Programmable Photonic Integrated Circuits

Wim Bogaerts

NB Photonics – 11 October 2019

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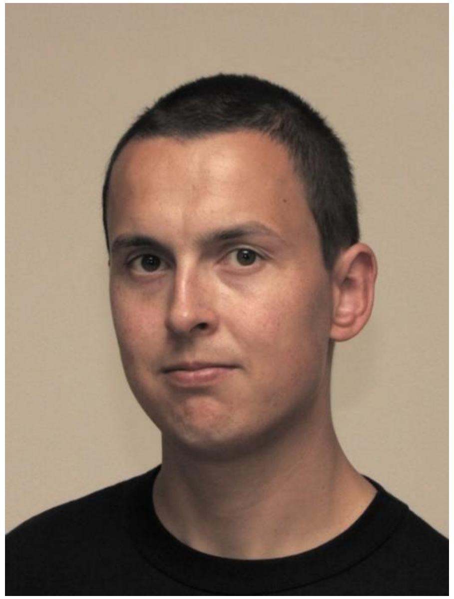
embracing a better life

Wim Bogaerts



1998 – Ghent University - M.Sc. Engineering - Applied Physics
2004 – Ghent University, imec - Ph.D. EE. Engineering (Photonics)

“Nanophotonic Waveguides and Photonic Crystals in SOI”

2004 – 2010 – Ghent University, imec - Postdoc

2010 – Lecturer

2011 – Senior lecturer (tenure)

2013 – Black belt in LEAN

2014 – Spin-off company *Luceda Photonics*

2016 – ERC consolidator grant PhotonicSWARM

2018 – Travelling Lecturer for the OSA

2019 – Invited Professor at EPFL (Q-LAB)

LUCEDA PHOTONICS

EPFL

erc European Research Council

OSA Traveling Lecturer Program

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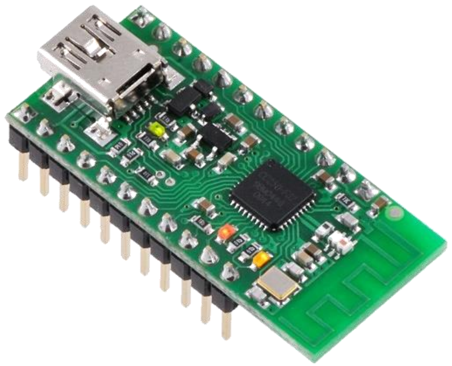
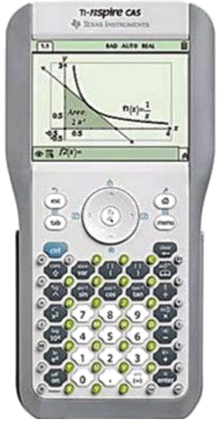
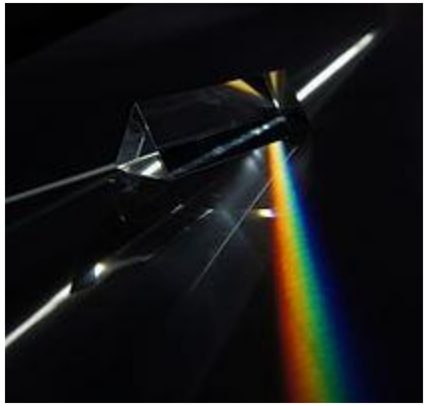
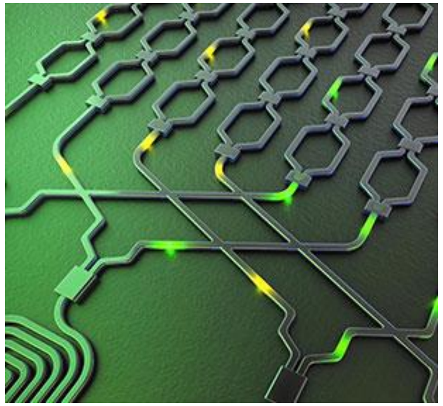
Programmable Photonics: What is in a name?



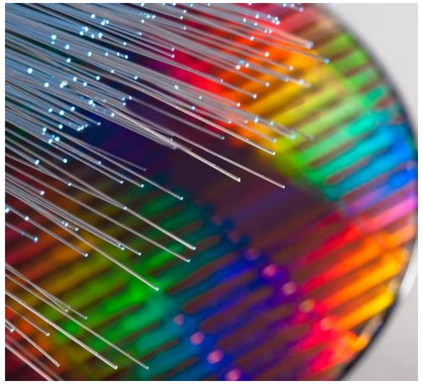
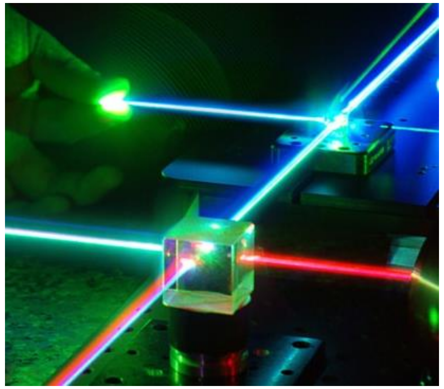


Programmable Photonics

We manipulate functionality in software

We manipulate light on a small scale

Programmable Photonics: What is in a name?

Programmable Photonics

We manipulate light in software on a small scale

Why? Because light contains information

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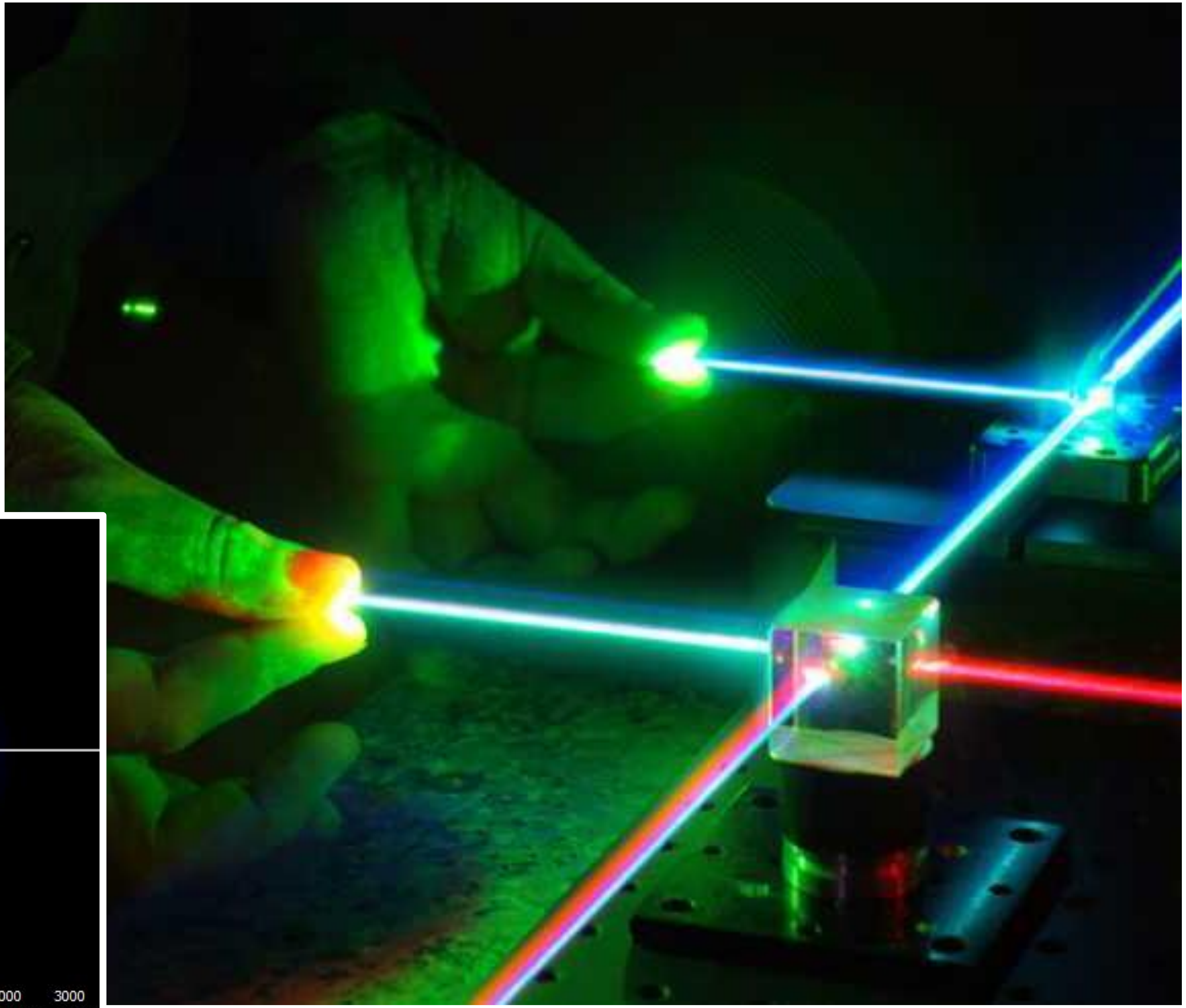
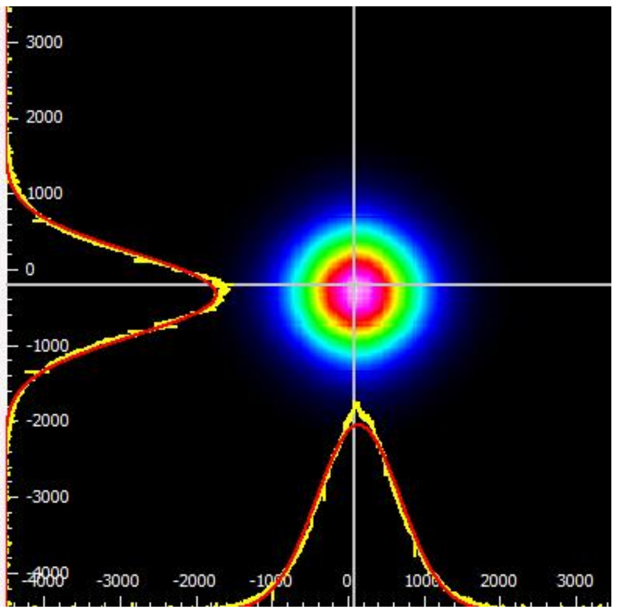
Manipulating Beams of Light

Beams of light contain information

- Total power
- Intensity profile
- Phase profile
- Wavelength
- Polarization





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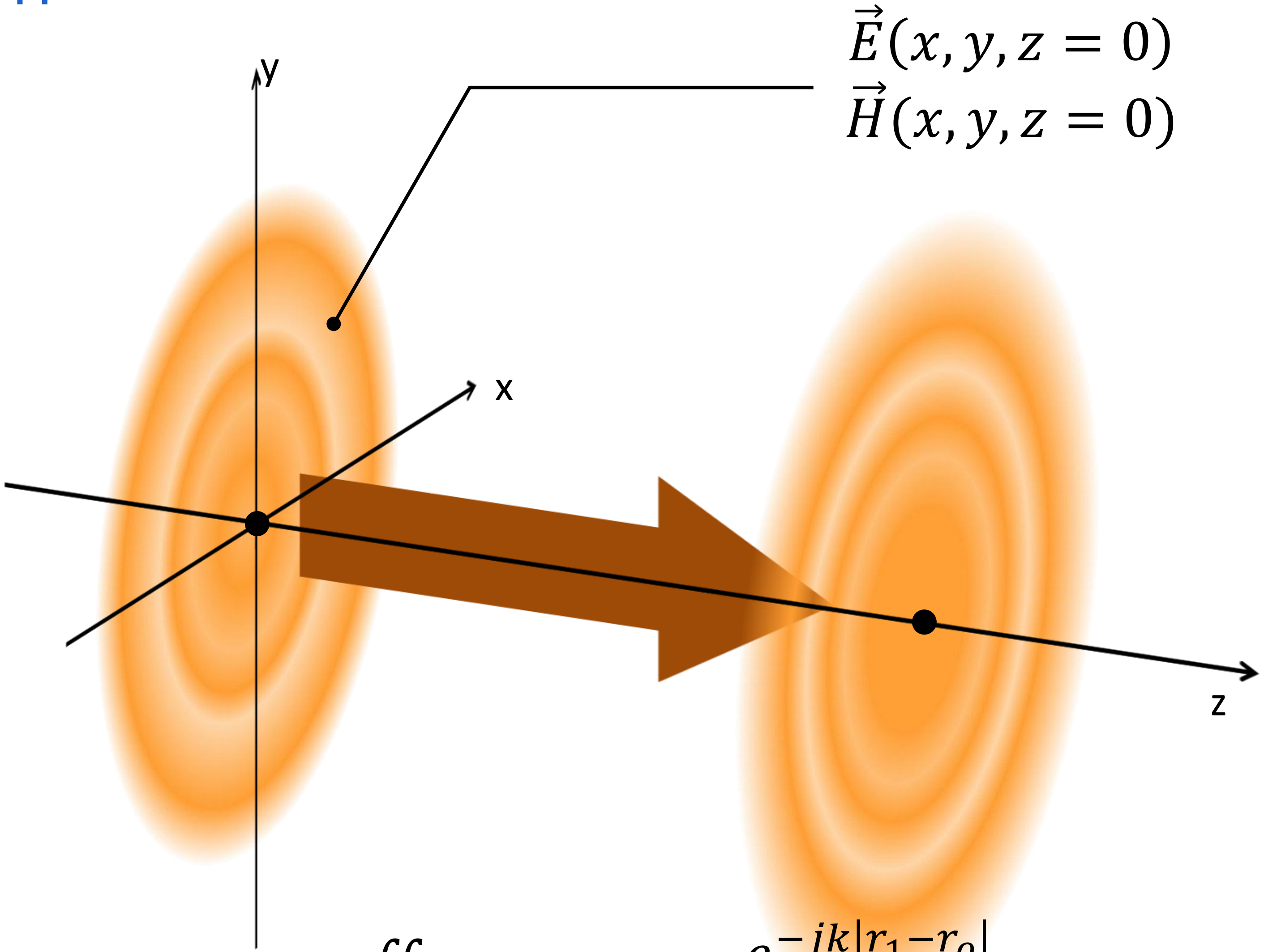


Can we process this information?

yes, as the beam propagates

$$\vec{E}(x, y, z_0) \cong \iint j\vec{E}(x', y', 0).\frac{e^{-jk|r_1 - r_o|}}{\lambda z} dx'dy'$$

(Fresnel diffraction)

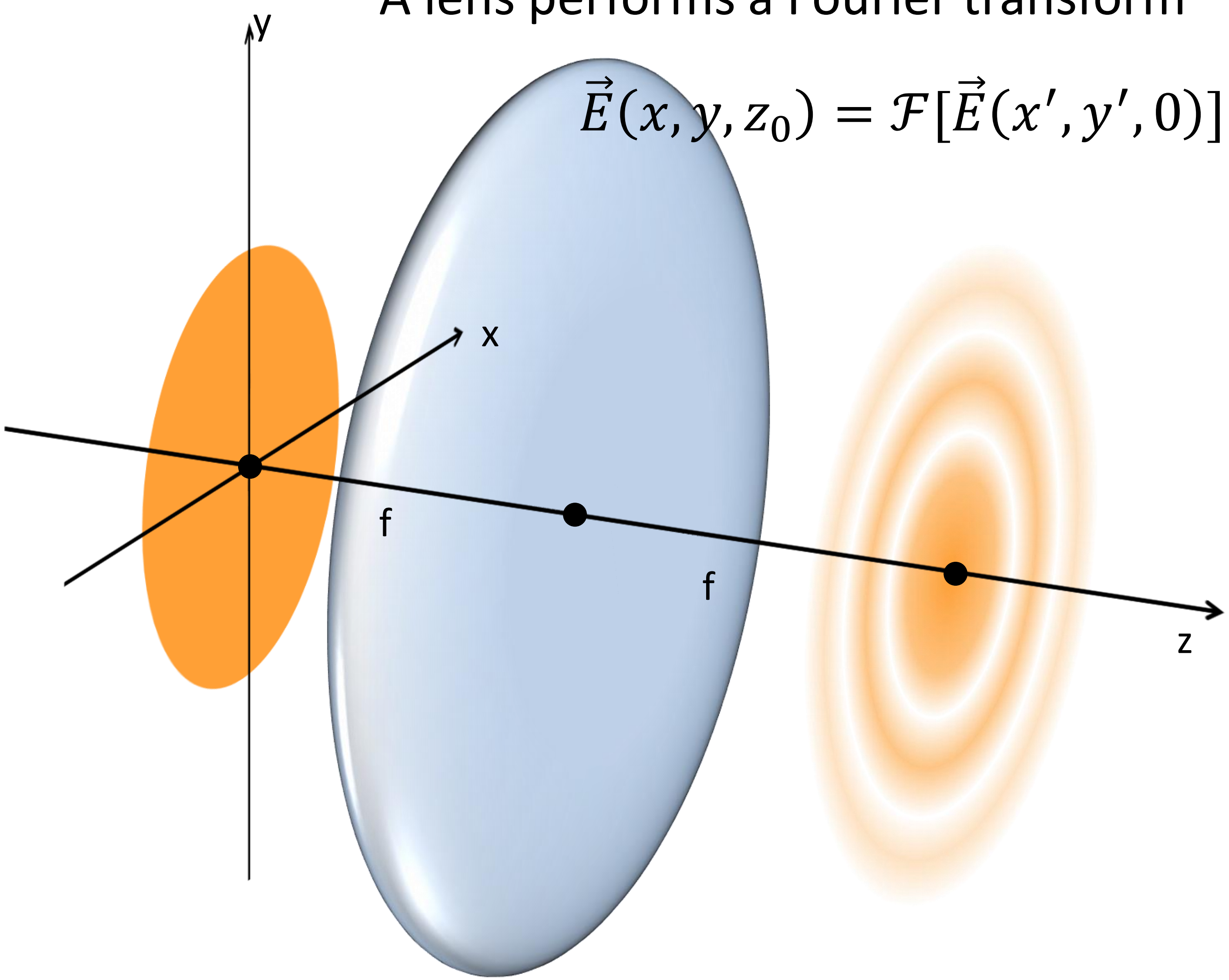
Manipulating Beams of Light

Using optical elements

- Lenses
- Mirrors
- Polarizers
- Shutters
- Spatial filters
- Wavelength filters
- Phase plates
- Spatial light modulators

A lens performs a Fourier transform

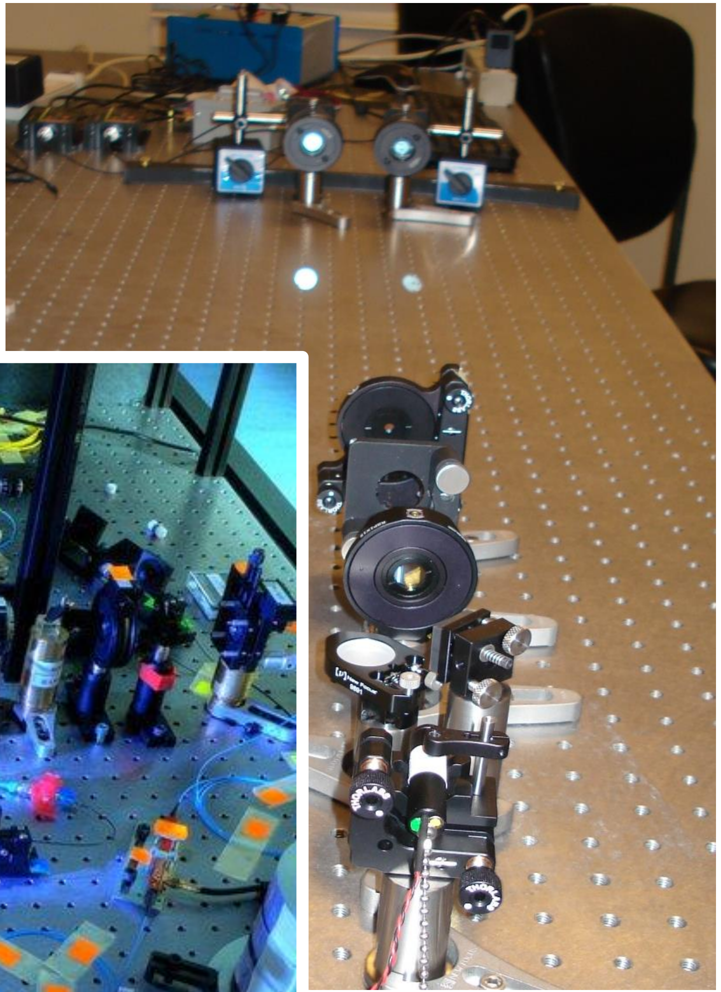
$$\vec{E}(x, y, z_0) = \mathcal{F}[\vec{E}(x', y', 0)]$$



