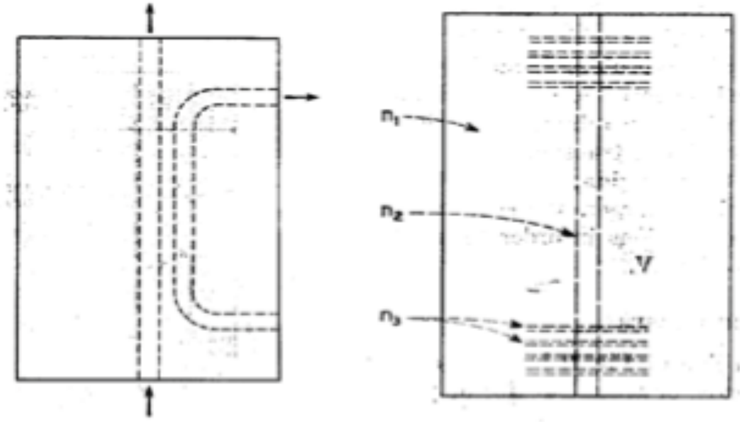


Fig. 6 — Directional coupler type hybrid. ; 3 — Resonator using planar waveguide.

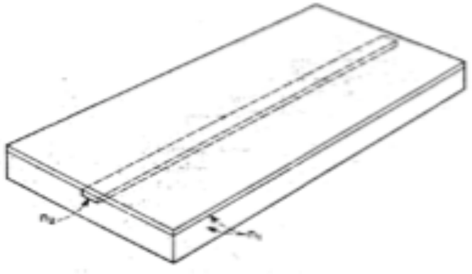


Fig. 2 — Planar waveguide formed using photolithographic techniques.

Bends in Optical Dielectric Guides

By E. A. J. MARCATILI

(Manuscript received March 3, 1969)

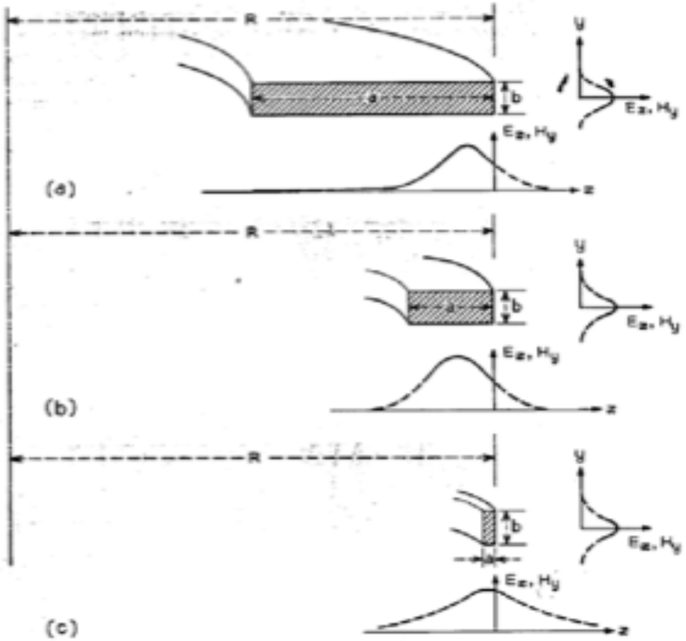


Fig. 6 — Field distribution as a function of guide width a with (a) $a/A \gg 1$, (b) $a/A \simeq 1$, and (c) $a/A \ll 1$.

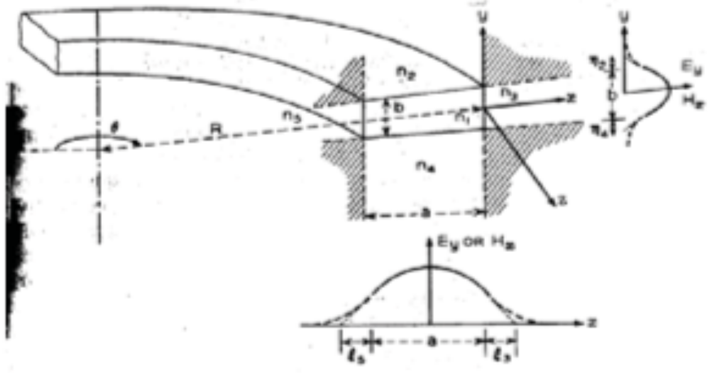


Fig. 2 — Curved dielectric guide.

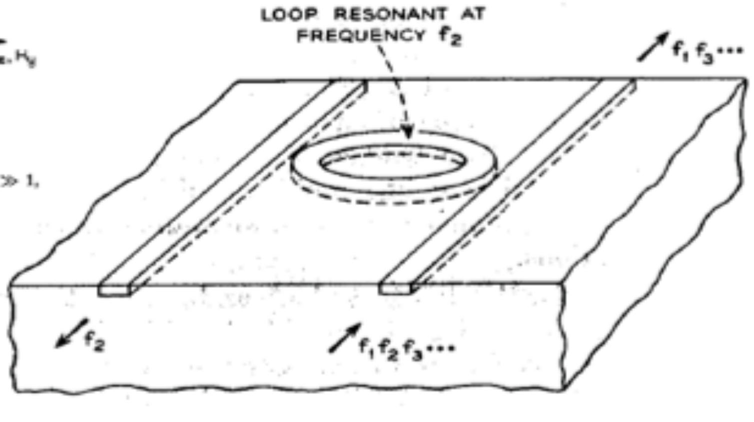


Fig. 1 — Channel dropping filter (ring type).

Is there really anything new
under the Sun?
Yes! (hopefully…)

TOWARDS 2020 – PHOTONICS DRIVING ECONOMIC GROWTH IN EUROPE

Multiannual Strategic Roadmap 2014–2020

PHOTONICS21

Photonics Research and Innovation Challenges

- **2.1** Information & Communication
- **2.2** Industrial Manufacturing & Quality
- **2.3** Life Science & Health
- **2.4** Emerging Lighting, Electronics & Displays
- **2.5** Security, Metrology & Sensors
- **2.6** Design and Manufacturing of Components & Systems
- **2.7** Education, Training & Disruptive Research

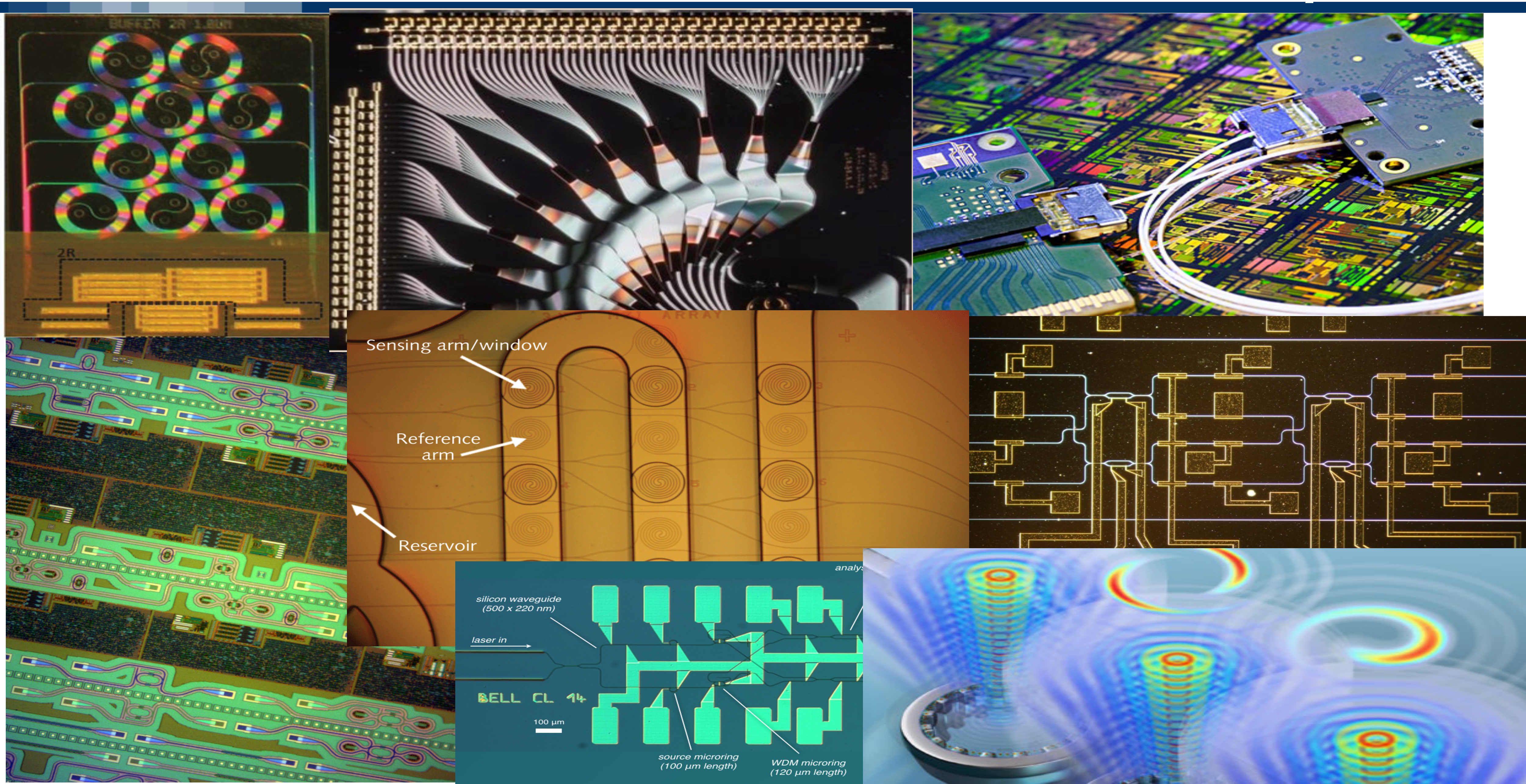
Roadmaps

JEPPIX

IPSR

Integrated Photonic Systems Roadmap

Integrated photonics: towards ubiquitousness

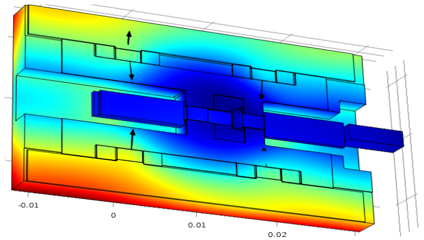


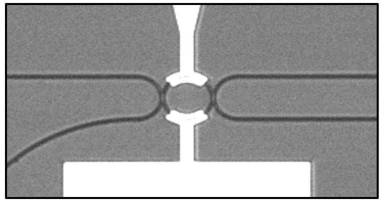
It’s a long way (in my view) …

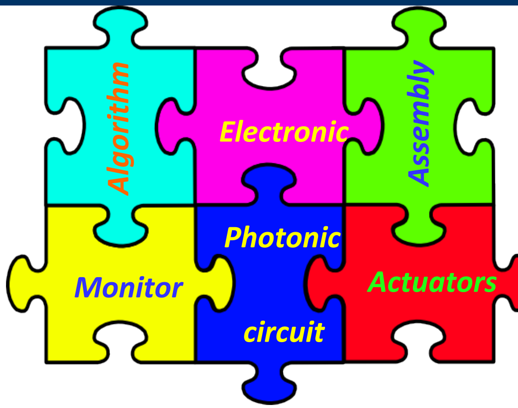
- Moore law in photonics… No scaling in photonics !
- Photonics as electronics…. Photonics is analog !
- Plasmonic, graphene, quantum, …
- CMOS Compatibility… Mendeleev on chip !
- More Moore or More than Moore? … Integration, synergy
- Everyone does their job! … generic foundry scheme
- **Control & feedback, toward “system-on-a-chip” paradigm**

Summary

Control layer motivations

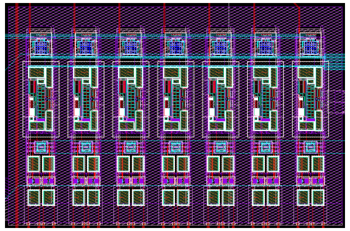


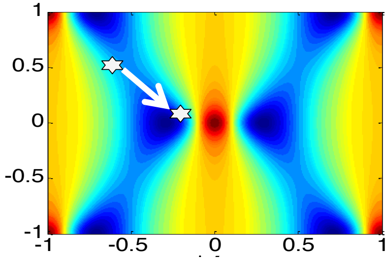




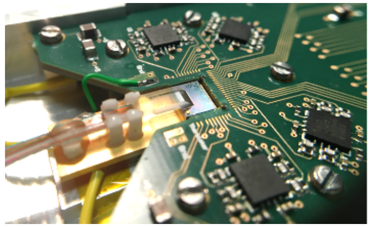
Monitor (CLIPP)

Electronics for PICs control

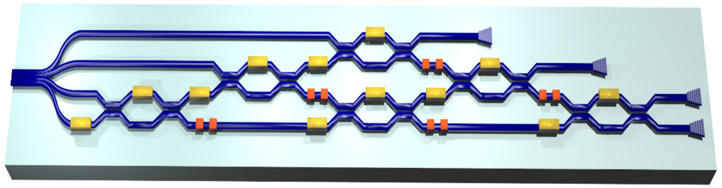




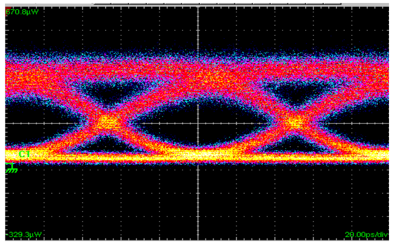
Algorithms and techniques



Signal labelling techniques

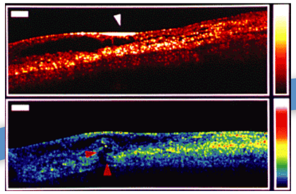


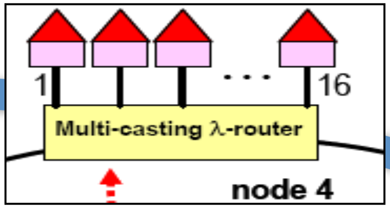
Mode unscrambling



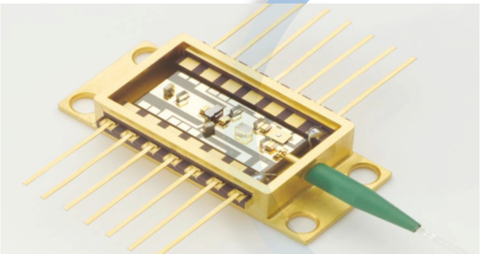
The generic foundry model

Users



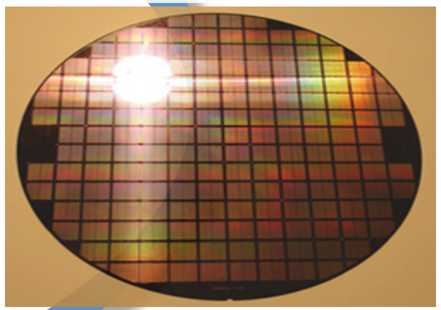


Packaging

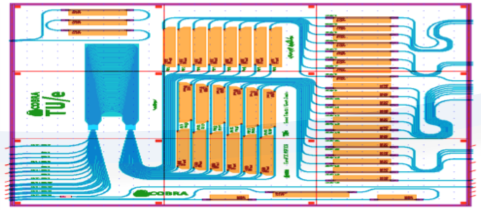


Building Blocks
Design rules
Design kits
Software

Foundries



Design Houses



HELIOS
pHotonics ELectronics functional Integration on CMOS

Memphis
Merging Electronics and Micro & Nano-Photonics in Integrated Systems

PhotonFAB
Support Action

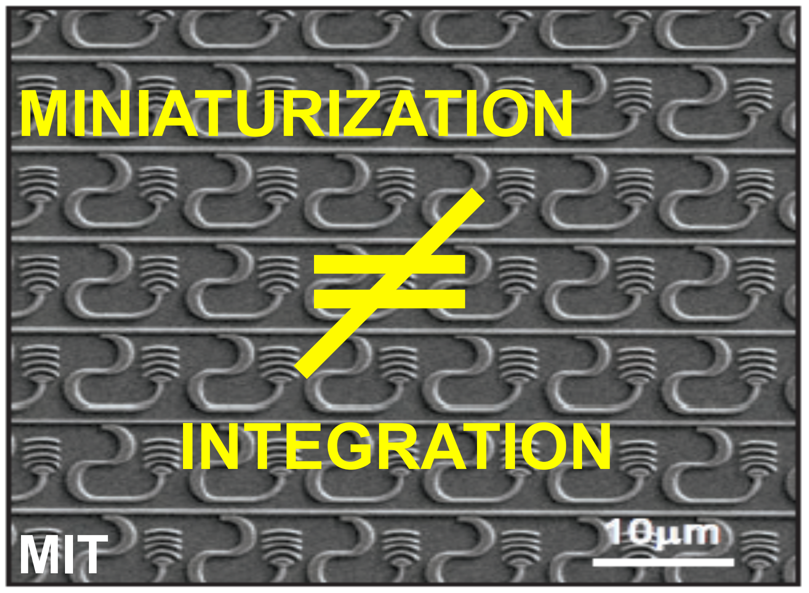
PARADIGM

europIC

Control & Feedback: motivations

- Benefits of photonic integration lies in the aggregation of several components

- Technology can squeeze many devices in small chips



- Complex photonic systems-on-chip are still struggling to emerge...

Technology is critical…

High Index contrast technologies

ΔT = 1 K → Δf = 10 GHz

$\Delta n = 10^{-4}$ → Δf = 10 GHz

Δw = 1 nm → Δf = 100 GHz

TE/TM and λ dependence…

(Interferometric) devices suffer from temperature drifts, xtalk, fabrication tolerances, nonlinearities, aging…

Control & Feedback: motivations

- Benefits of photonic integration lies in the aggregation of several components
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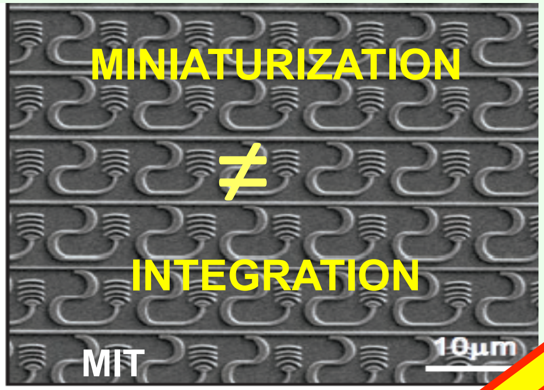


- Complex photonic systems-on-chi... g to emerge...

Tec... ology is critical

Silic... :

... Δf = 10 GHz

... → Δf = 10 GHz

... = 1 nm → Δf = 100 GHz

... TE/TM and λ dependent

(Interferometric) devices suffer from temperature drifts, xtalk, fabrication tolerances, nonlinearities, aging…

The key to large-scale integration is keeping photonics under control

Toward a "LESS" ...orld

Less Latency

FormatLESS

ContentsLESS

Less costs

ColorLESS

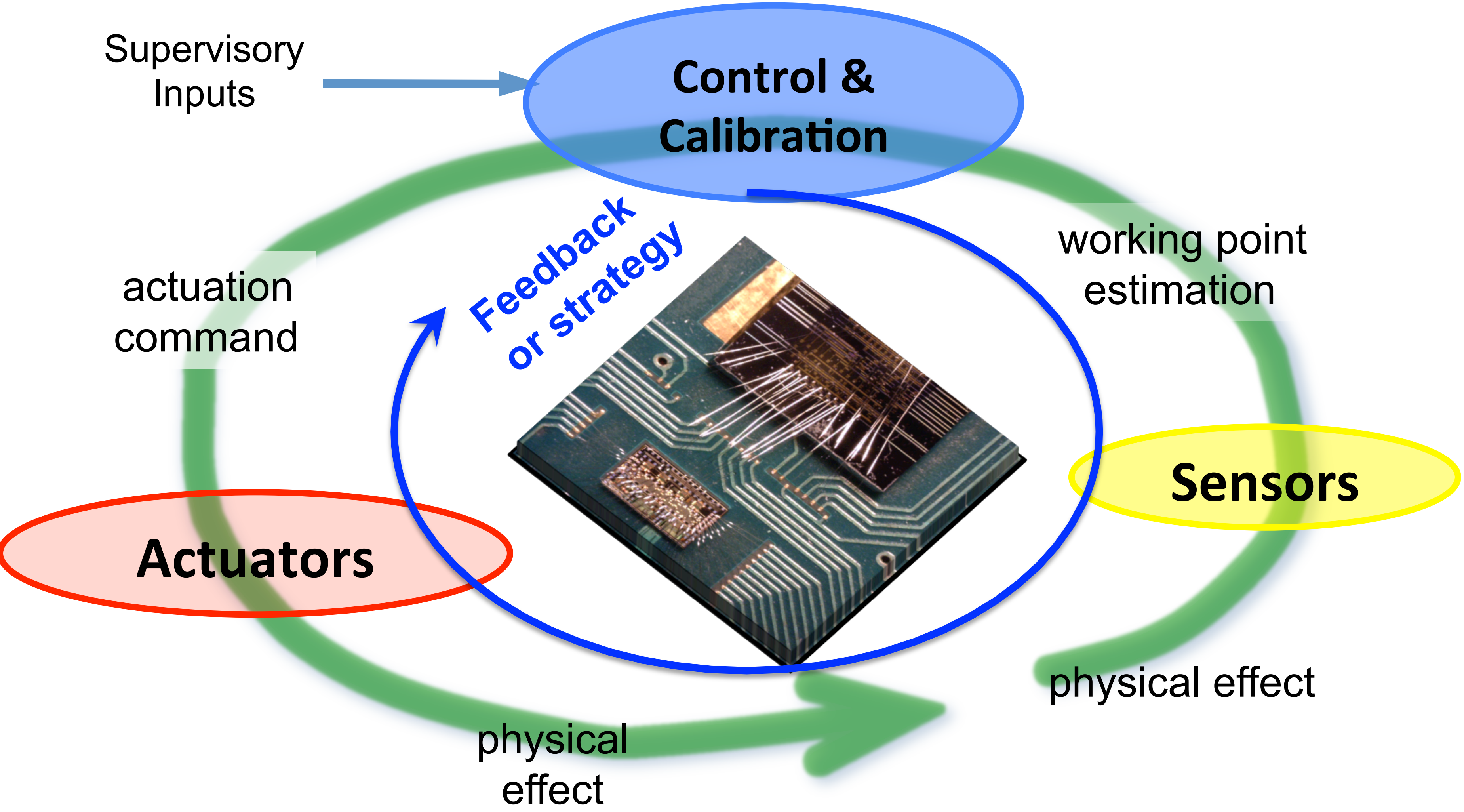
DirectionLESS

Less space

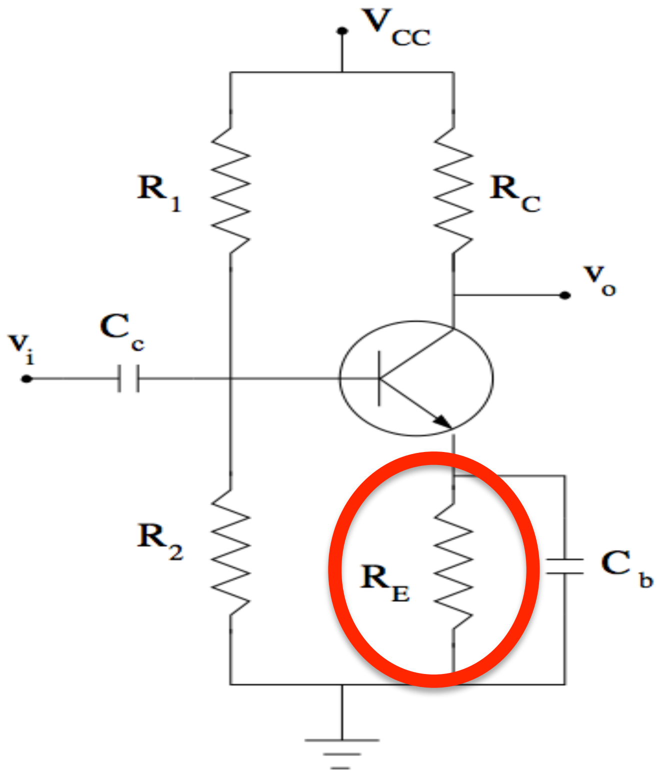
Less energy

GridLESS

Definition of “System”



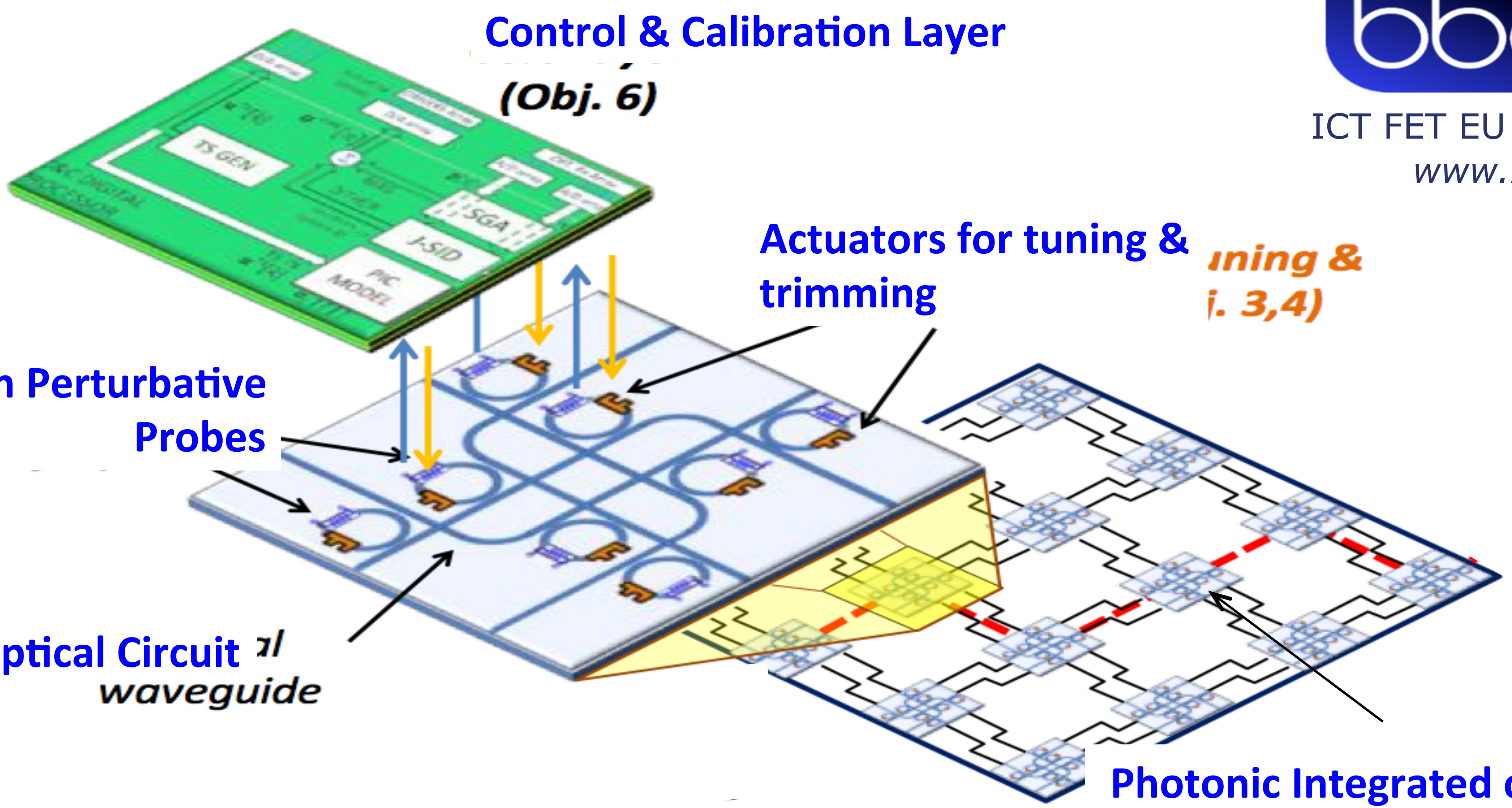
Feedback…



Photonics needs feedback and control

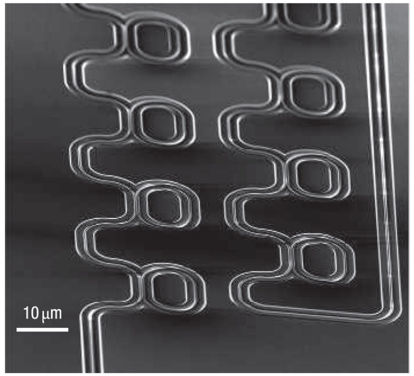
Feedback controlled VLSI photonics

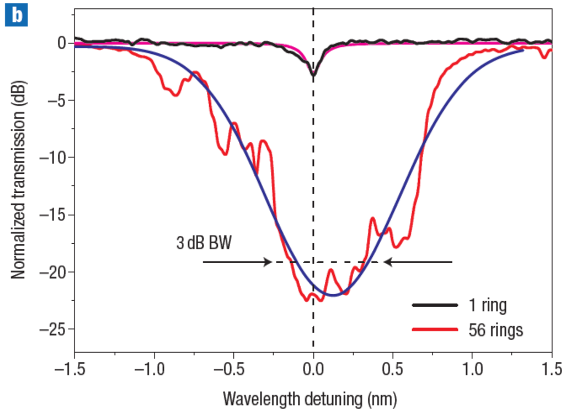
ICT FET EU Project
www.bboi.eu



PICs: uncertainties and variability

... fabrication tolerances





Courtesy of IBM, 2007

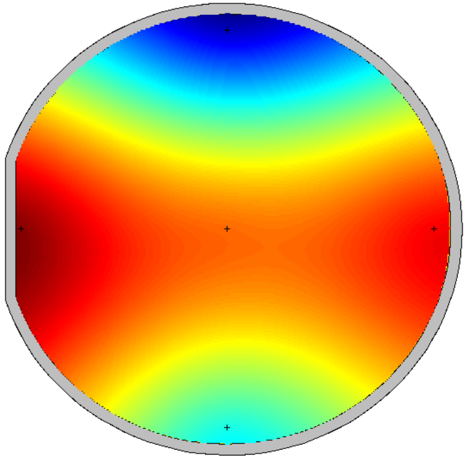
F. XIA, et al, Nat. Photonics, 2007

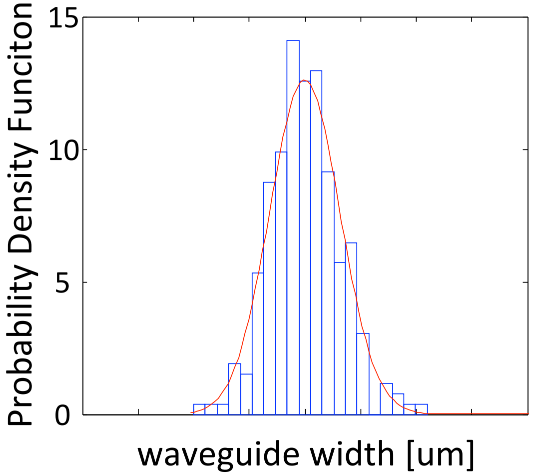
1nm tolerance in waveguide width, 100 GHz wavelength shift

... temperature dependence

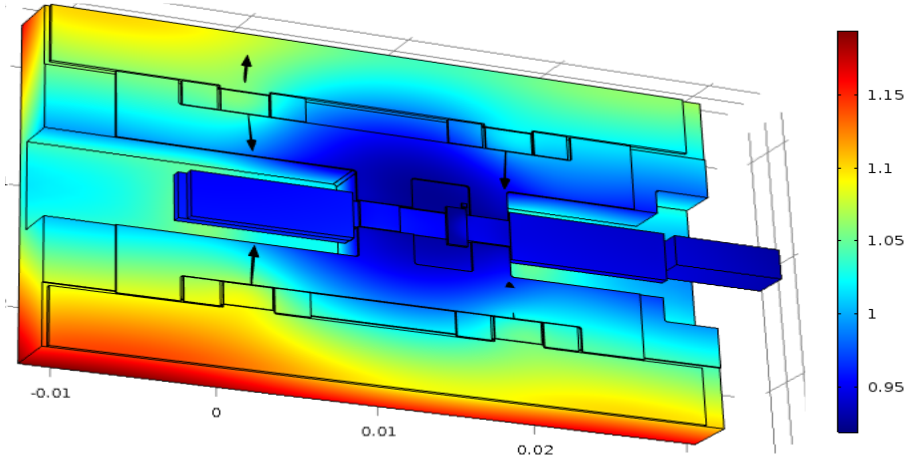
Material	K_{th} [K^{-1}]	$\Delta f/\Delta T$ [GHz K^{-1}]
SiO_2	10^{-5}	1.5
Si, InP,...	$2\ 10^{-4}$	10

... stochastic nature of parameters





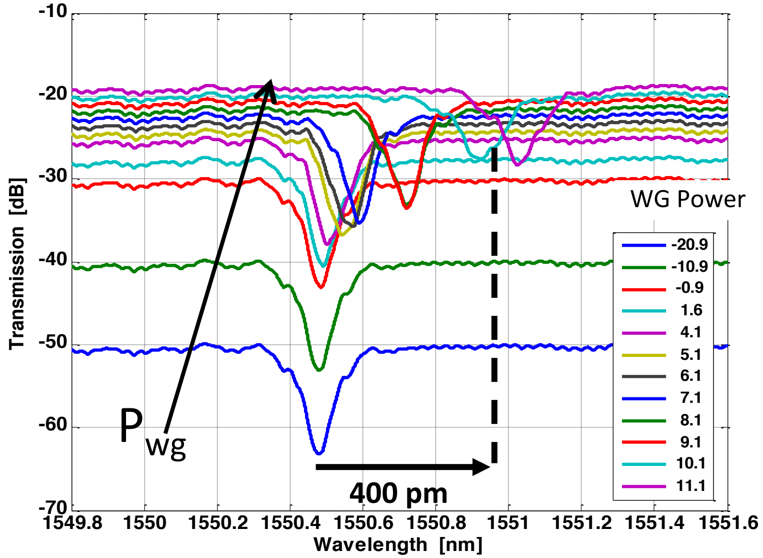
... operational conditions



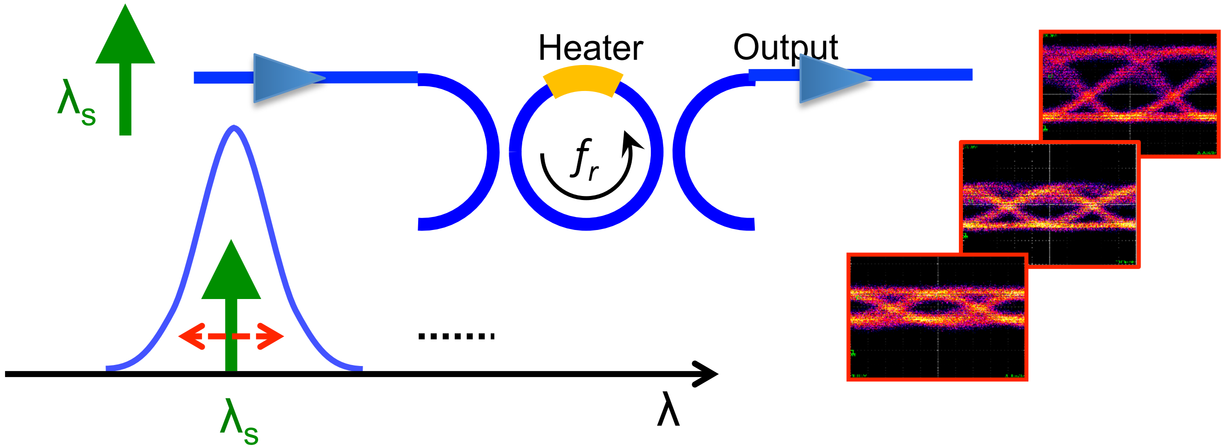
PICs: adapting and programming

... non linear effects

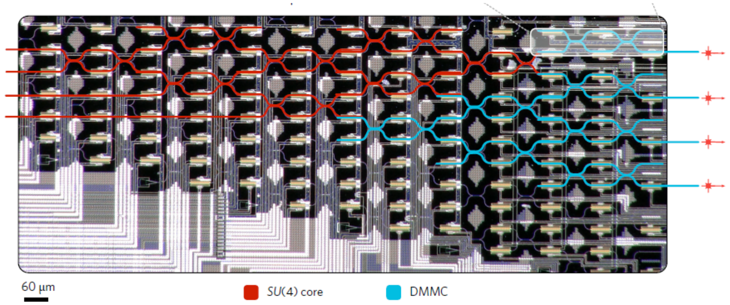
Nonlinear frequency shift, Two photon Absorption