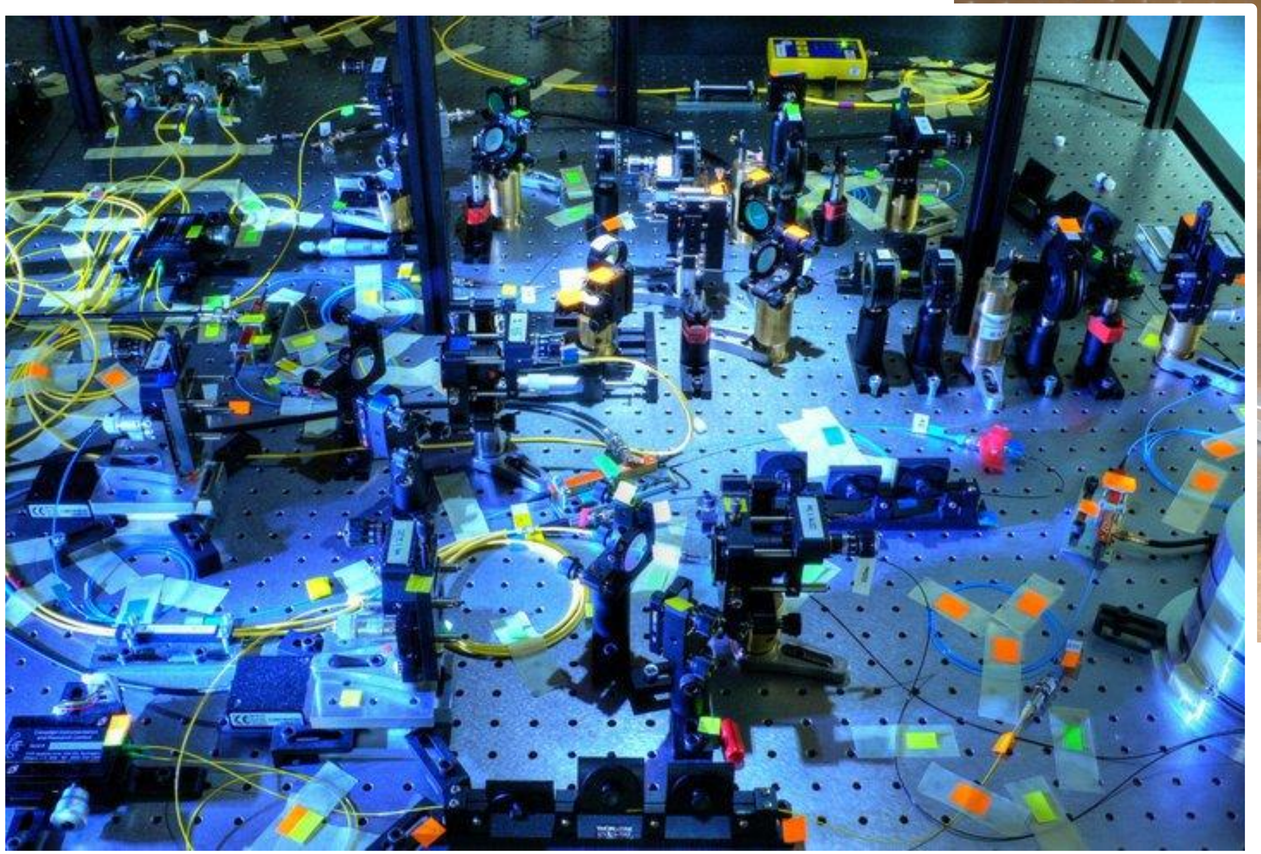
Manipulating Beams of light in Free space

Using optical elements

- Lenses
- Mirrors
- Polarizers
- Shutters
- Spatial filters
- Wavelength filters
- Phase plates



Still quite coarse



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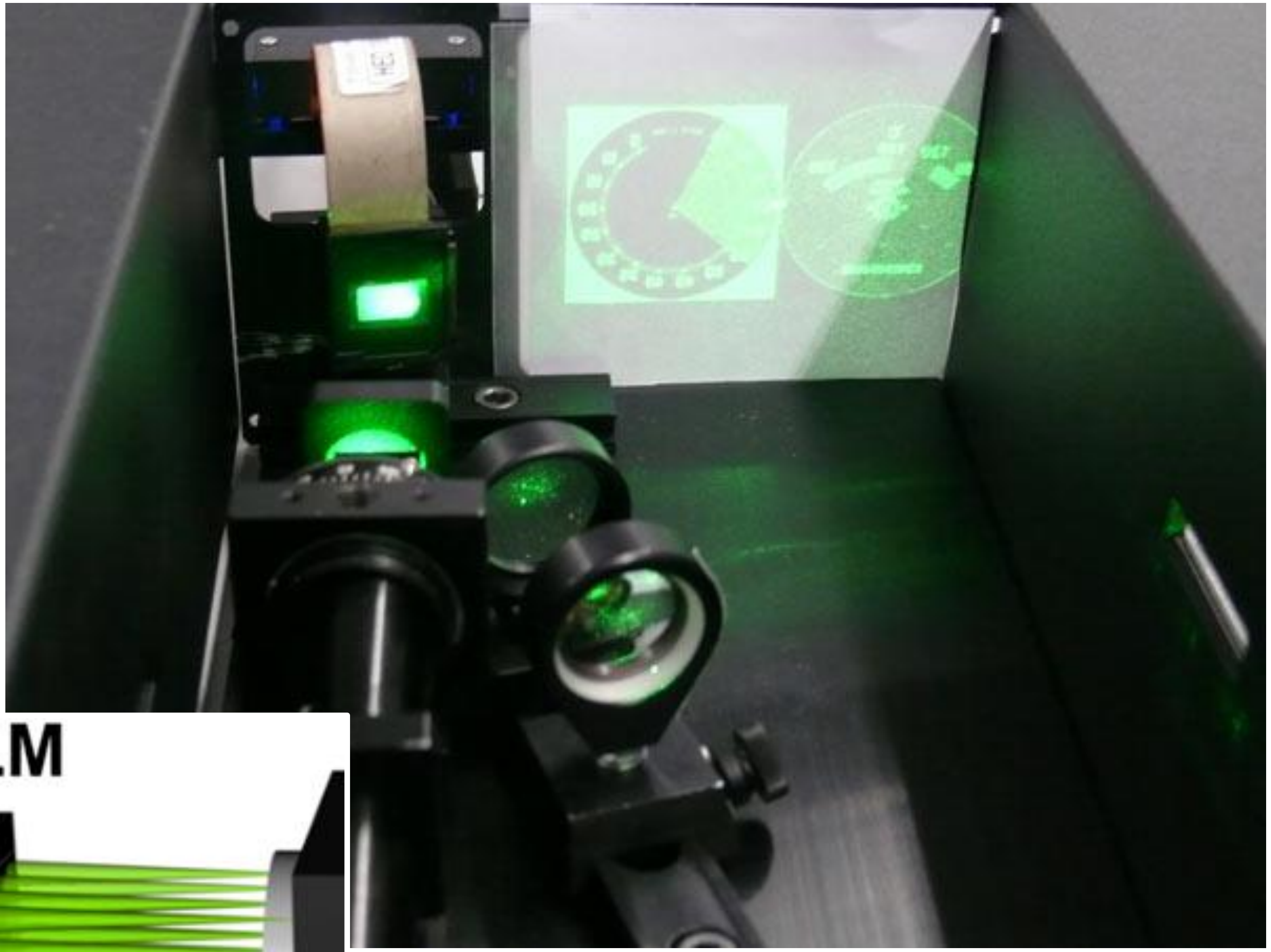
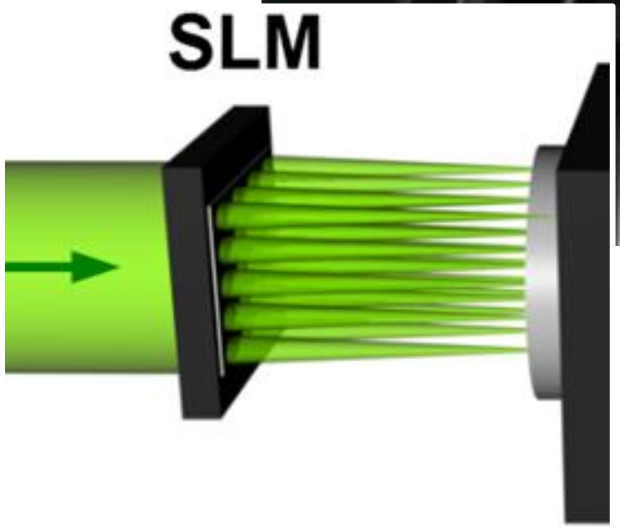
MANIPULATING BEAMS OF LIGHT

Active, granular manipulation

- Spatial light modulators
  - amplitude
  - phase
  - polarization
- Micromirror arrays
- Grating light valves
- Deformable mirrors





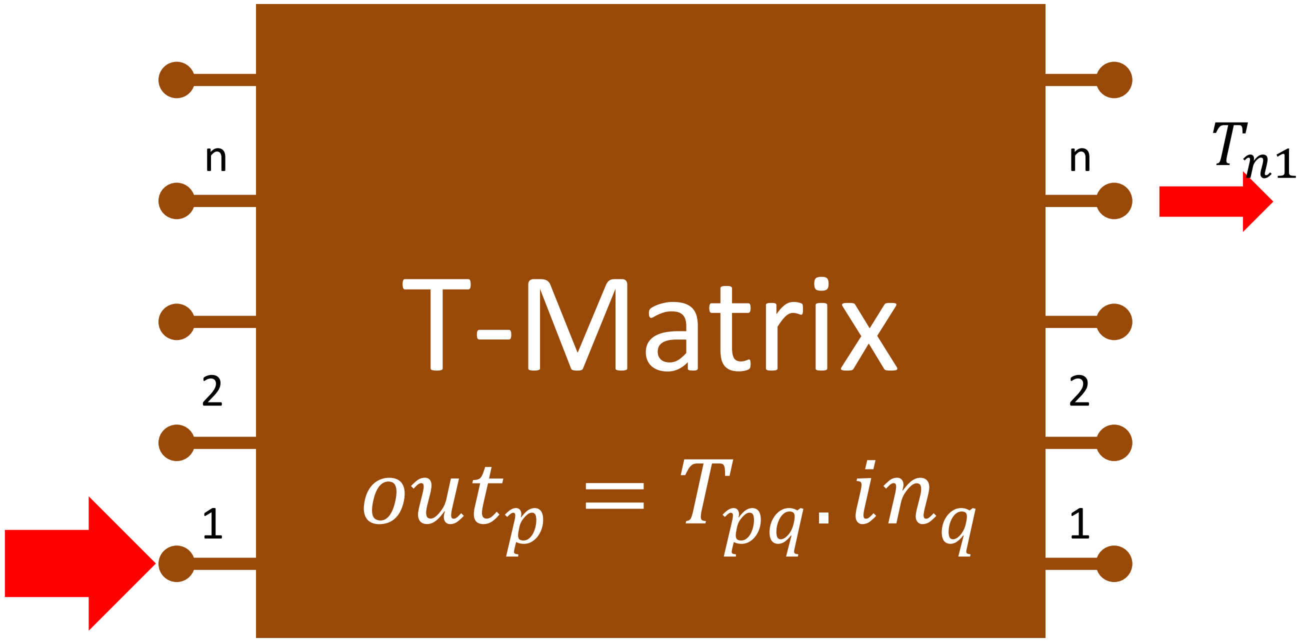
Can be controlled in Software

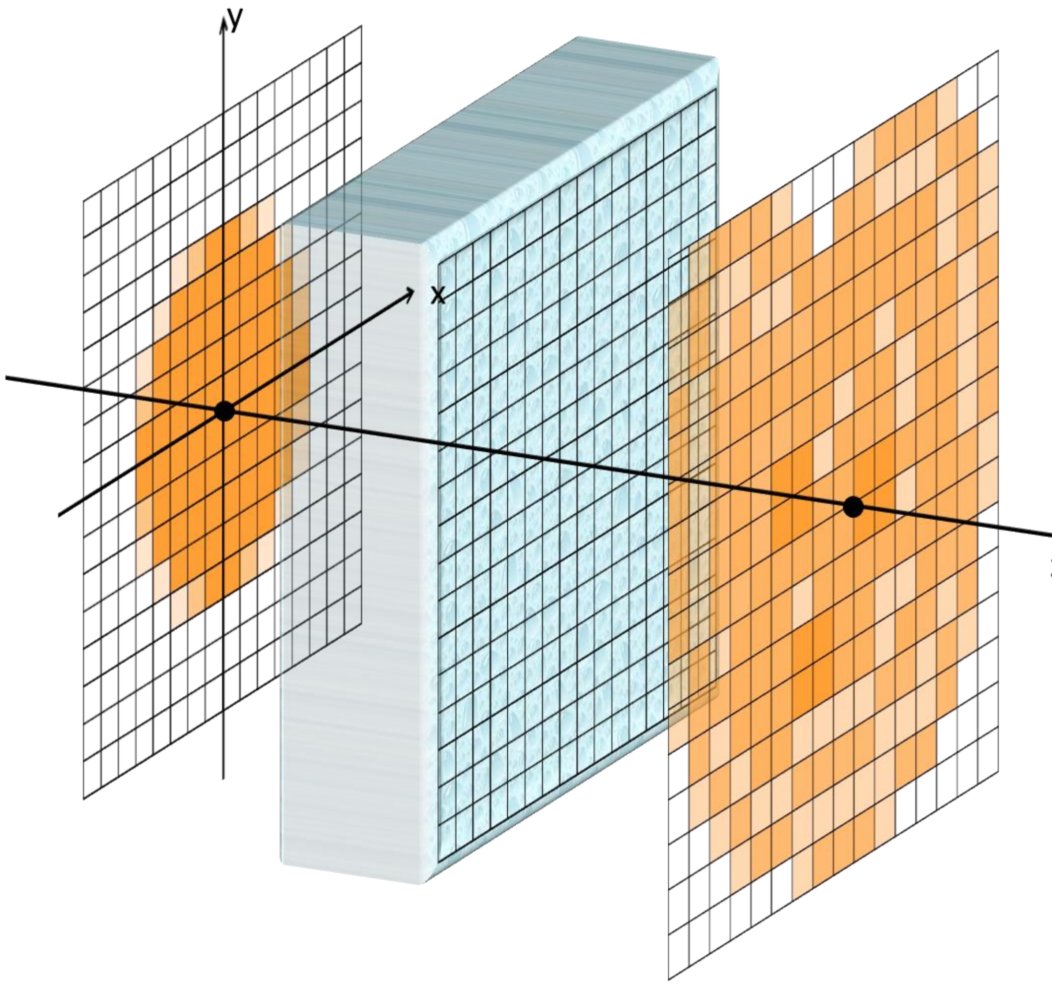
Discretized Linear Operations

Discretized linear operation

Matrix is unitary if

- no reflection
- no loss

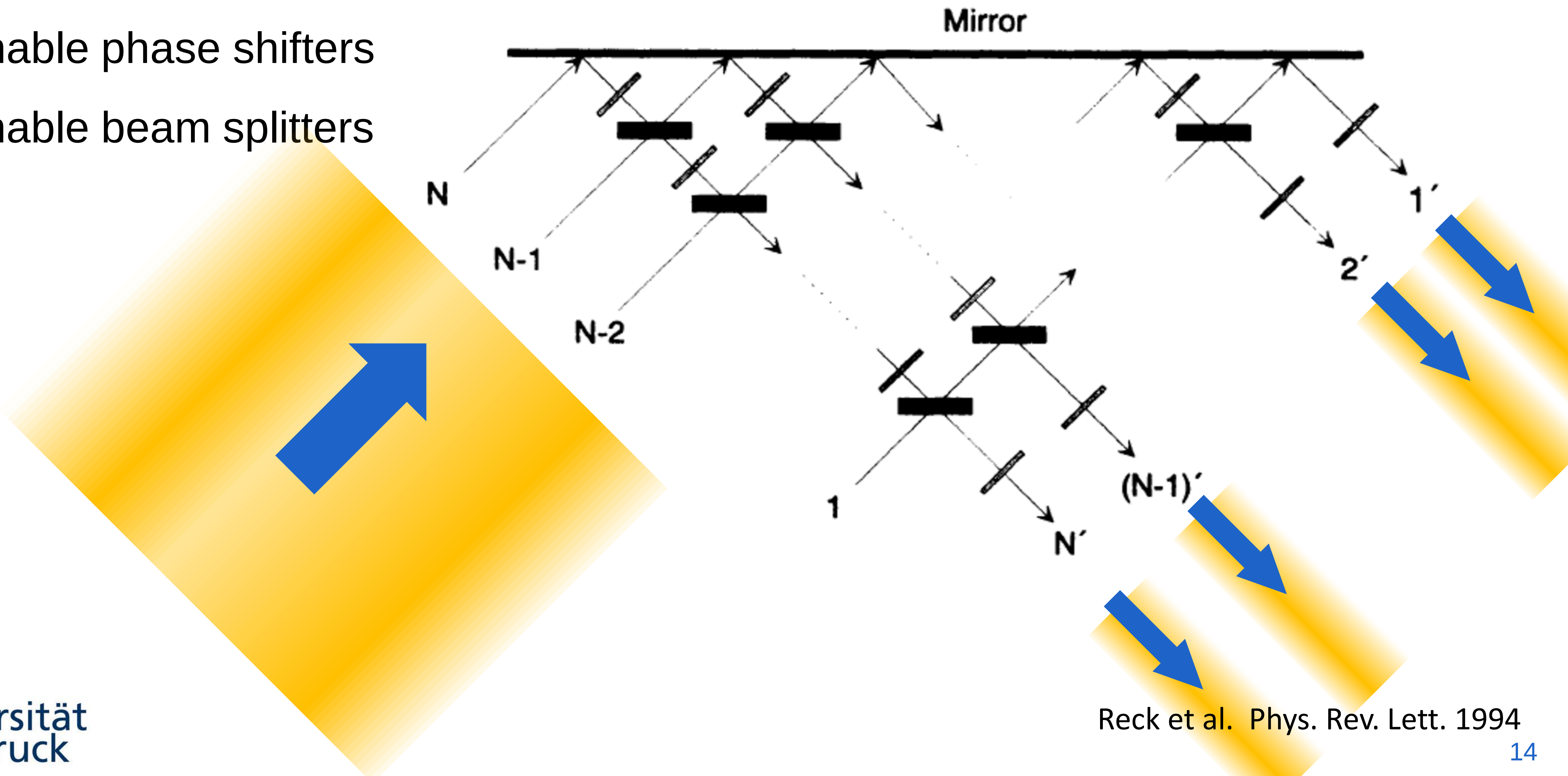




Discretized Linear Operations (Reck 1994)

Processing with

- tunable phase shifters
- tunable beam splitters



Reck et al. Phys. Rev. Lett. 1994

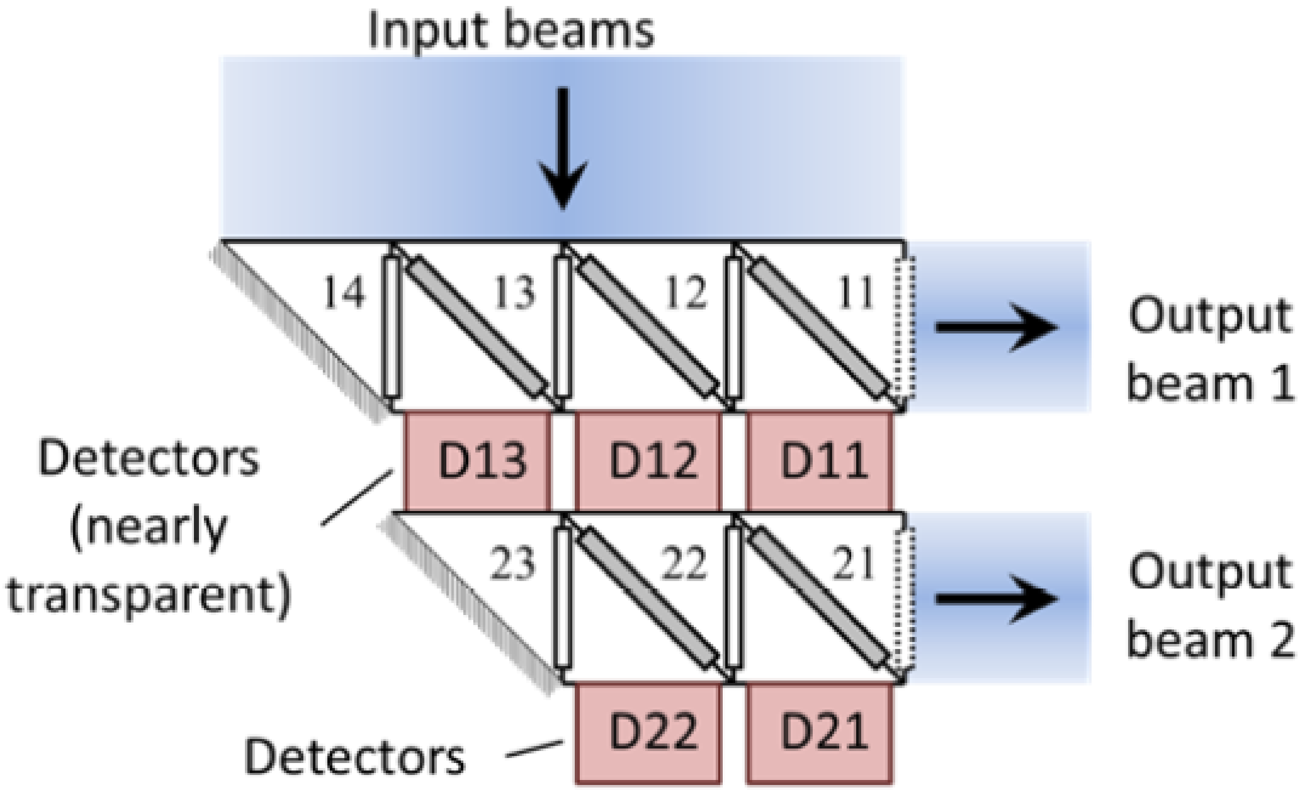
Universal Linear Optics (Miller 2013)

Processing with

- tunable phase shifters
- tunable beam splitters

+ monitor detectors

+ control algorithms

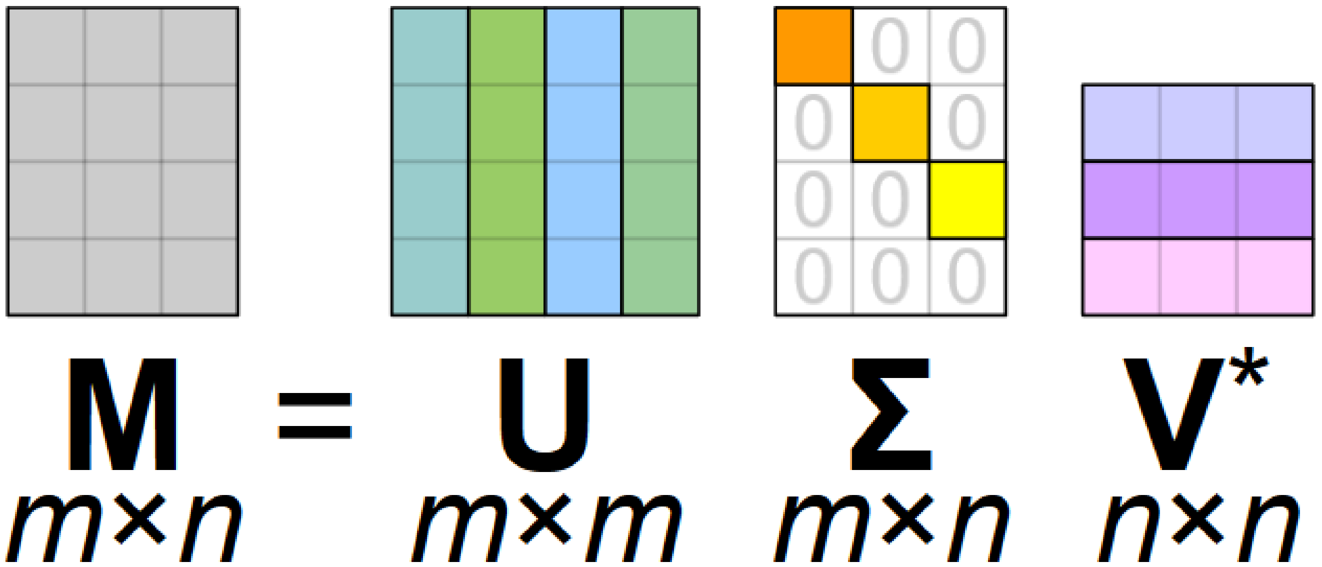


CONTRUCTING AN ARBITRARY T-MATRIX

Singular Value Decomposition: A general $m \times n$ matrix

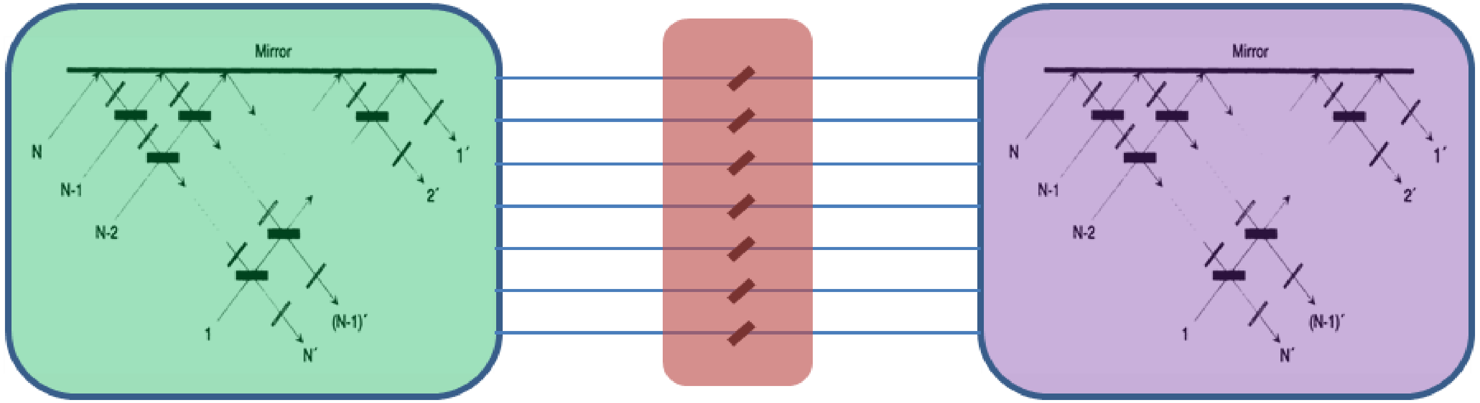
can be decomposed into:

- A unitary $m \times m$ matrix
- A diagonal $m \times n$ matrix
- A unitary $n \times n$ matrix



(this is not the only way

to construct this matrix)



Manipulating Beams of light in Free space

Using optical elements

- Lenses
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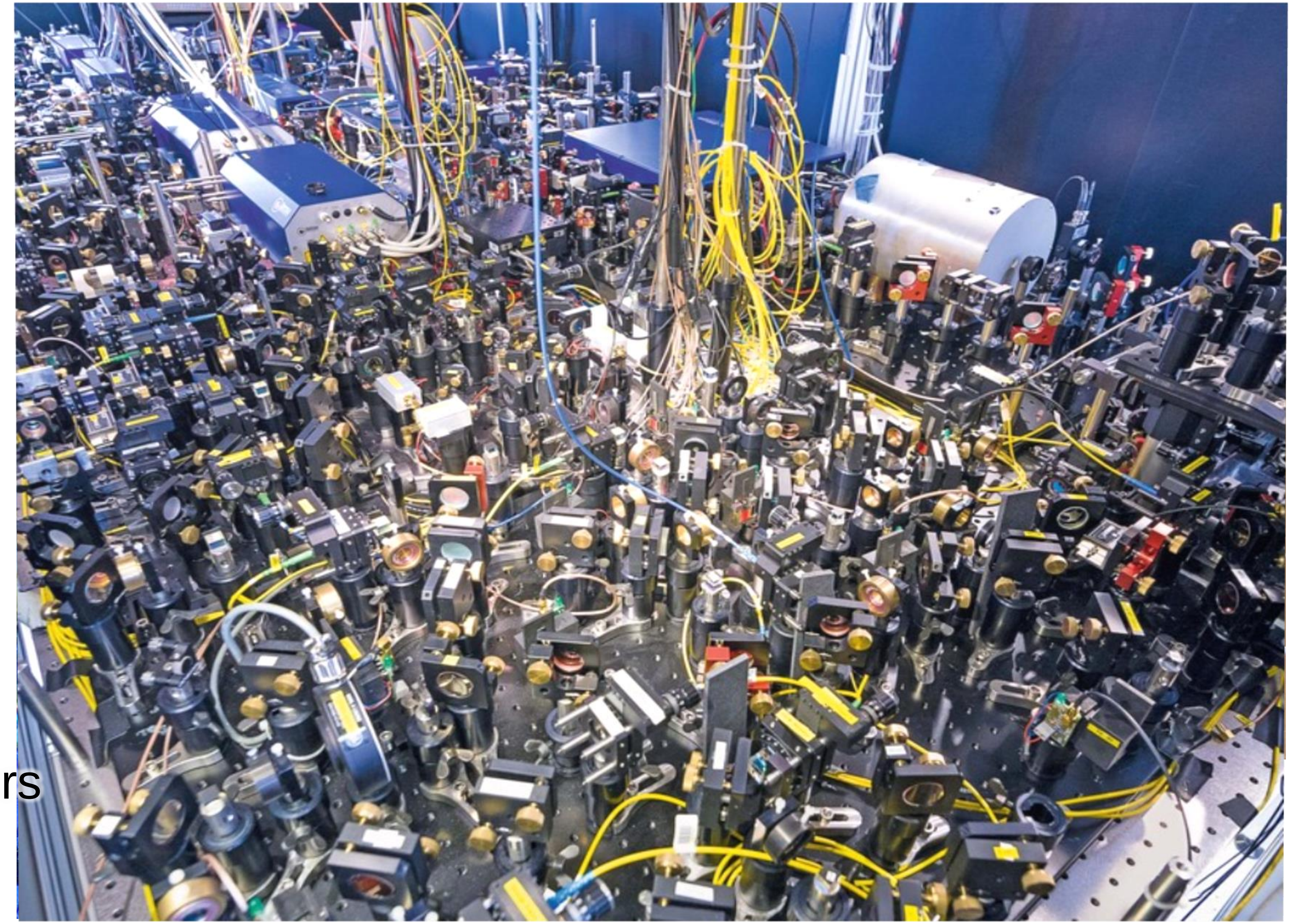

Does not scale very well

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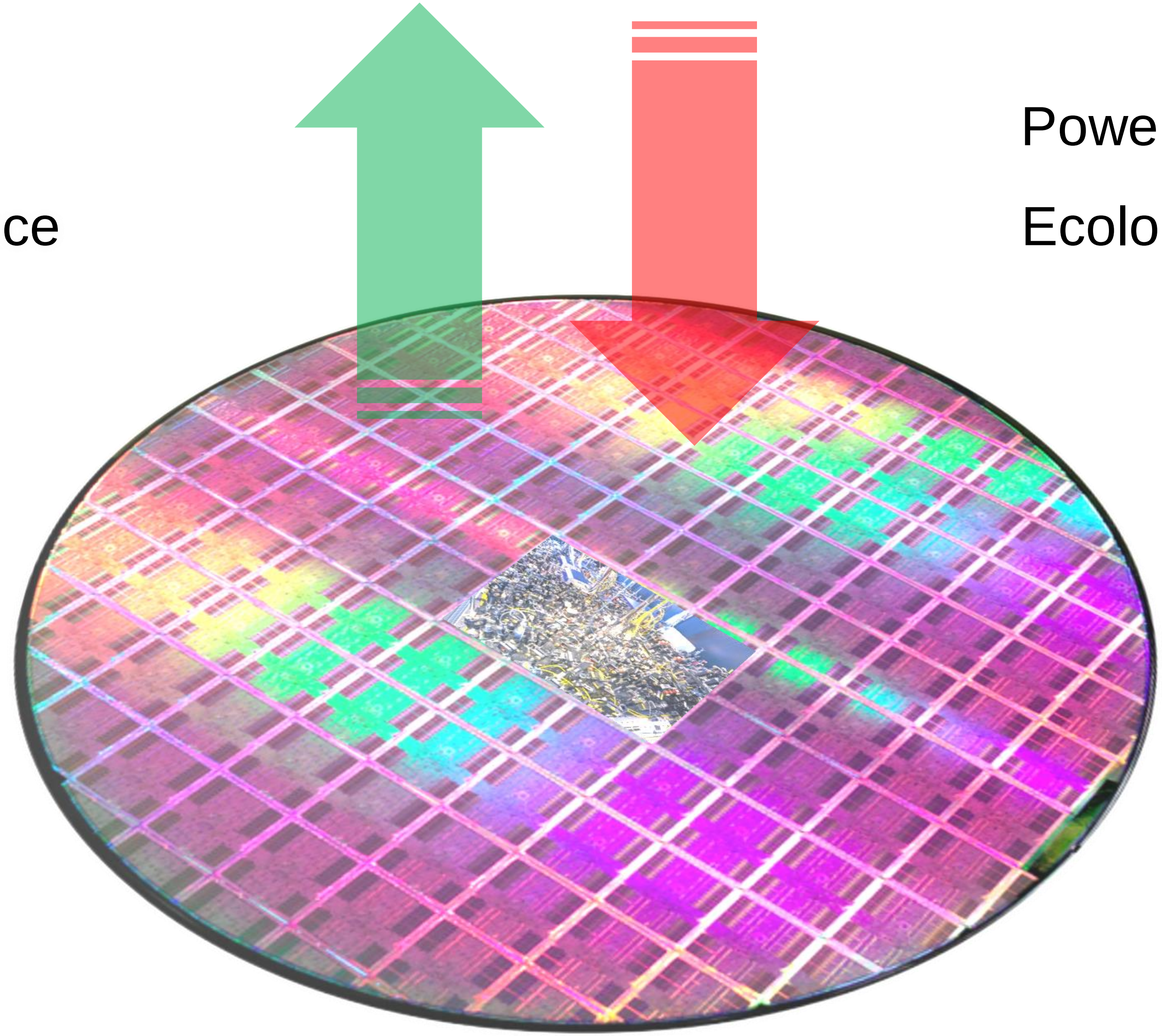
Bringing Beams of light to the chip



Complexity

Overall Performance

Reliability

Ergonomy

goes up

Power consumption

Ecological Footprint

Cost

goes down

Photonic Integrated Circuits: What's in a Name?

Probably something to do with light…

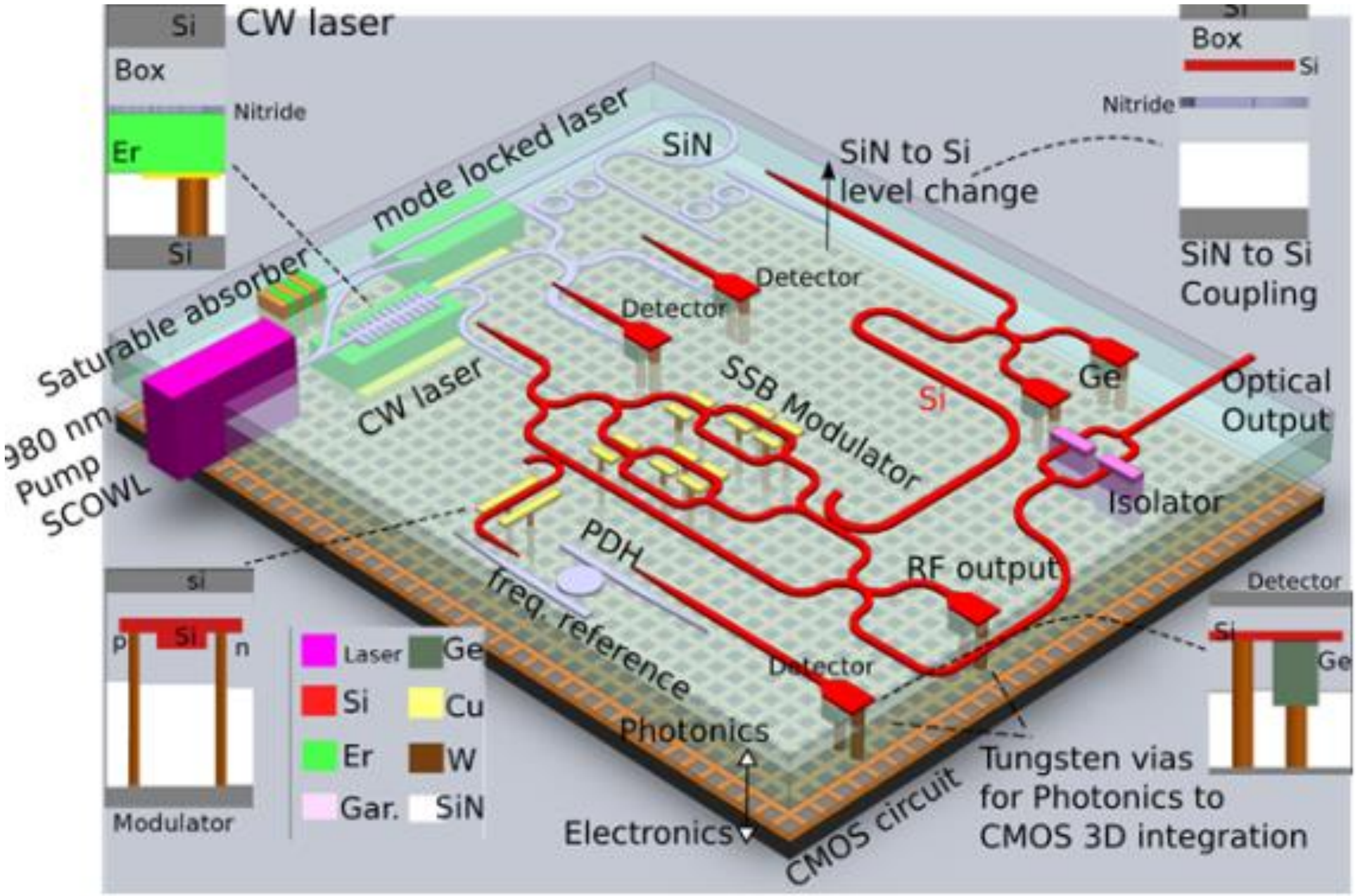
Photonic Integrated Circuit

Combining stuff together into something coherent

signals travel around from one element to another

PHOTONIC INTEGRATED CIRCUITS (PIC)

Integration of (many) optical functions on a chip



Source: EECS Berkeley

What is <u>silicon</u> photonics?

The implementation of <u>high density</u> photonic integrated circuits by means of CMOS process technology <u>in a CMOS fab</u>

Complex functionality, compact chip, low cost, high volumes

WHY SILICON PHOTONICS?