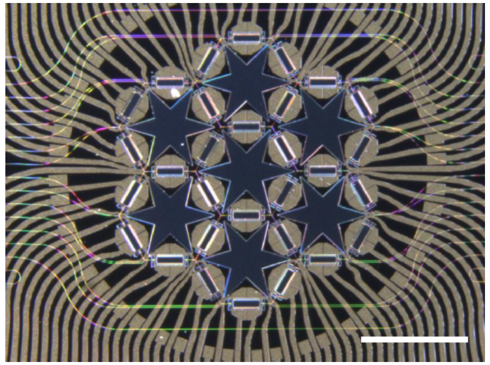
... adaptive tuning and locking to "external" drifts



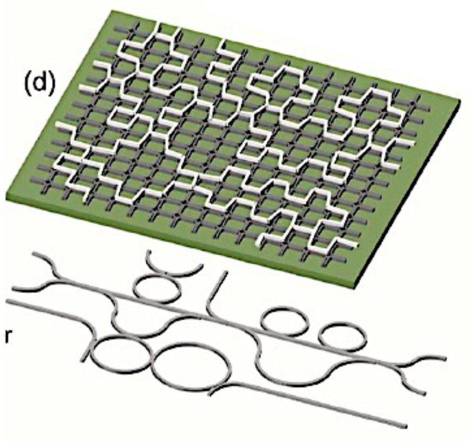
... programmable integrated photonics



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



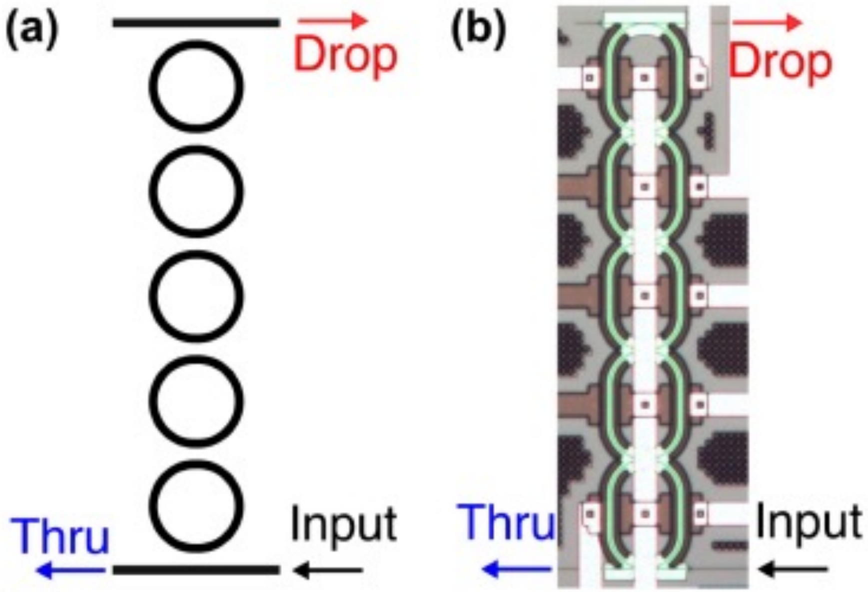
D. Perez et al., Nat Communications **8**:636 (2017)

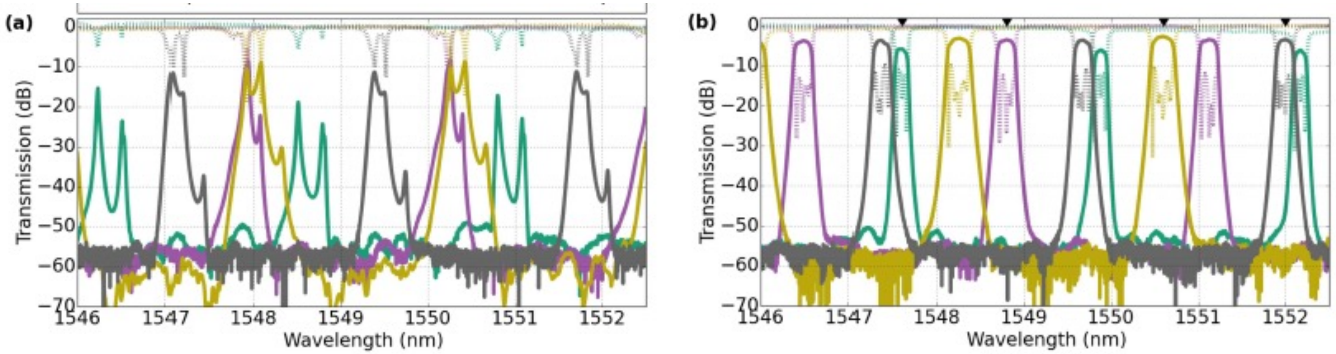


L. Zhuang et al., Optica **2** (2015)

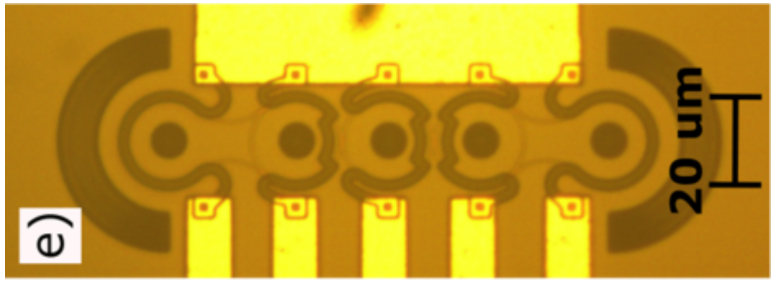
PICs: tuning and locking

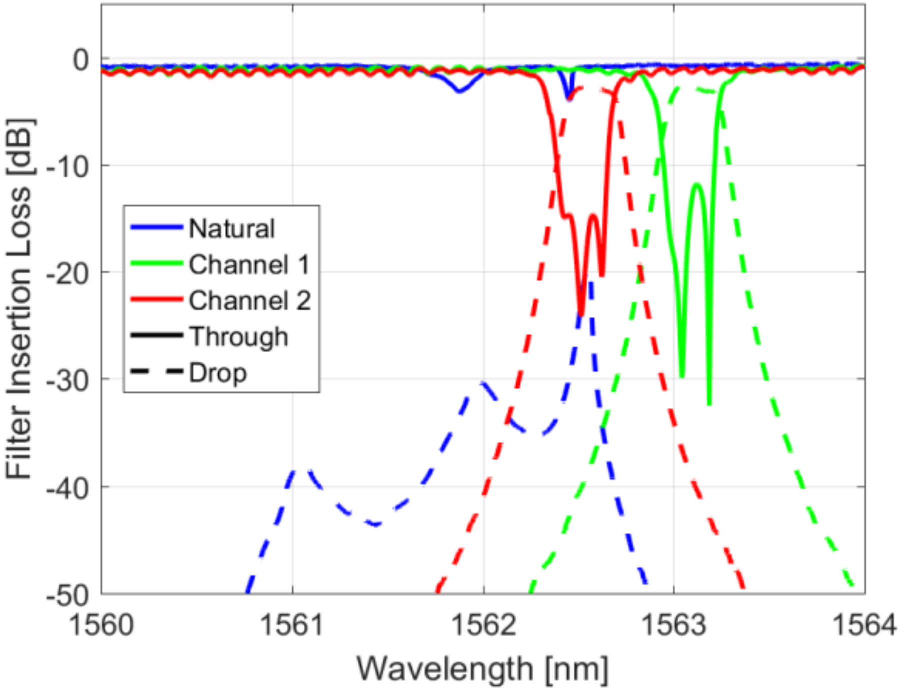
Need for automatic procedures for tuning and locking





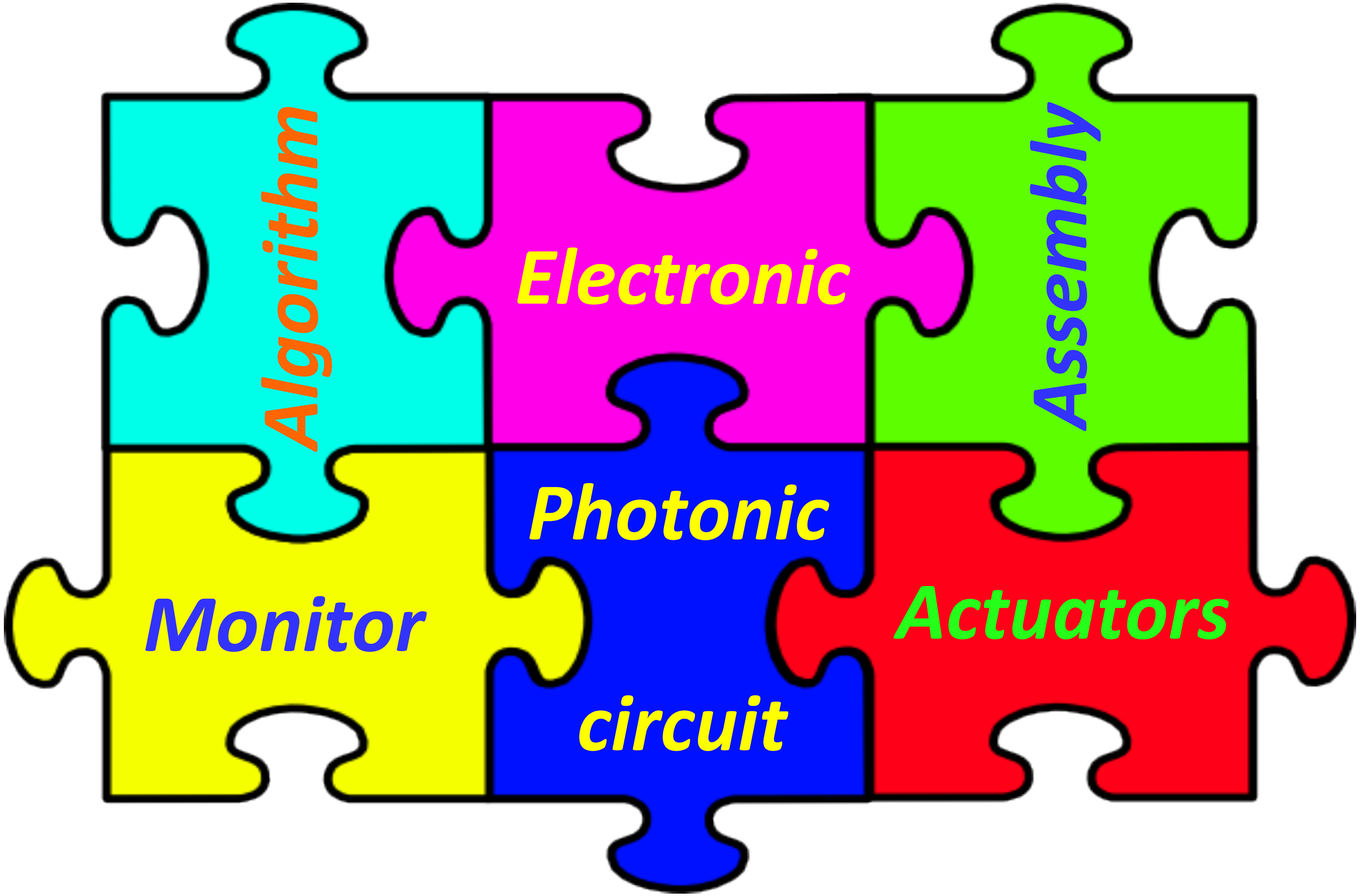
J. C. C. Mak et al. JLT 51(11), 2015





Automatic hitless reconfiguration of silicon photonics microring filters, F. Morichetti [10686-40]

The control layer



Feedback controlled VLSI photonics

OPTICAL PROBES

- Non-perturbative (= test-pin)

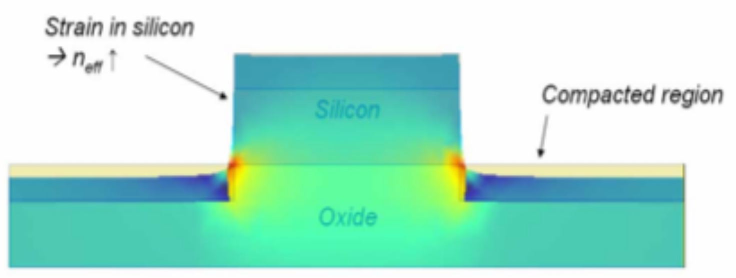
ACTUATORS

- **Tunable** ('fast') for tuning, circuit control and adaptive reconfiguration through feedback signals
- **Permanent,** self holding to avoid to feed actuators. For programmable photonics and post fabrication trimming (fabrication tolerances compensation)
- (**Non-**) **Reversible** for programmable photonics (only once by foundry and/or final users or re-programmable), trimming
- **Analog / Digital** - circuit control / switches
- **Amplitude / Phase**

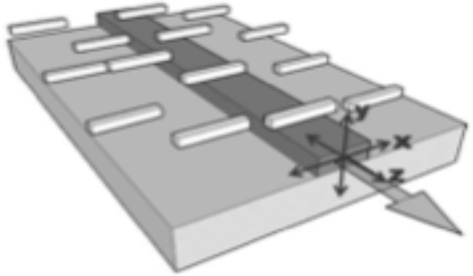
- Tuning /Trimming **STRATEGY** (**control layer**)

"Actuators" (for trimming) in literature

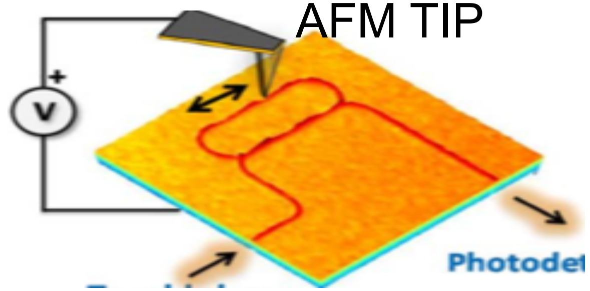
- *FIB:* C. Shu, 2003 (rib wg, birefringence, TE/TM coupling)
- *e-beam*: Ghent, 2008 (4.9 nm, Q decrease, strain in cladding)
- *nano-oxidation*: S. Mookherjea, 2011 (AFM tip)
- *Liquid crystals:* Gent, KIT, 2011, 2013 (80 V, 1 nm, complex)
- femtosecond "ablation": Vien Van, 2011 ($0.25 J/cm^2$, 10nm, reversible, low Q)
- *Polymer coating, UV irradiation*: some groups (stability, loss)



J. Schrauwen, OE 2008



Wout De Cort, JOSAB 2011

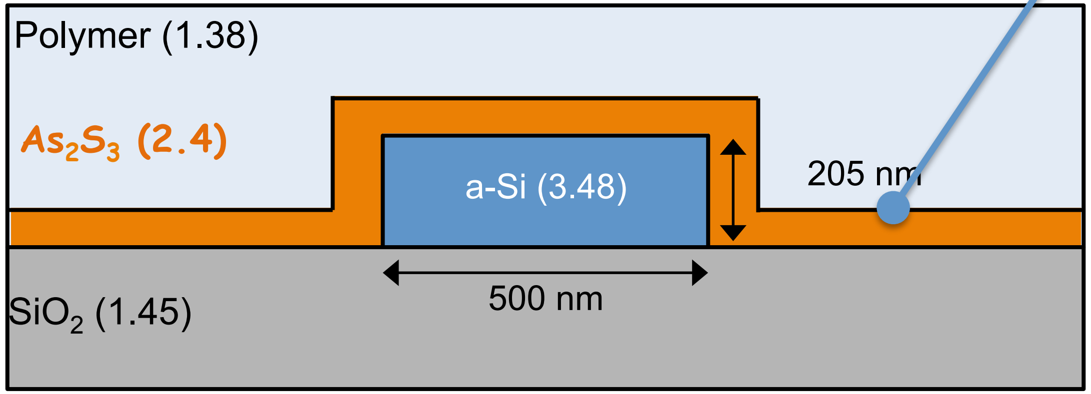


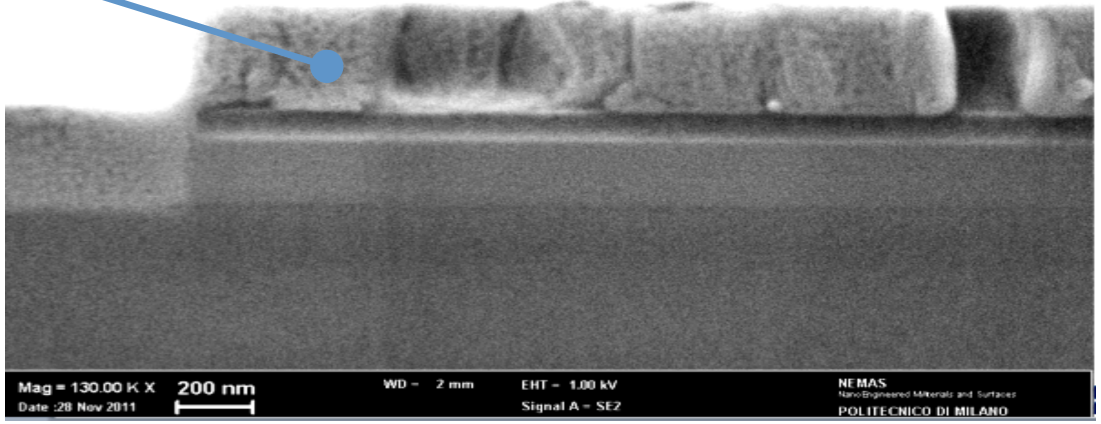
S. Mookherjea, OL 2011

An athermal and trimmable waveguide

SOI covered with Chalcogenide glass **As_2S_3**

Patent pending





e-beam lithography of an amorphous Silicon layer and As_2S_3 evaporation

Propagation loss: 3 dB/cm

As_2S_3 Band-gap wavelength ≈ 550 nm (green)

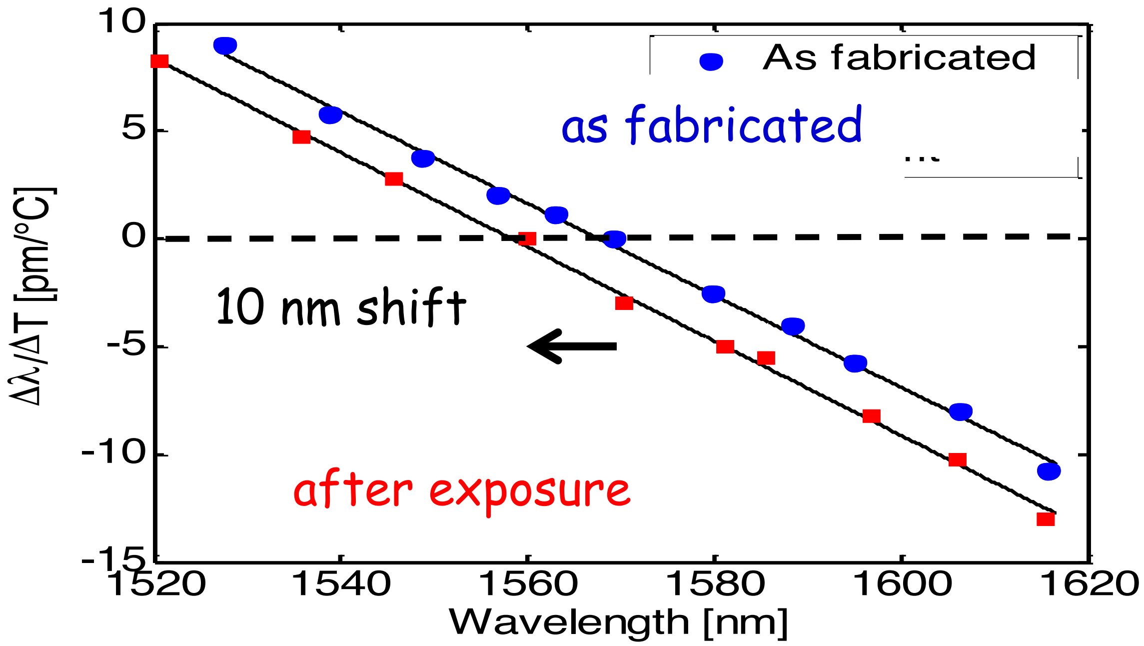
Fluorinated Polymer top layer (negative thermooptic coefficient)

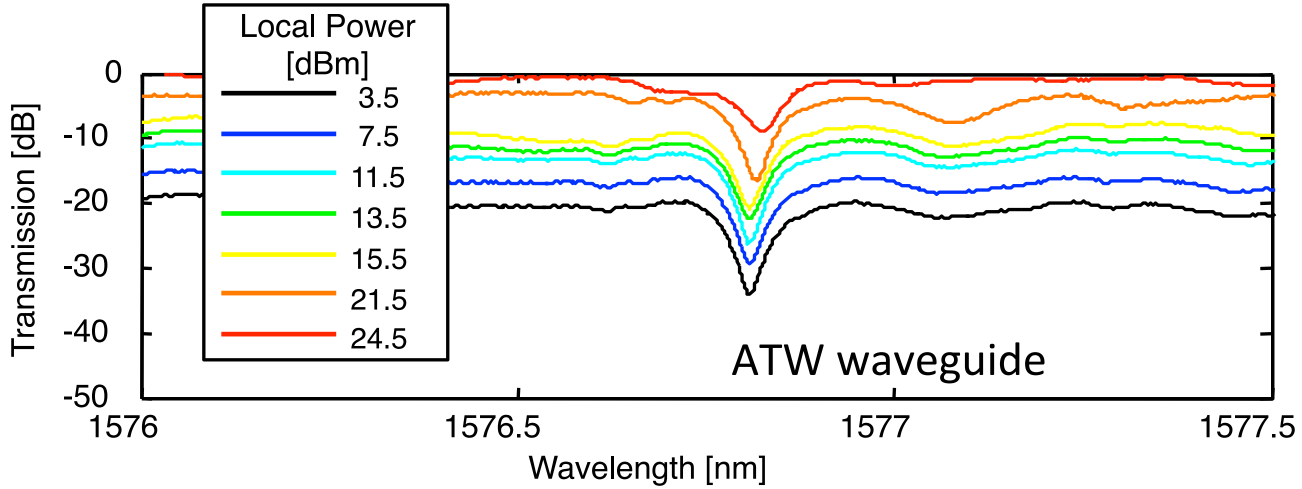
A collaboration between …

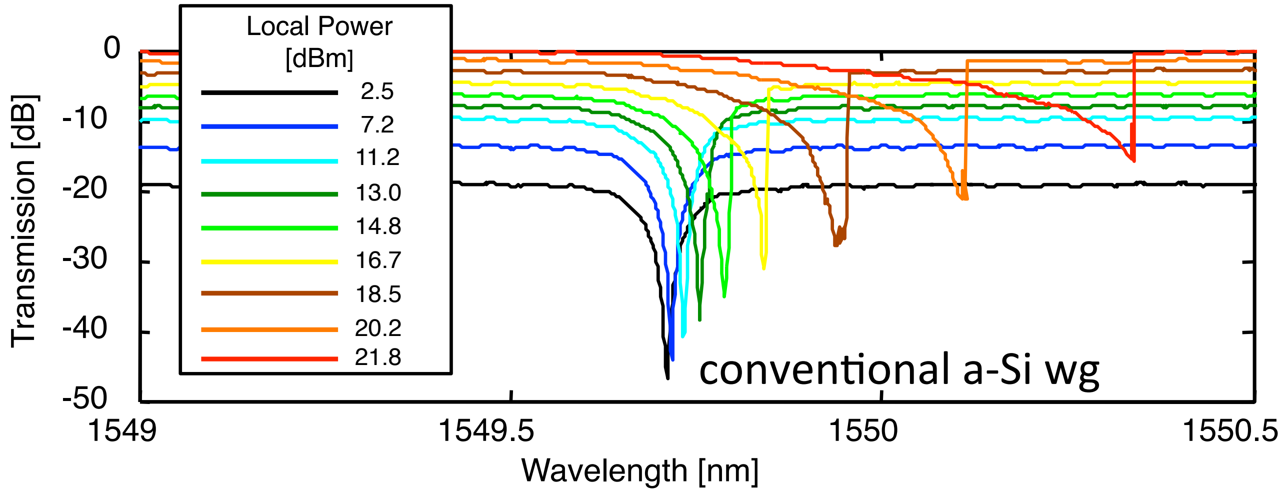
PoliMi Glasgow U. U. Delaware Clemson U. MIT

An athermal and trimmable waveguide

Temperature sensitivity





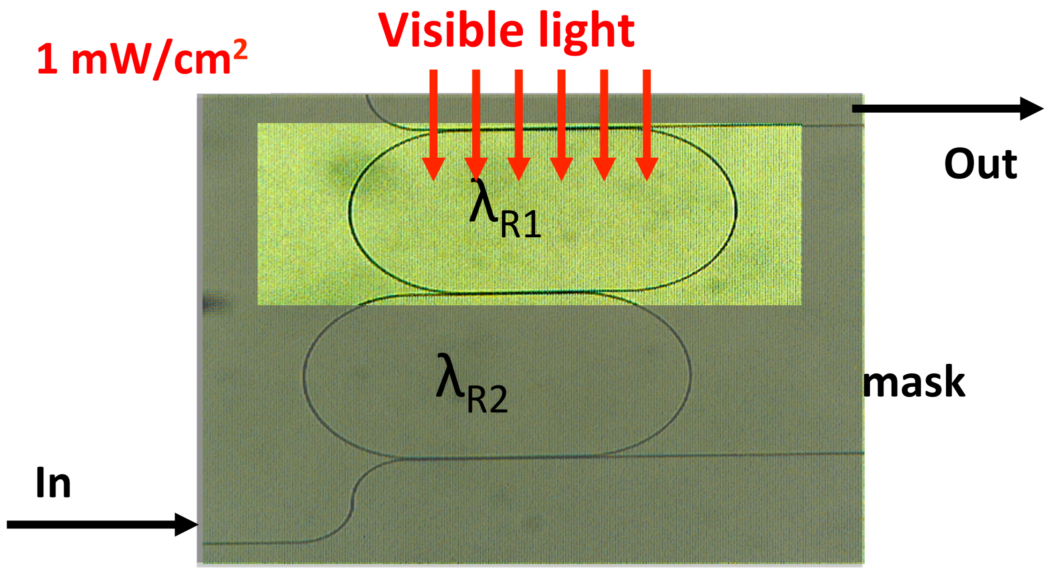


10X reduced temperature sensitivity across > 50 nm

(50 pm/°C in conventional Si waveguides)

10X reduced sensitivity to NL induced thermal shift

Trimming of fabrication imperfections



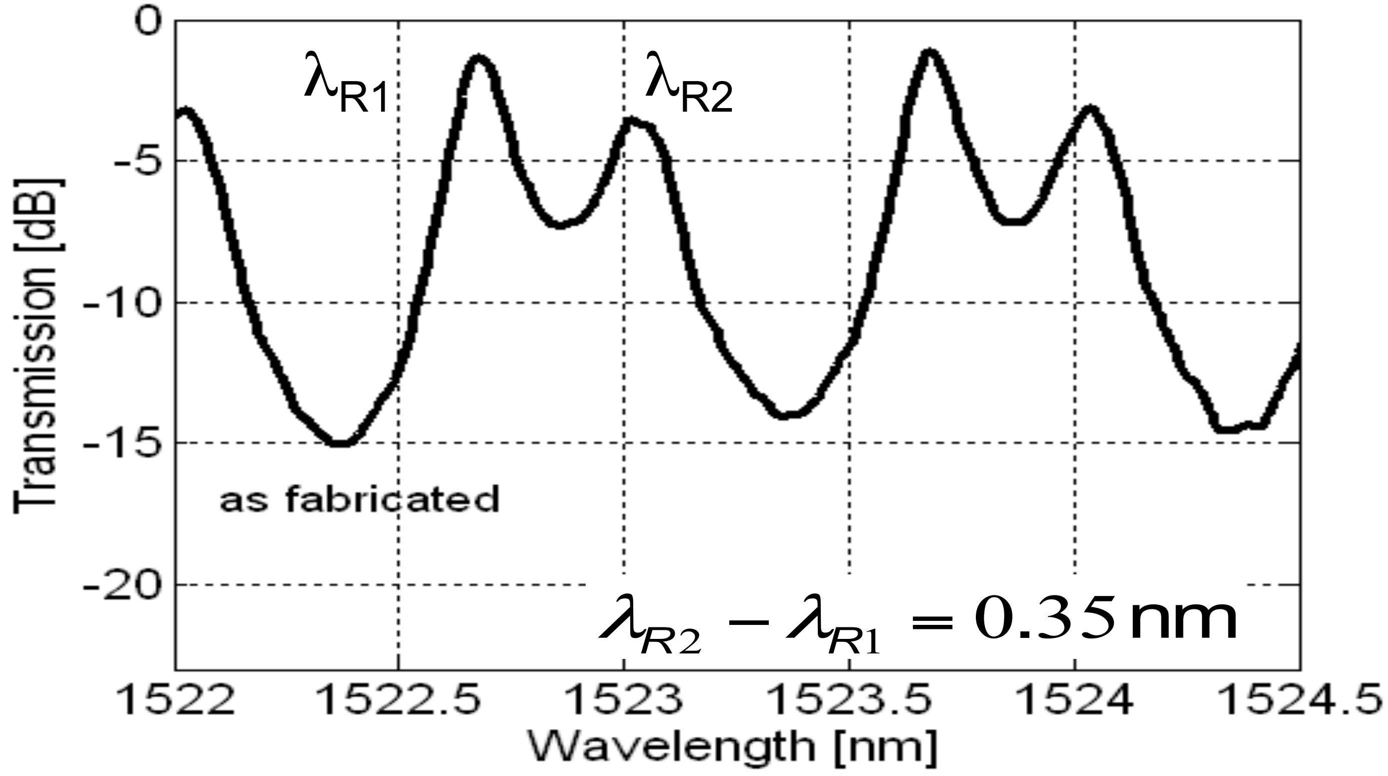
Halogen light source

Light trimming

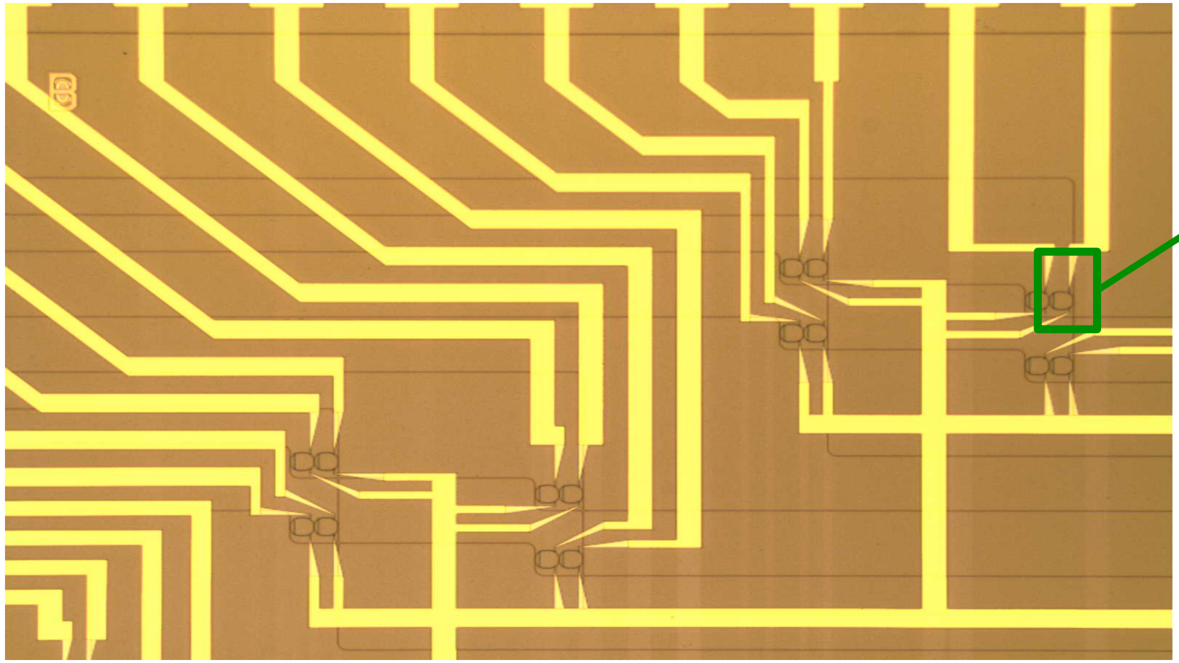
- Moving λ_{R1} only
- Permanent compensation of fabrication imperfections

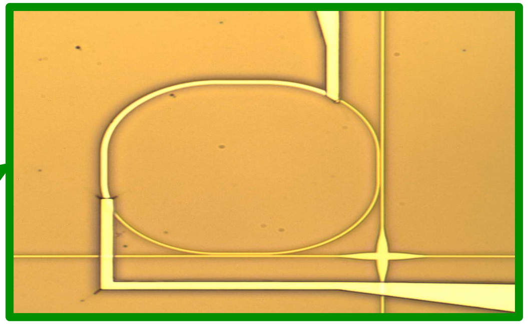
Double-ring filter

Radius = 100 μm
FSR = 130 GHz
Bandwidth = 32.5 GHz

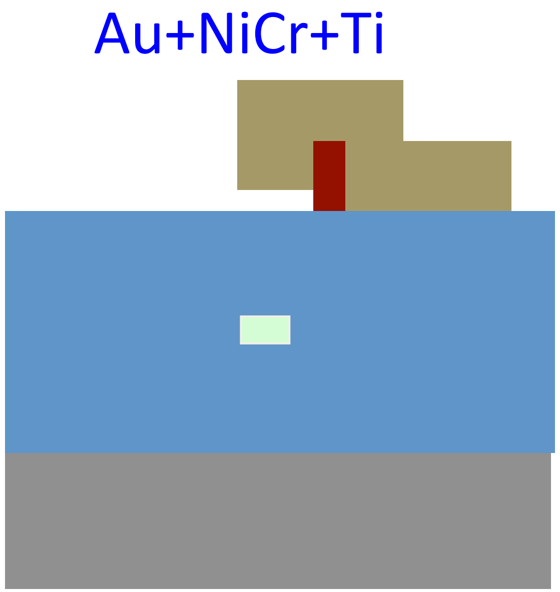


Heater: "The" actuator



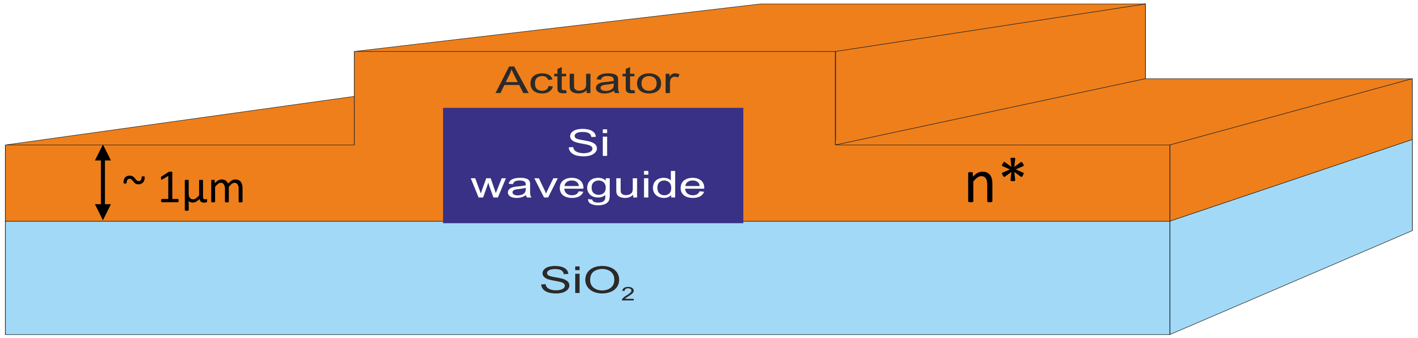


$$\Delta n = K \; \Delta T$$



	SiO_2	Silicon
Length	1-3 mm	10-50 μm
π shift	300-400 mW	10-20 mW
$\Delta n_{eff} / \Delta T$	$1{\cdot}10^{-5}$ °C^{-1}	$2{\cdot}10^{-4}$ °C^{-1}
Response time	1 ms	10 μs
Crosstalk	high	low

Actuators for Tuning, still a dream…



Light within the waveguide interacts with the actuator

The phase and/or intensity of the light can be influenced by changing the optical properties (n, k) of the actuator.