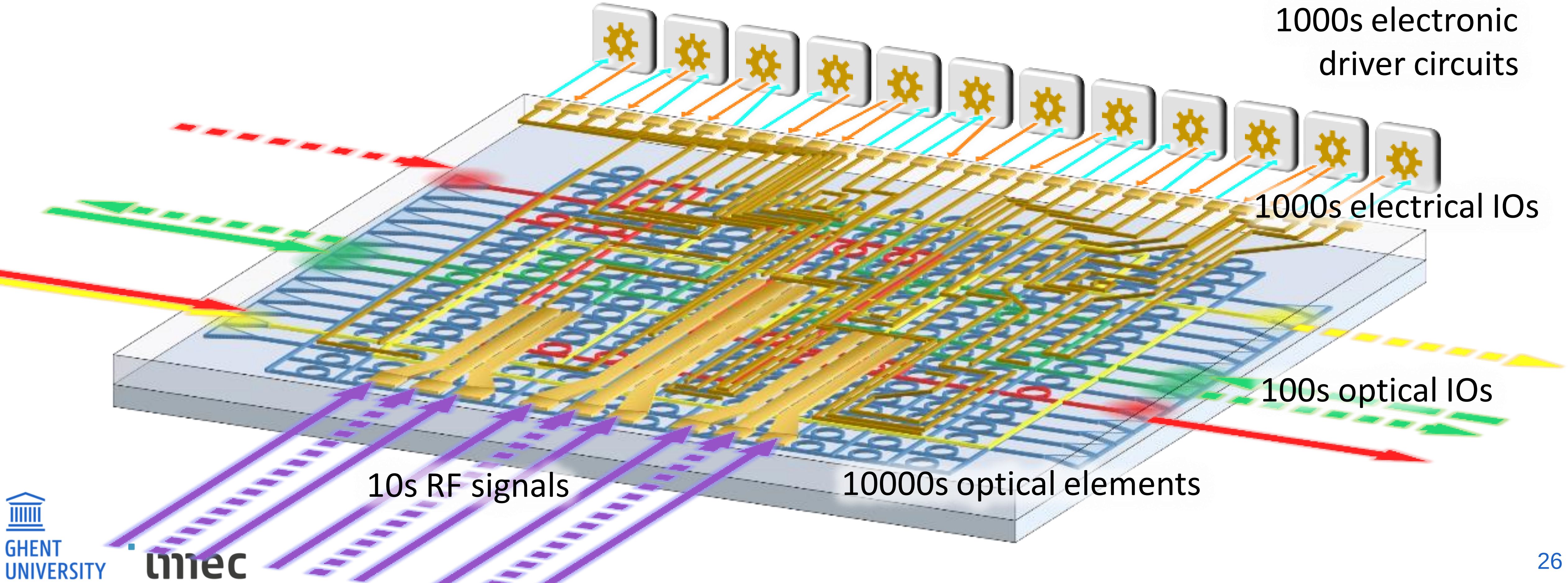
Large scale manufacturing

Scale

Submicron-scale waveguides

More than just photons

Silicon photonics goes beyond the optical chip

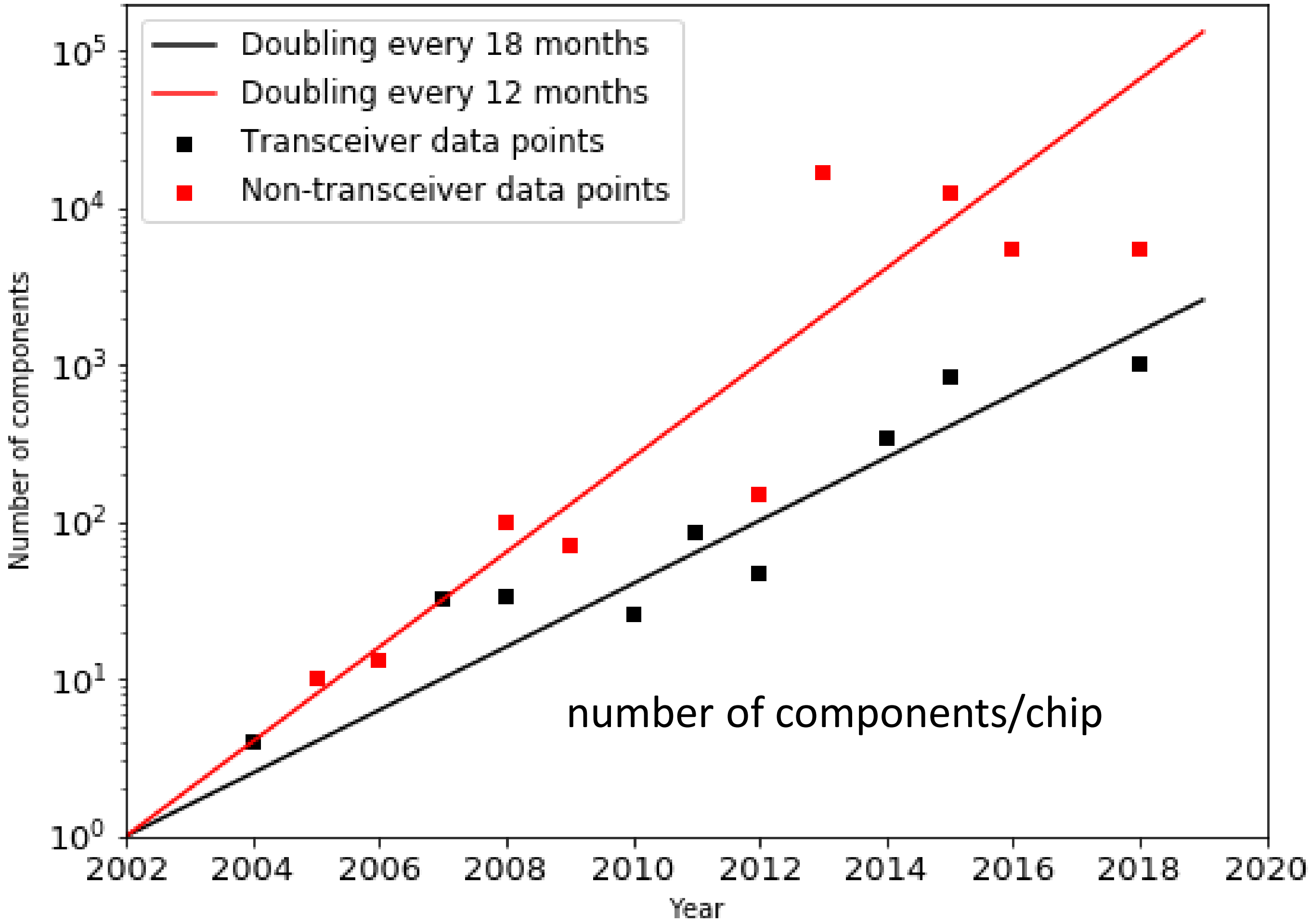


Silicon Photonic Circuits Today

Rapidly growing integration

- O(1000) components on a chip
- photonics + electronic drivers
- different applications
  (still mostly communication)
- Relatively small chip volumes
  (compared to electronics)

All photonic circuits are ASICs

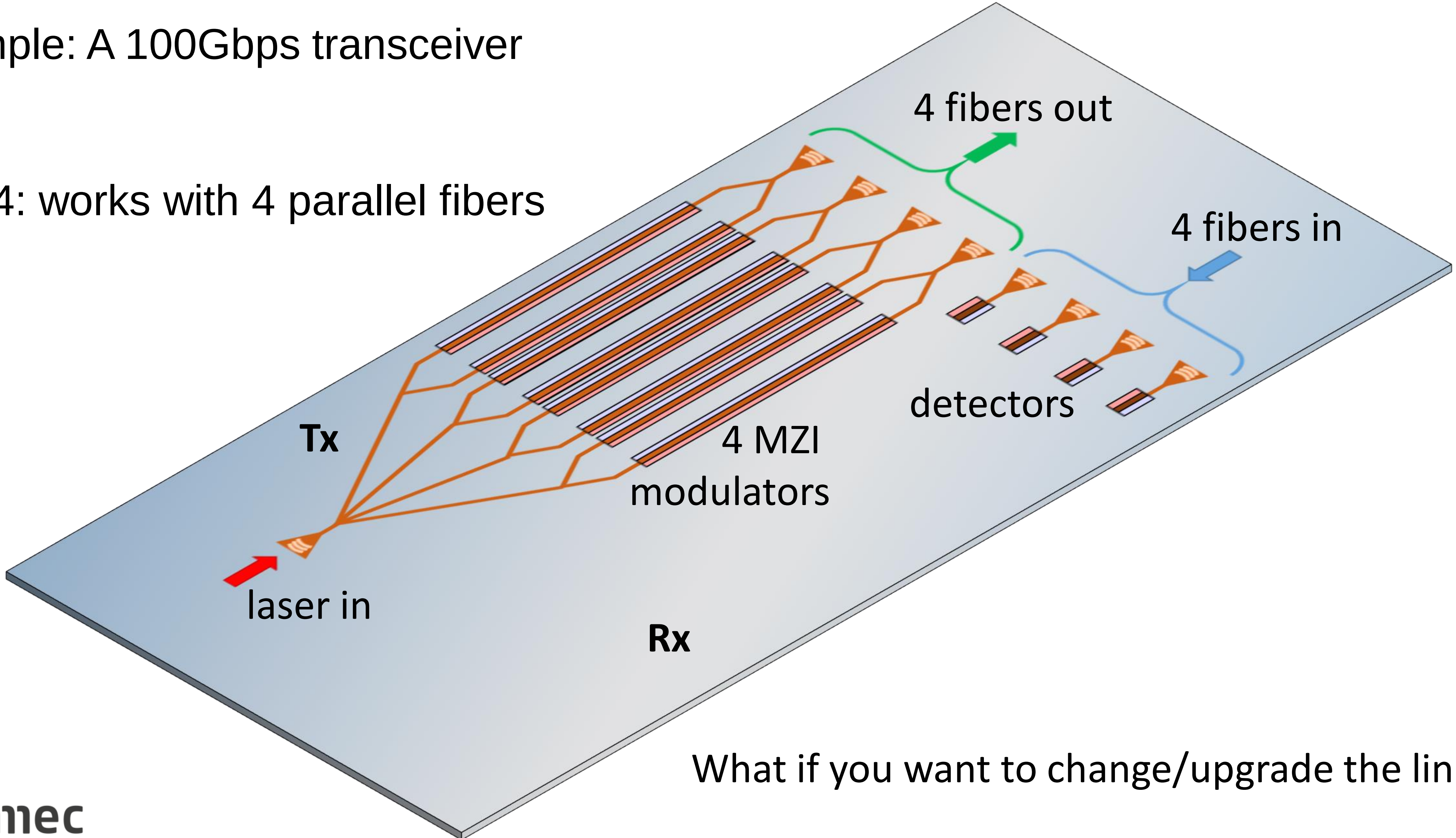


Khanna et al. 2016

Today's Photonic Chip: Designed for one purpose

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers



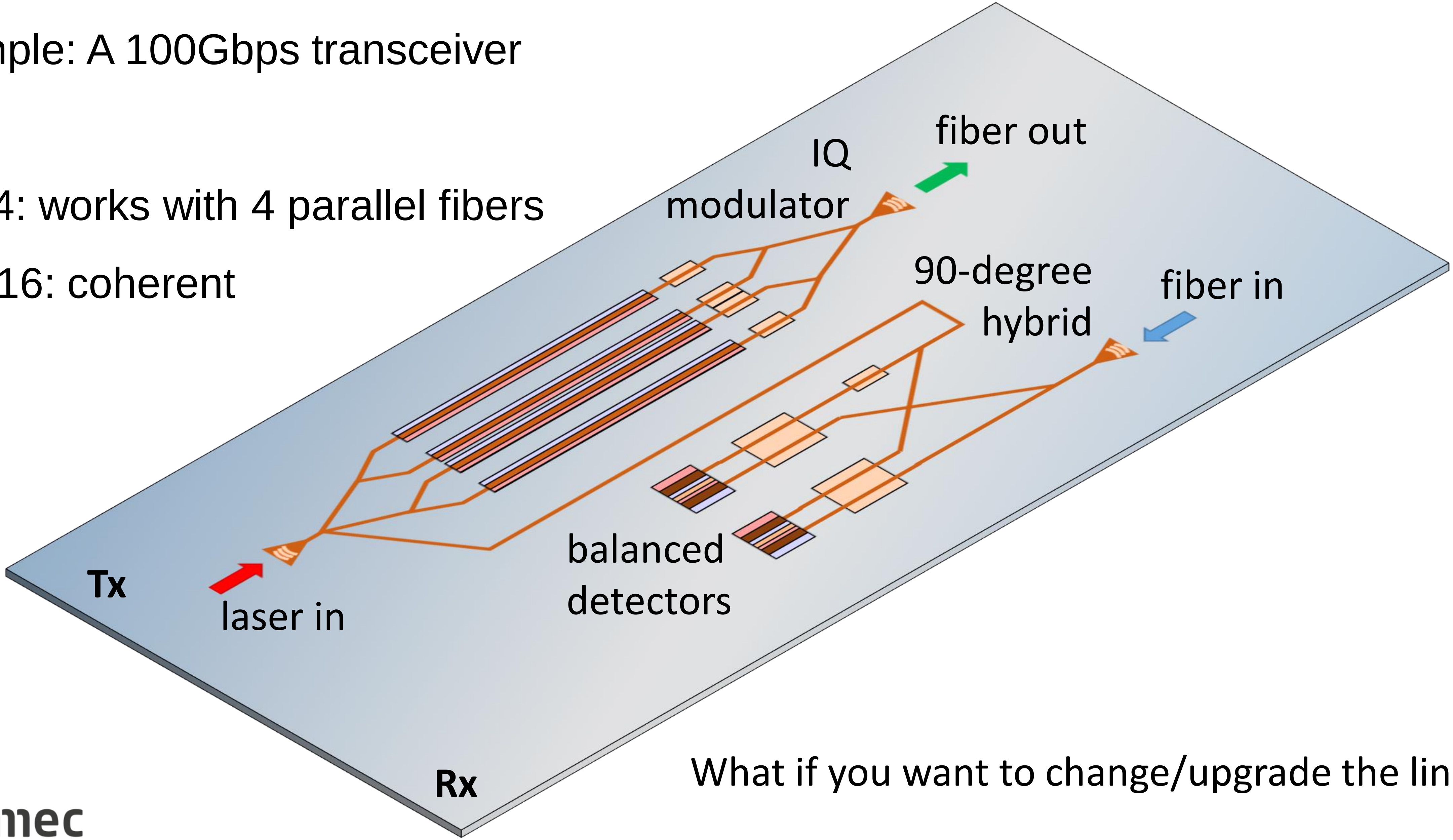
What if you want to change/upgrade the link?

TODAY'S PHOTONIC CHIP: DESIGNED FOR ONE PURPOSE

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers

QAM16: coherent



What if you want to change/upgrade the link?

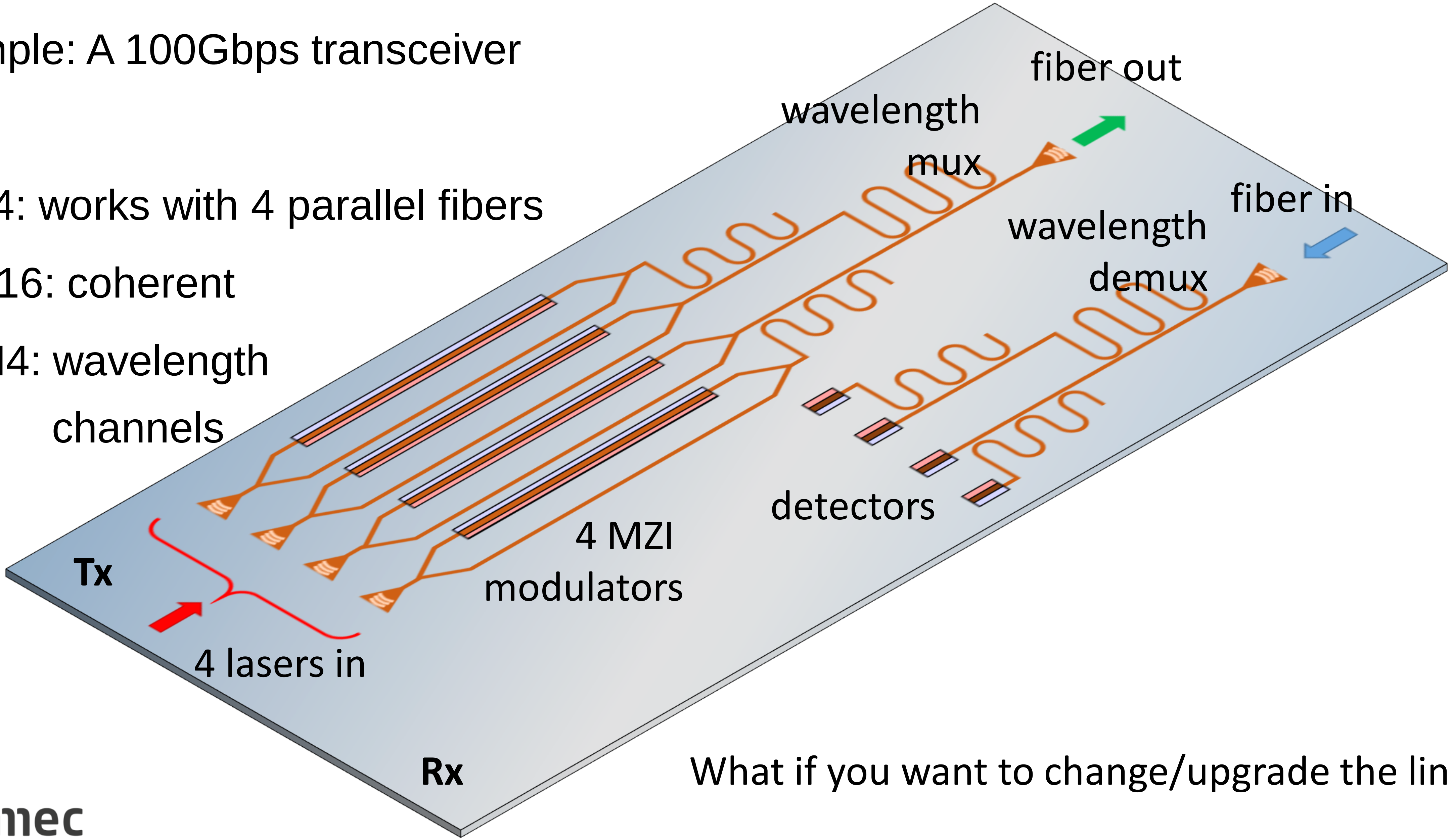
Today's Photonic Chip: Designed for one purpose

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers

QAM16: coherent

WDM4: wavelength channels



What if you want to change/upgrade the link?

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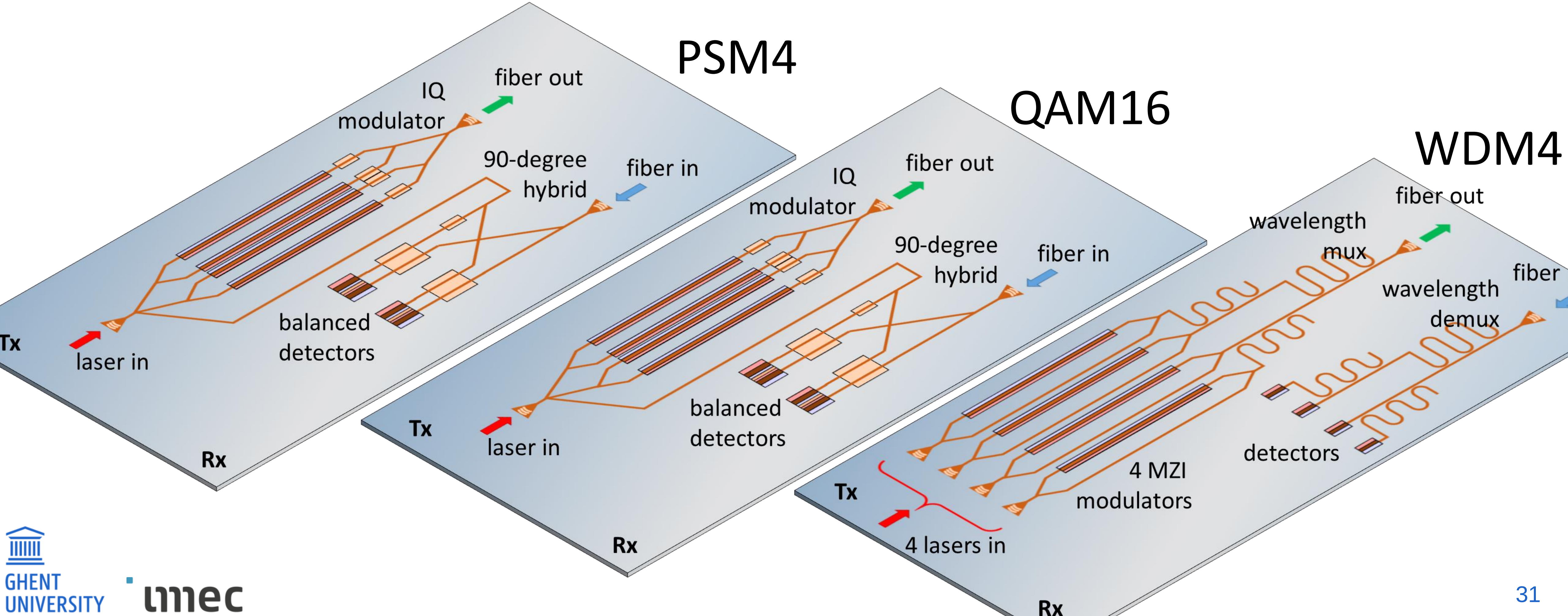
Flexible optical communication

Today: if you want to change protocol…

you need to make a new chip



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Prototyping a New (Silicon) Photonic IC

Design (4M)

Fabrication (6M)

Package (1M)

Test (2M)

Then you discover the bugs…

Repeat!

PROTOTYPING A NEW ELECTRONIC CIRCUIT

Select a suitable programmable IC: FPGA, DSP, µC (1d)

Program and test the chip (1-4w)

Only then, if needed:

- Design ASIC …

anysilicon	FPGA	ASIC
Time to Market	Fast	Slow
NRE	Low	High
Design Flow	Simple	Complex
Unit Cost	High	Low
Performance	Medium	High
Power Consumption	High	Low
Unit Size	Medium	Low

AnySilicon.com

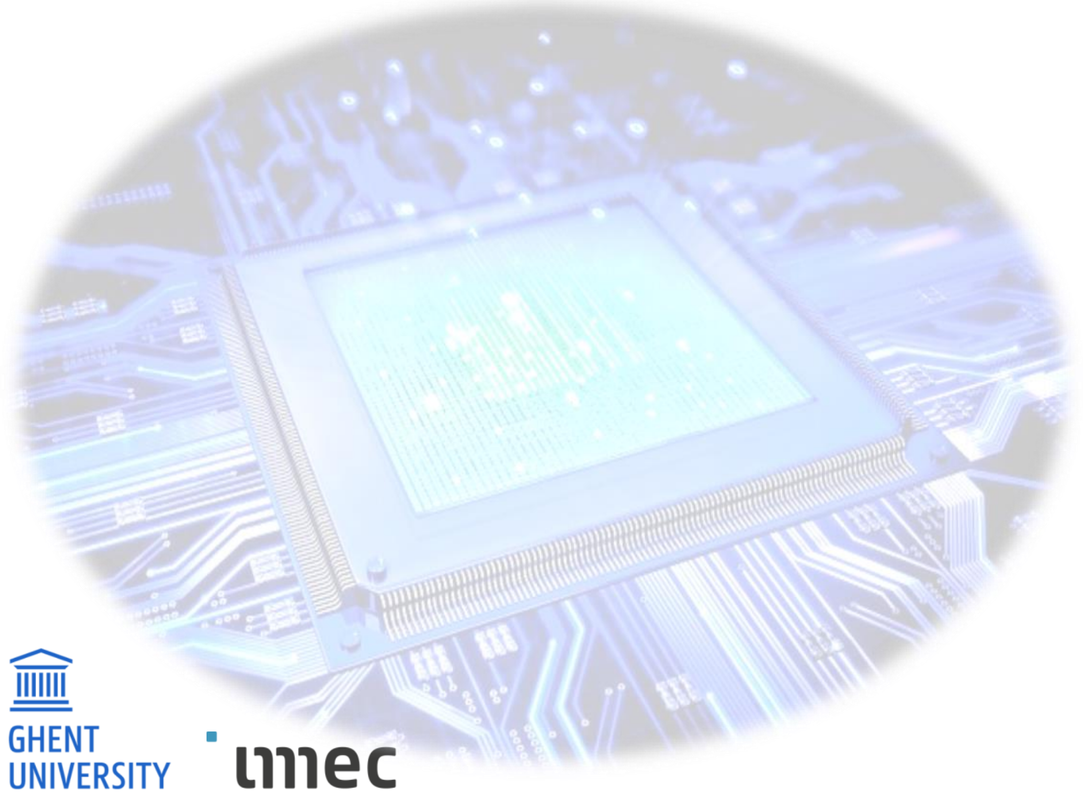
Where are the Photonic FPGAs?

or programmable photonics

reconfigurable photonics

photonic processors

universal photonic circuits …



Photonic Integrated Circuits

that **can be reconfigured**

using **software**

to perform **different functions**.

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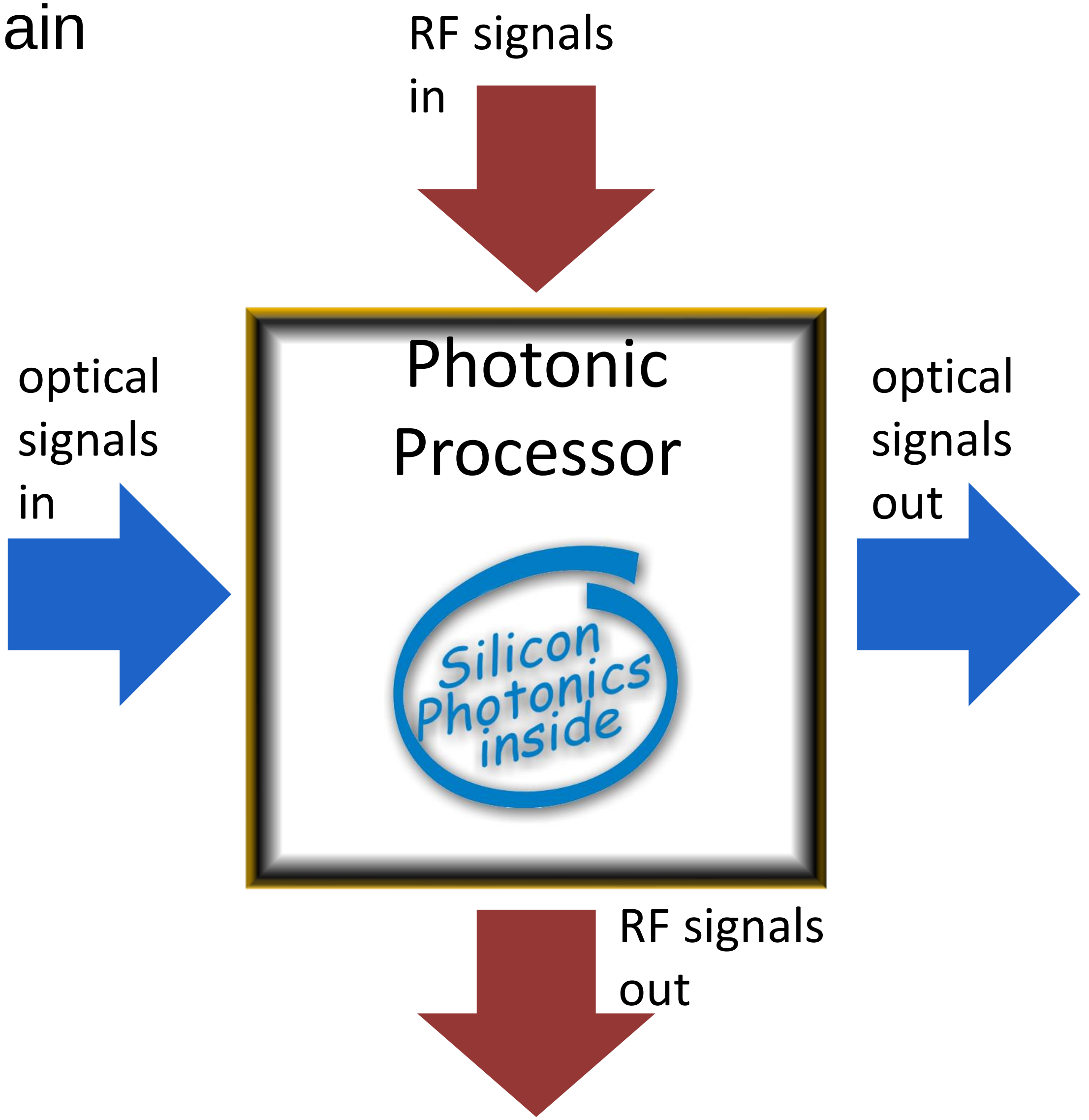
PROGRAMMABLE PHOTONIC CHIP

Can processes signals in the optical domain

- balancing
- filtering
- transformations

Both on Optical and RF



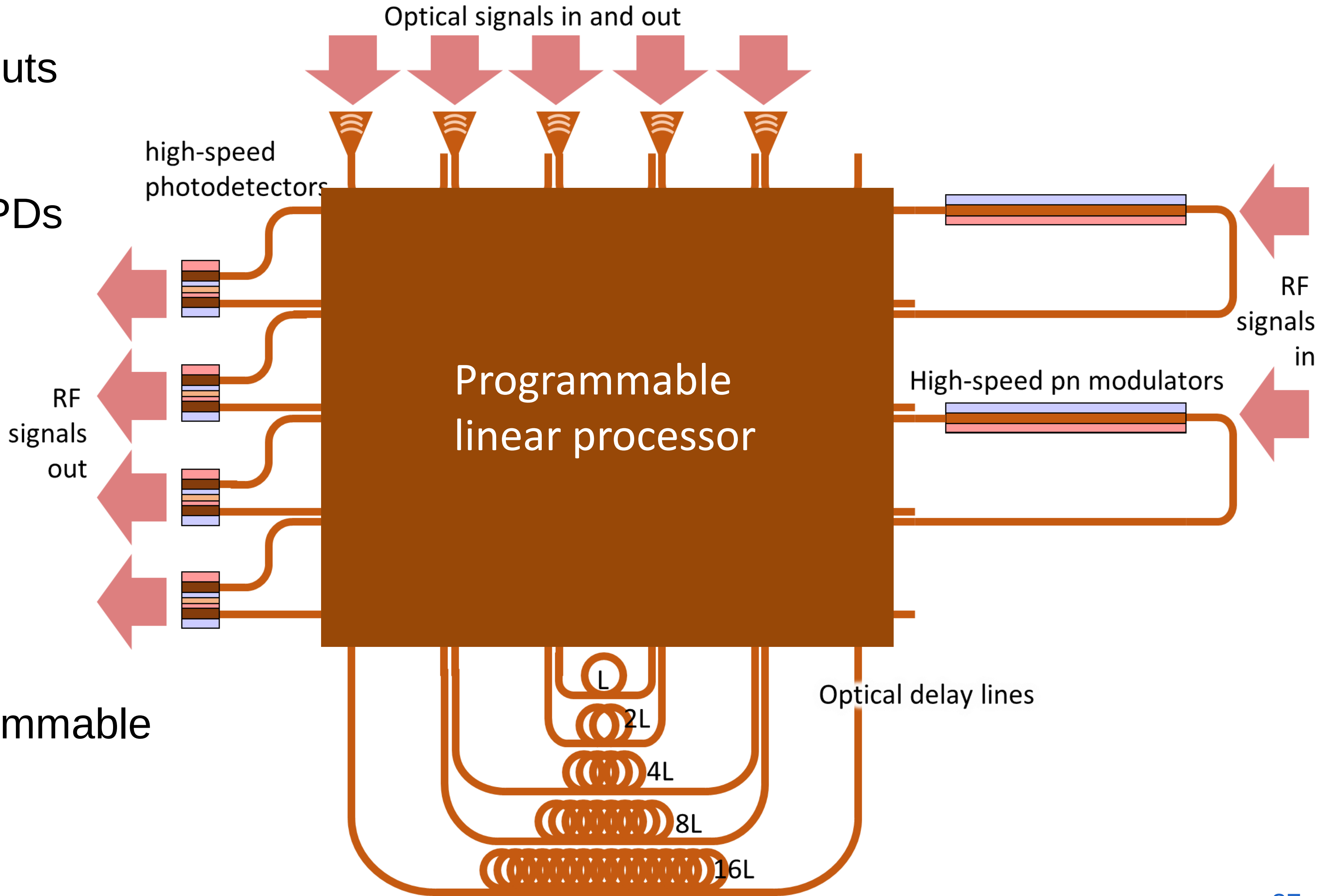
Generic Programmable Photonic Circuit

Optical inputs and outputs

RF inputs: modulators

RF outputs: balanced PDs

Long delays for filters



Connected by a programmable linear optical circuit

Optical Linear Processing

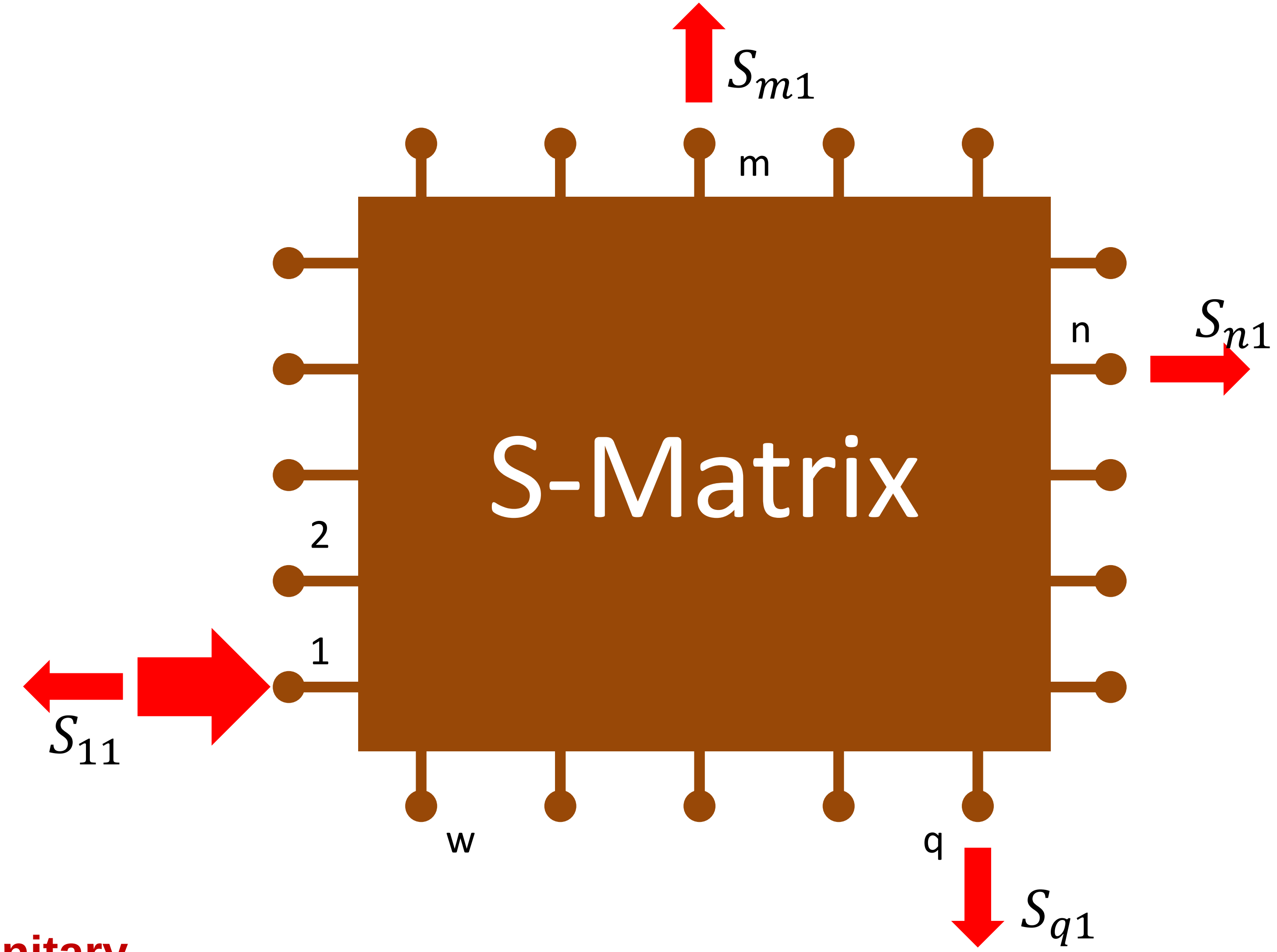
Linear optical circuits

can be described by an

S-matrix

$$out_p = S_{pq}.in_q$$

- Frequency domain
- Complex numbers
- Wavelength dependent
- Includes reflection
- Reciprocal
- **IF NO LOSS $\Rightarrow$ $\boldsymbol{S}$ is unitary**



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Optical Linear Processing (transmissive)

Transmissive linear optical circuits

can be described by an

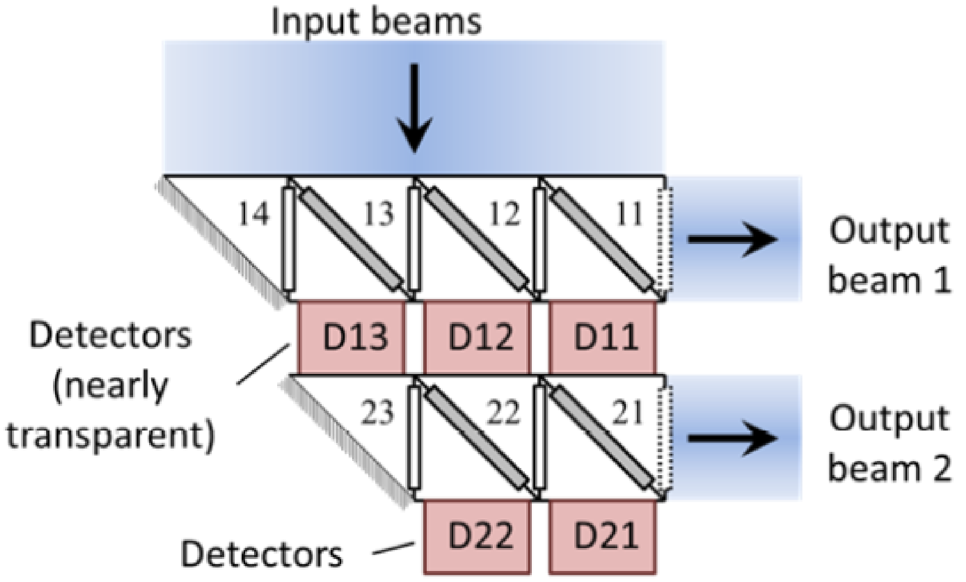
T-matrix

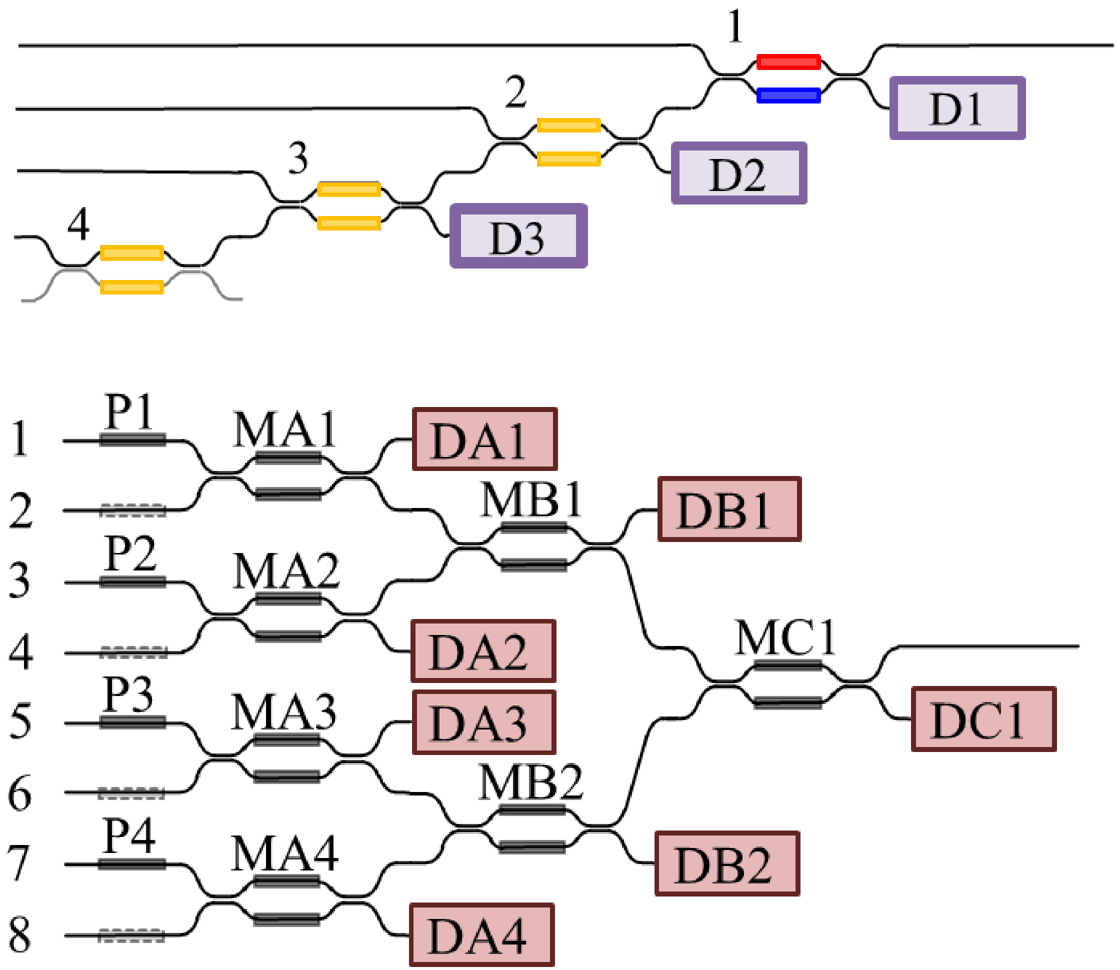
$$out_p = T_{pq}.in_q$$

- Frequency domain
- Complex numbers
- Wavelength dependent
- **NO REFLECTION**
- **IF NO LOSS $\Rightarrow$ $\boldsymbol{T}$ is unitary**

Implementing T-matrices on a Chip

Network of phase shifters and tunable 2x2 couplers (beamsplitters)



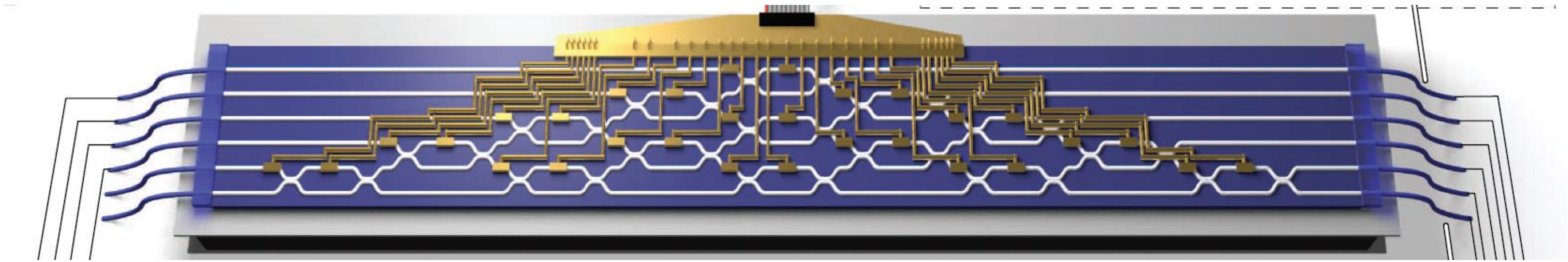


Miller, OpEx 2013

FIRST PROGRAMMABLE T-MATRIX CIRCUIT

First implementation in silica (low contrast): 2015

6x6 T-matrix



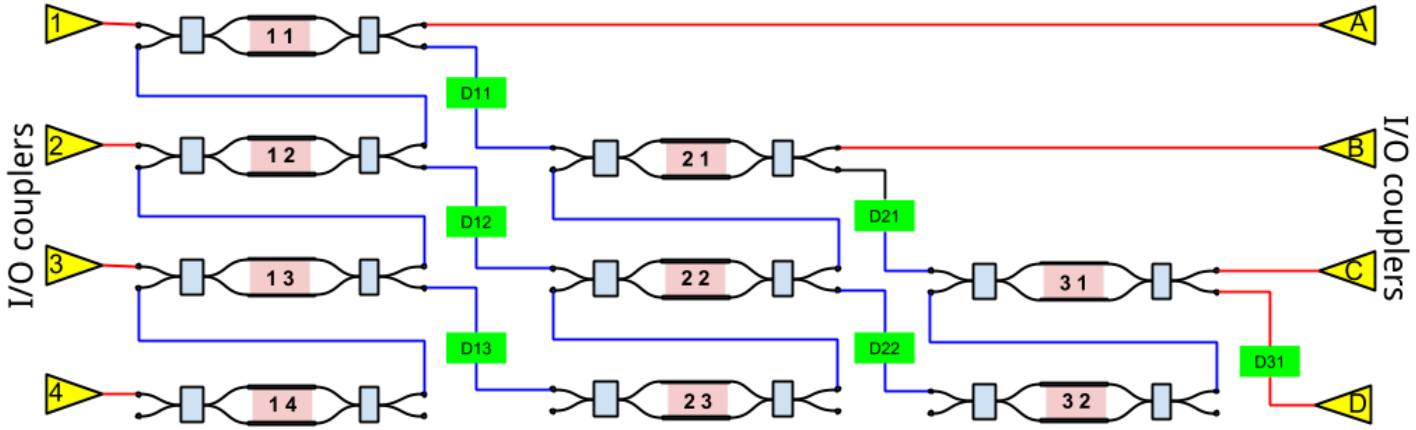
Application: linear optical quantum operations:
CNOT gate, boson sampling, random walks, etc.