Complex refractive index: $n^* = n - i \cdot k$

Two different types of actuators

Intensity actuators

ON/OFF → loss = 0.1 - 0.25 dB

$$\Rightarrow \frac{\Delta k}{k} \geq 200$$

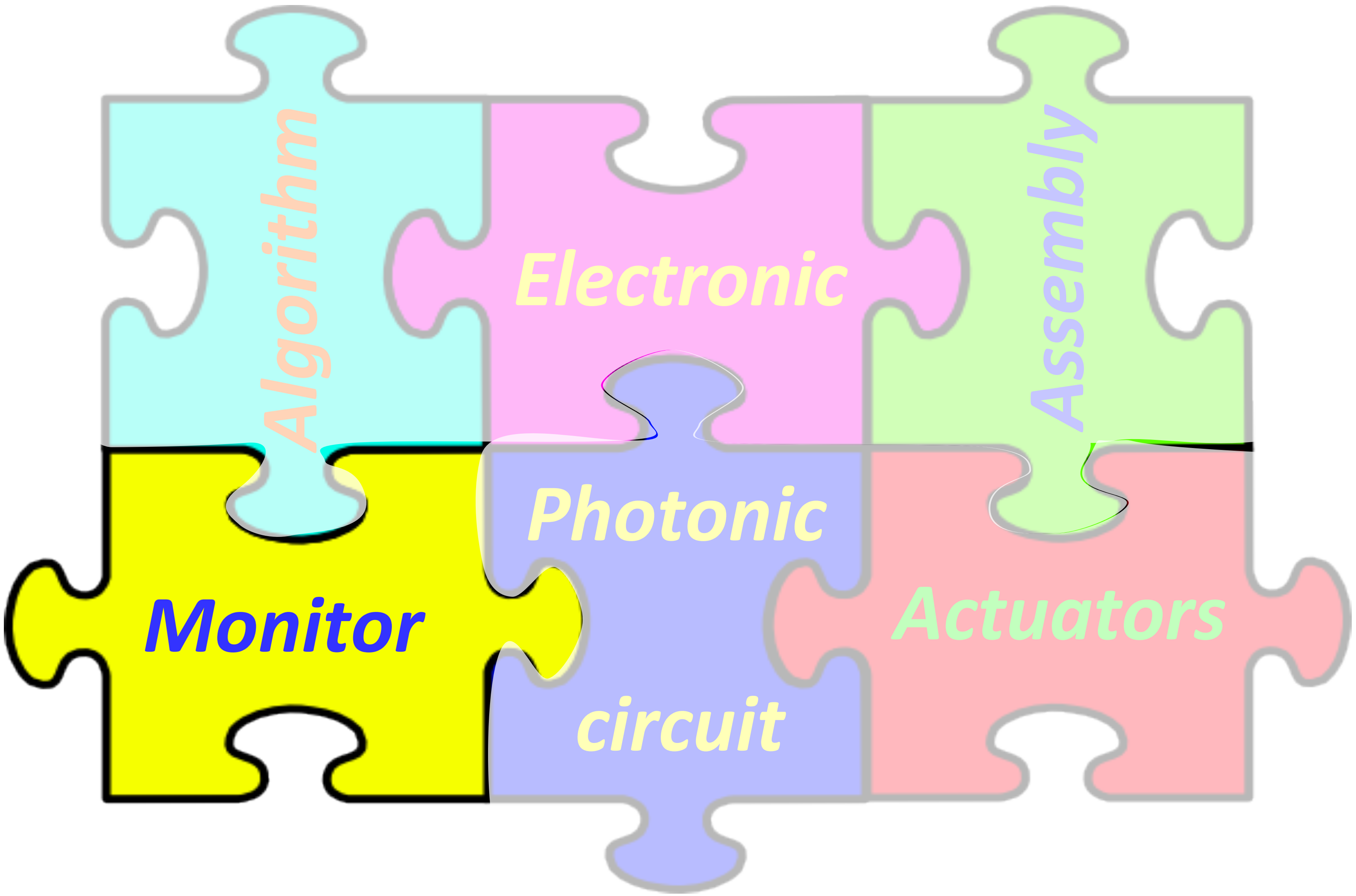
Phase actuators

ON/OFF → $\Delta n = \pi$

(large Δn, moderate Δk)

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

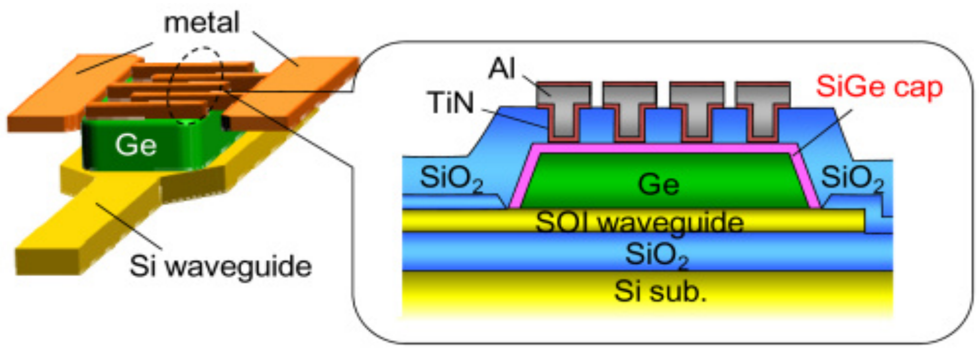
The control layer: monitor



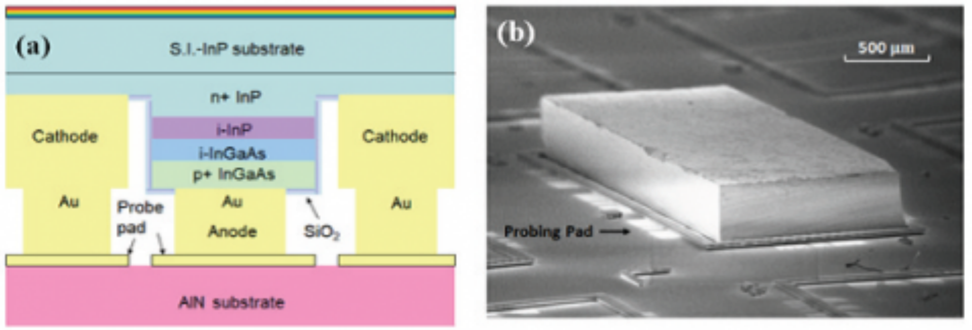
Light monitors: Ge, InP, hybrid, monolithic...

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

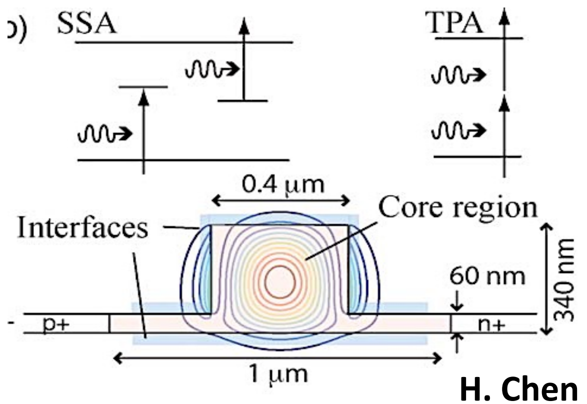
Ge on Silicon



III-V compounds

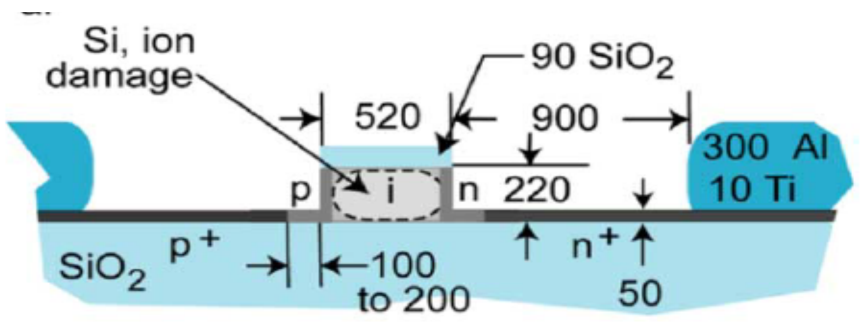


Silicon itself can be used for light detection in the near-IR



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

Surface state absorption (SSA) PDs
Photogeneration due to defect states at the edges of a c-waveguide (symmetry breaking & dangling bonds)



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

Defect State Absorption (DSA) PDs
Photogeneration by ion implantation into the Si lattice

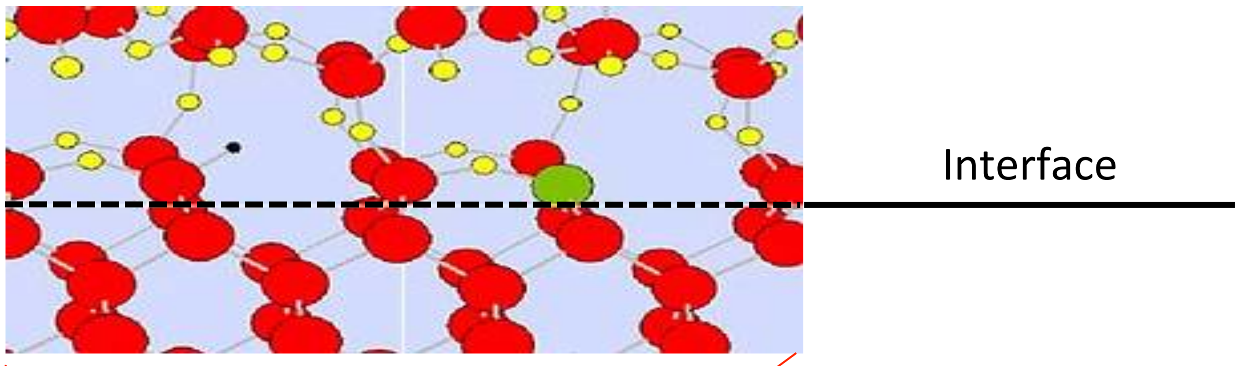
- λ-range 1270 to 1740 nm, bandwidth > 20 GHz
- exploited also in carrier depletion silicon modulator

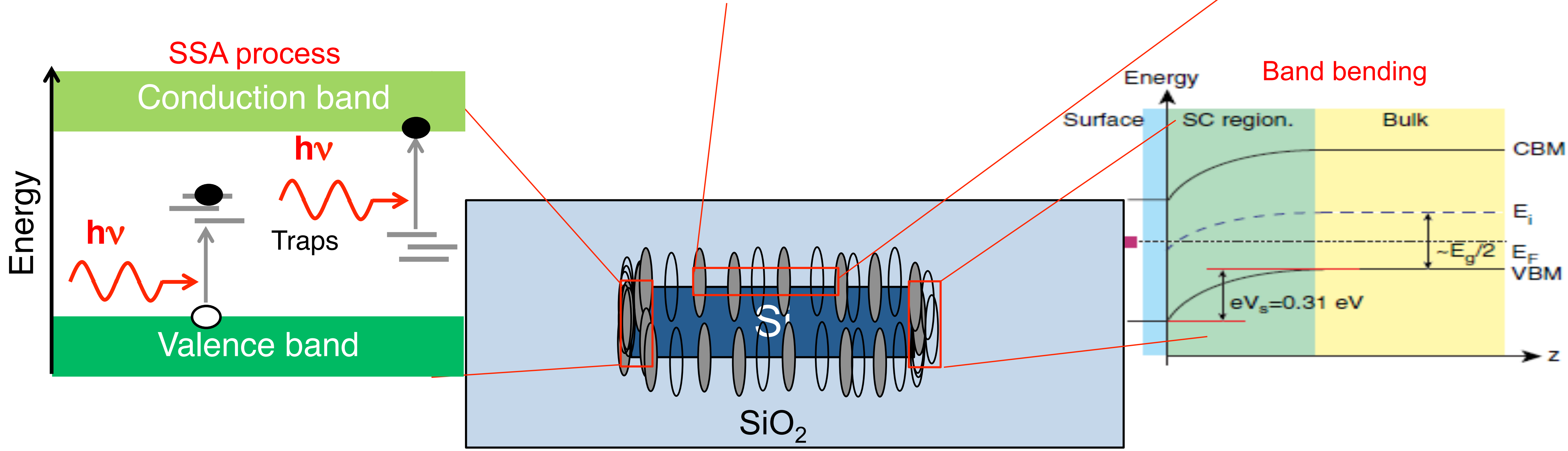
Light-waveguide interaction

- *Surface State Absorption*

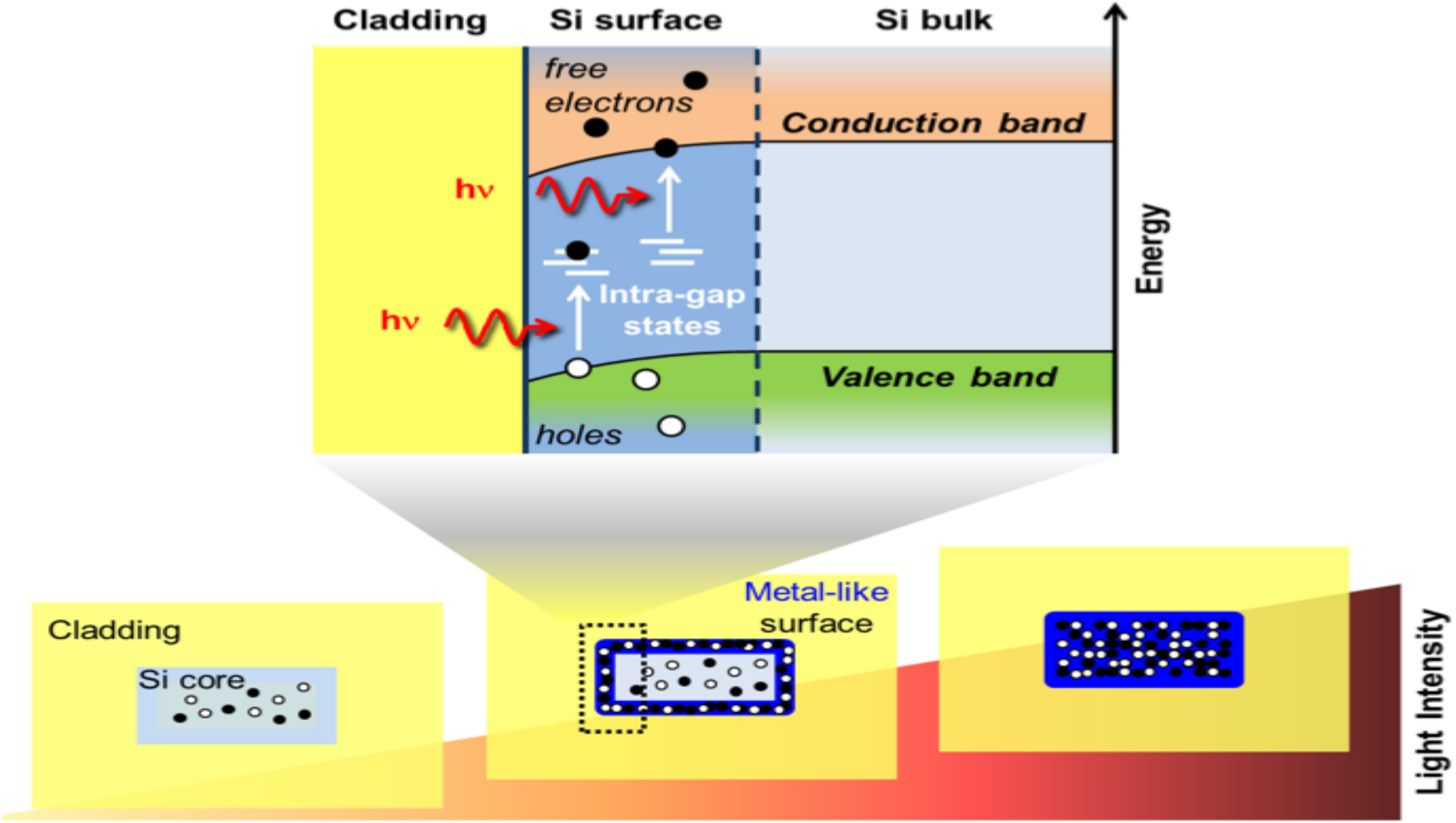
- Surface states are located typically within the first two/three silicon atomic layers (≈ 1 nm)

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





Light dependent waveguide surface

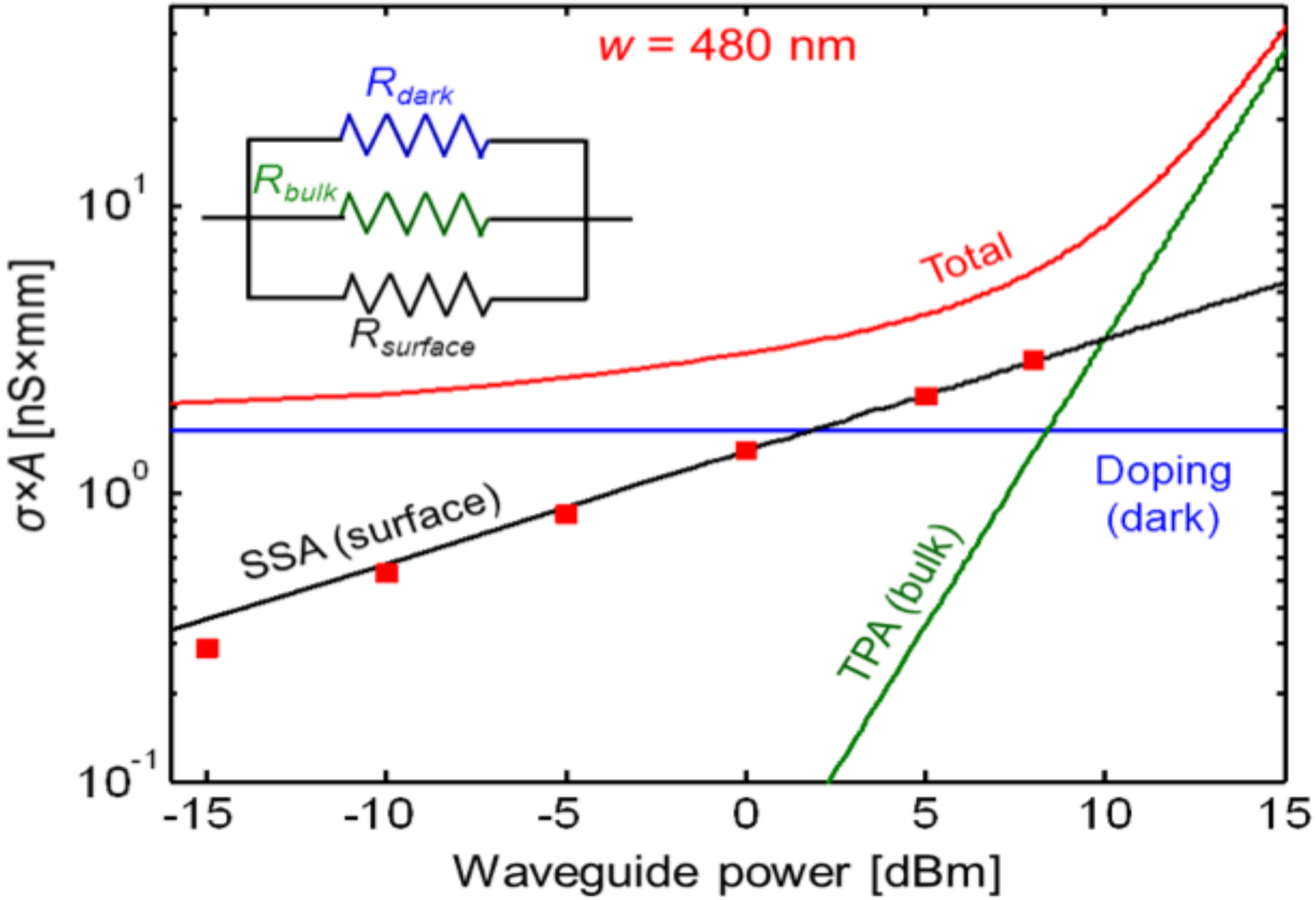


Low light intensity

Moderate light intensity

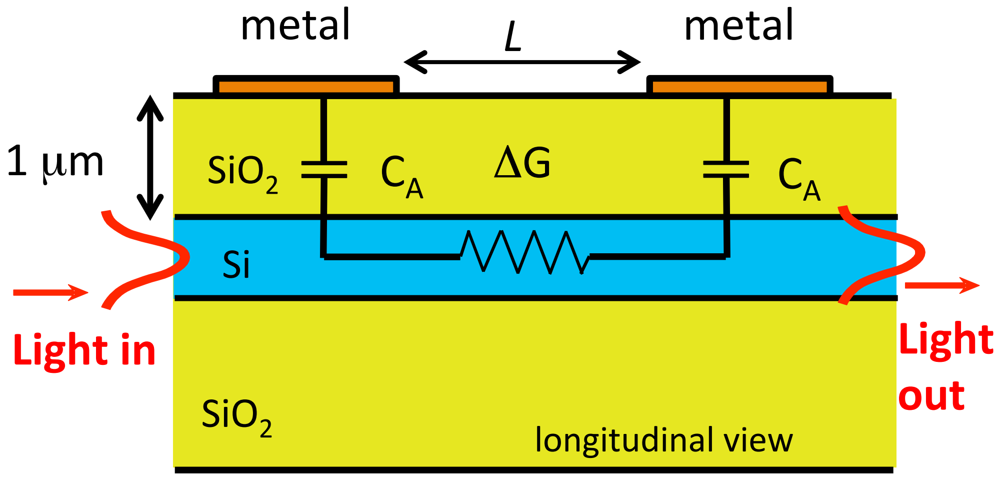
Large light intensity

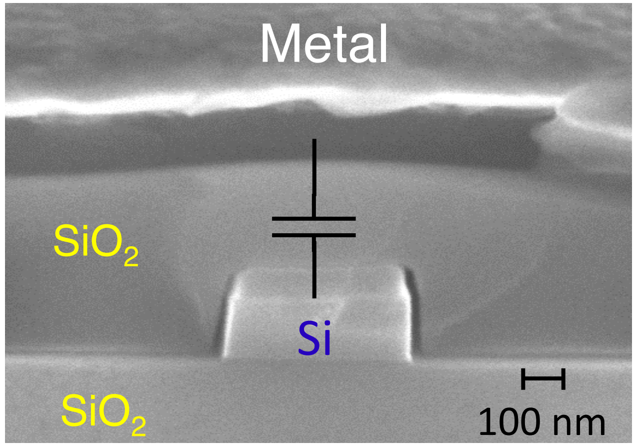
Waveguide electrical conductivity



The CLIPP concept

ContacLess Integrated Photonic Probe (CLIPP)





Contactless capacitive access to the waveguide

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

Light dependent conductance variation

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

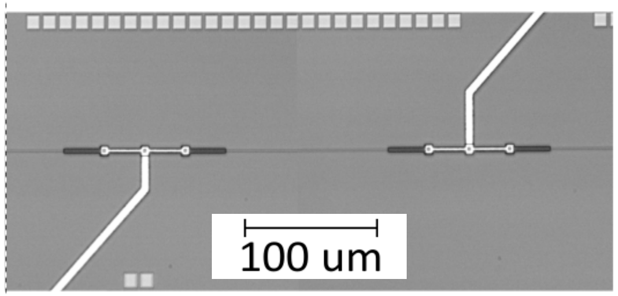
Free carriers generated on the surface by SSA

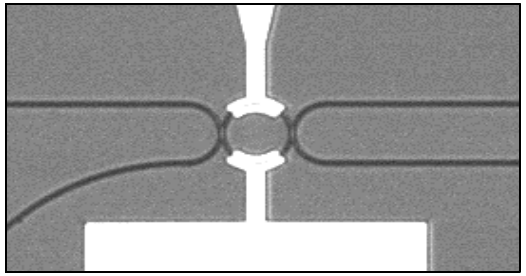
Si conductivity change induced by light

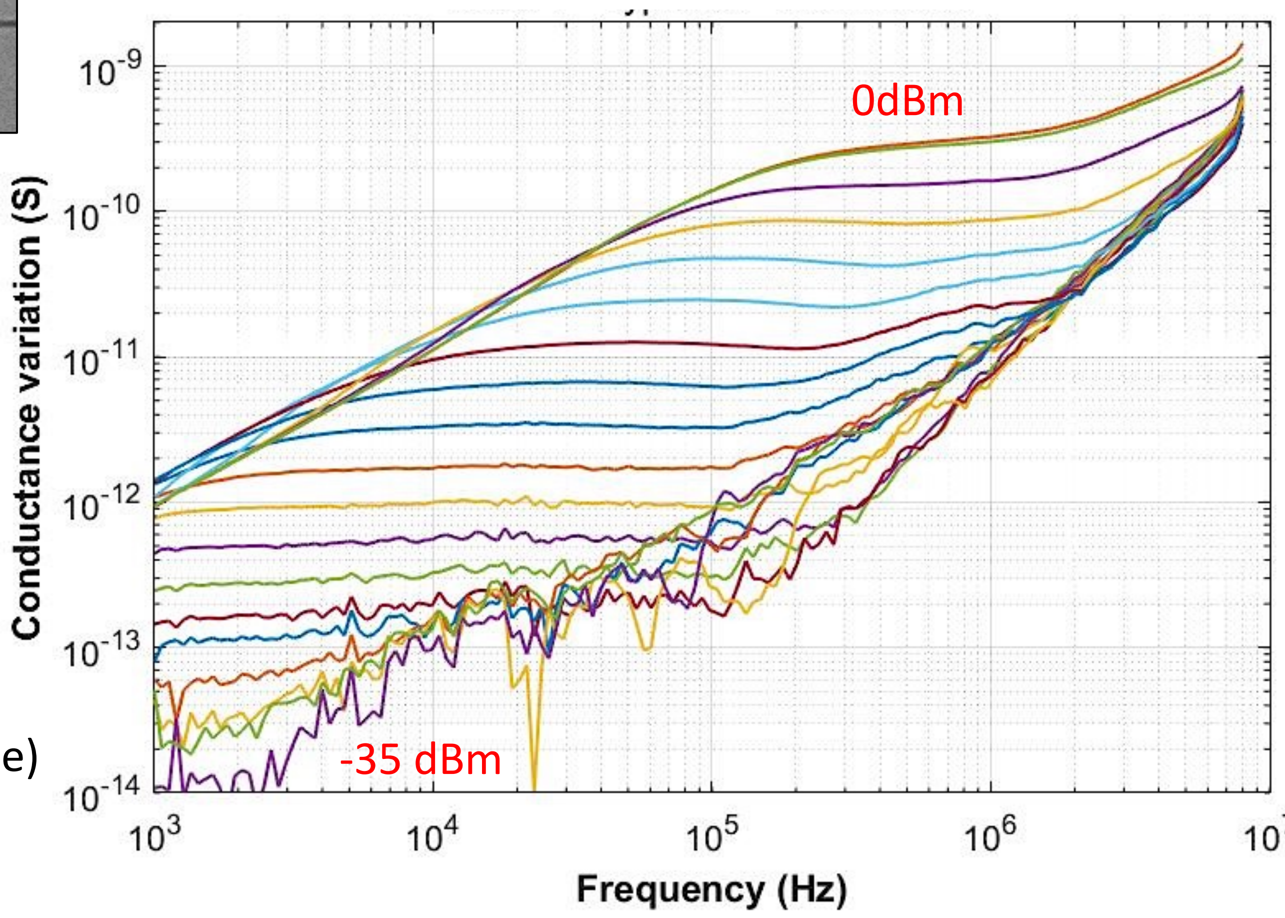
Carrier mobility is typically lower on the surface compared to the bulk

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

CLIPP performance



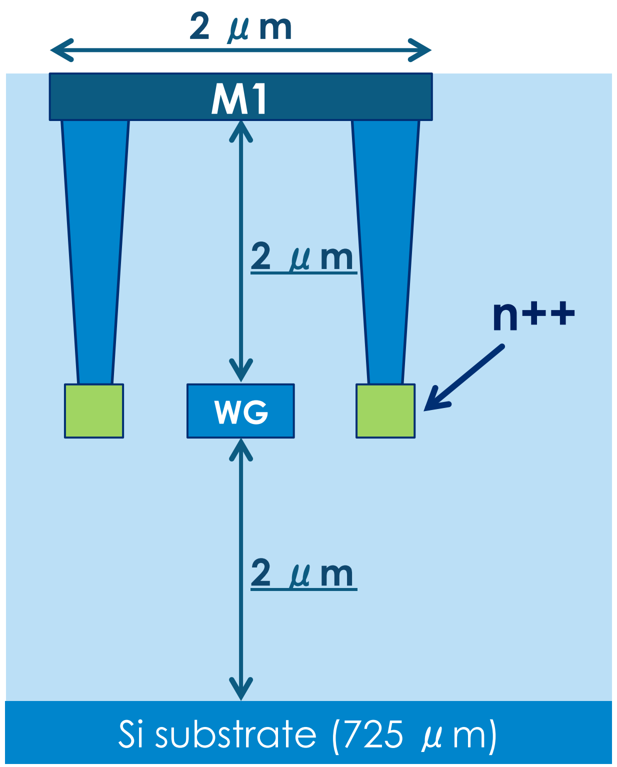




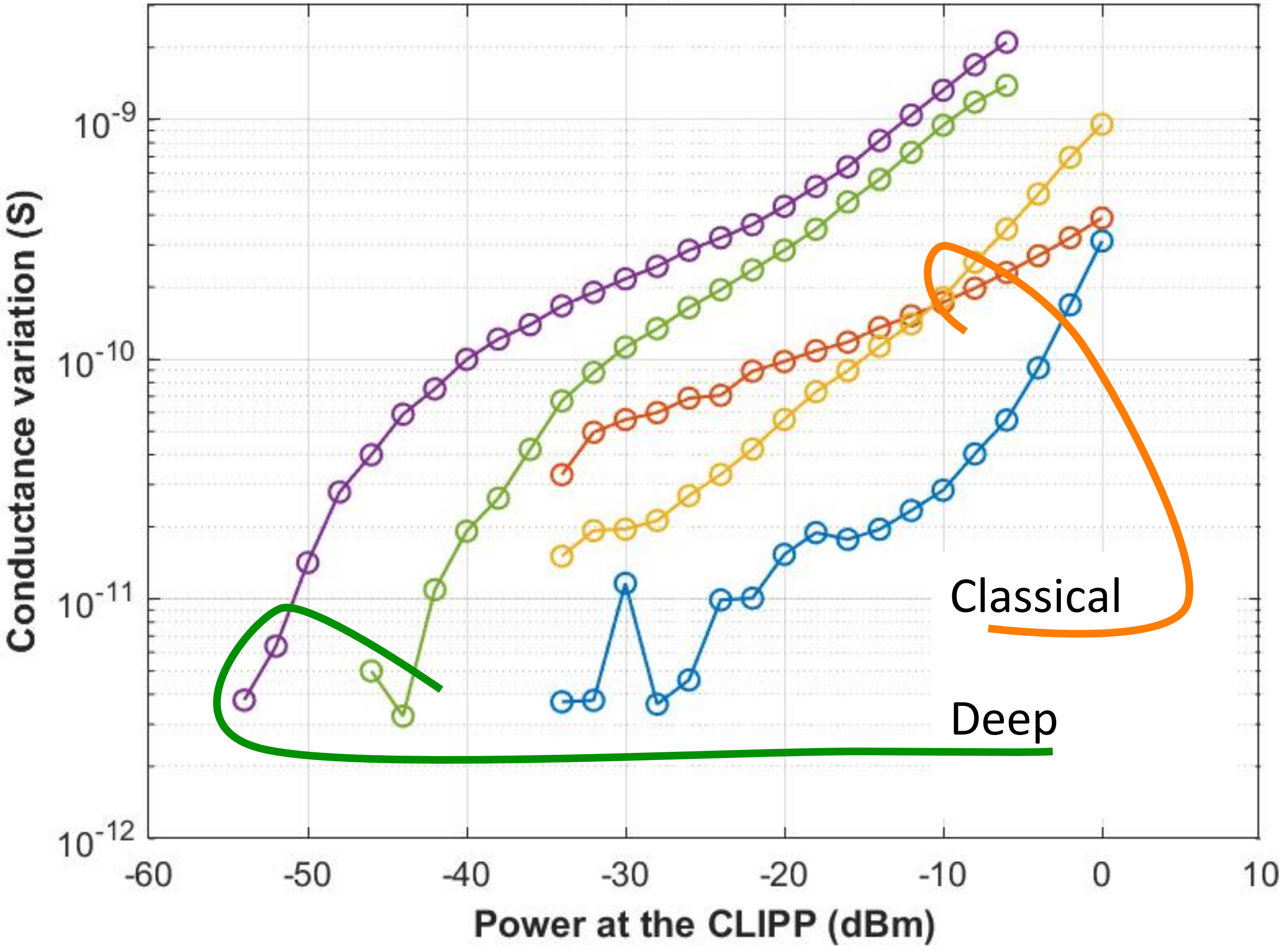
Performance match monitoring requirements:

- 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 Deep CLIPP

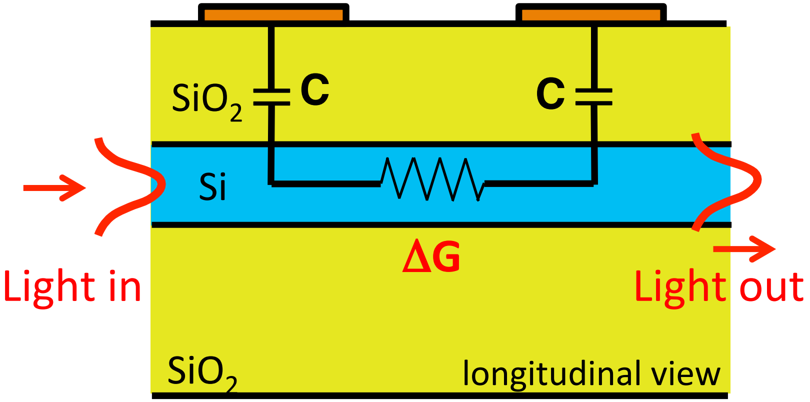


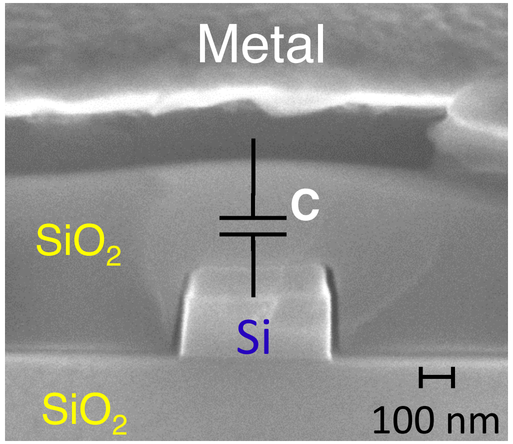
Sensitivity record with deep CLIPP



A transparent detector: the CLIPP concept

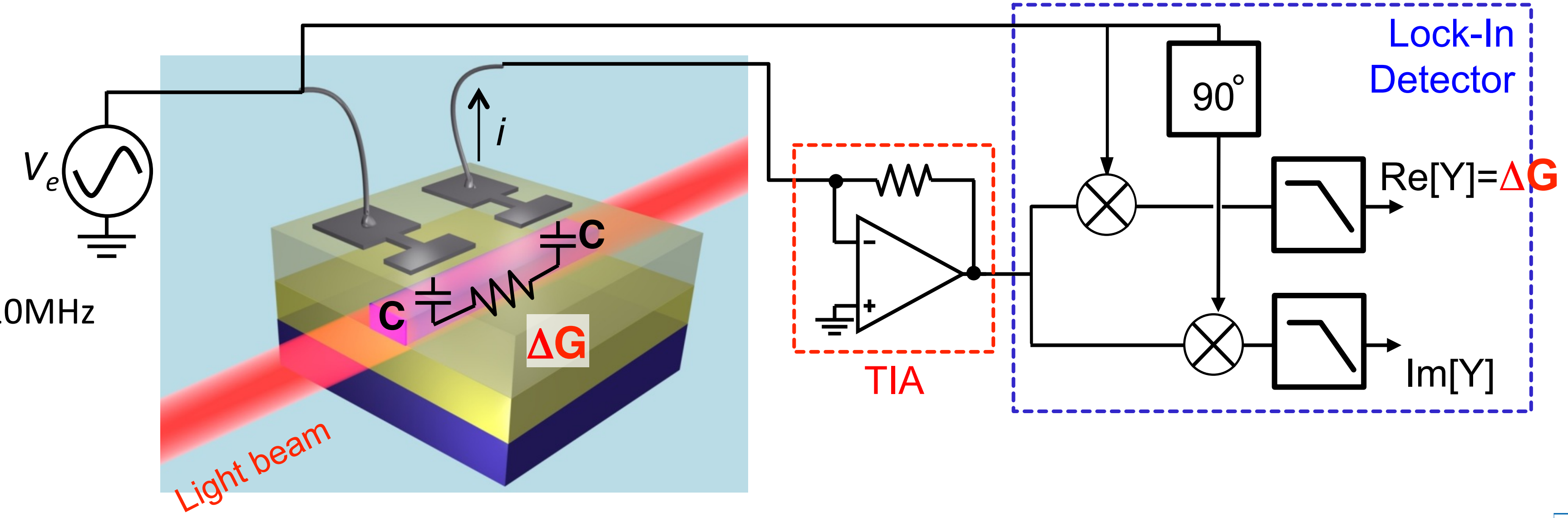
ContacLess Integrated Photonic Probe (CLIPP)





Contactless capacitive access to the waveguide

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

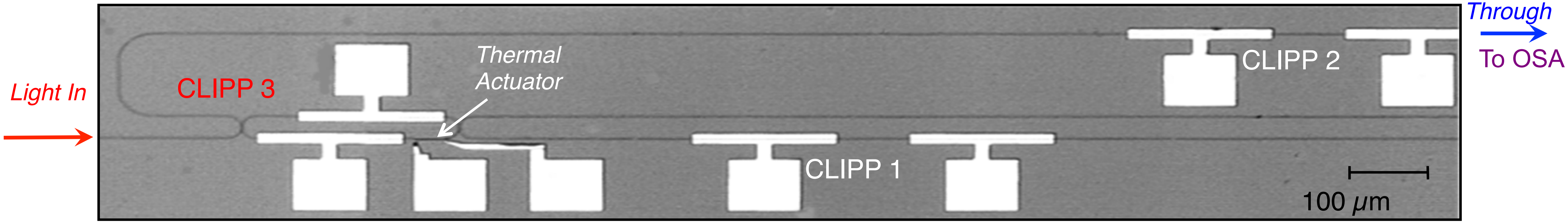


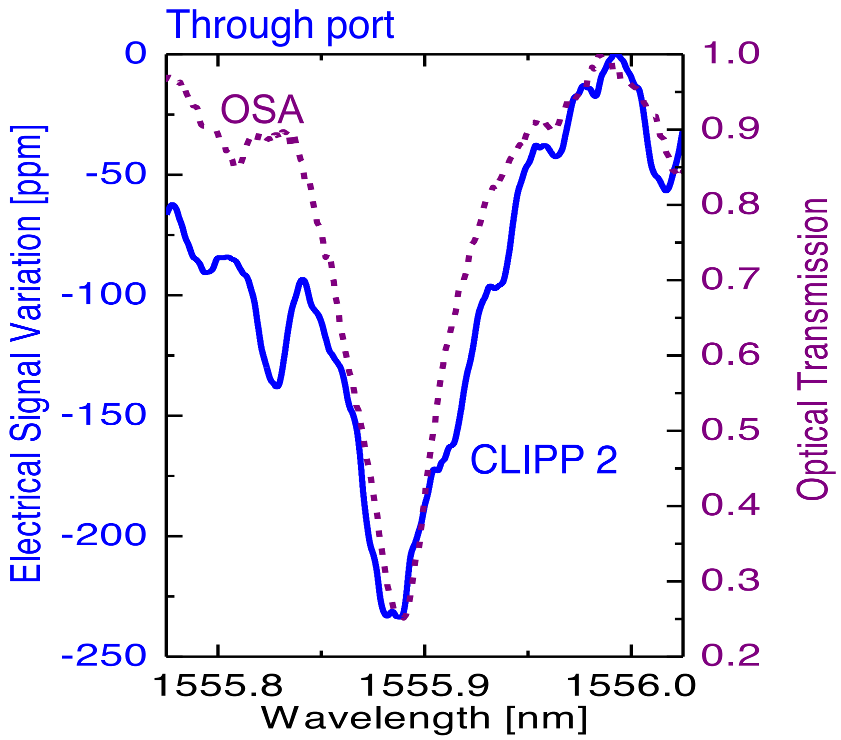
V_e = 1 V
f_e = 10kHz - 10MHz

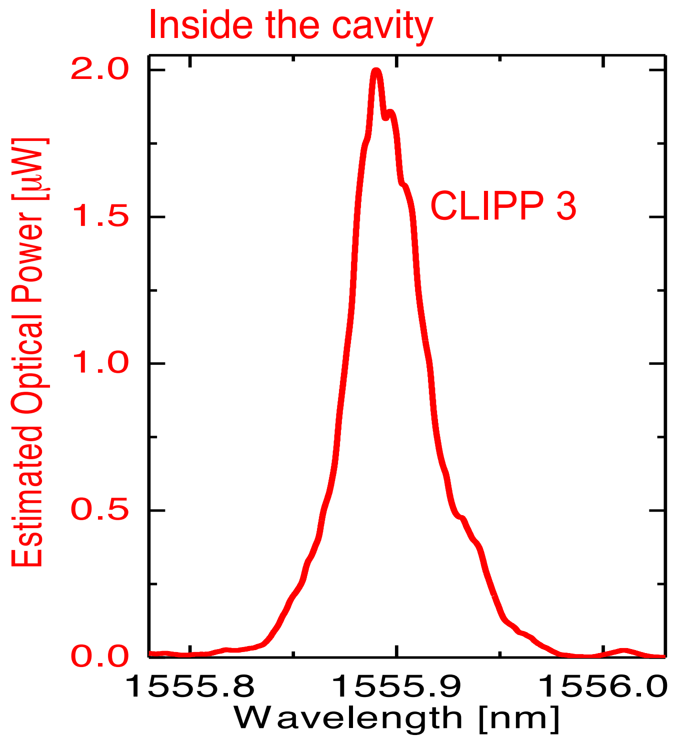
S. Grillanda, Nature Communications 6, 8182 (Sept. 2015)

F. Morichetti *et al.*, JSTQE 20(4), 2014
Stalking light, Nature Photonics Highlights 2014

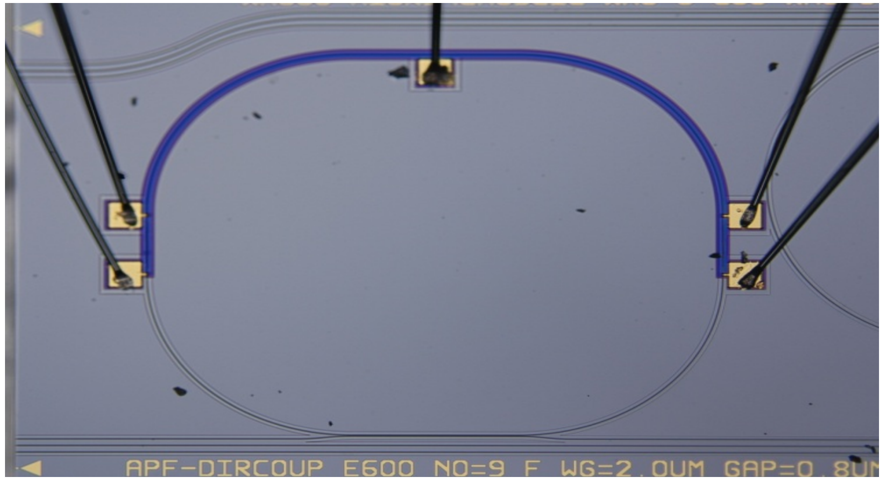
Multipoint on-chip monitoring



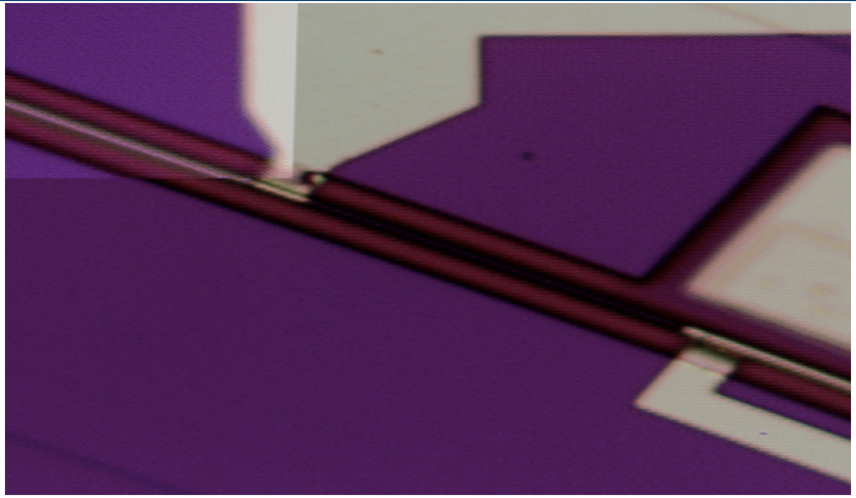




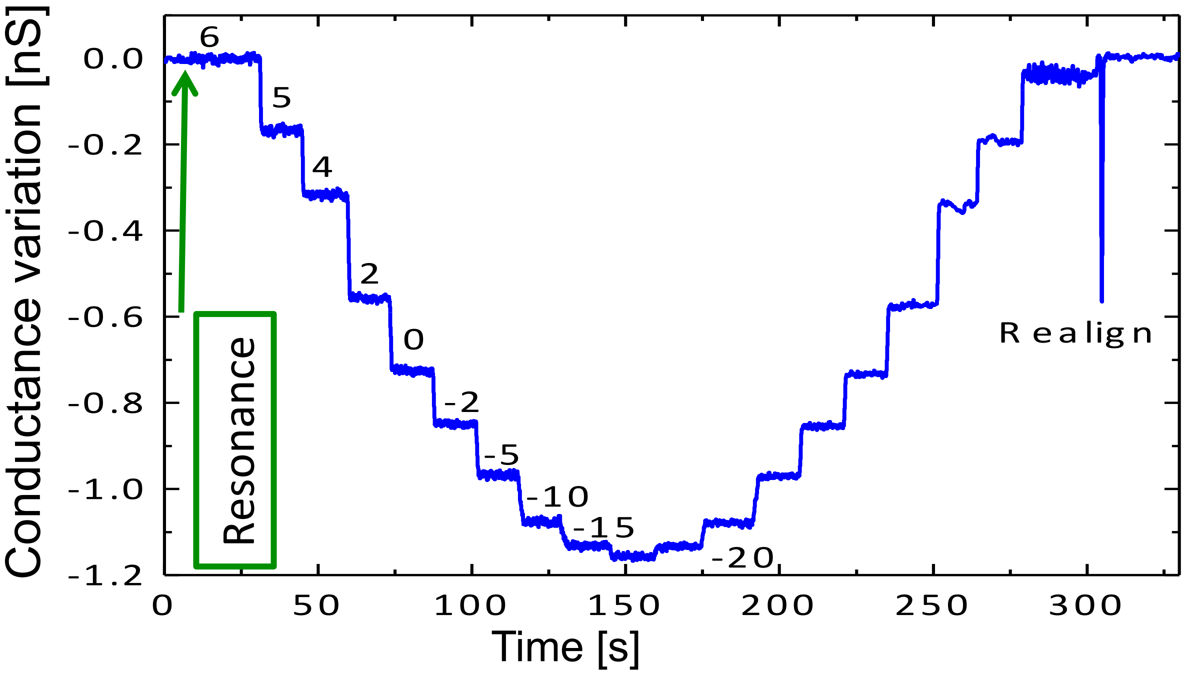
Indium Phosphide

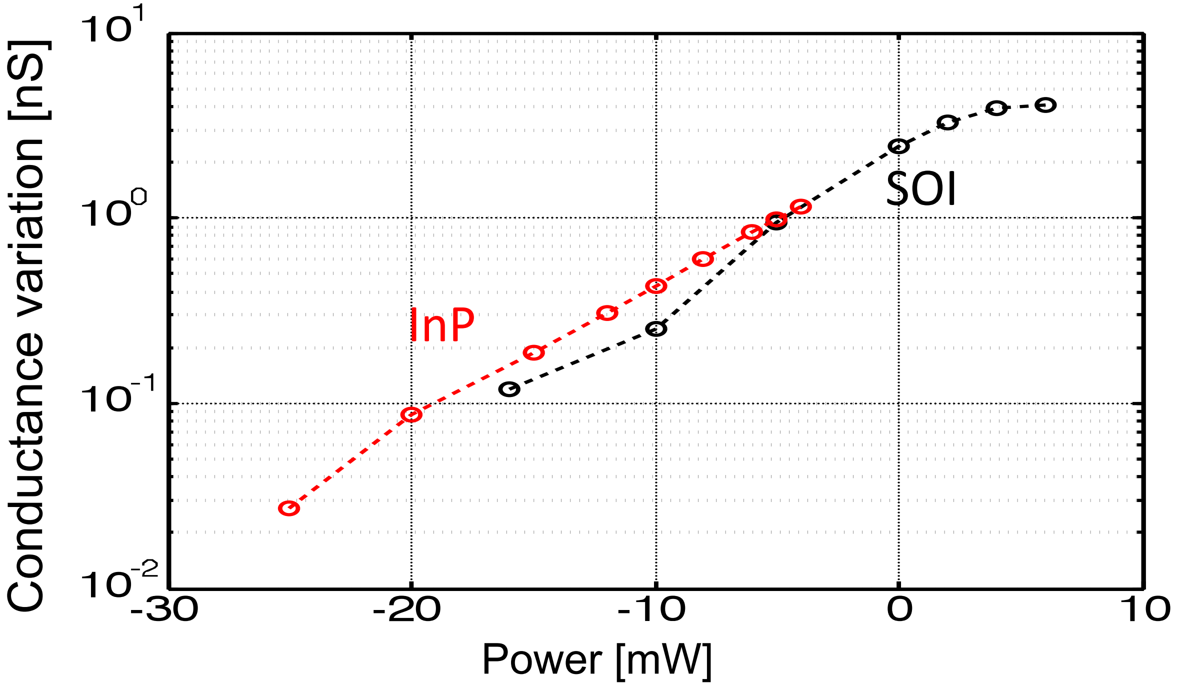


HHI InP Ring Resonator

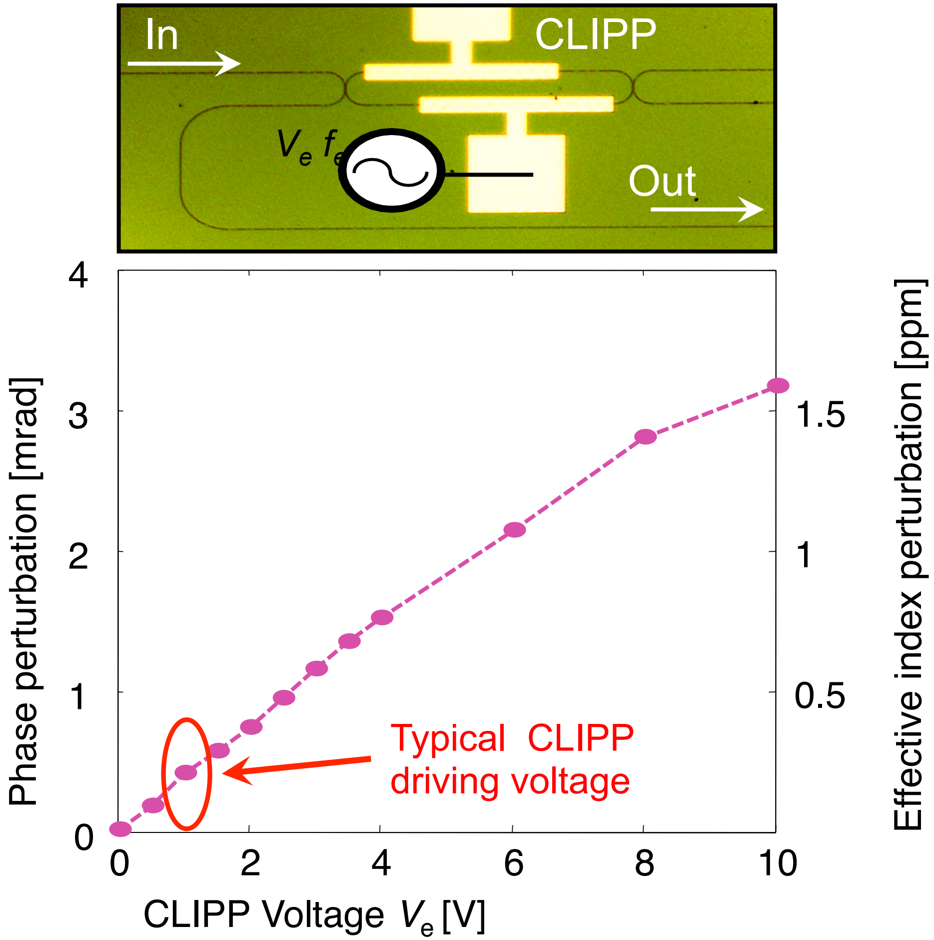


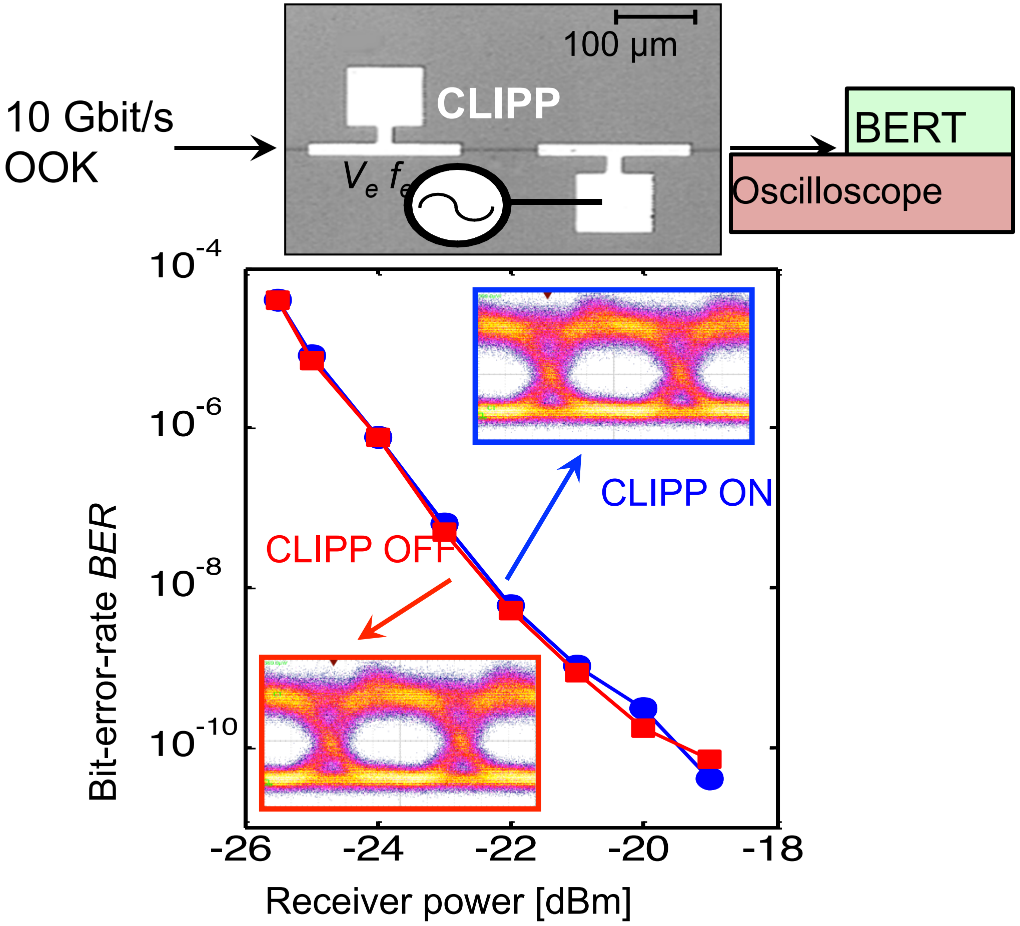
Oclaro InP Straight Waveguide





What does non-invasive mean?

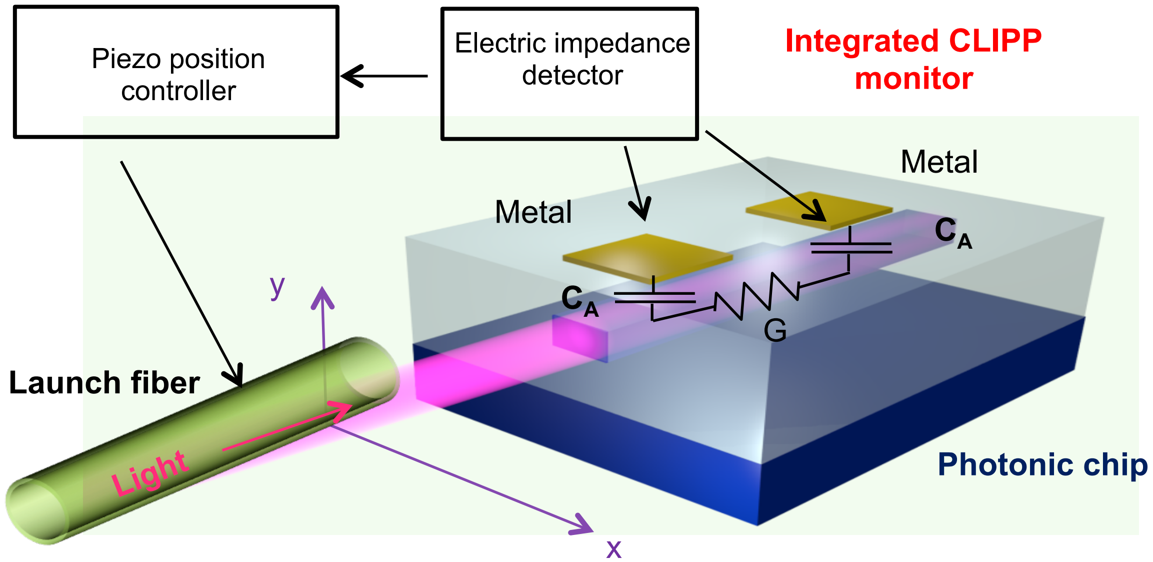


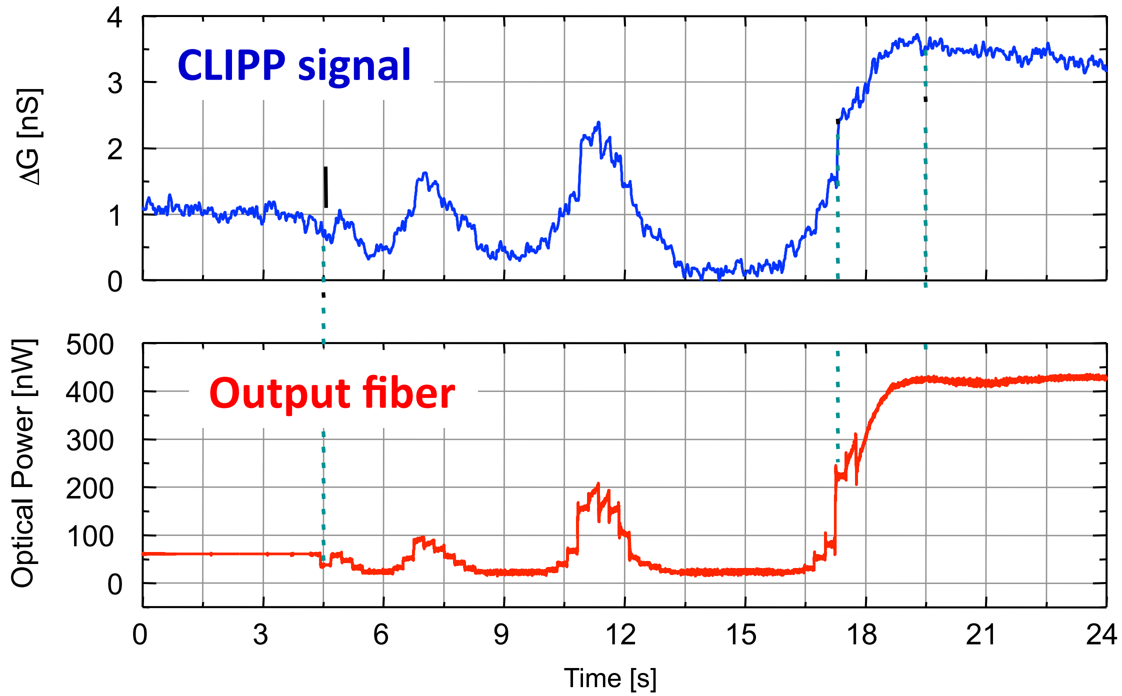


- Tiny resonant wavelength shift (55fm or 7MHz)→negligible for resonators with Q up to 10^6
- Effective index perturbation **< 0.5 ppm** (comparable to **3 mK** thermal fluctuation)
- **No appreciable penalty on the quality of transmitted signals!**

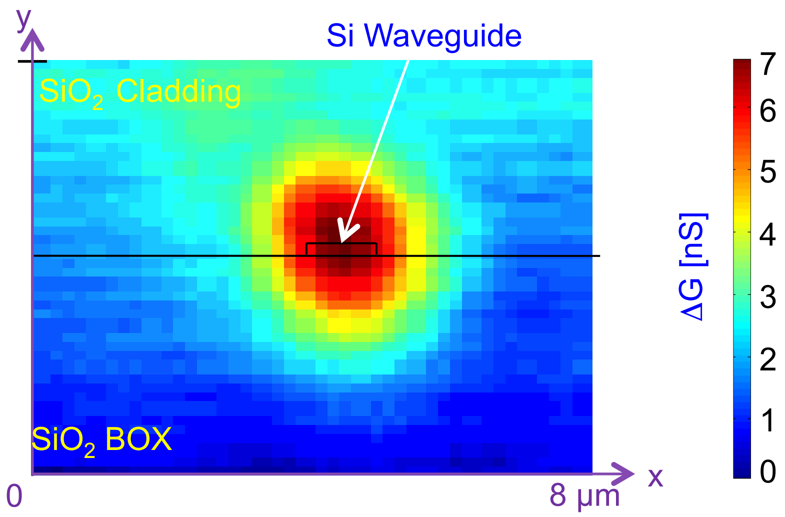
CLIPP assisted automated fiber alignment

patented





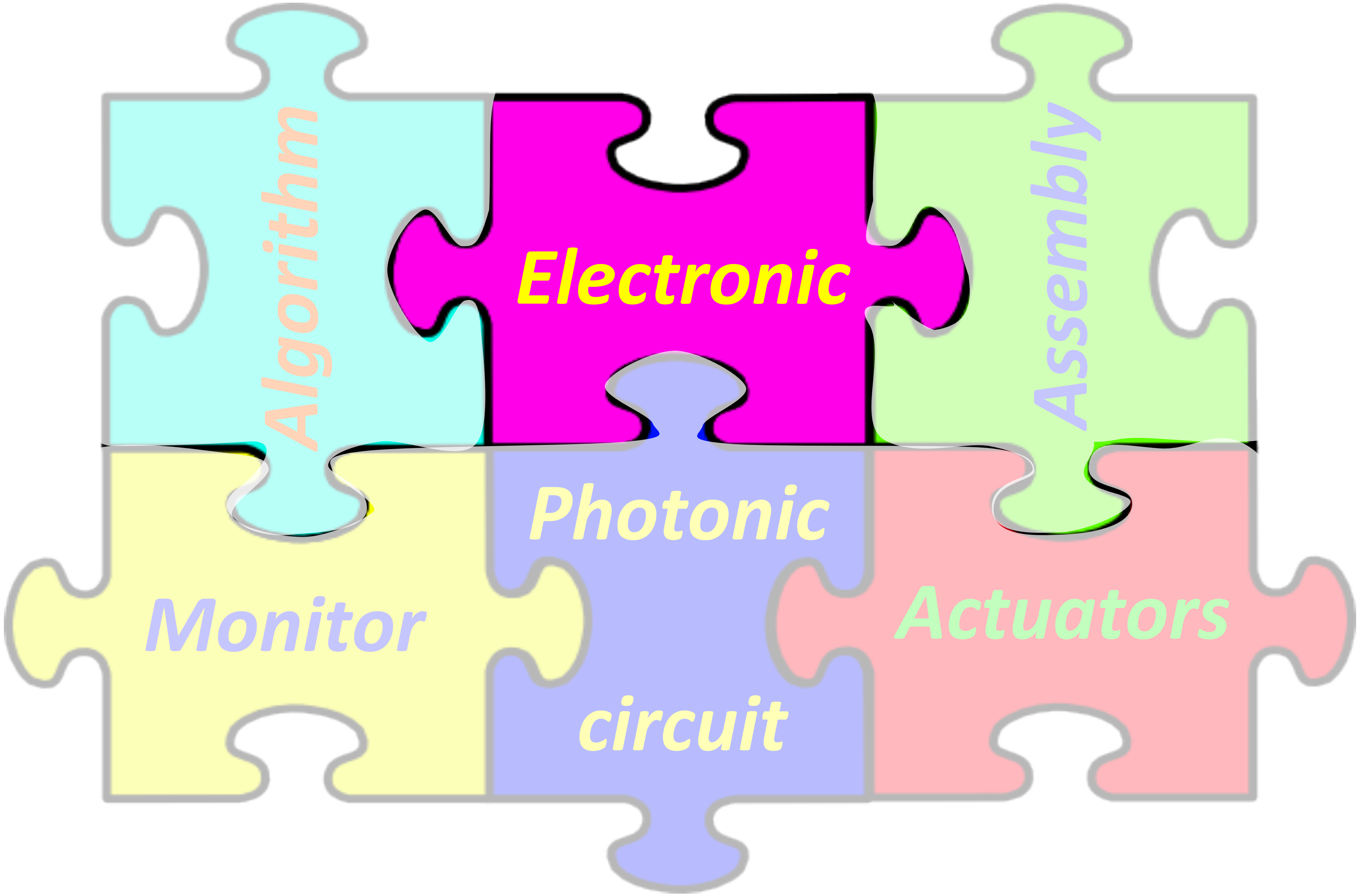
Map of the fiber-to-waveguide coupling



- No need for an output collection fiber
- Light coupling independent of the PIC integrated onto the chip
- Compared with tap detectors is completely transparent when switched off
- Suitable also for grating coupler alignment

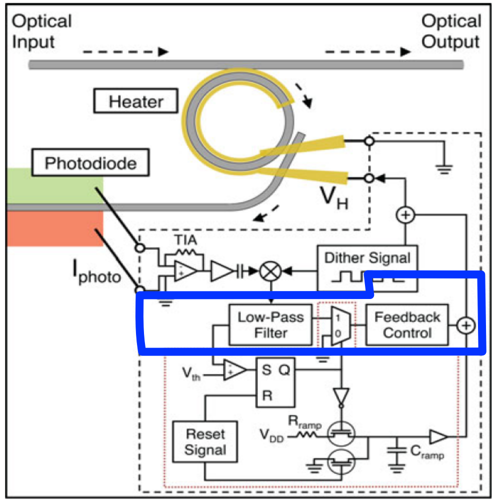
M. Carminati et al., PTL, PP, 99, Dec. 2014