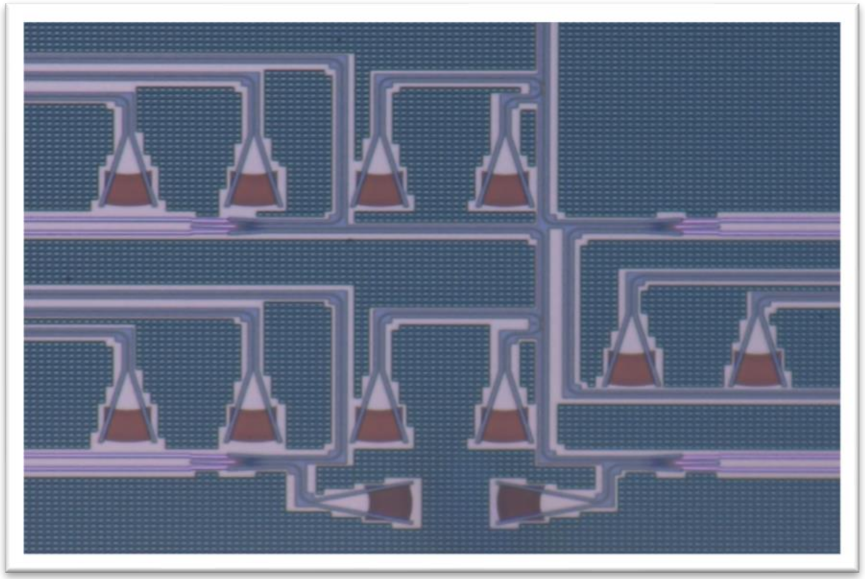
University of BRISTOL

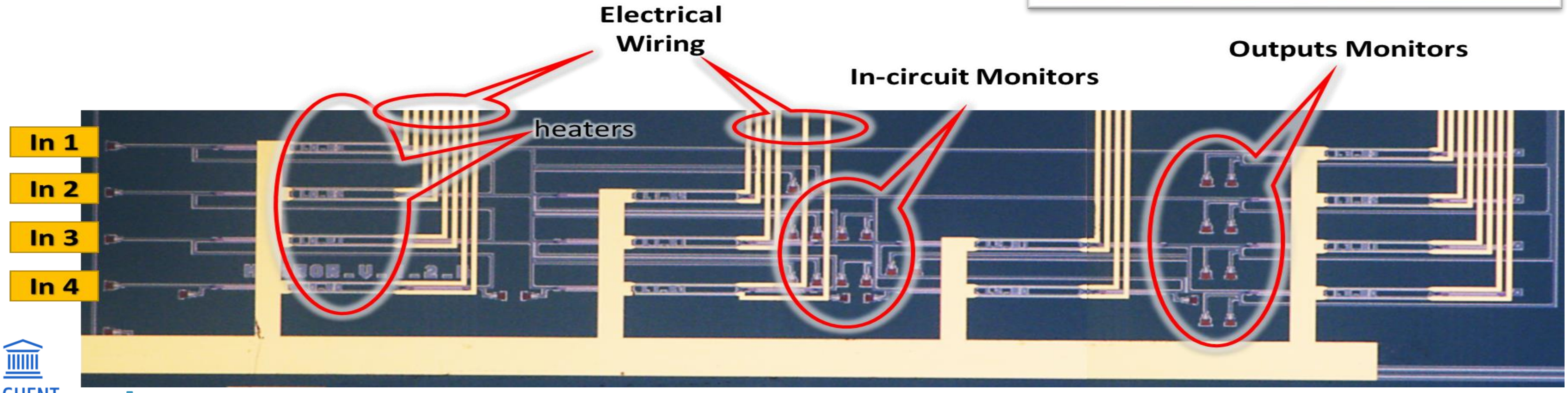
Carolan et al. Science 2015

First T-Matrix circuit in silicon

4x4 circuit: 2.5 x 0.4 mm^2

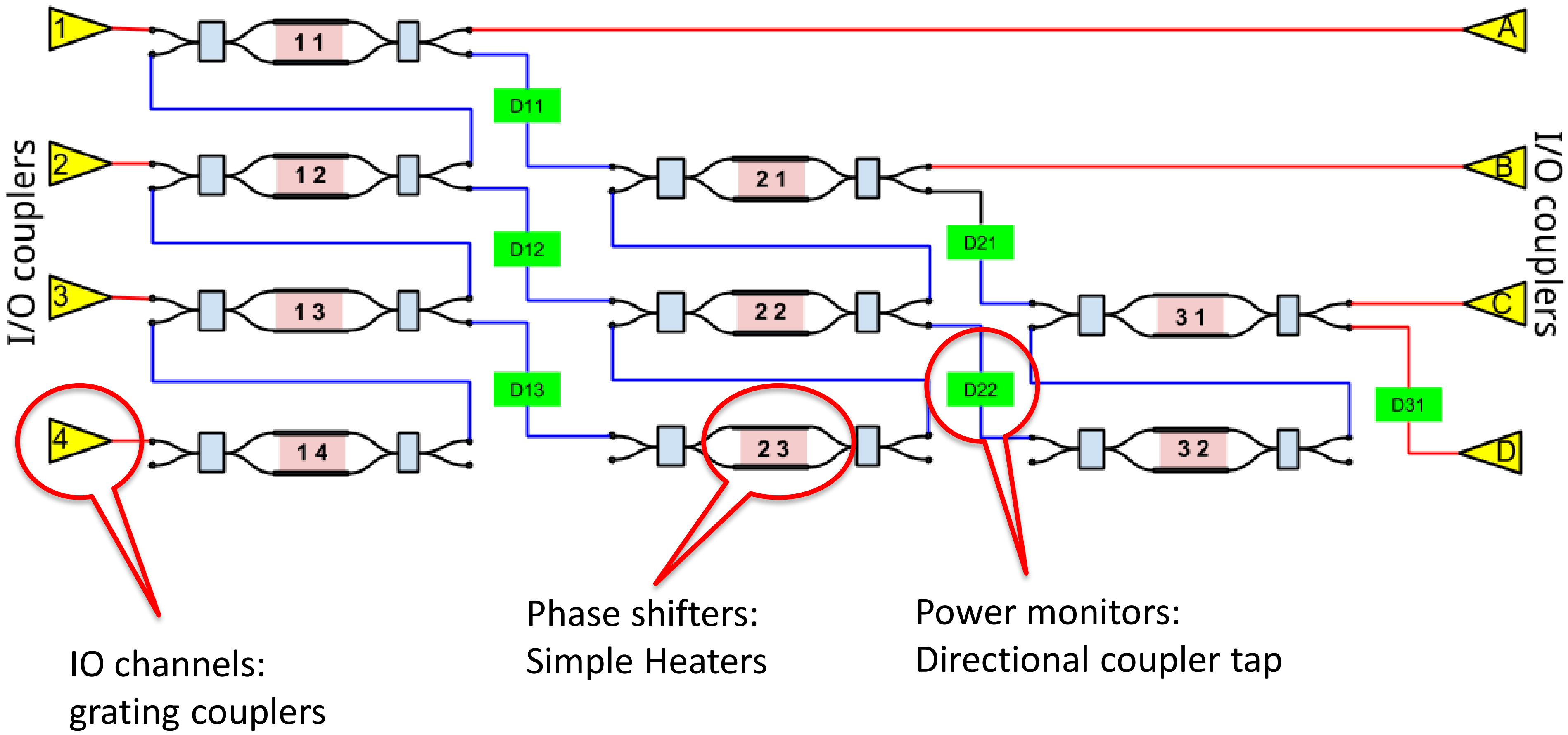






Universal linear circuit in silicon

Tunable couplers = MZI with thermo-optic phase shifters

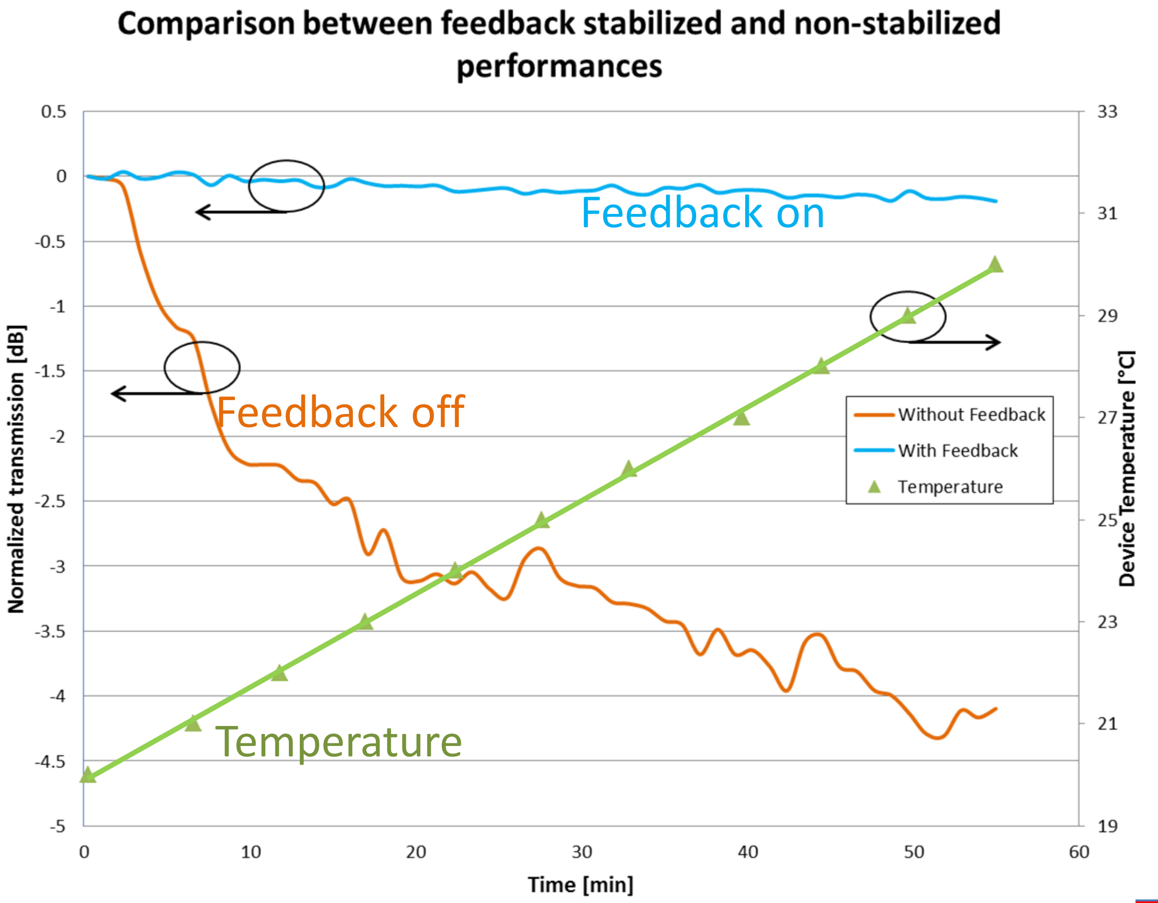


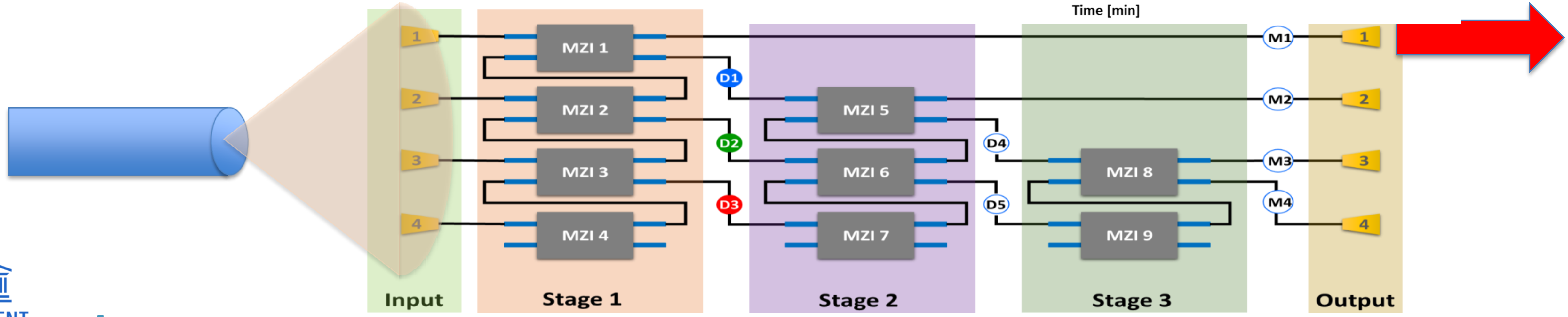
Ribeiro et al, Optica 2016

Adaptive Beam Coupler

Circuit adapts itself to maximize output to a single mode waveguide

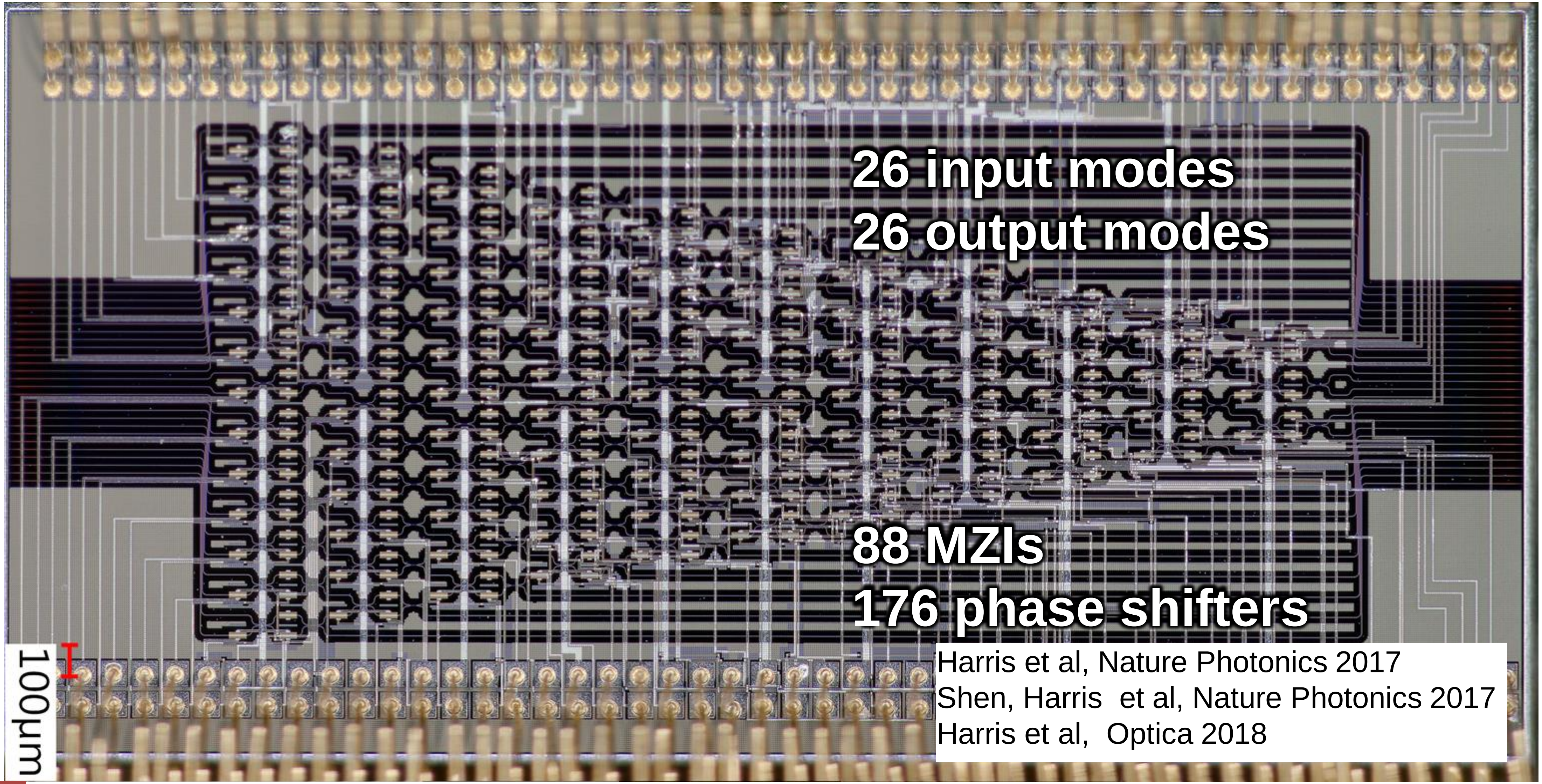
Local feedback loops stabilize the entire circuit.





Ribeiro et al, Optica 2016

Large-scale T-matrix Circuit



Harris et al, Nature Photonics 2017
Shen, Harris et al, Nature Photonics 2017
Harris et al, Optica 2018

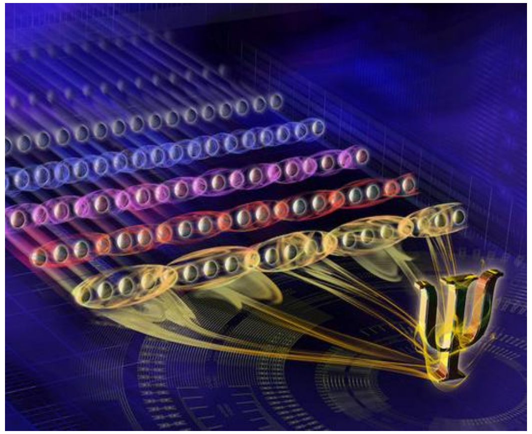
Michael Hochberg (opsis), Michael Fanto (RIT), Paul Alsing (AFRL), Stefan Preble (RIT), Philip Walther (U. Vienna)

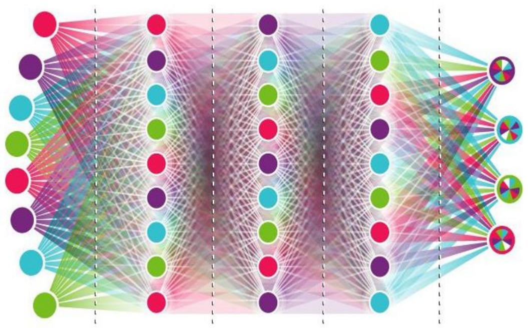
Where are Matrix multiplications useful?

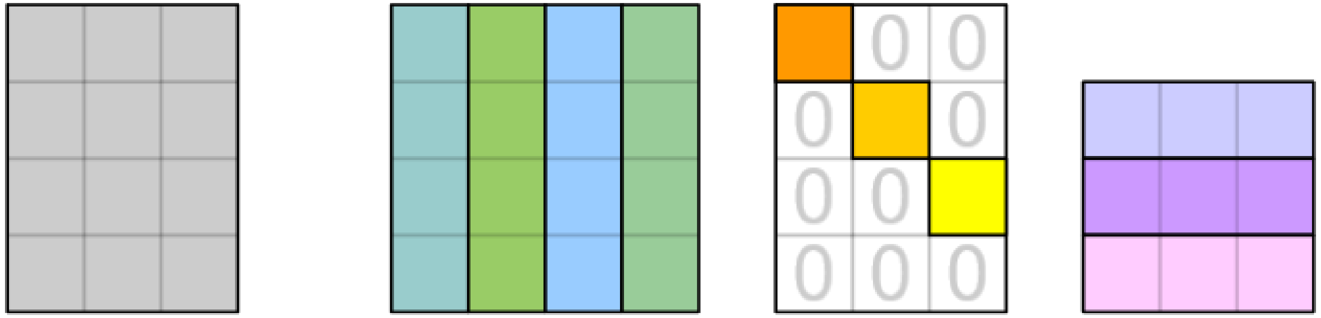
Pattern Recognition

Linear Quantum Optics

Artificial Neural Networks



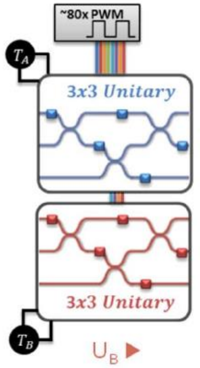




$$\underset{m\times n}{\mathbf{M}} = \underset{m\times m}{\mathbf{U}}\ \underset{m\times n}{\mathbf{\Sigma}}\ \underset{n\times n}{\mathbf{V}^*}$$

QUANTUM PHOTONICS CIRCUITS

A whole string of demonstrations



Research Article Vol. 2, No. 6 / June 2015 / Optica 523
optica

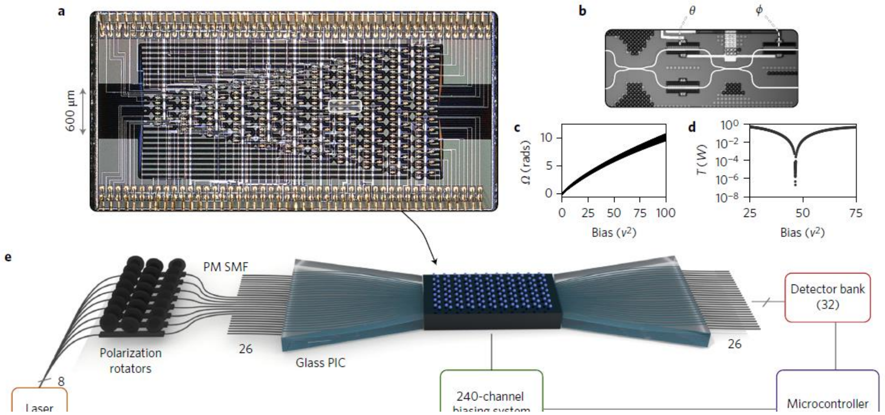
Experimental access to higher-dimensional entangled quantum systems using integrated optics

CHRISTOPH SCHAEFF,[1,5] ROBERT POLSTER,[1] MARCUS HUBER,[2,3] SVEN RAMELOW,[1] AND ANTON ZEILINGER[1,4,*]

nature photonics ARTICLES
PUBLISHED ONLINE: 19 JUNE 2017 | DOI: 10.1038/NPHOTON.2017.95

Quantum transport simulations in a programmable nanophotonic processor

Nicholas C. Harris[1]*, Gregory R. Steinbrecher[1], Mihika Prabhu[1], Yoav Lahini[2], Jacob Mower[1], Darius Bunandar[3], Changchen Chen[4], Franco N. C. Wong[4], Tom Baehr-Jones[5], Michael Hochberg[5], Seth Lloyd[6] and Dirk Englund[1]



Letter Vol. 5, No. 9 / September 2018 / Optica 1087
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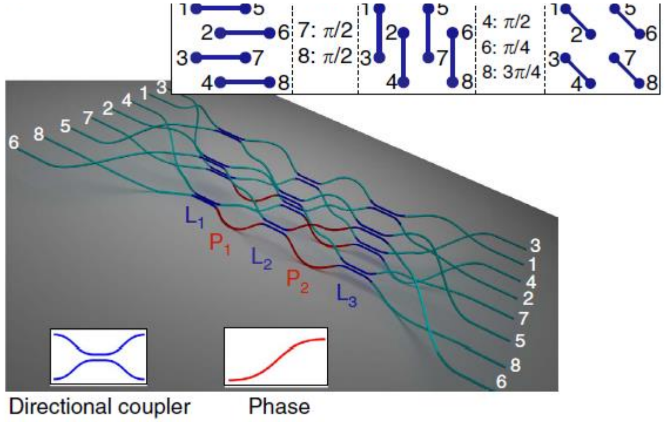
Modular linear optical circuits

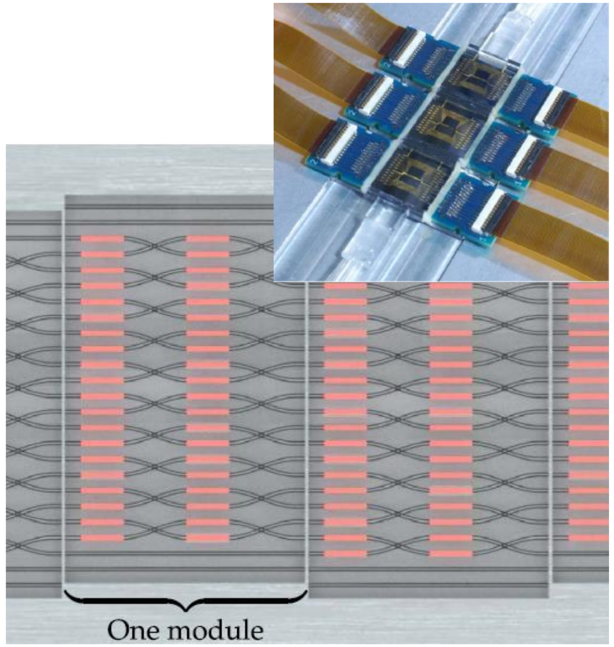
PAOLO L. MENNEA,[1] WILLIAM R. CLEMENTS,[2] DEVIN H. SMITH,[1] JAMES C. GATES,[1] BENJAMIN J. METCALF,[2] REX H. S. BANNERMAN,[1] ROEL BURGWAL,[2] JELMER J. RENEMA,[2] W. STEVEN KOLTHAMMER,[2,3] IAN A. WALMSLEY,[2] AND PETER G. R. SMITH[1,*]

nature COMMUNICATIONS
ARTICLE
Received 27 Jul 2015 | Accepted 14 Dec 2015 | Published 4 Feb 2016
DOI: 10.1038/ncomms10469 OPEN

Suppression law of quantum states in a 3D photonic fast Fourier transform chip

Andrea Crespi[1,2], Roberto Osellame[1,2], Roberta Ramponi[1,2], Marco Bentivegna[3], Fulvio Flamini[3], Nicolò Spagnolo[3], Niko Viggianiello[3], Luca Innocenti[3,4], Paolo Mataloni[3] & Fabio Sciarrino[3]





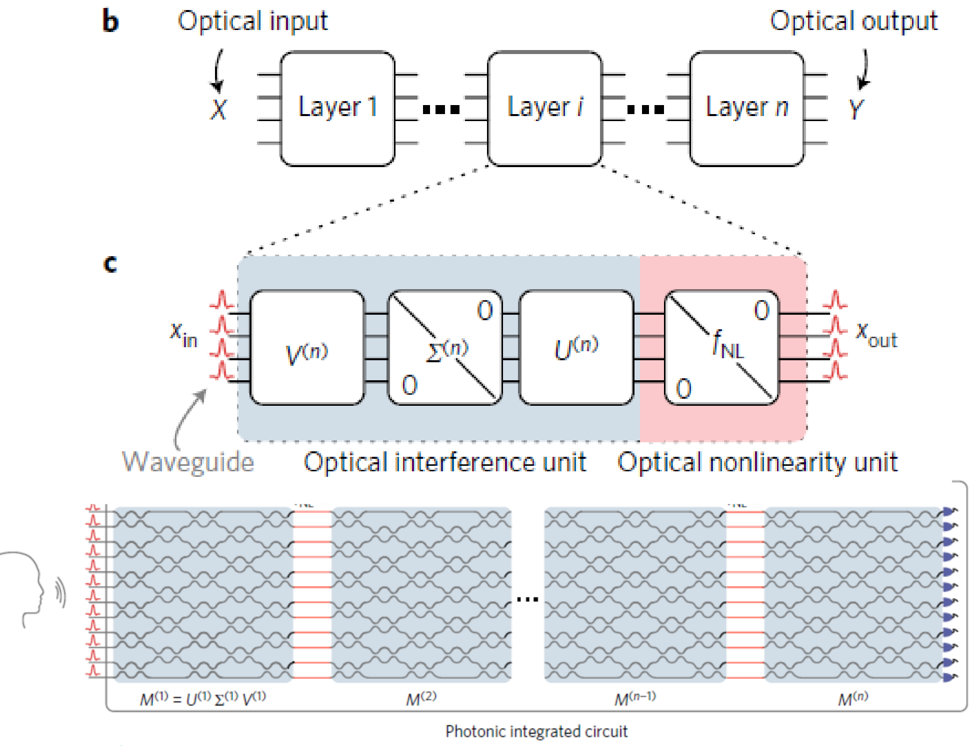
Research Article Vol. 3, No. 12 / December 2016 / Optica 1460
optica

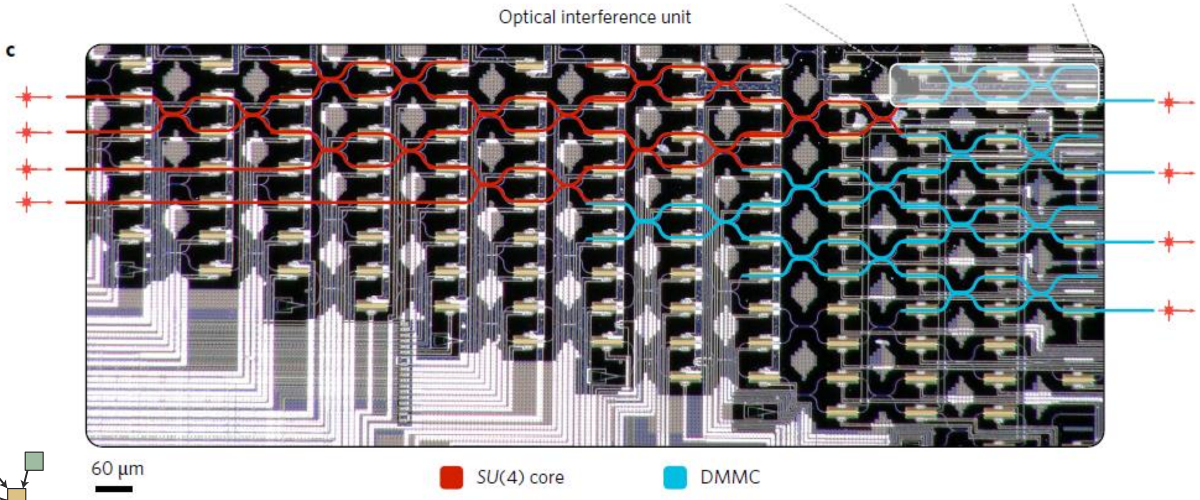
Optimal design for universal multiport interferometers

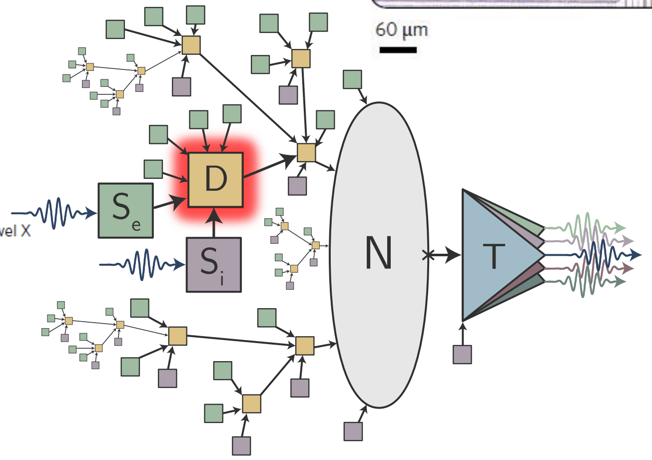
WILLIAM R. CLEMENTS,* PETER C. HUMPHREYS, BENJAMIN J. METCALF, W. STEVEN KOLTHAMMER, AND IAN A. WALMSLEY

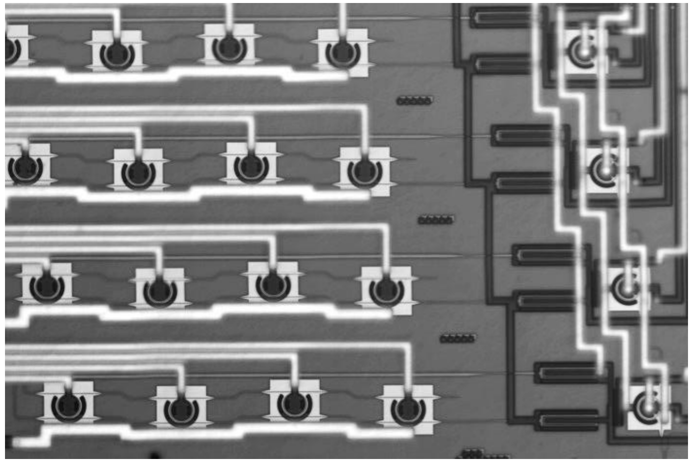
Photonic Accelerators for AI

Neural networks need fast multiplications of large matrices









LIGHTELLIGENCE

MIT

PRINCETON UNIVERSITY

Queen's UNIVERSITY

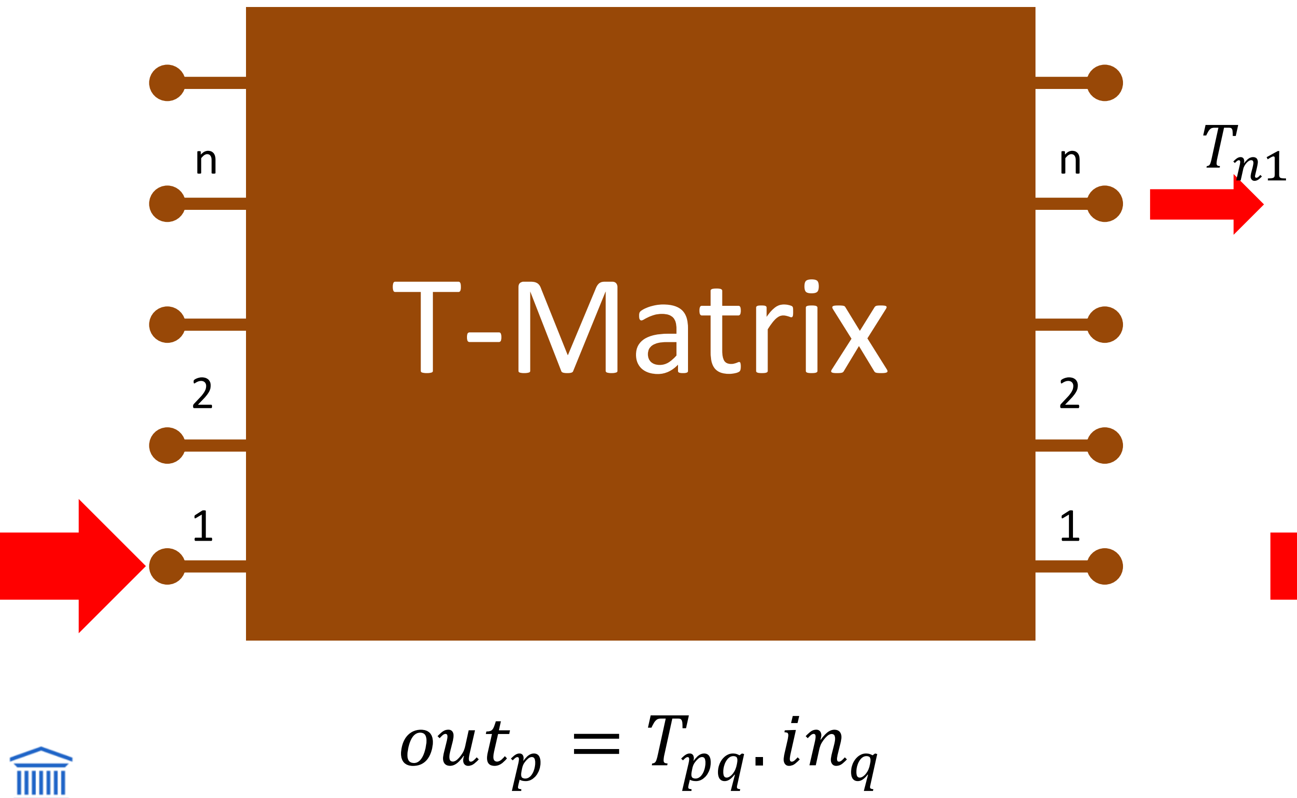
NIST

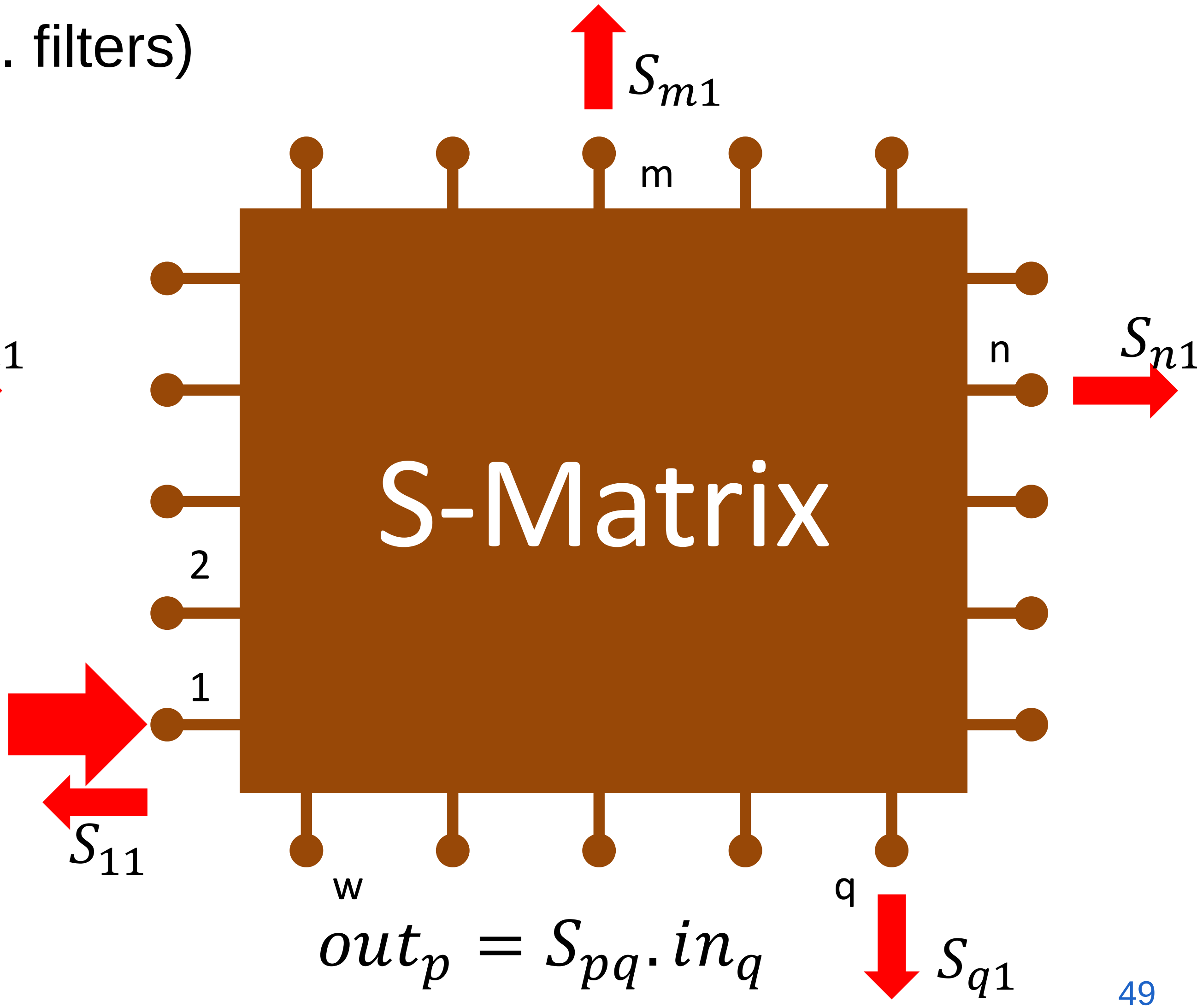
LIGHTMATTER

Optical T-matrix has limits

Strict separation of inputs and outputs

Difficult to implement flexible delays (e.g. filters)