The control layer: electronic



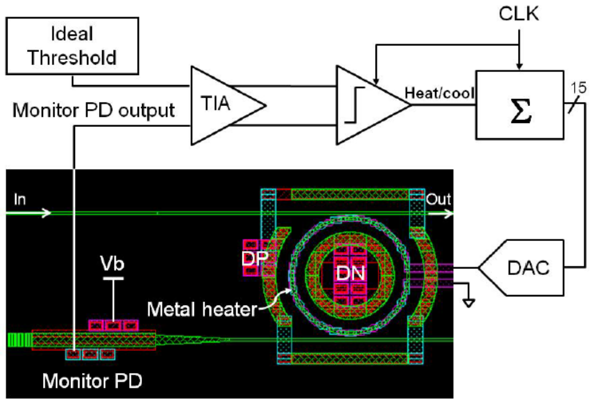
The control layer from literature

Dithering, analog,
Columbia Univ. 2014



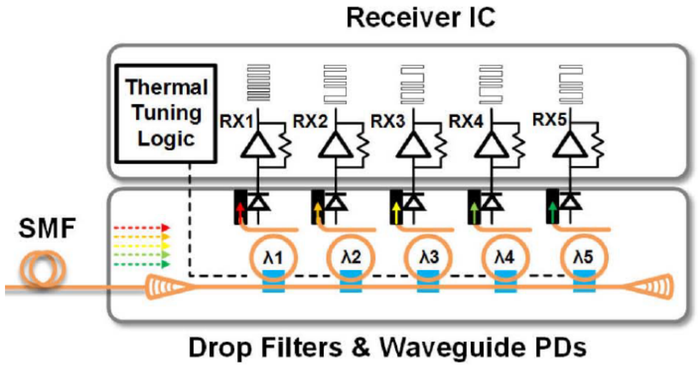
K. Padmaraju, et al, JLT 32(3), 2014

Bang-bang, digital 15 bits
Oracle 2014



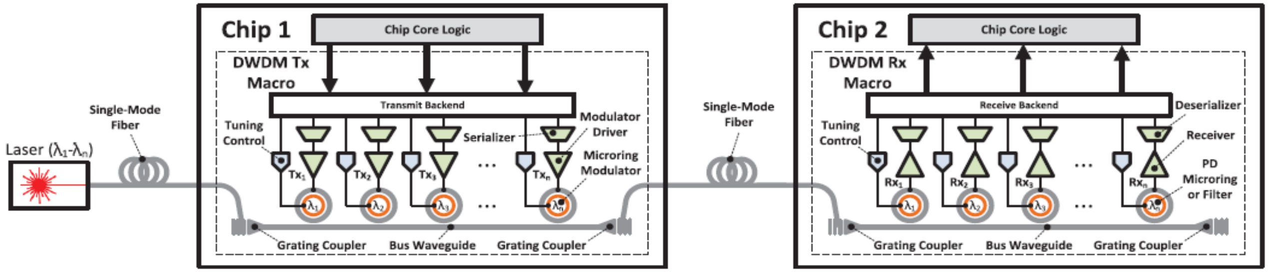
X. Zheng, Opt. Express, 22(10) 2014

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



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

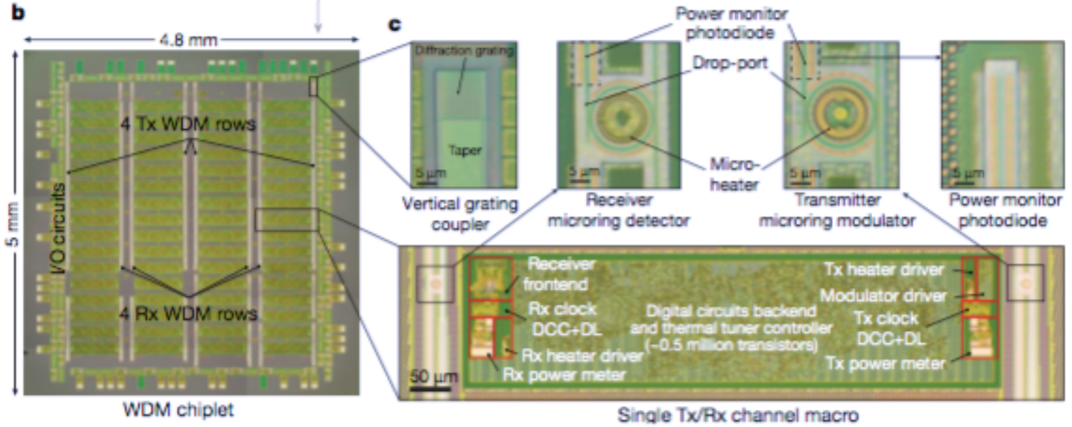
MIT-Berkely-Boulder 2016



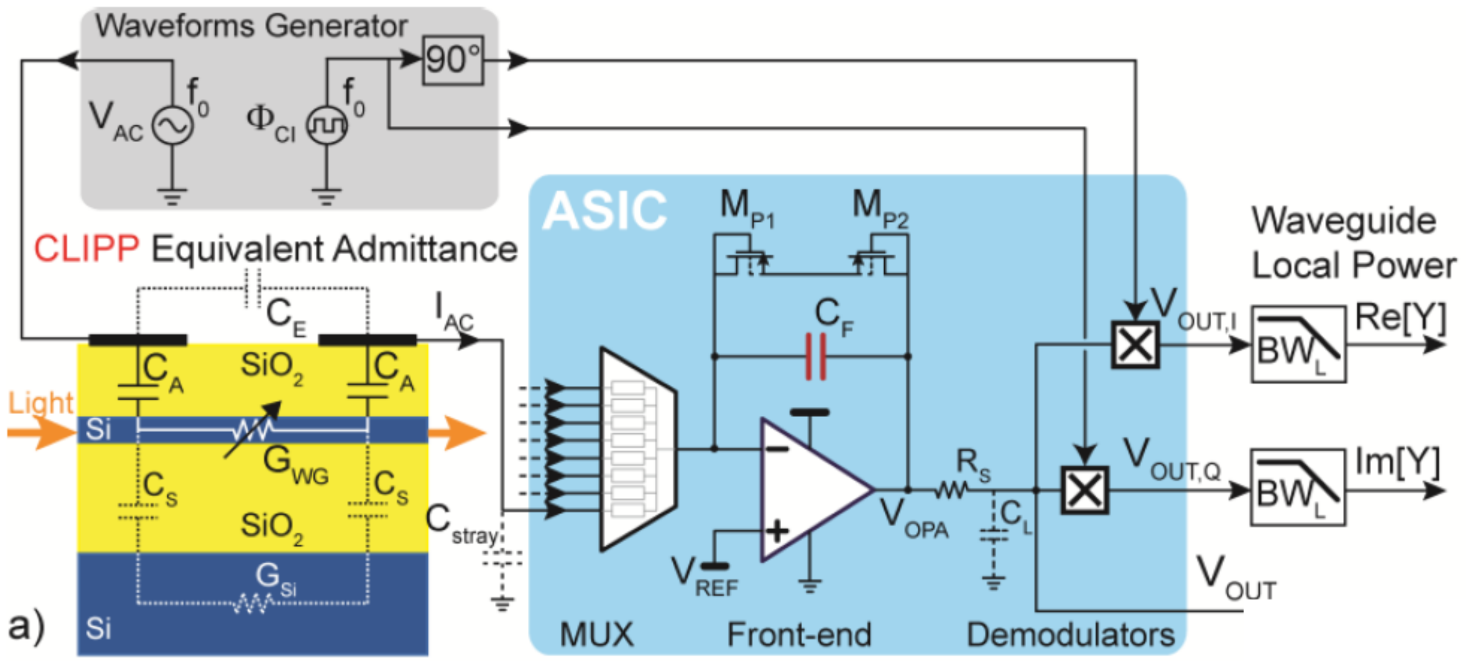
C. Sun, et al., JSSC, 51(4) 2016

DWDM transmitter and receiver
Monolithic platform, commercial 45 nm CMOS SOI process

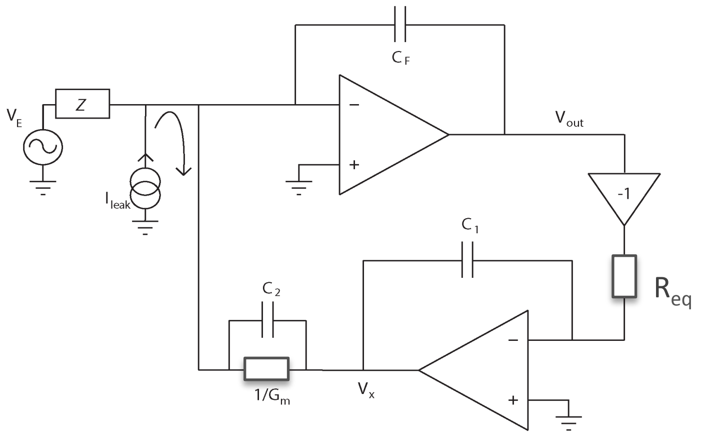
Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip, Nature, 19 April 2018

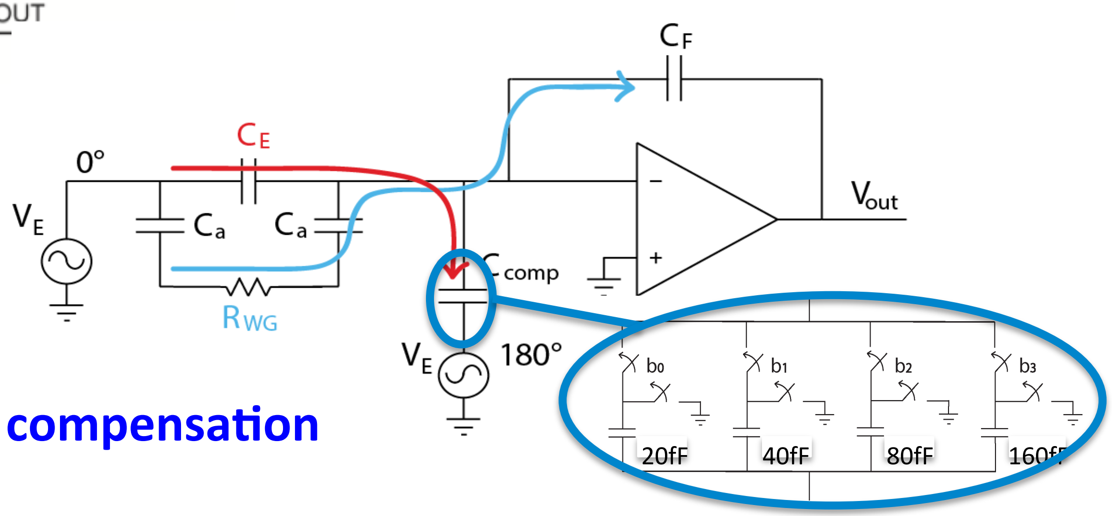


Electronic ASIC for CLIPP reading



Immunity to input leakage current variations

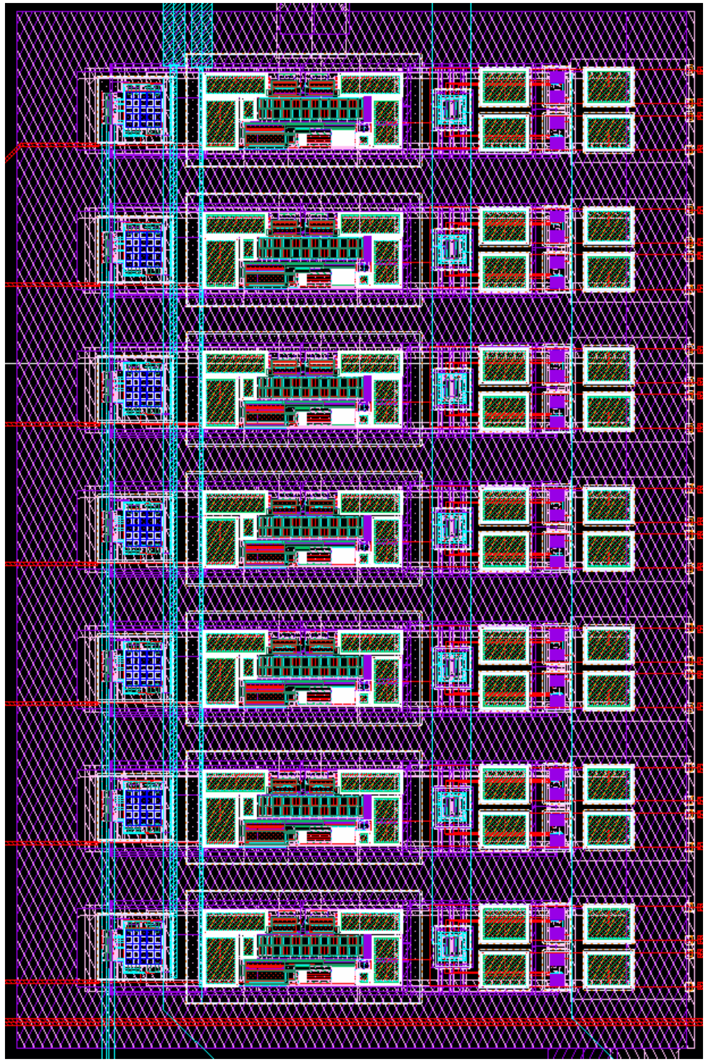




Intra-PAD capacitance compensation

Electronic ASIC for CLIPP reading

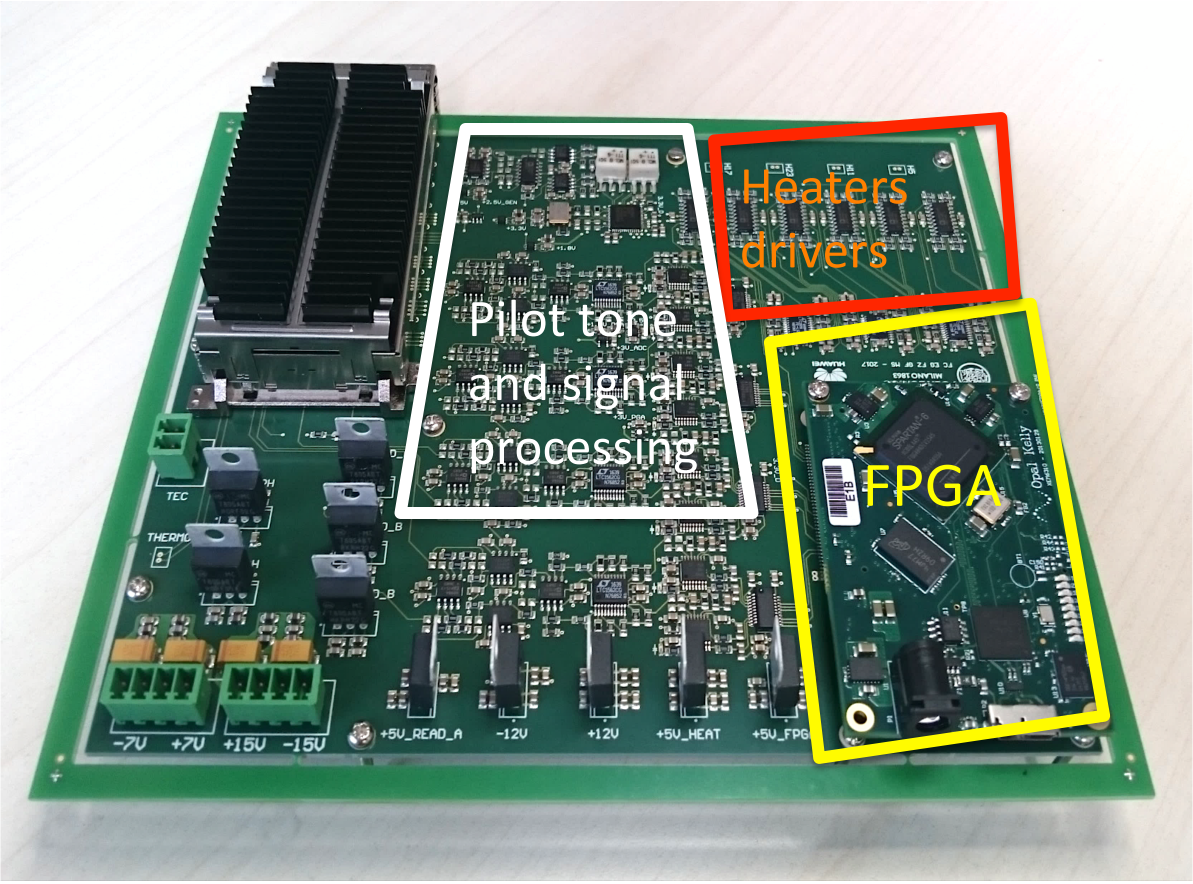
- 7 channels
- 80 MHz analog bandwidth
- On-chip I/Q lock-in demodulators
- Output filters (-3dB BW = 100kHz)
- 40 $fA/\sqrt{Hz}$ input noise (@500kHz)
- **16pS resolution** @500kHz (BW=100kHz) with integrated filters and 1V stimulus
- **1.6pS resolution** @500kHz (BW=1kHz) with external filters and 1V stimulus
- P_{TOT} = 62mW (9mW per Channel @1.8V)



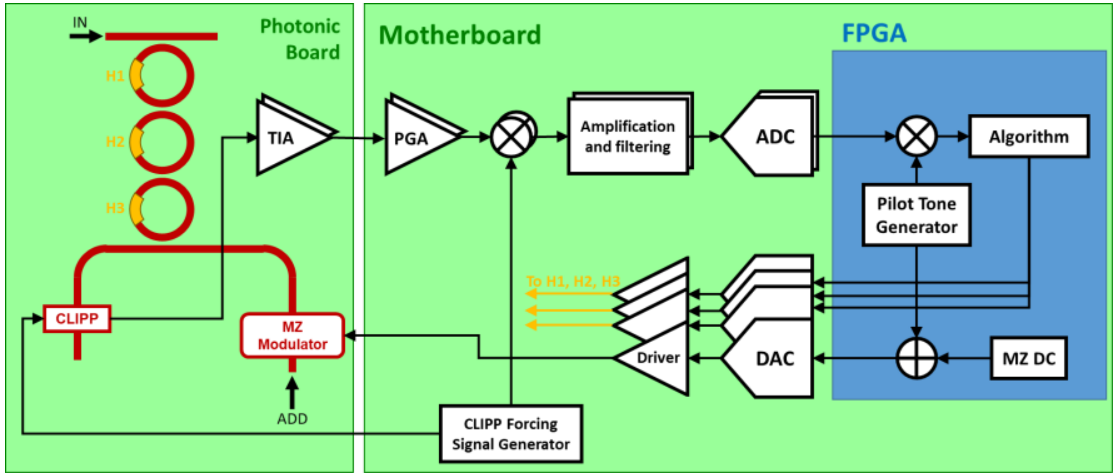
STmicroelectronics BCD8sp MPW

Assembly and control hardware

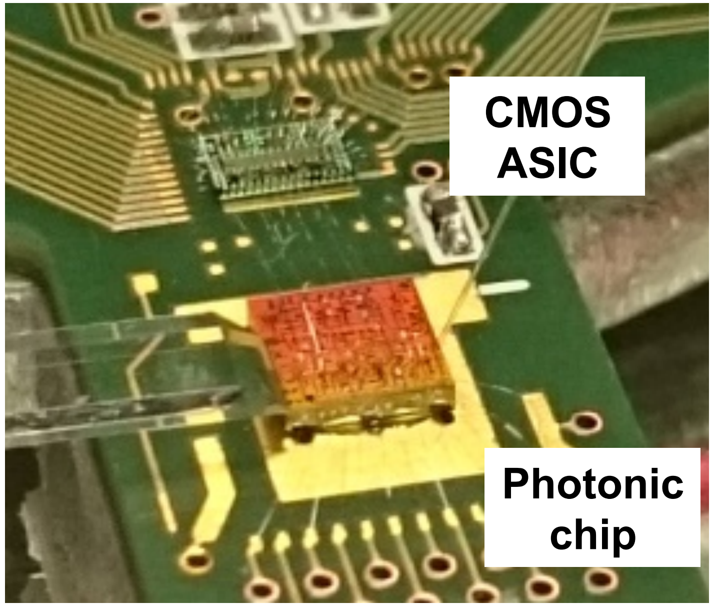
Electronic controlling board with heater drivers, CLIPP readout circuitry and embed FPGA controller



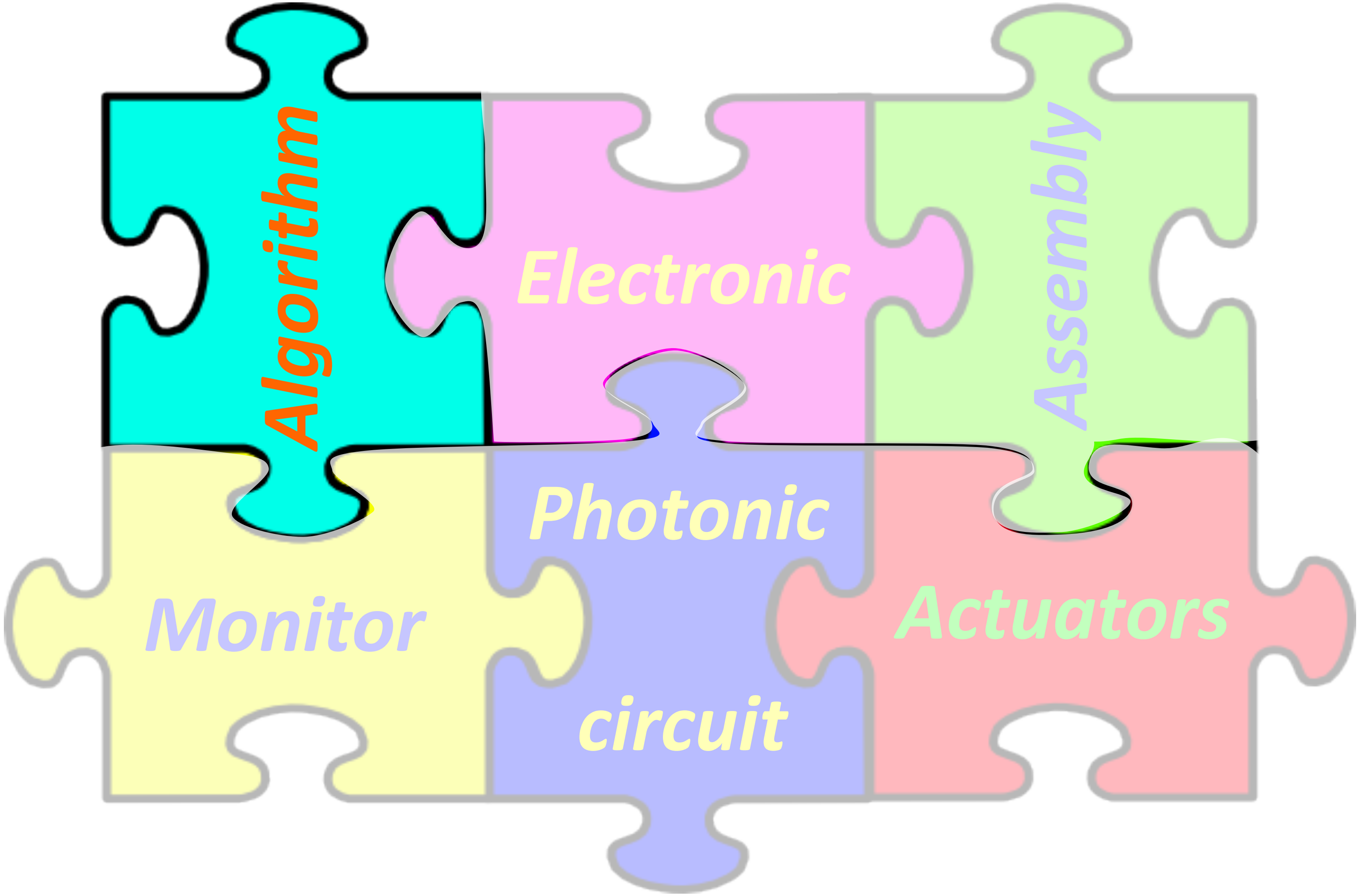
Label demodulation within FPGA



Quasi-planar transposer coupling to gratings with PM fibers

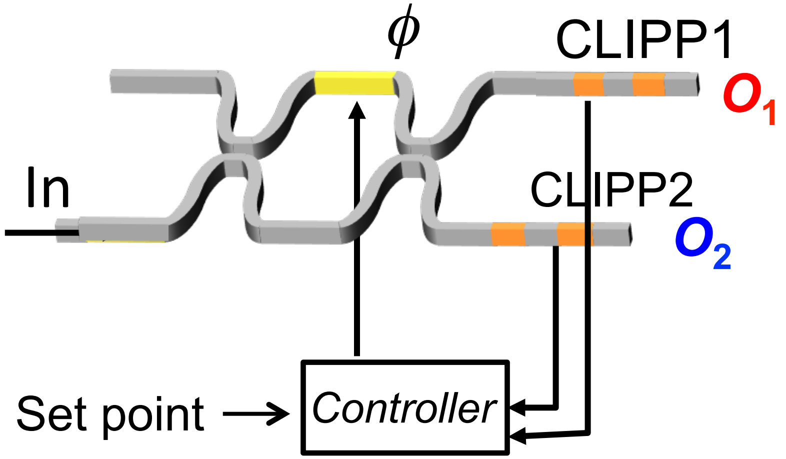


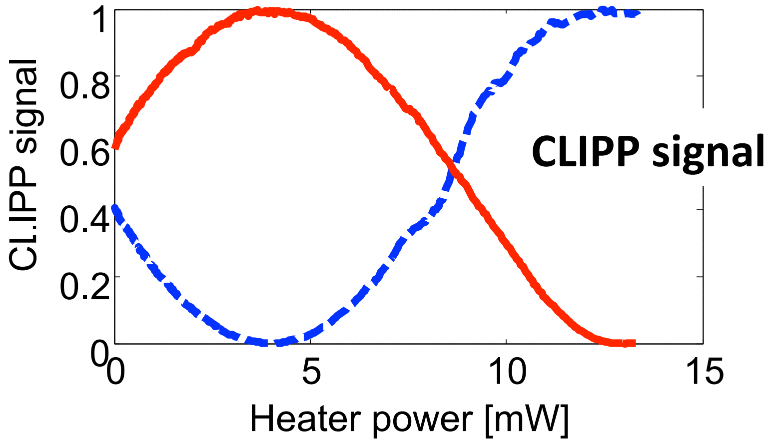
The control layer: algorithms and techniques

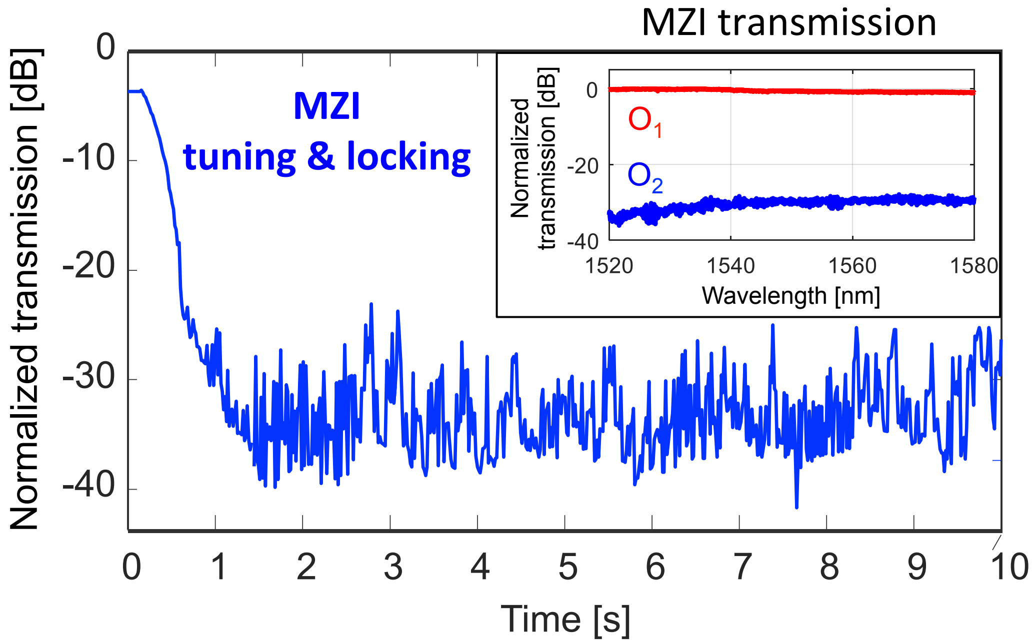


Mach-Zehnder stabilization, locking, tuning…

Local feedback loop





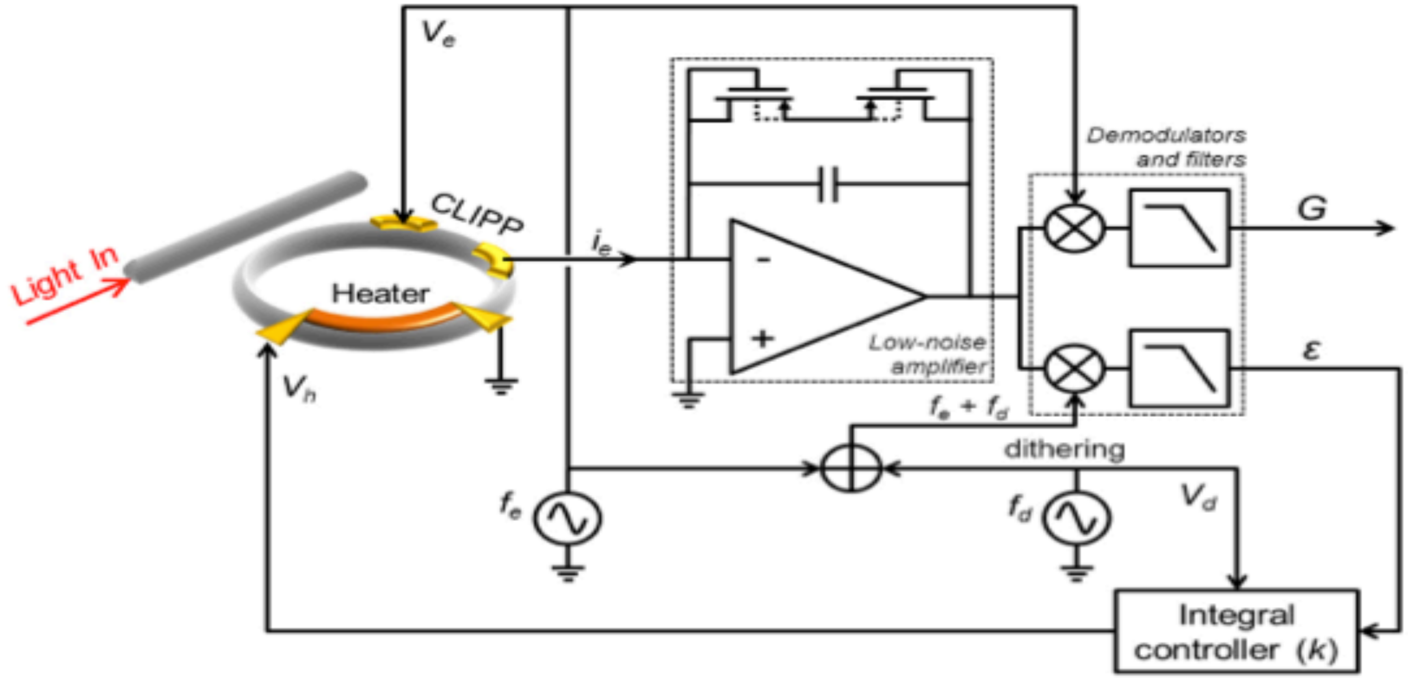


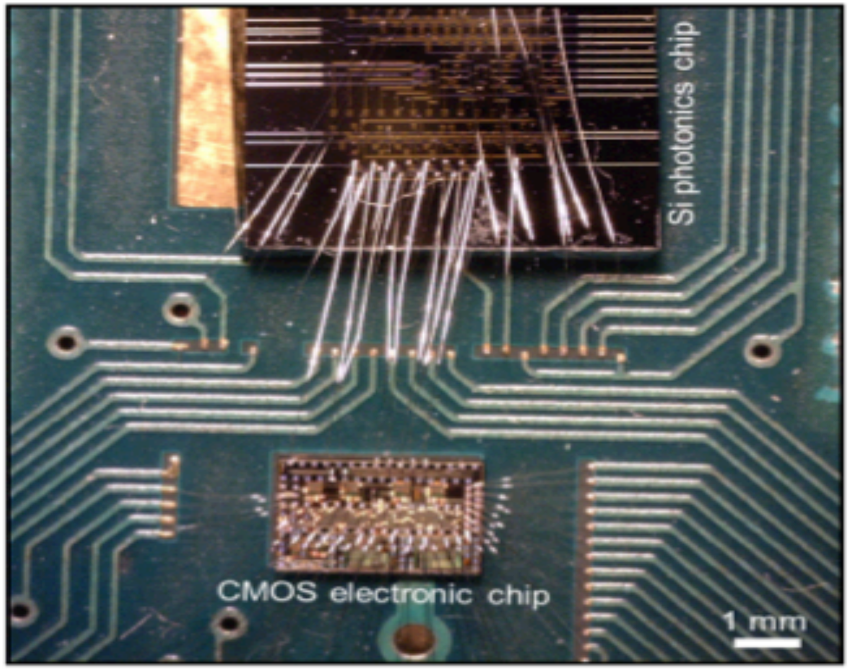
- Automatic tuning and locking of MZI
- Maximum/Minimum locking
- Any bias locking (Ratio O_1/O_2 set point)
- Local feedback loop
- No TEC needed

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

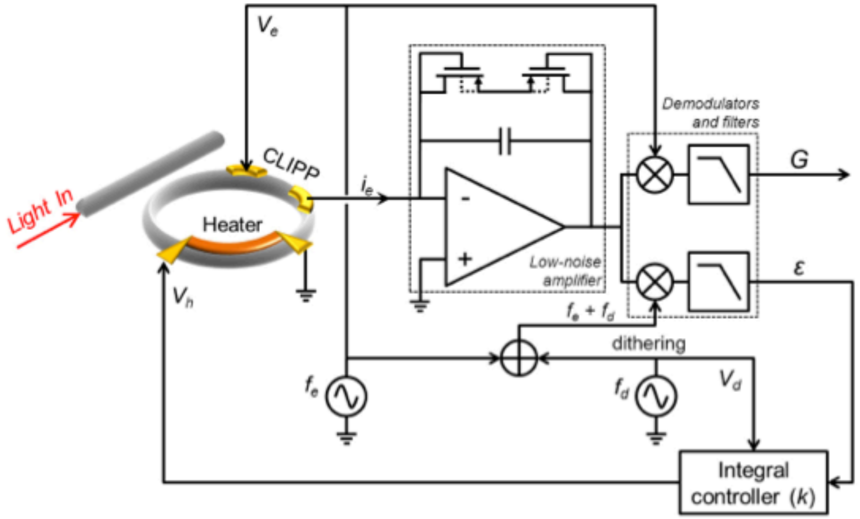
Ring stabilization, locking, tuning

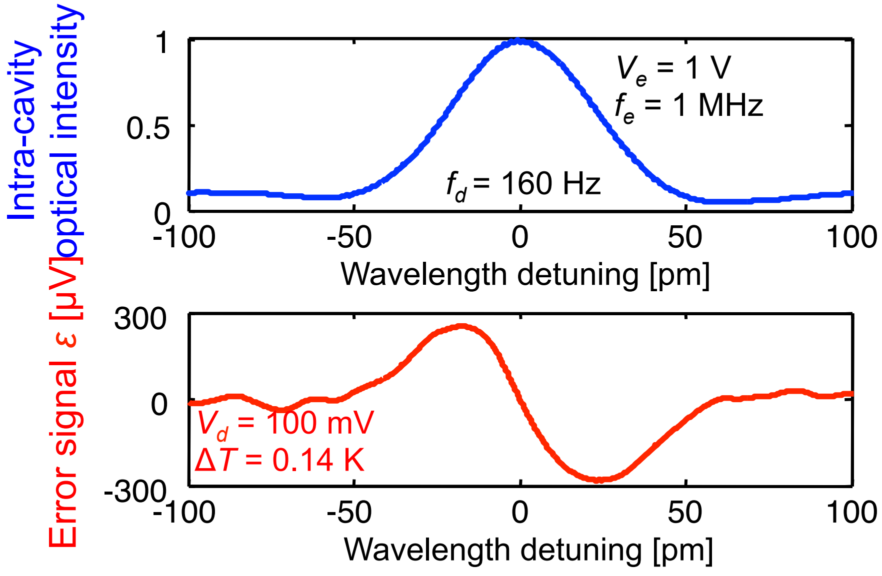
Electronic helps photonic ....



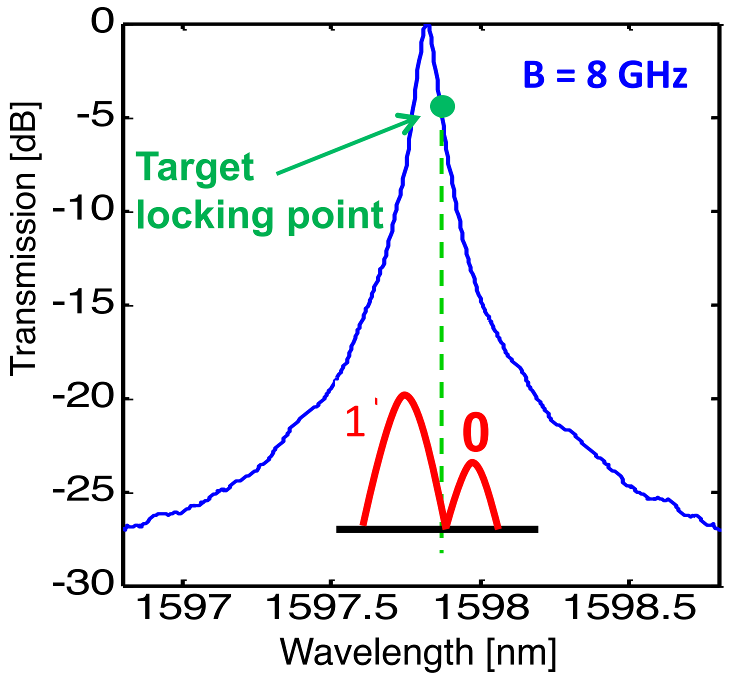


Ring stabilization, locking, tuning…

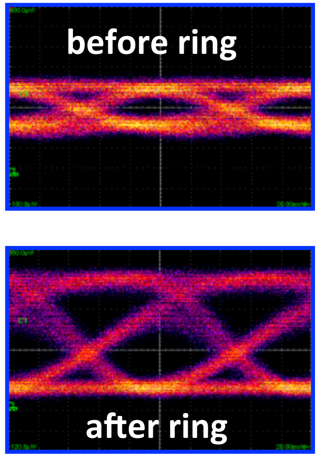




S. Grillanda *et al.*, Optica 1(3), 129-136 (2014)



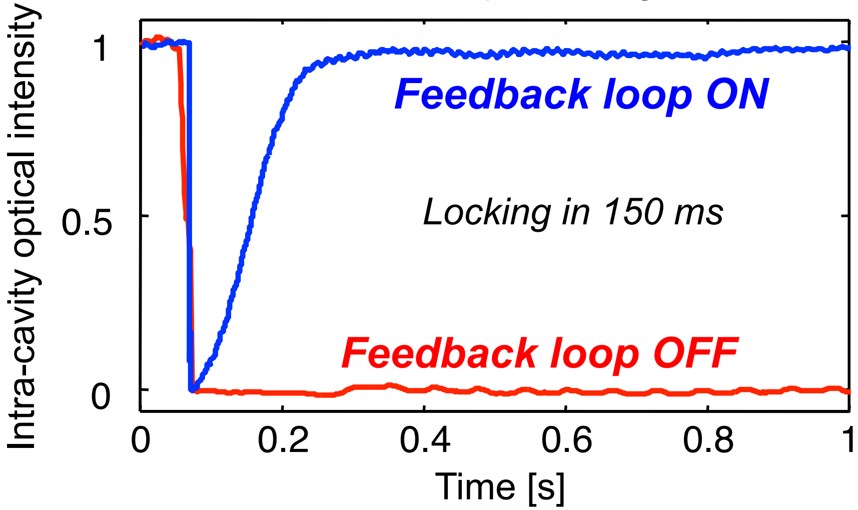
Locking on ring slope for ER-enhancement of DML



2.6dB

8.3dB

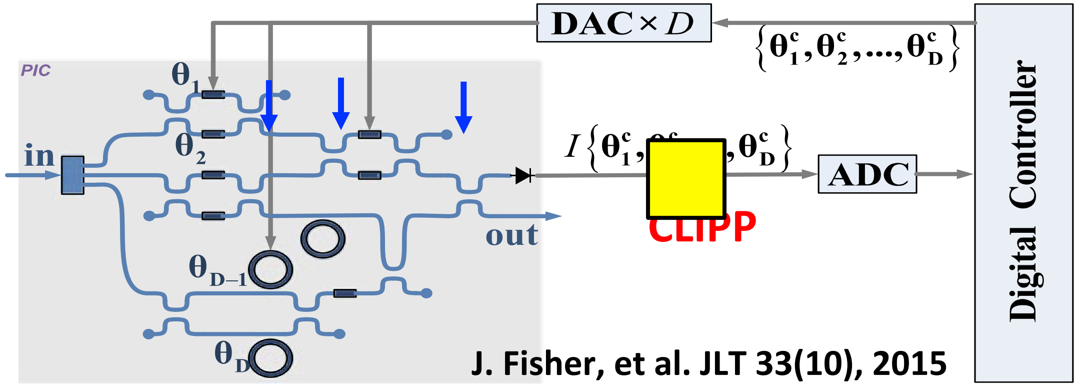
Perturbation equal to ring bandwidth



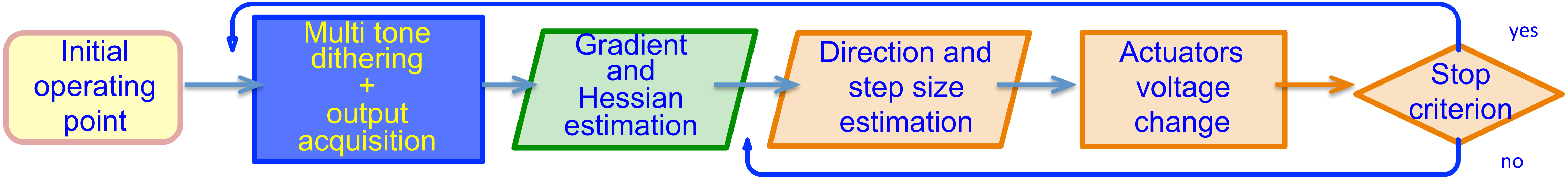
Handling multiple degrees of freedom

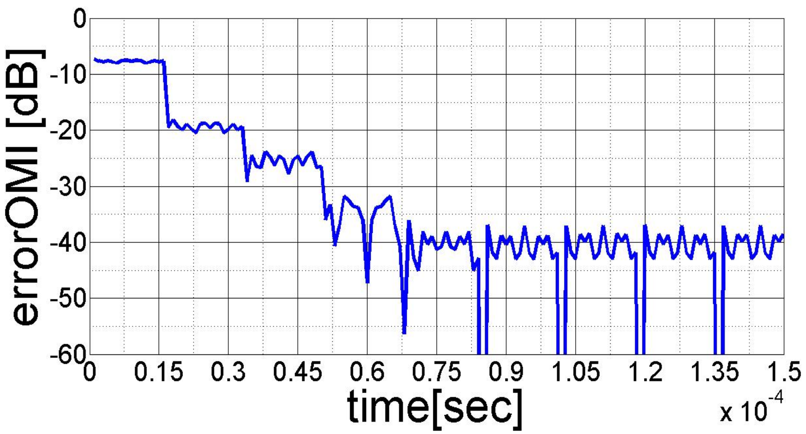
Control **many degrees-of-freedom** (DOFs) using a **single monitoring point**

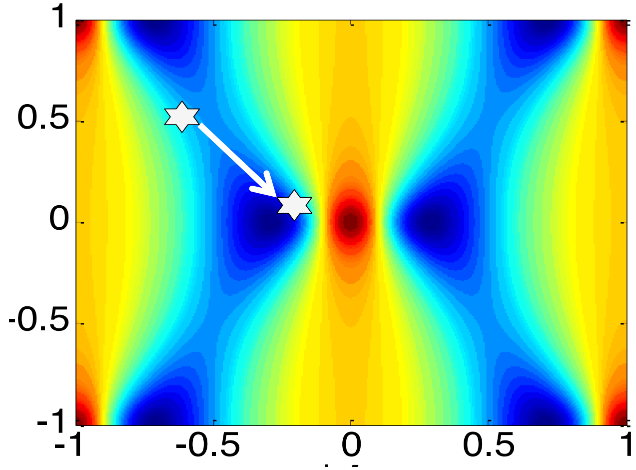
Several DOFs **simultaneously dithered at orthogonal frequencies** generated from a discrete-multi-tone generator (DMT)



J. Fisher, et al. JLT 33(10), 2015



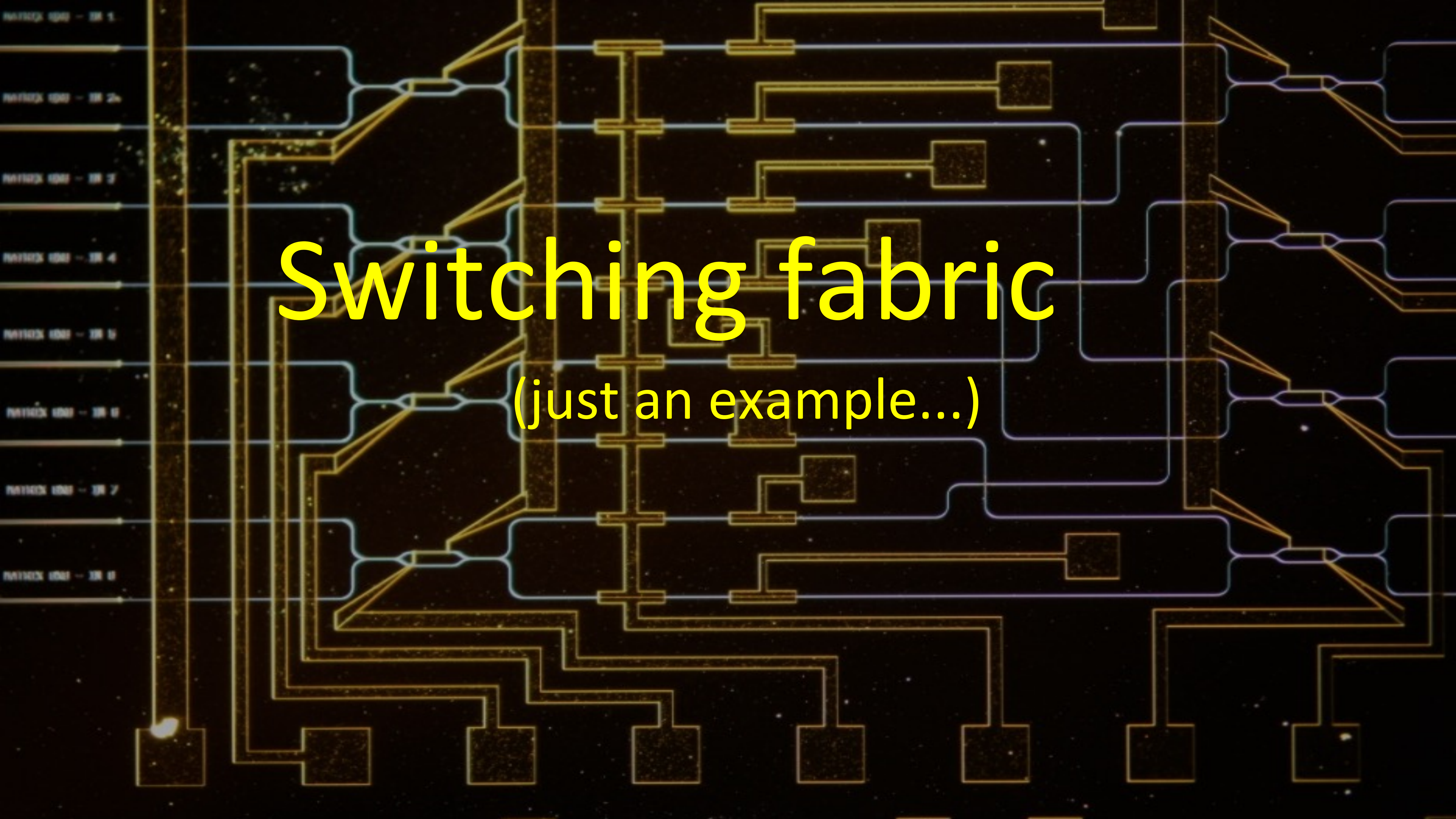




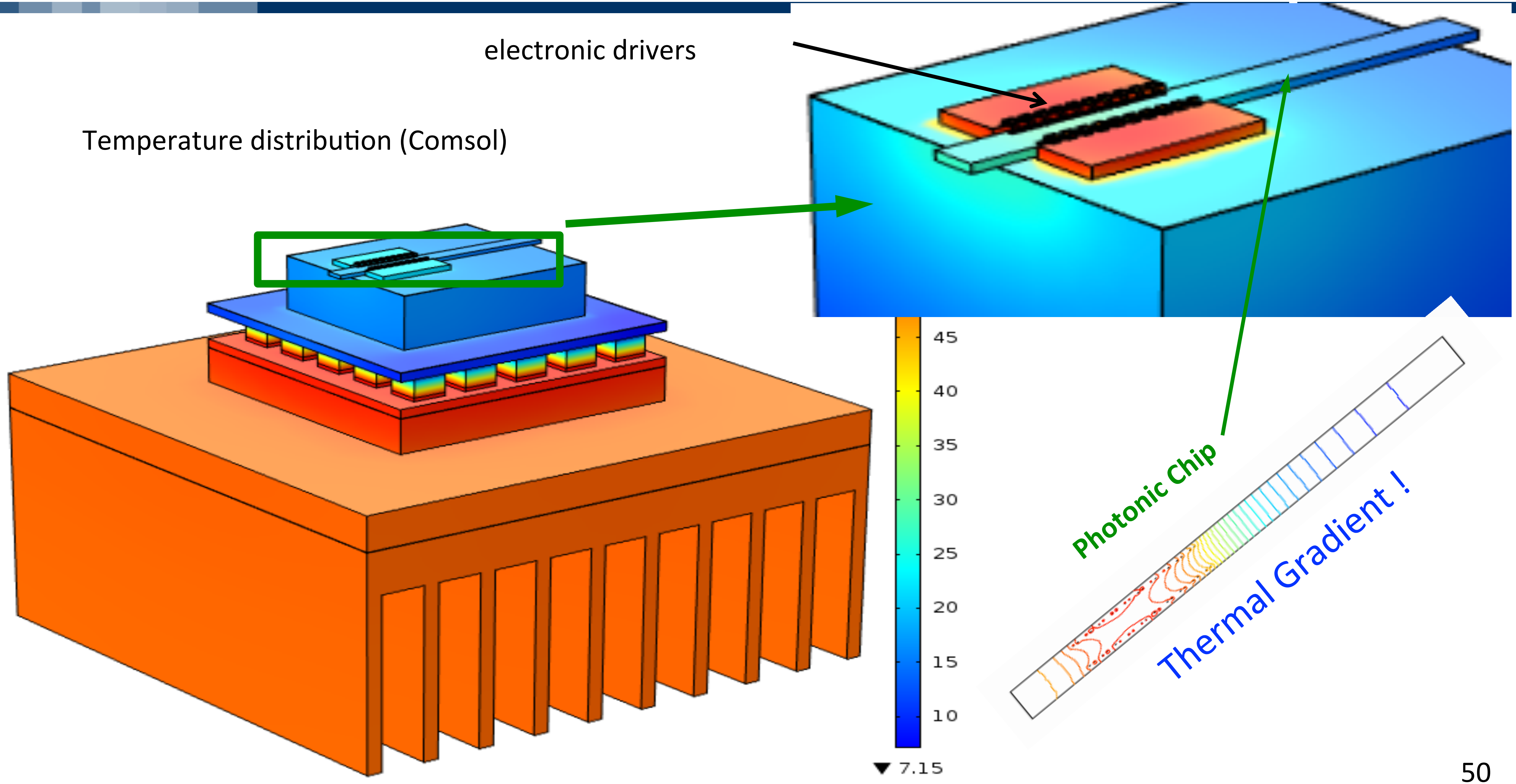
- Extract N derivatives vs dithering tones (**gradient, Hessian matrix**, …)
- Estimation of **descent direction & step size** (gradient or Newton method)
- **Step size refinement** (e.g. Back-Trace-Line-Search)
- **Bang-Bang** techniques

Switching fabric

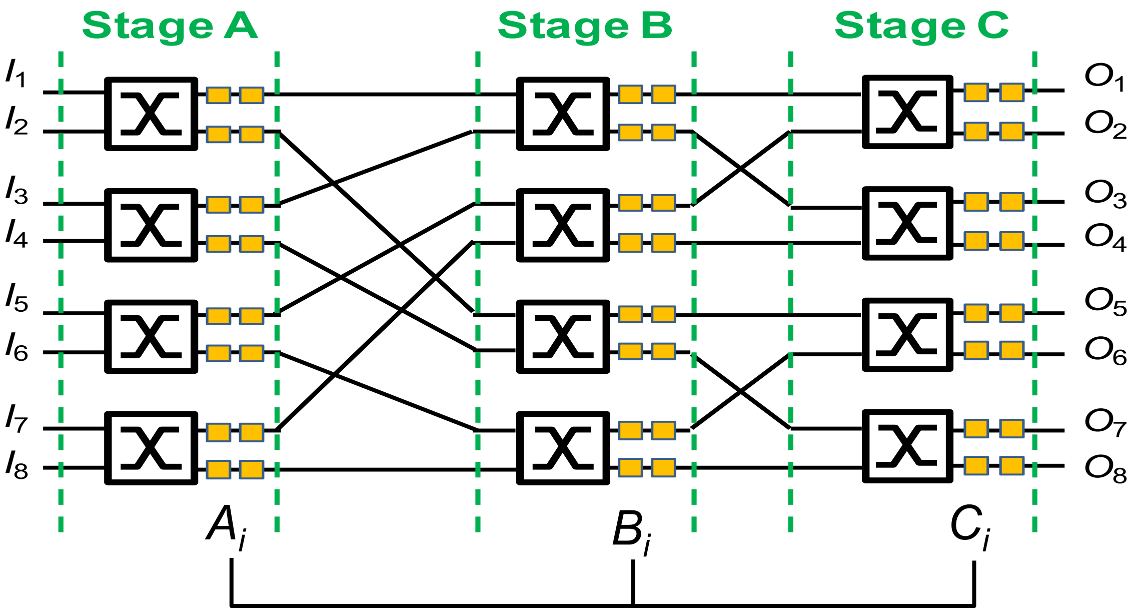
(just an example...)



Thermal distribution

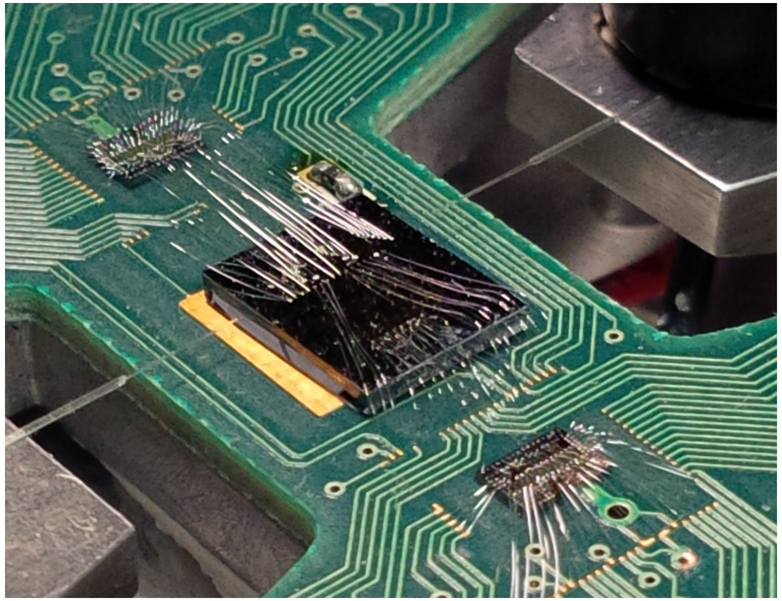


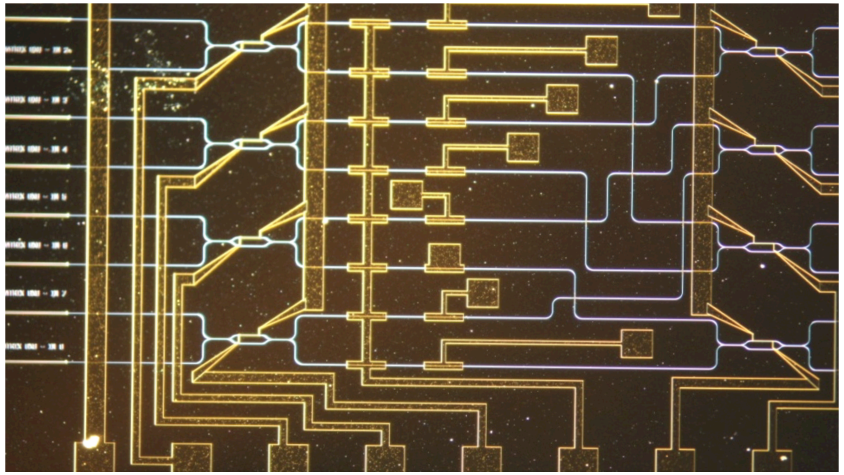
Crossbar router - Lightpath tracking and control

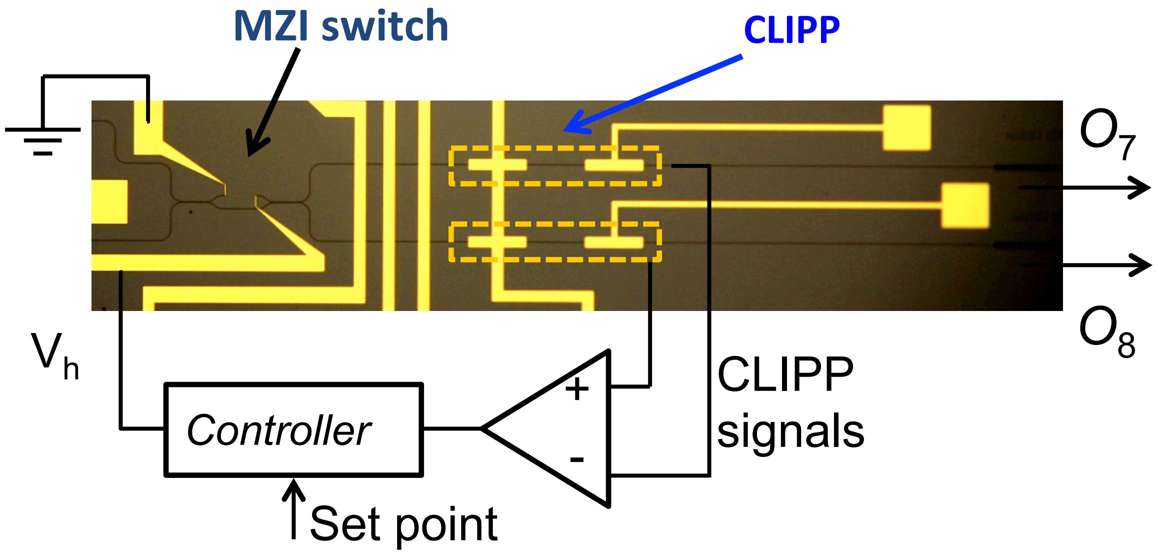


2 x 12 CLIPPs
12 heaters

A. Annoni *et al*., JSTQE, May 2016

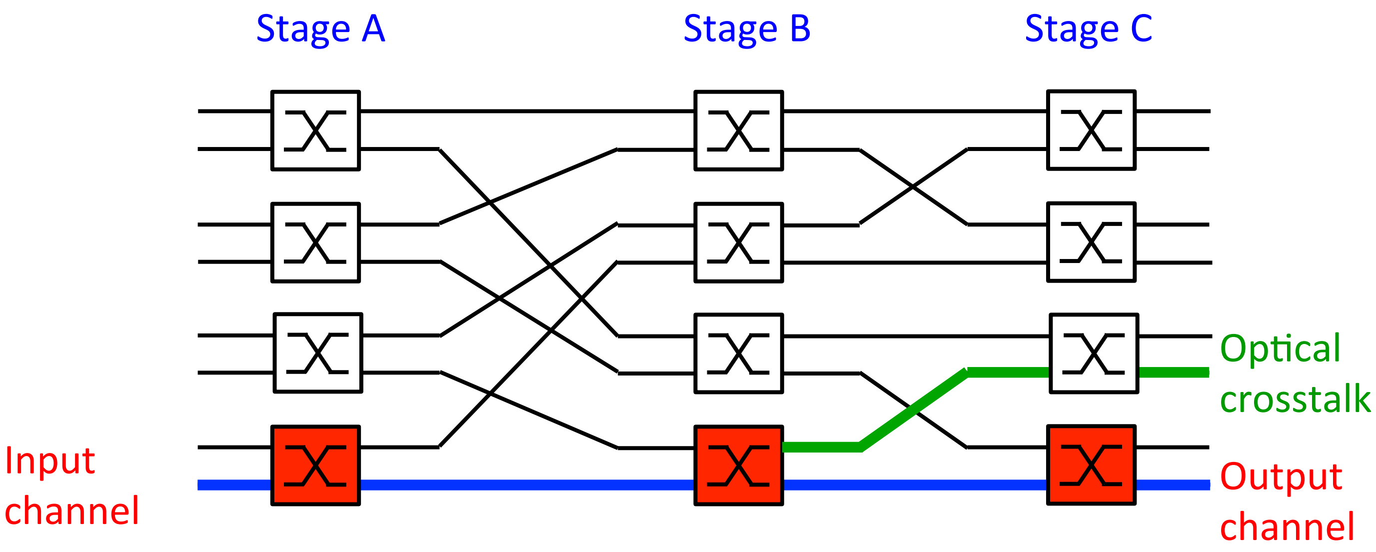


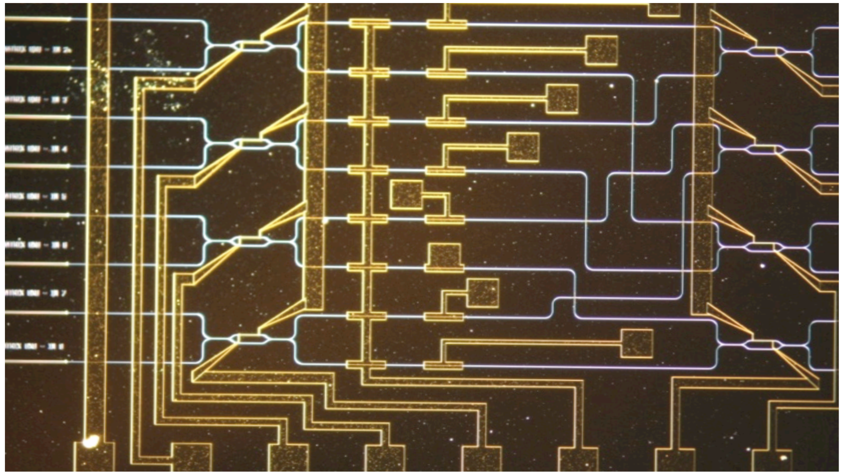


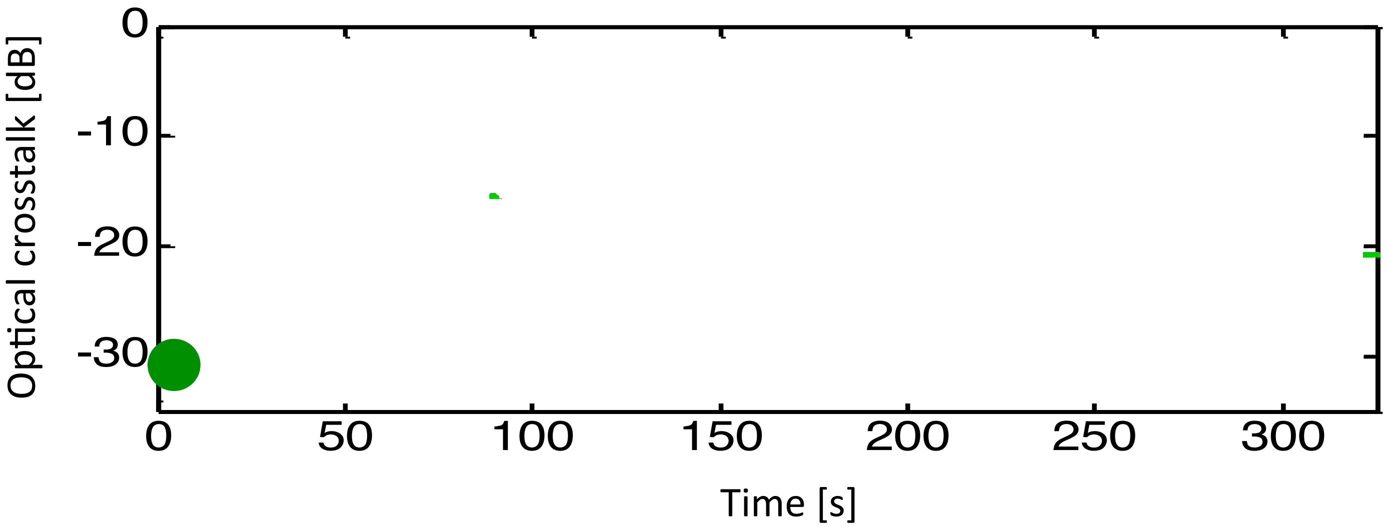


Thermal crosstalk compensation with feedback

8x8 Si photonic switch matrix

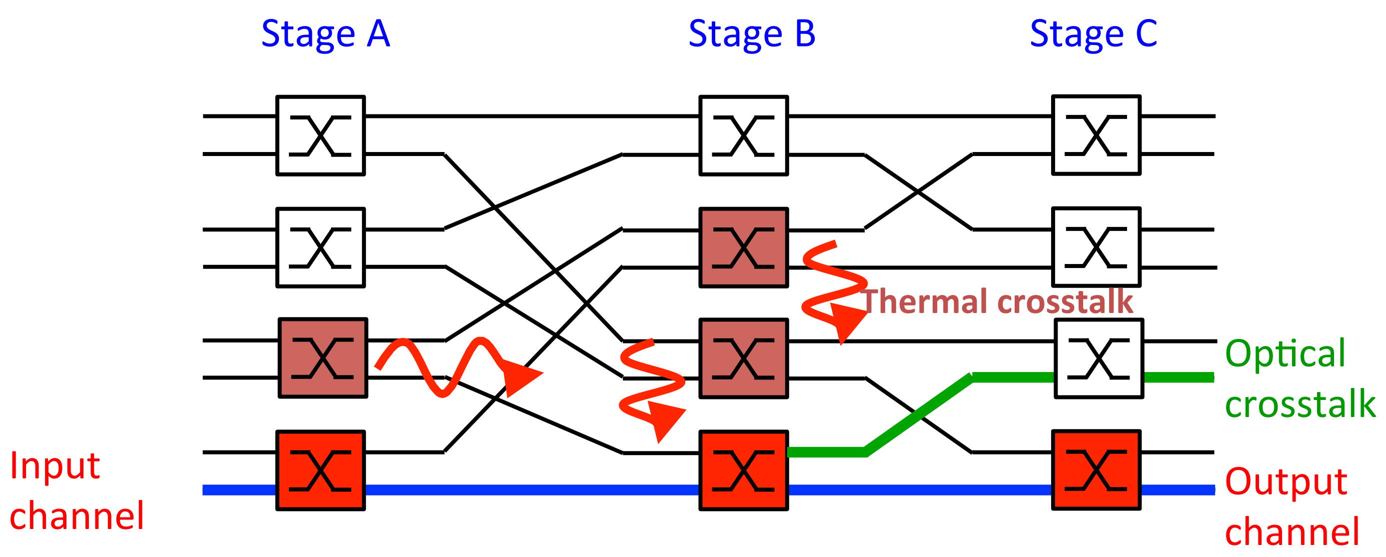


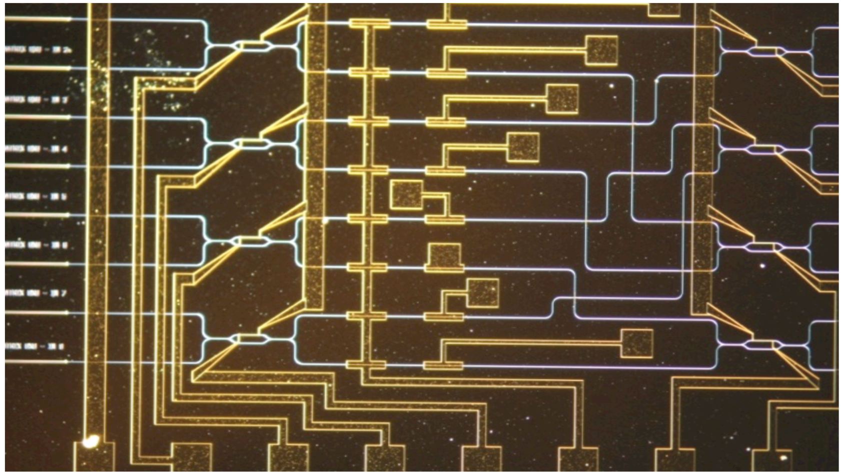


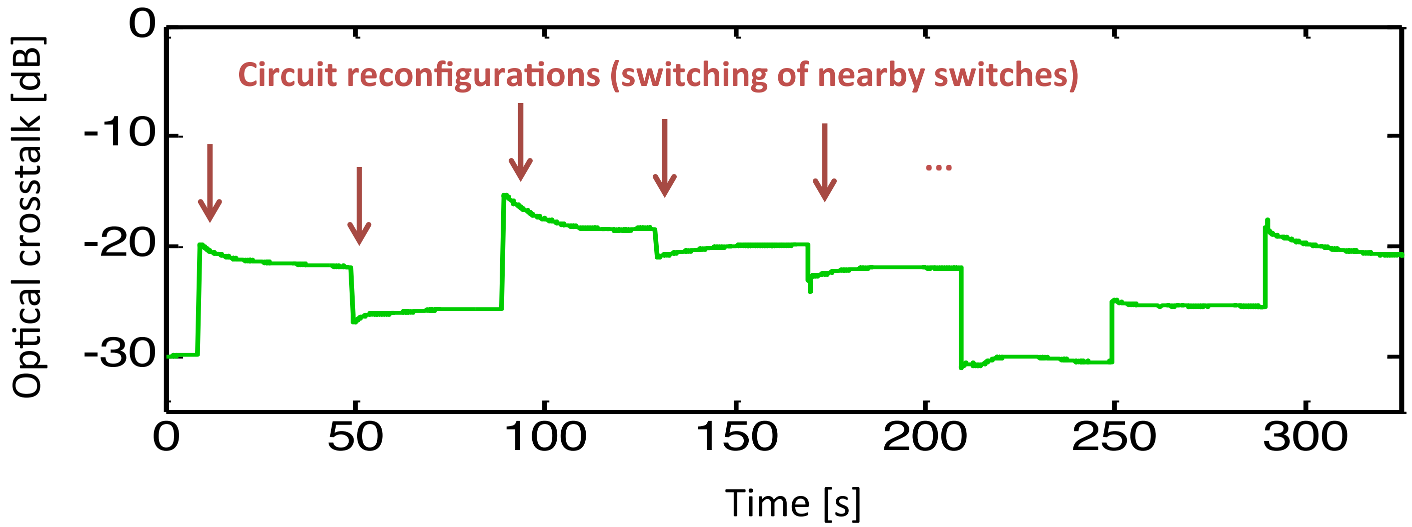


Thermal crosstalk compensation with feedback

8x8 Si photonic switch matrix

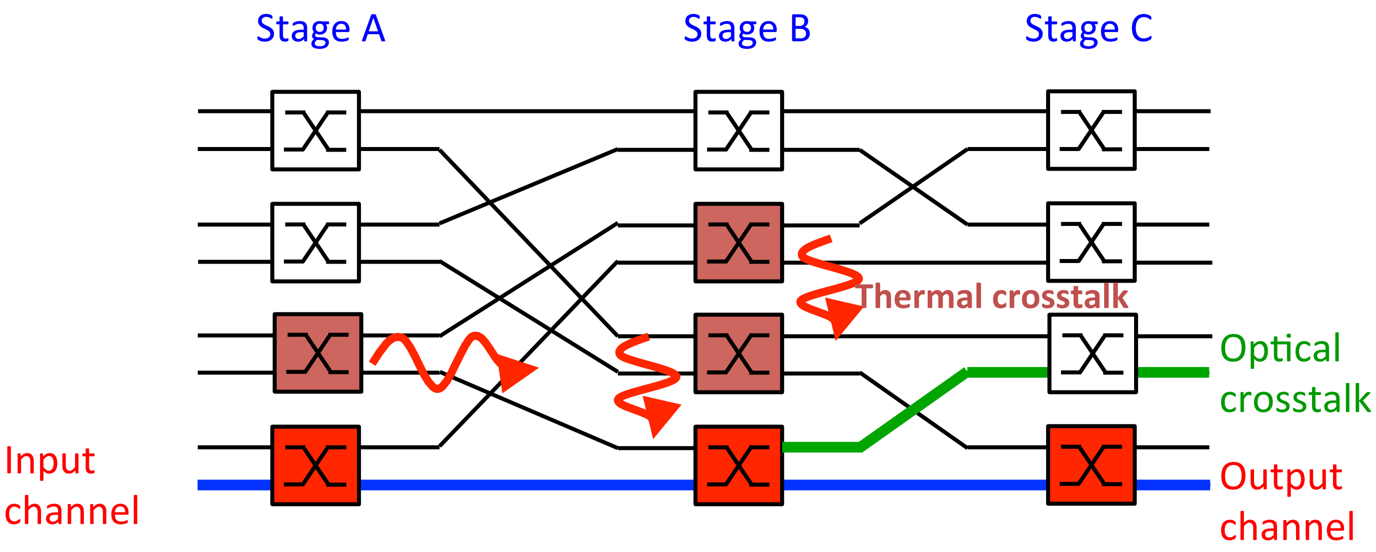


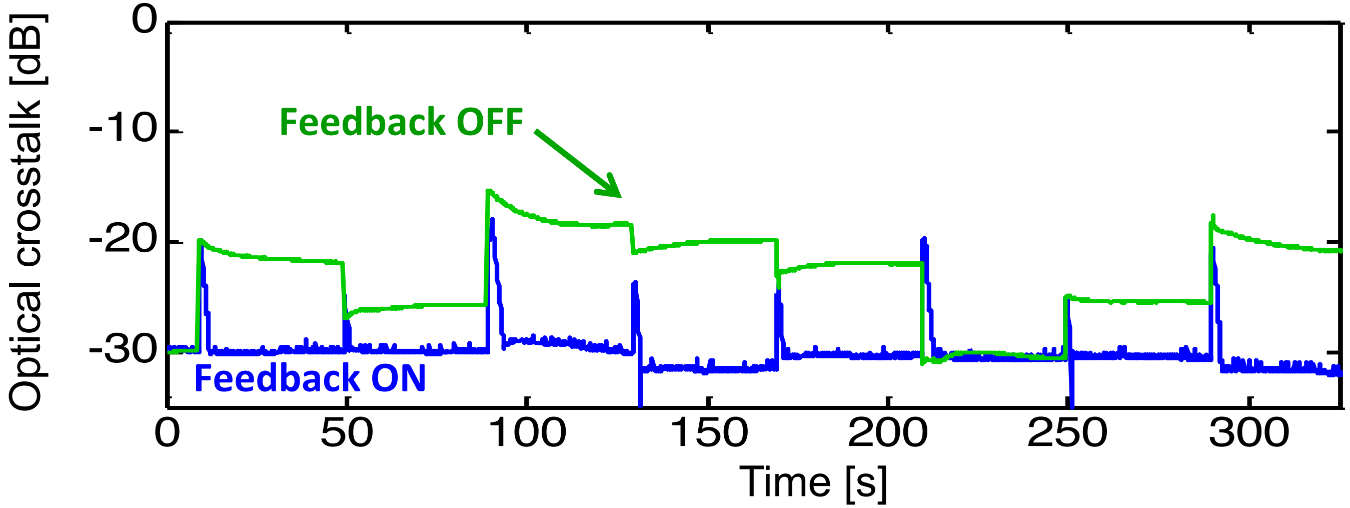


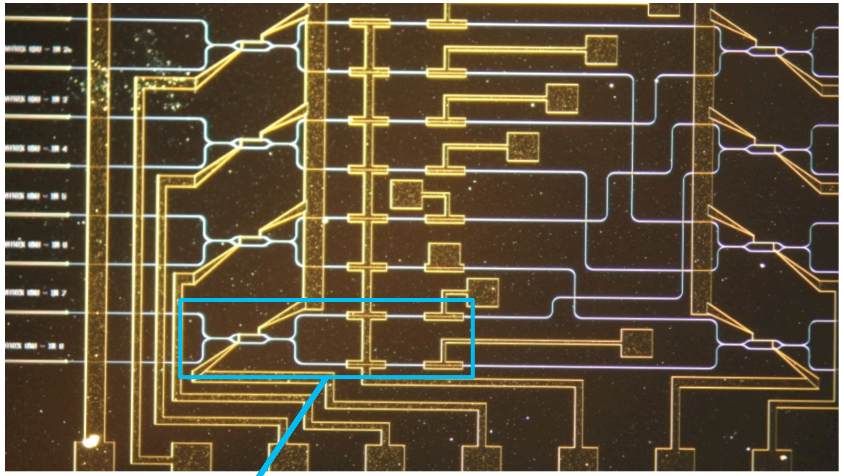


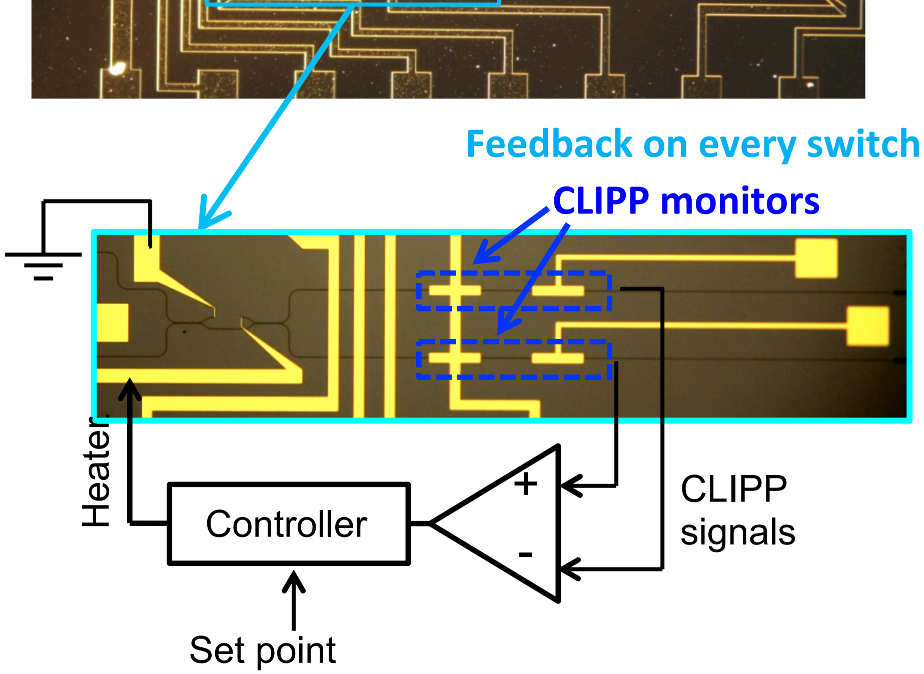
Thermal crosstalk compensation with feedback

8x8 Si photonic switch matrix



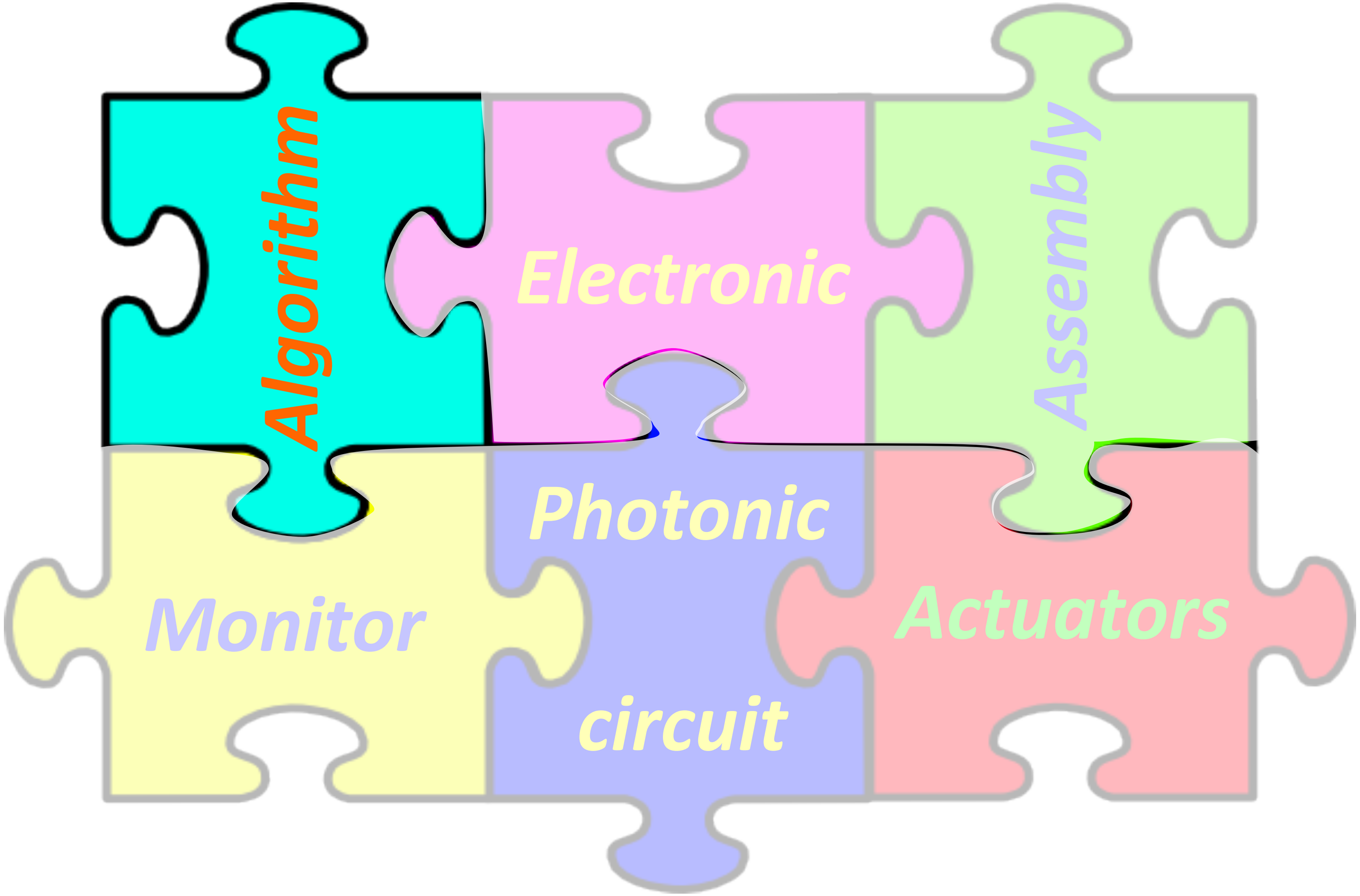






A. Annoni *et al.*, JSTQE, Nov 2016

The control layer: pilot tones (LABEL)

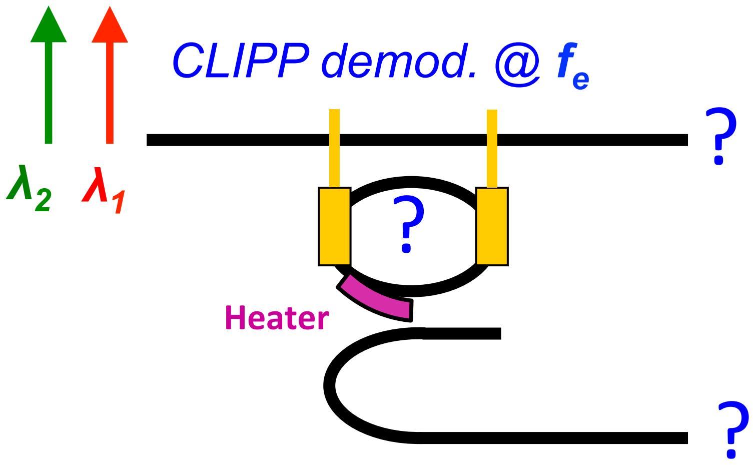


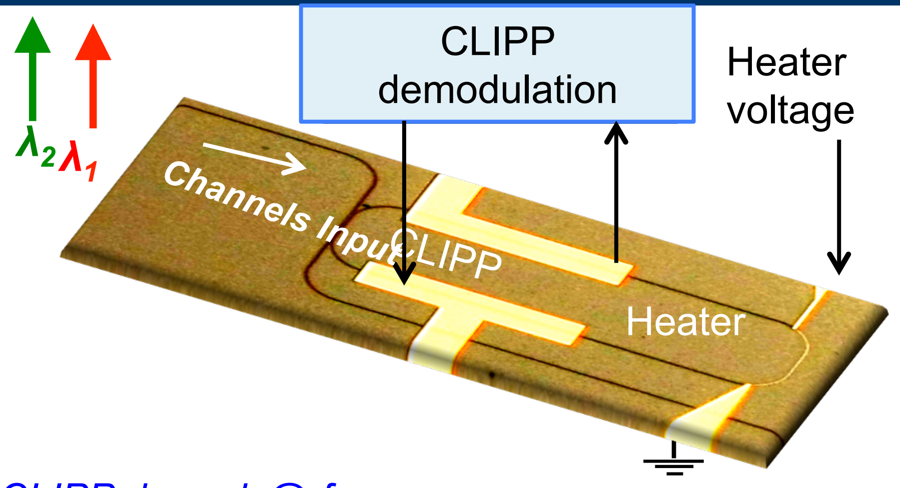
Pilot tones for wavelength monitor

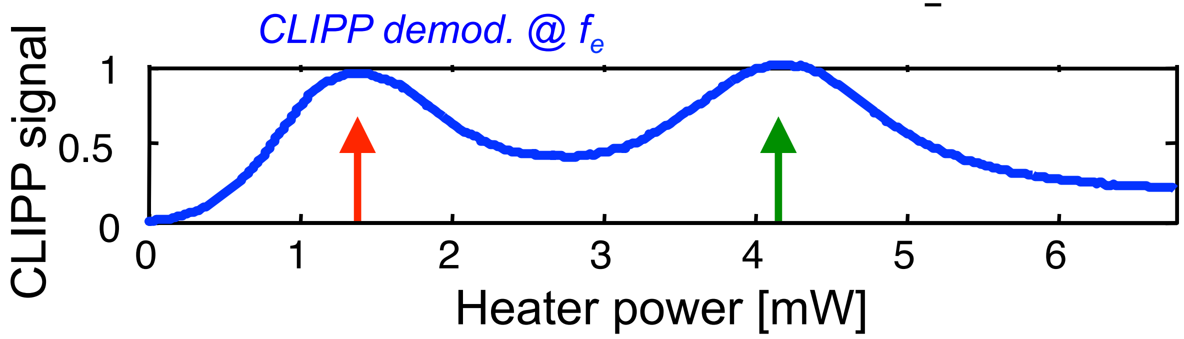
Two input channels at different wavelengths

$\lambda_1 = 1549.59$ nm

$\lambda_2 = \lambda_1 + 120$ pm





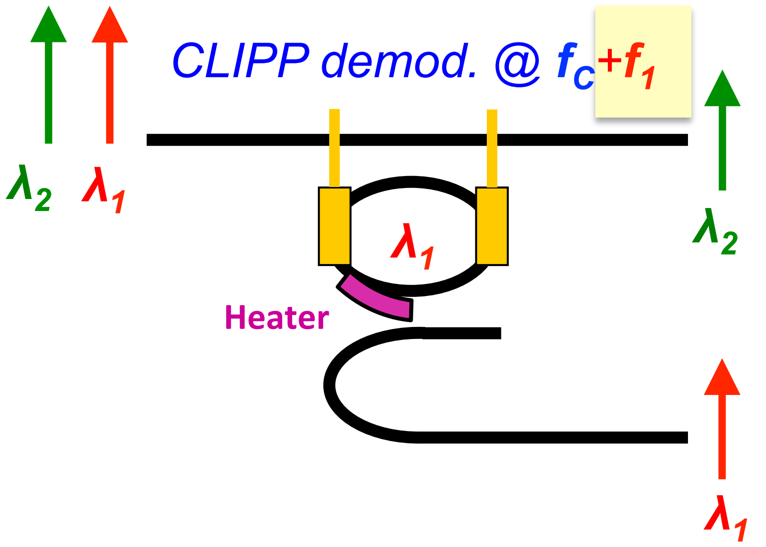


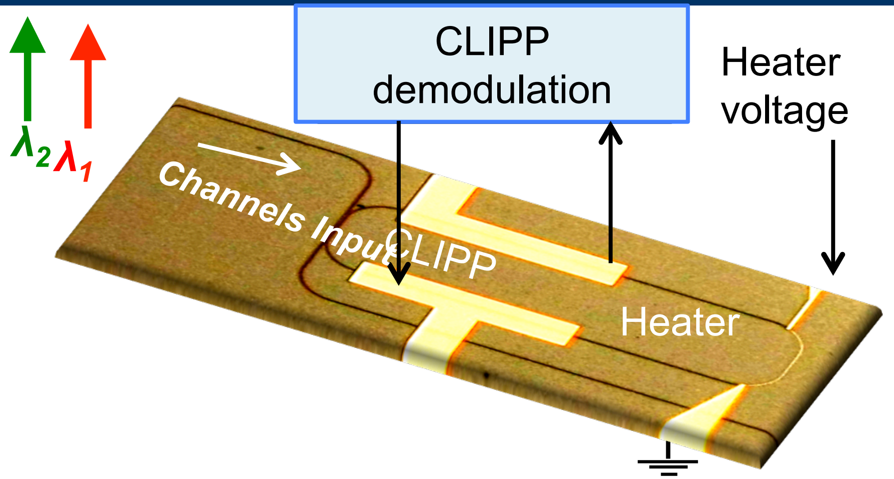
Pilot tones for wavelength monitor

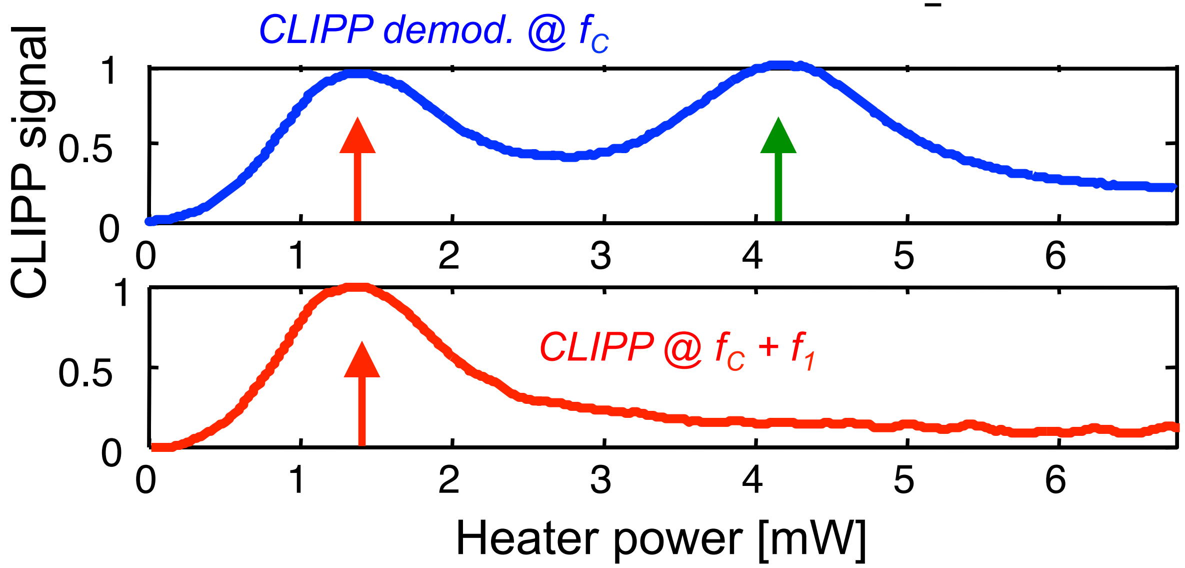
Two input channels at different wavelengths

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

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







λ_1 identified

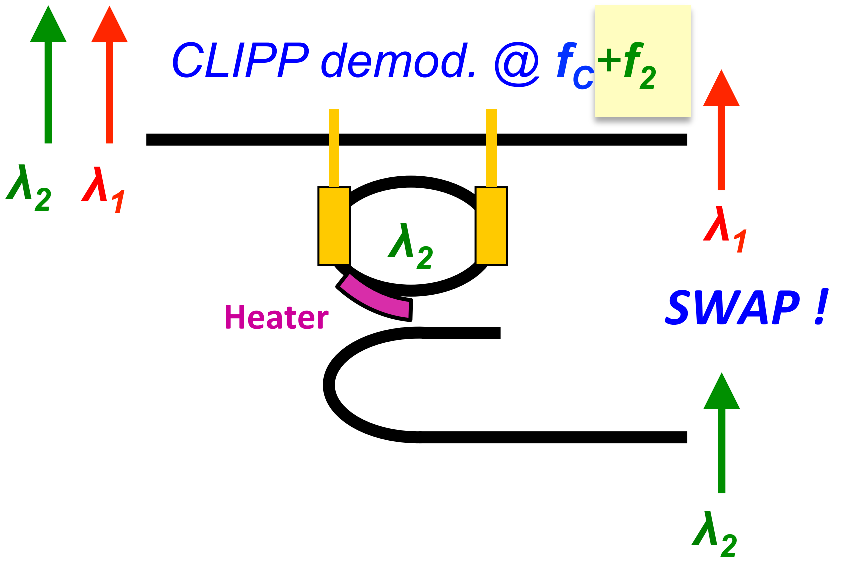
Automatic tuning and *locking at* λ_1

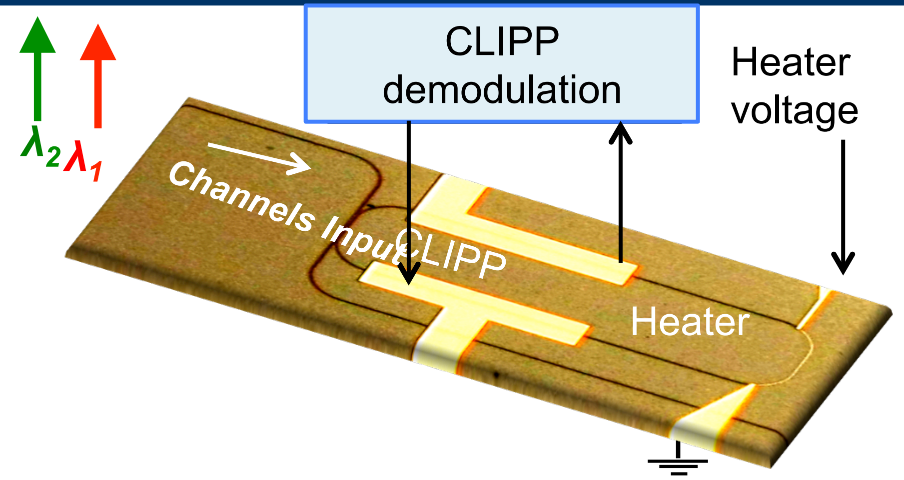
Pilot tones for wavelength monitor

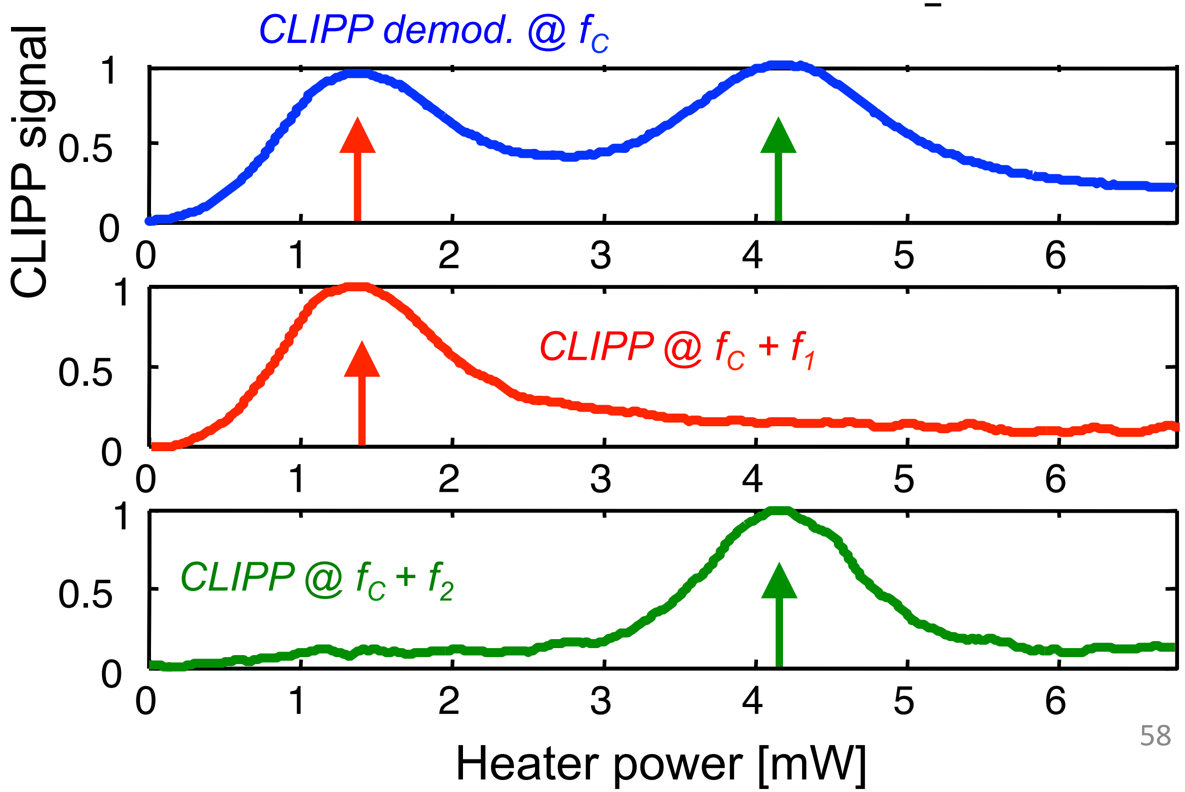
Two input channels at different wavelengths

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

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



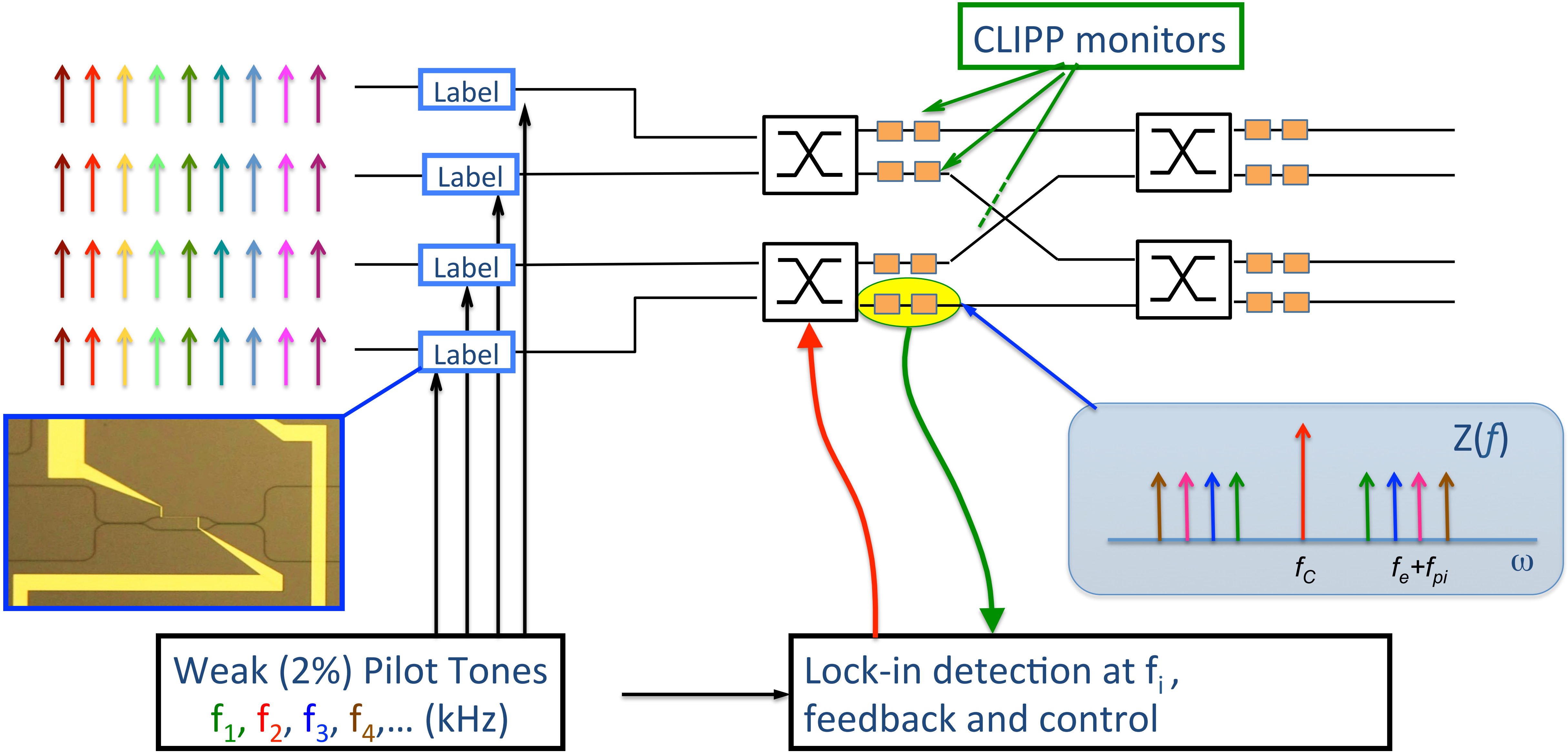




λ_2 identified

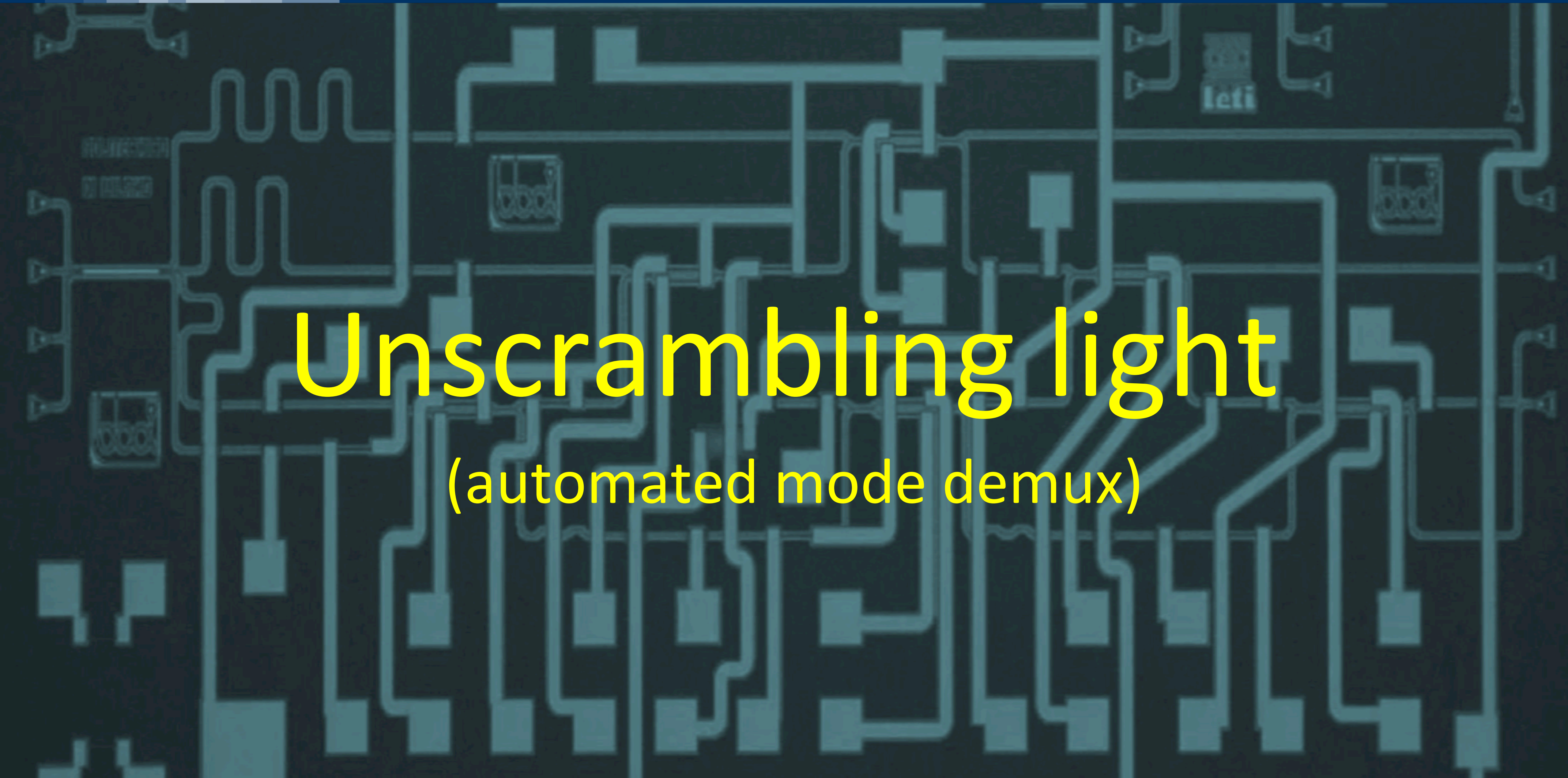
Automatic tuning and *locking at* λ_2

Pilot tones enable control

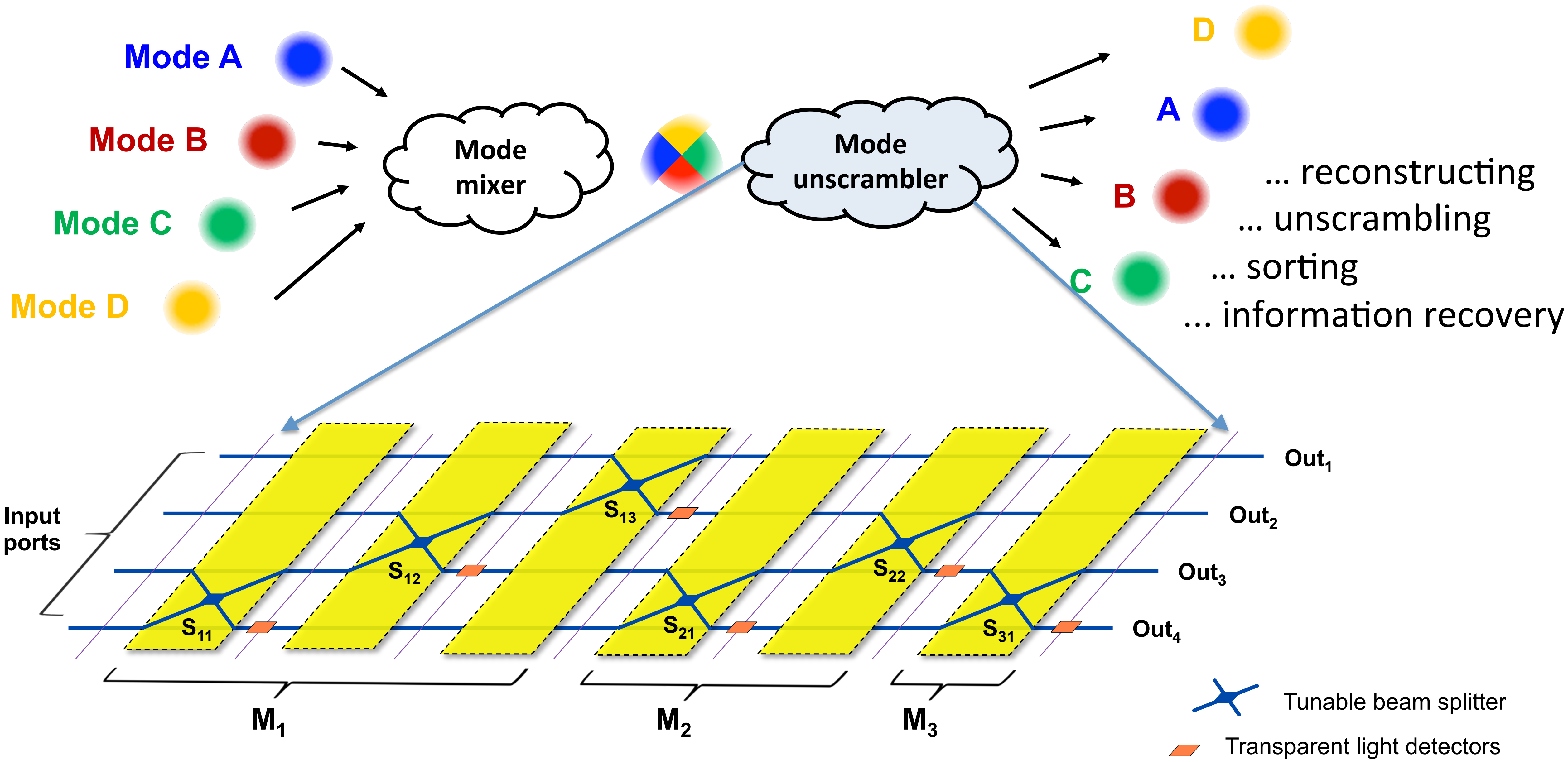


Unscrambling light

(automated mode demux)

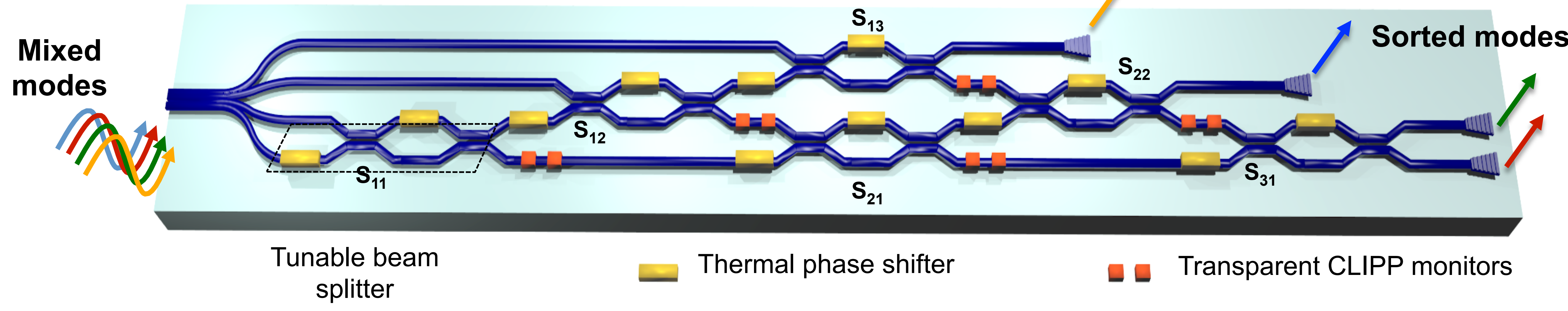


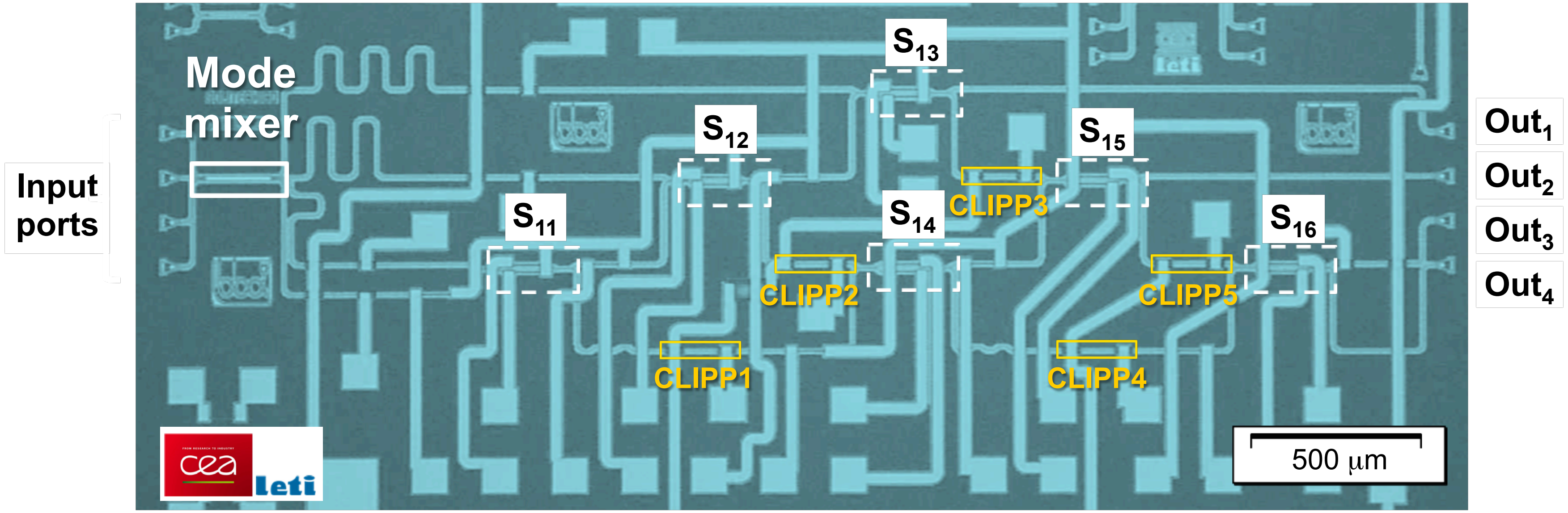
Unscrambling light

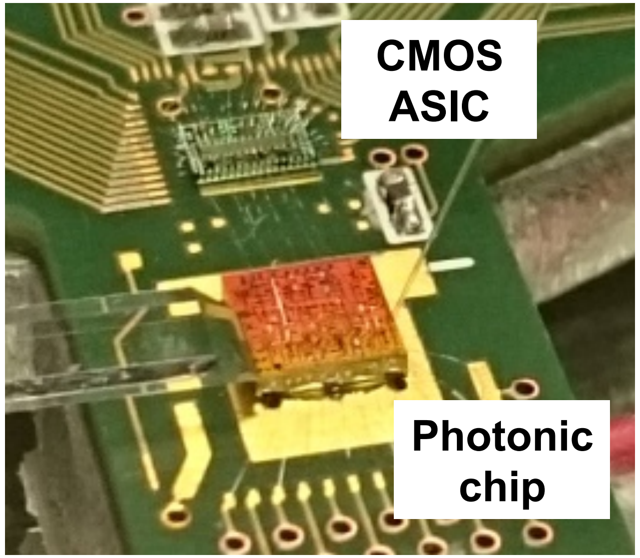


Integrated mode unscrambler

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

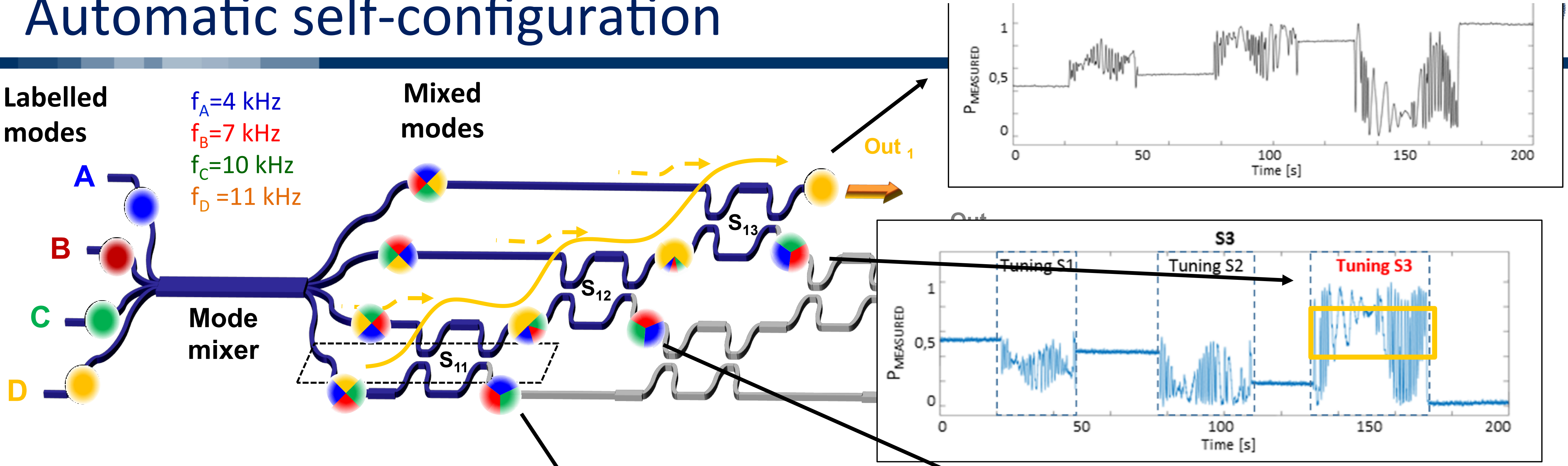


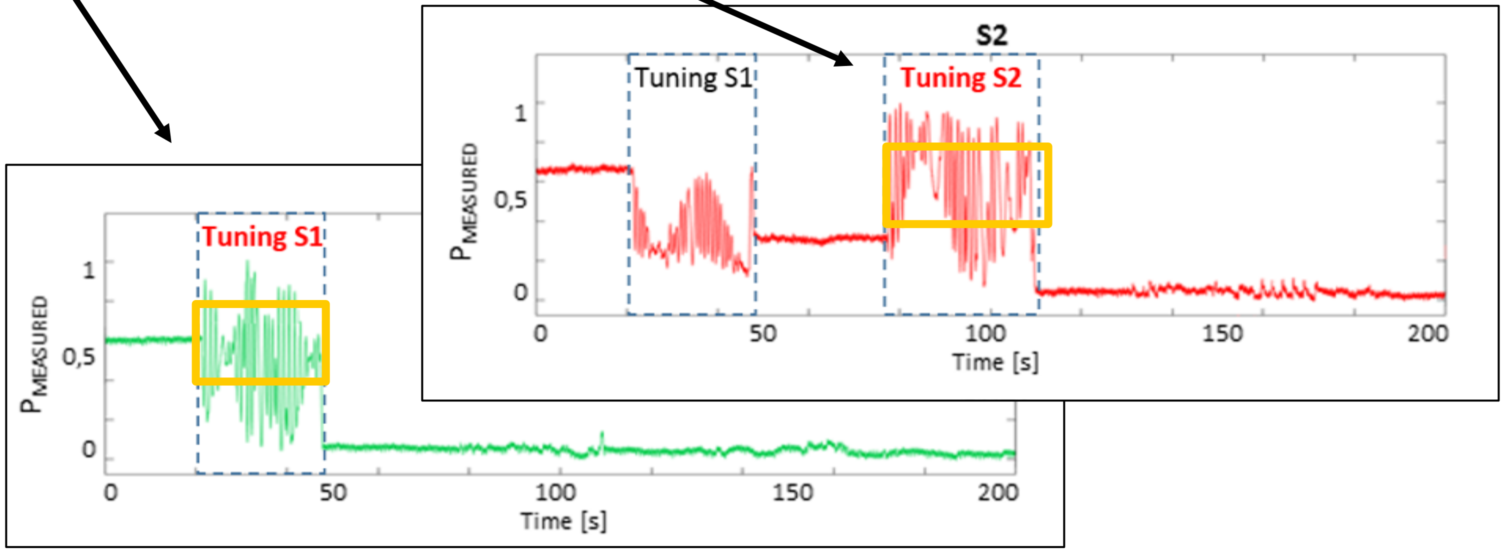




Automatic self-configuration

Output power is not maximized after each tuning step

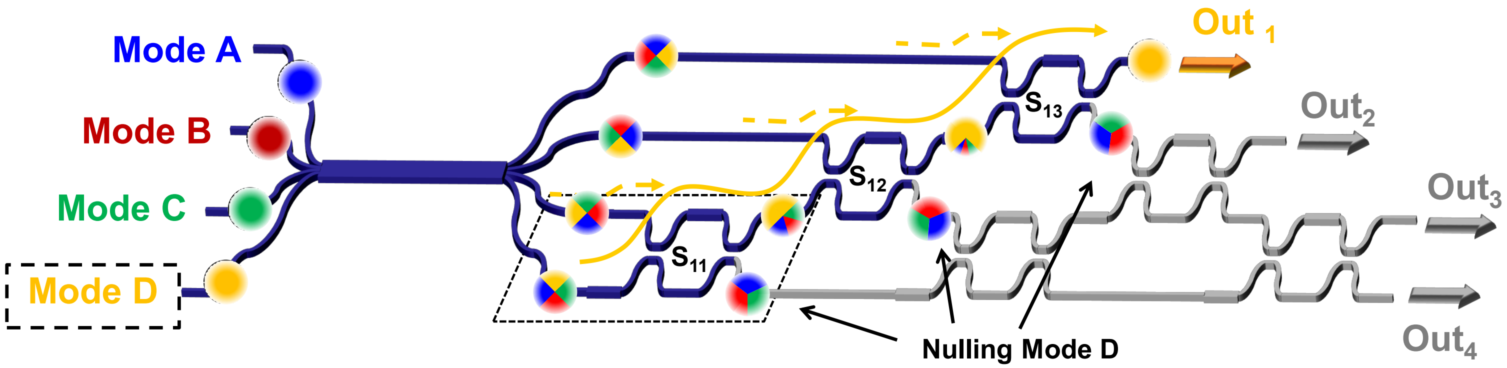




CLIPP monitoring enables…

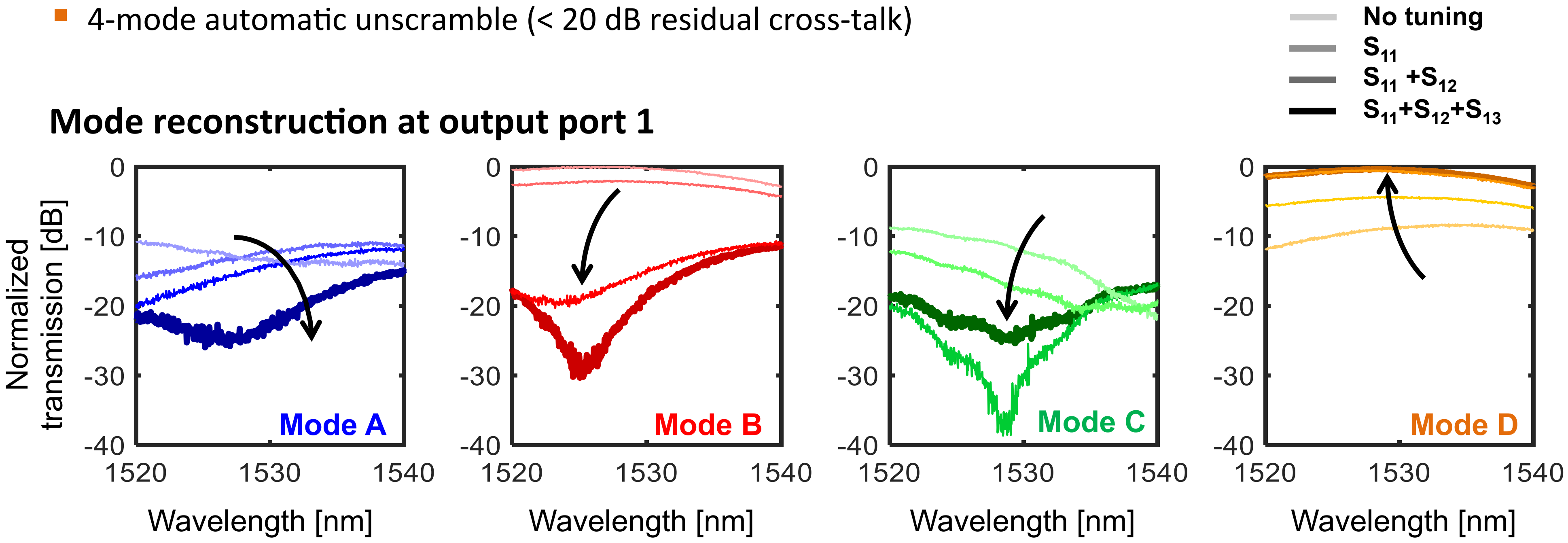
- mode monitoring preserving mode orthogonality
- mode unscrambling by <u>sequentially tuning</u> MZI stages (S_{11}, S_{12}, S_{33}, …)
- possibility to <u>feedback control</u> individual stages

All-optical mode reconstruction

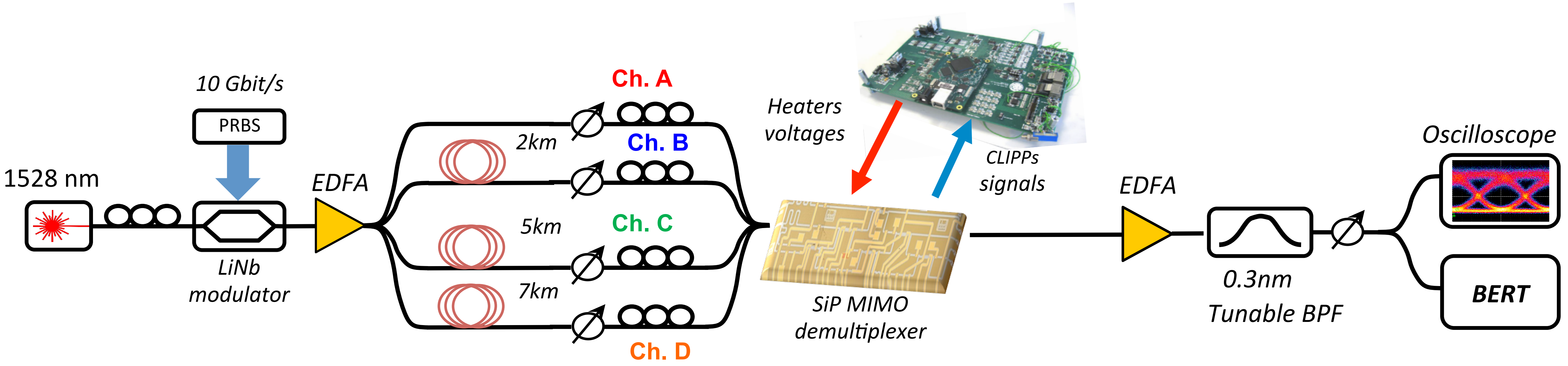


- the MZI mesh self-configures automatically and reset itself after significantly perturbing the mixing
- 4-mode automatic unscramble (< 20 dB residual cross-talk)

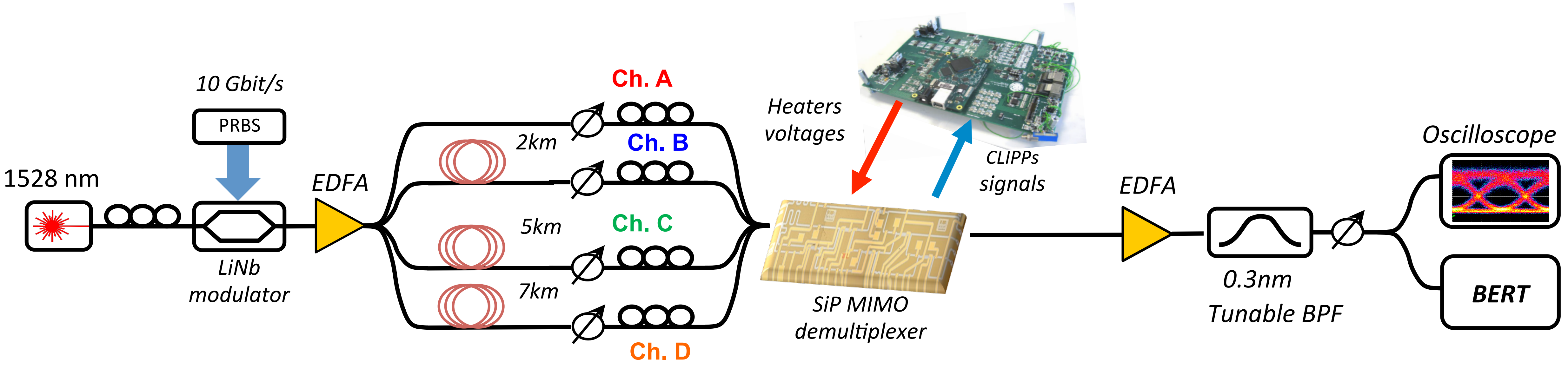
Mode reconstruction at output port 1



4x10Gbit/s channel unscrambling

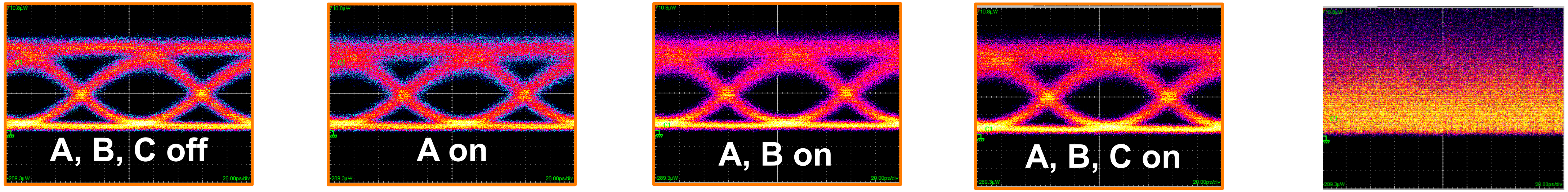


4x10 Gbit/s channel unscrambling



Extraction of Channel D from output port OUT1

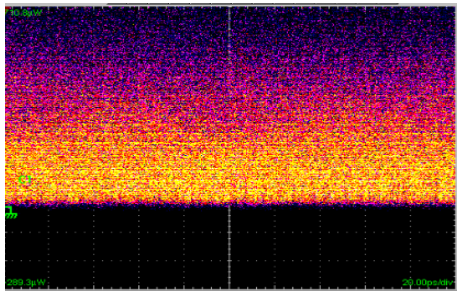
Concurrent channels OFF | 1 channel ON | 2 channels ON | 3 channels ON | 4 mixed channels No tuning



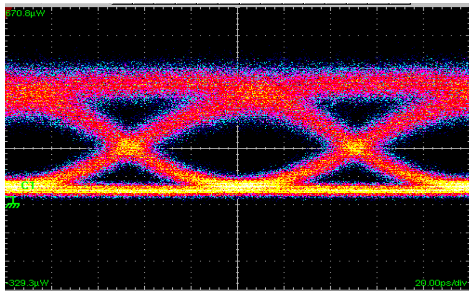
Signal unscrambling

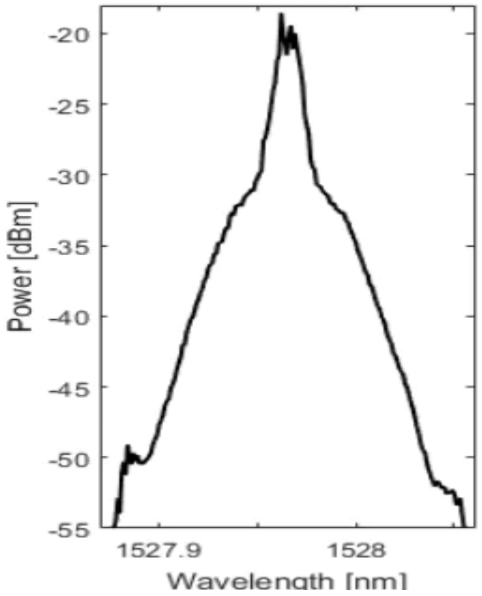
Frequency domain….

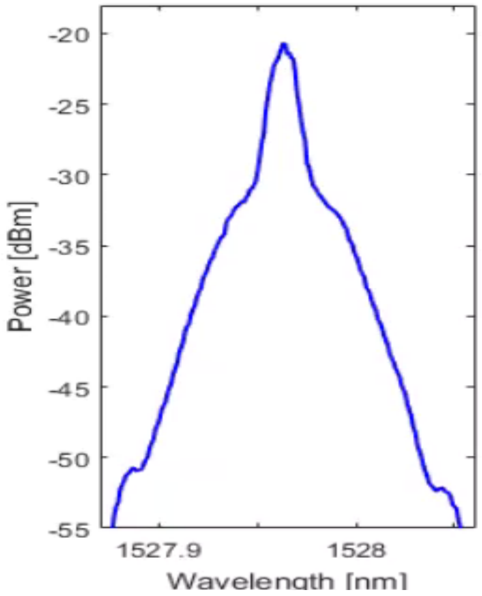
4-mixed signals



Unscrambled signal

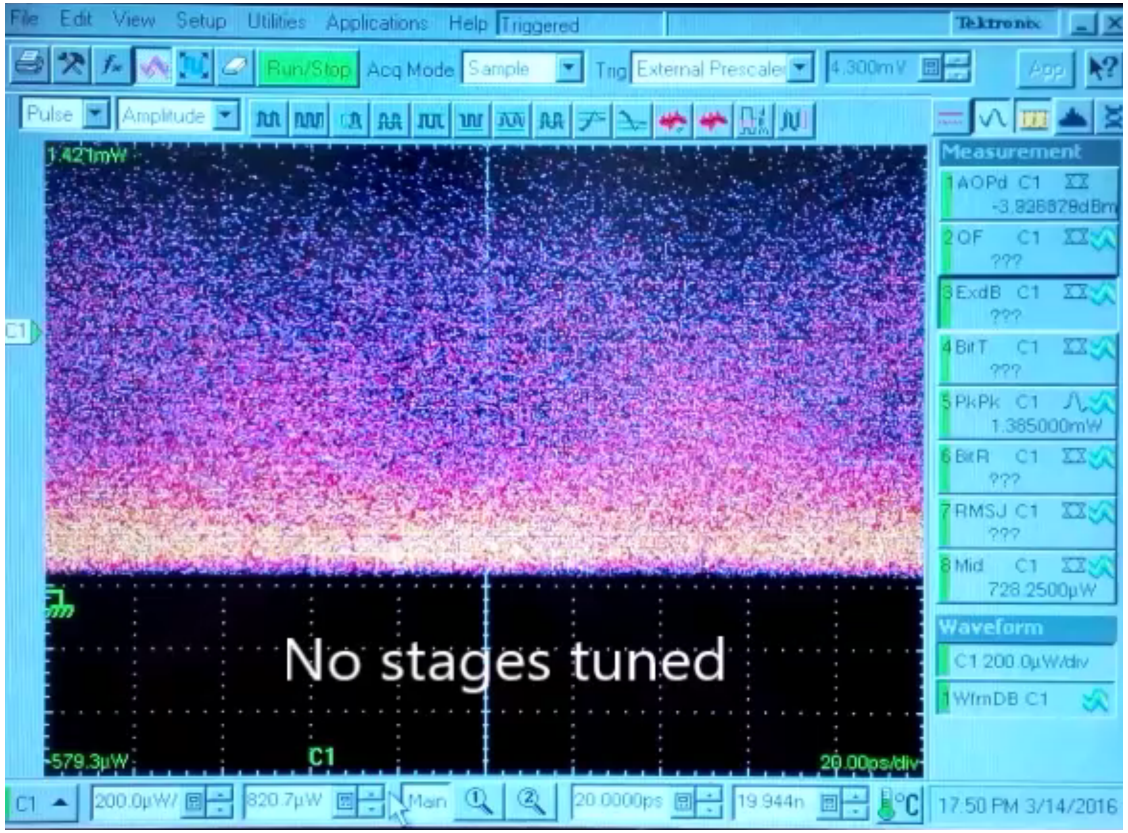






Time domain….

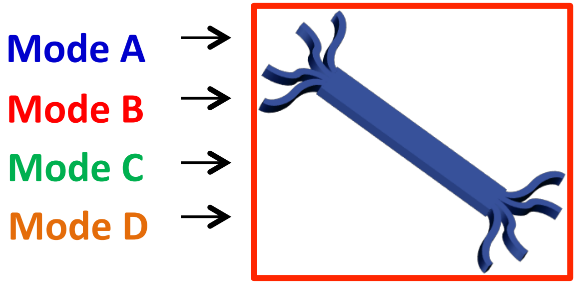
- All the 10 Gbit/s channels are switched on
- Sequential tuning of the MIMO demux for the extraction of channel A



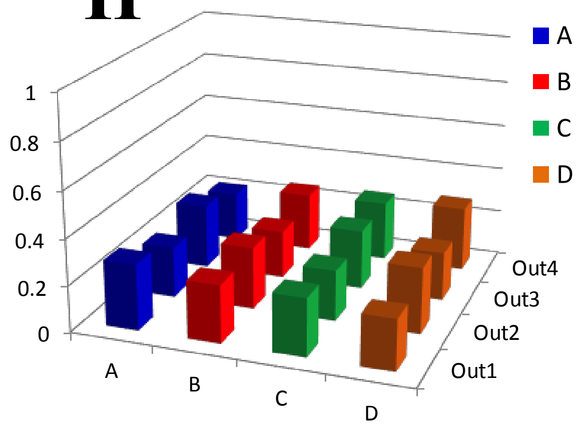
Mode sorting

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

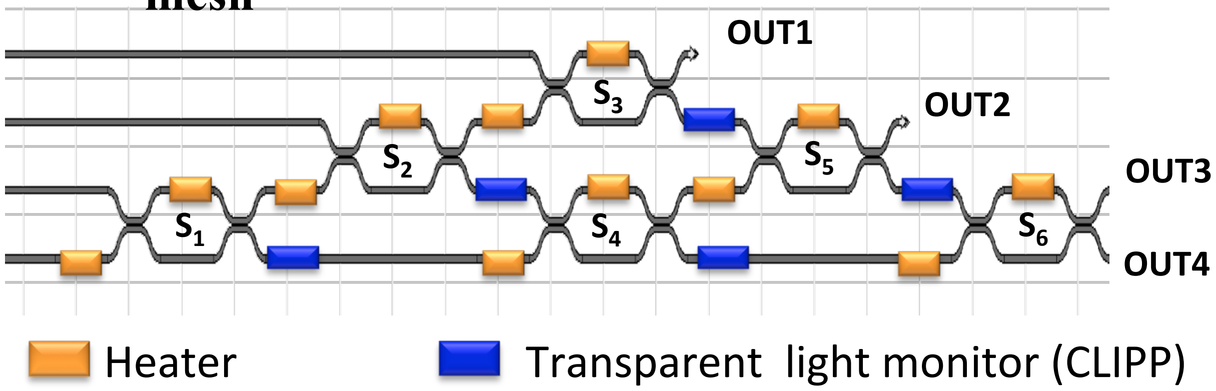
Mode mixer



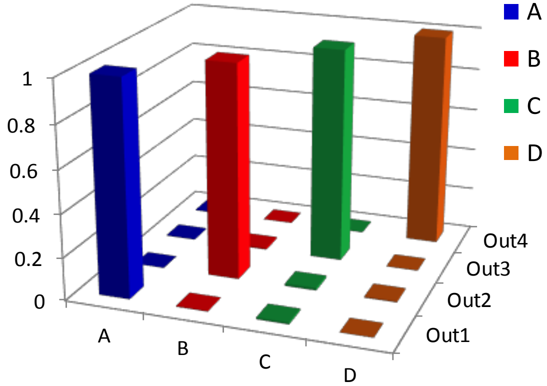
H



H$_{\mathbf{mesh}}$

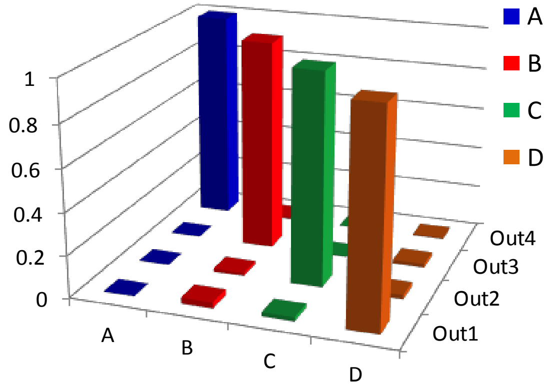


A, B, C, D



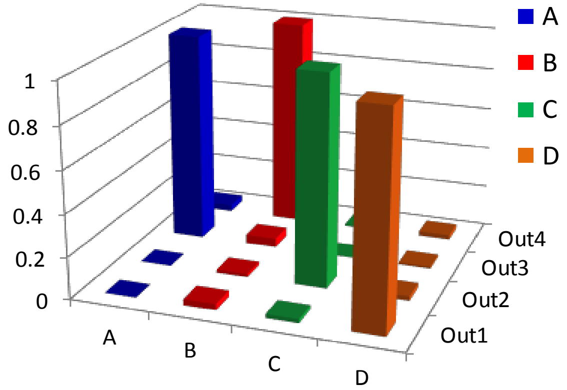
$$\left|\mathbf{H}_{mesh}\mathbf{H}\right|^2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

D, C, B, A



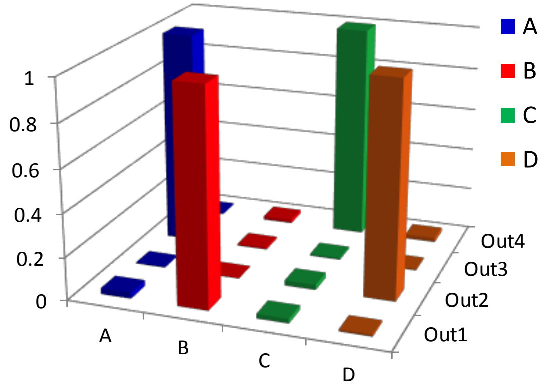
$$\left|\mathbf{H}_{mesh}\mathbf{H}\right|^2 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

D, C, A, B



$$\left|\mathbf{H}_{mesh}\mathbf{H}\right|^2 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

B, D, A, C



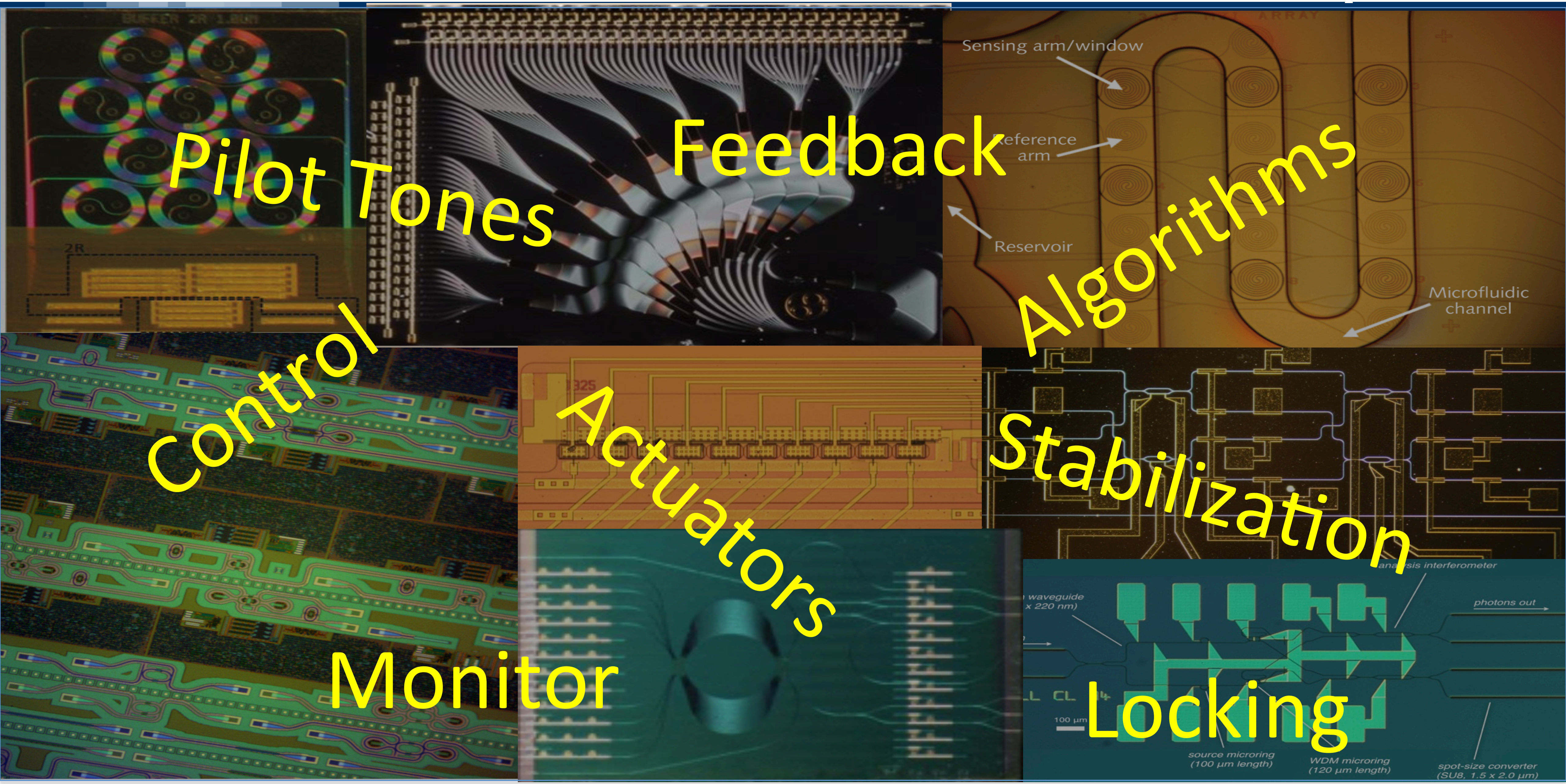
$$\left|\mathbf{H}_{mesh}\mathbf{H}\right|^2 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Conclusions

How many tools are needed... !

- Advanced (statistical) analysis software tools (circuit simulator)
- Robust design techniques (design on tolerance)
- Statistical PDKs
- Characterization techniques
- Hitless monitors... CLIPP !!
- Algorithms: Tuning, Locking, Routing (non invasive, circuit dependent)
- Pilot tones (for wavelength, polarization, mode and circuit routing)

Integrated photonics: ubiquitousness and complexity to be controlled



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http://www.ict-streams.eu/

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