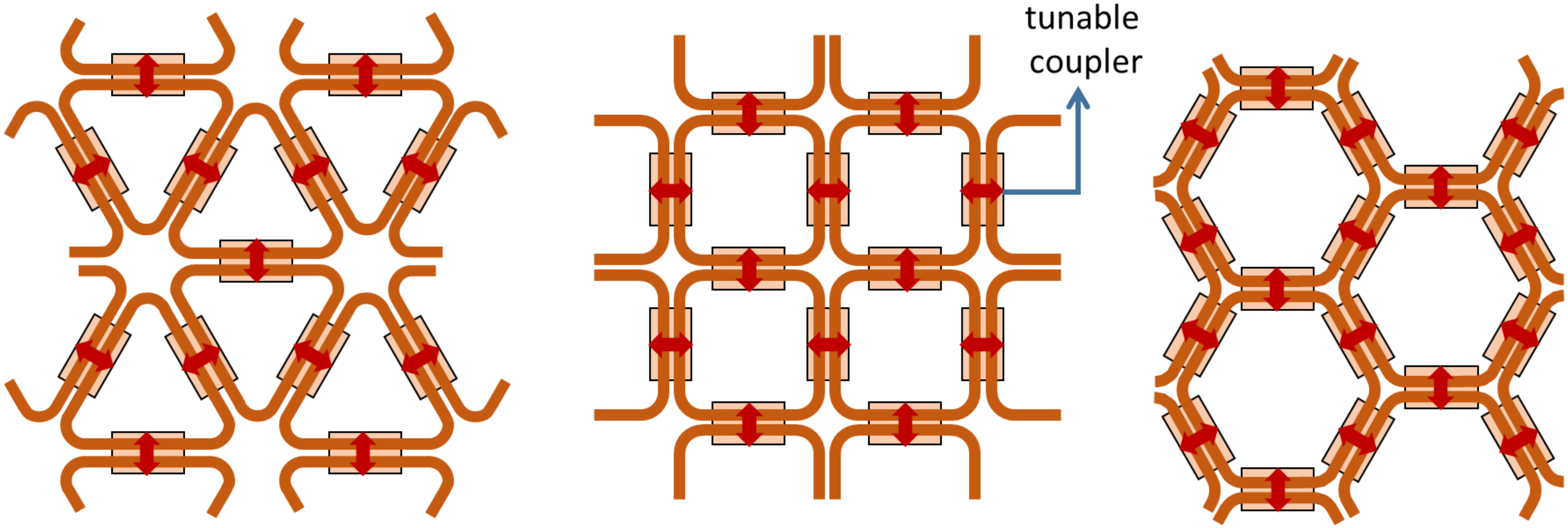




More generic: Full S-matrix processing

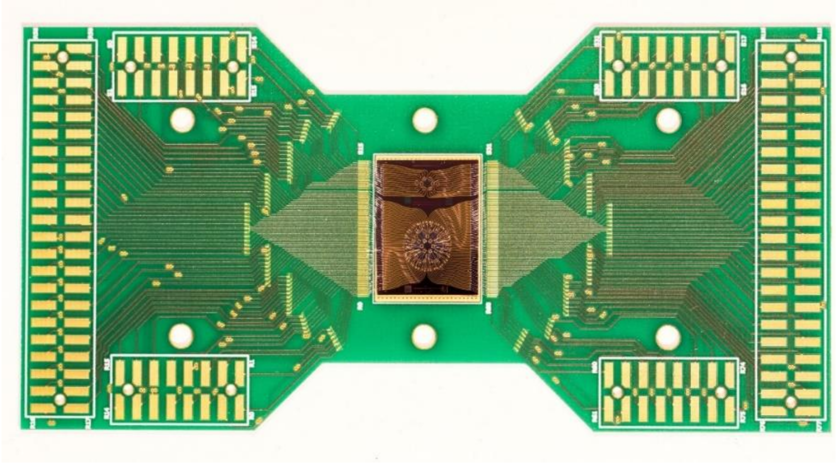
Adding feedback (loops)

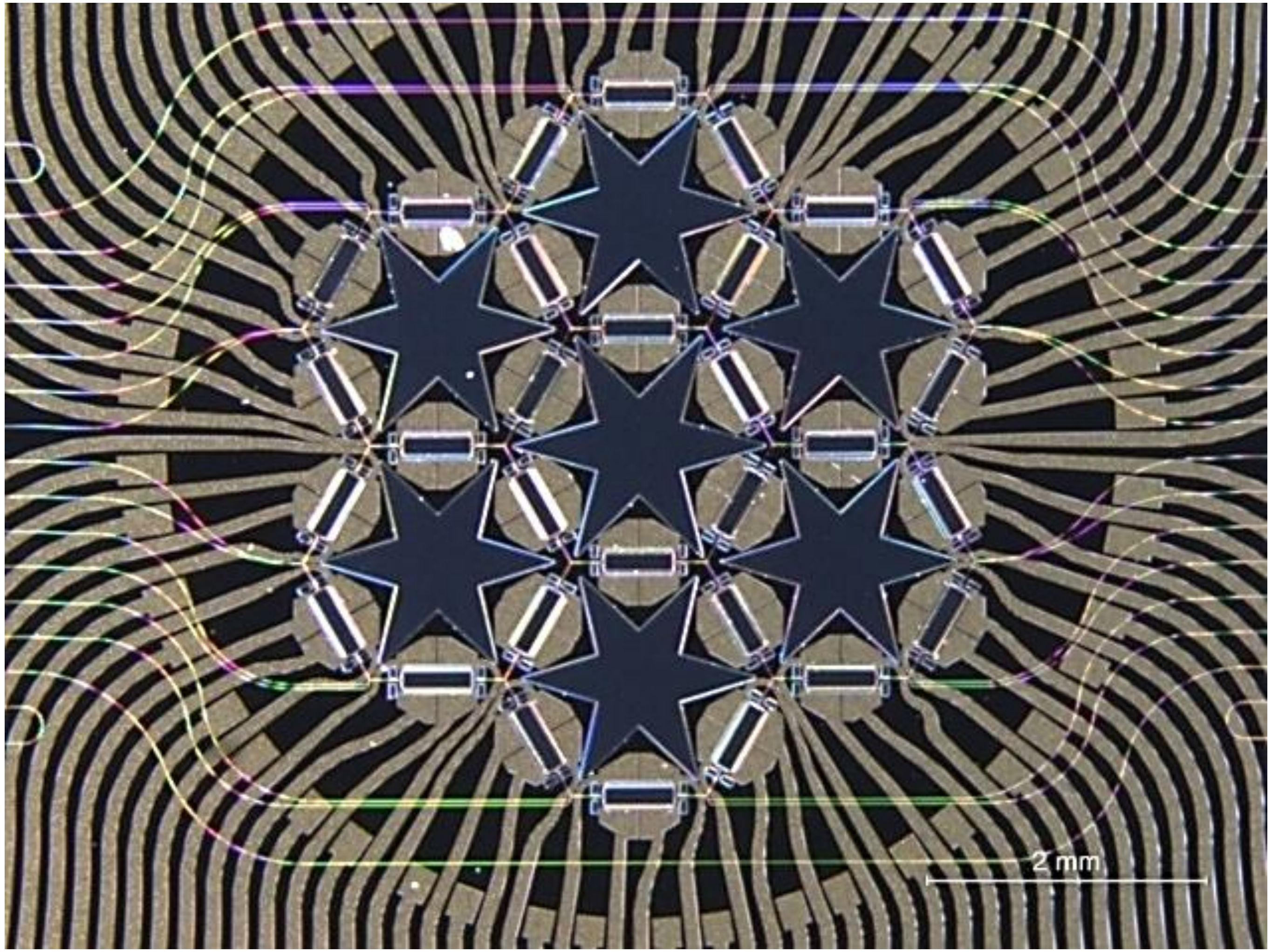
- Zhuang 2015: Square Meshes
- Capmany 2016: Triangular/Hexagonal meshes



HEXAGONAL MESH CIRCUIT

- 7 hexagonal cores
- 30 tunable couplers
  (2 heaters per coupler)
- >100 possible circuits





D. Pérez, et al., Nature Comms. 8, 636, 2017

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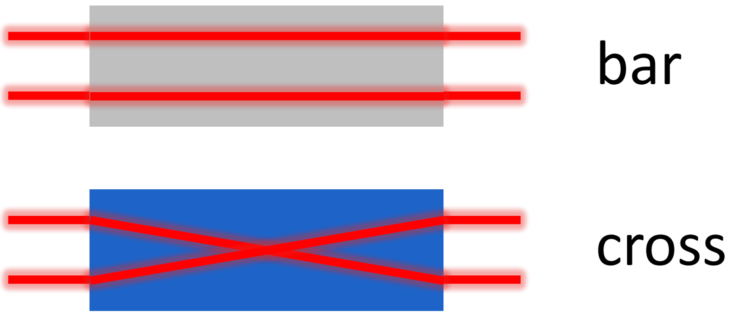
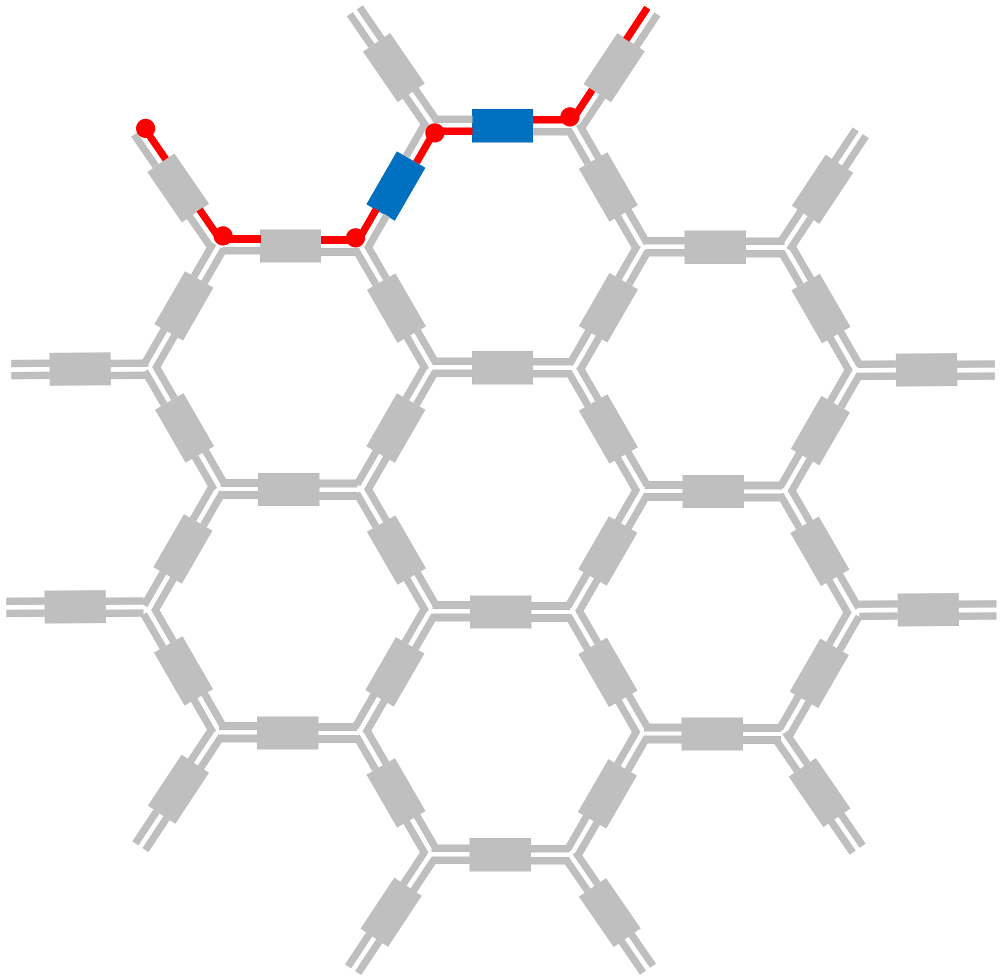
iTEAM Instituto de Telecomunicaciones y Aplicaciones Multimedia

Photonics Research Labs

(RE) ROUTING LIGHT

Light can be arbitrarily routed





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(RE) ROUTING LIGHT

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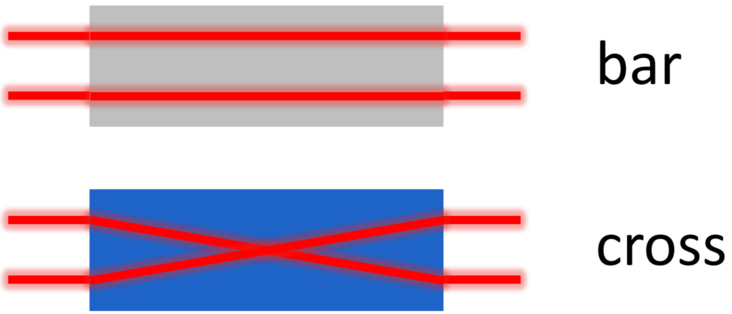

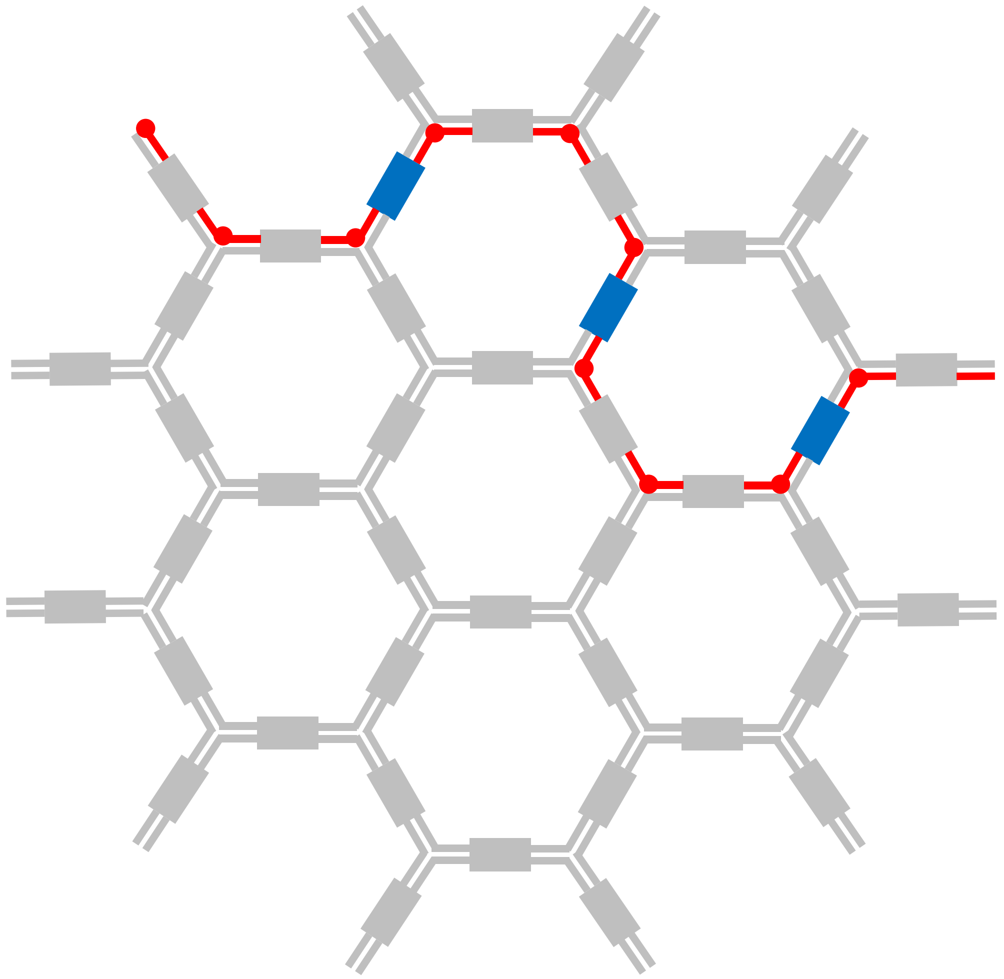

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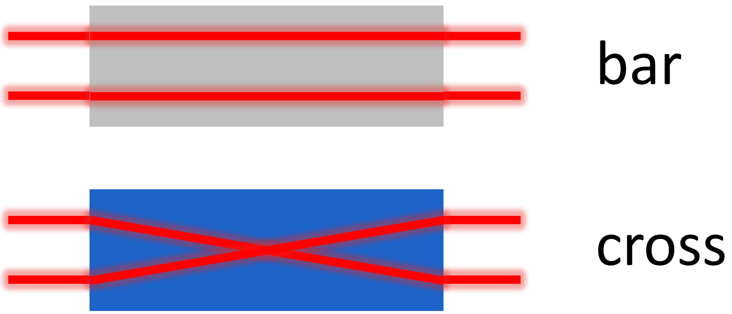
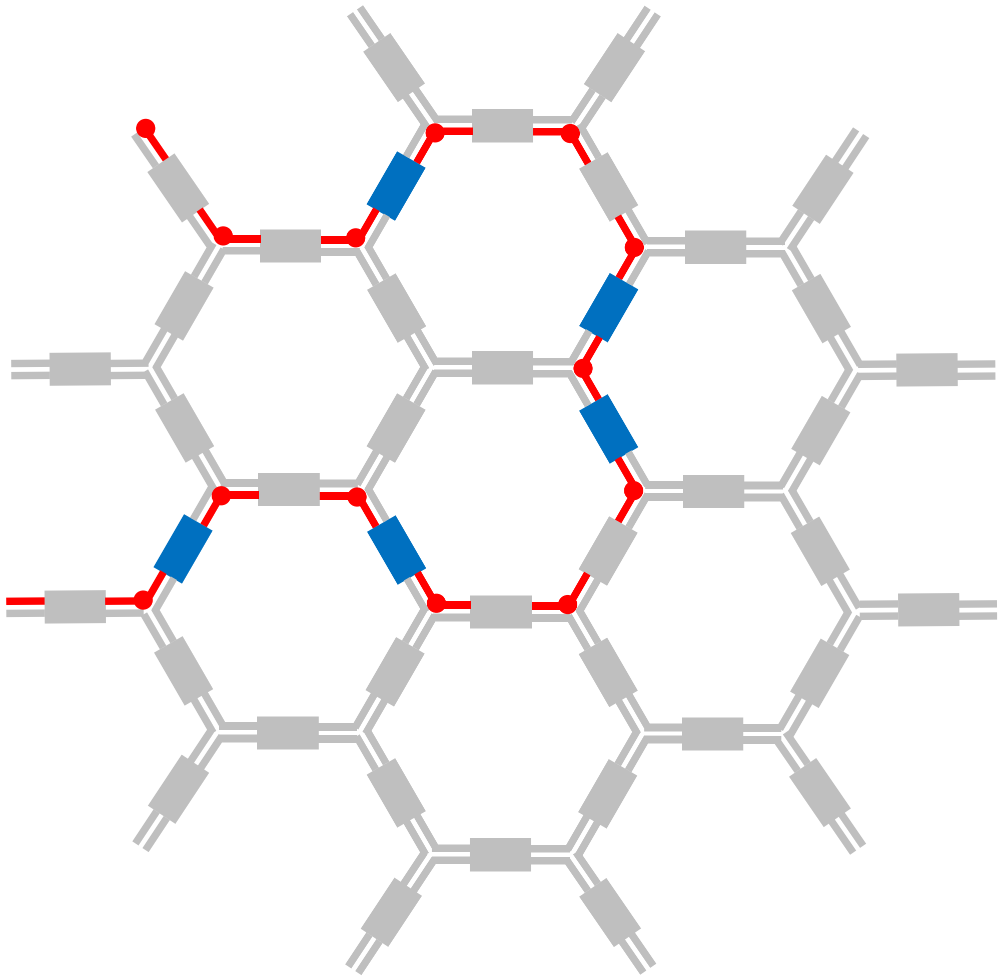
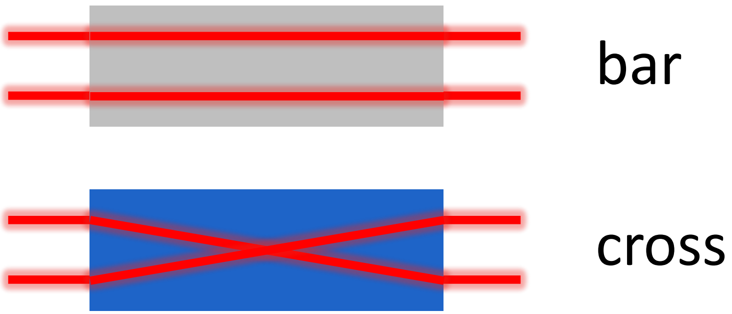


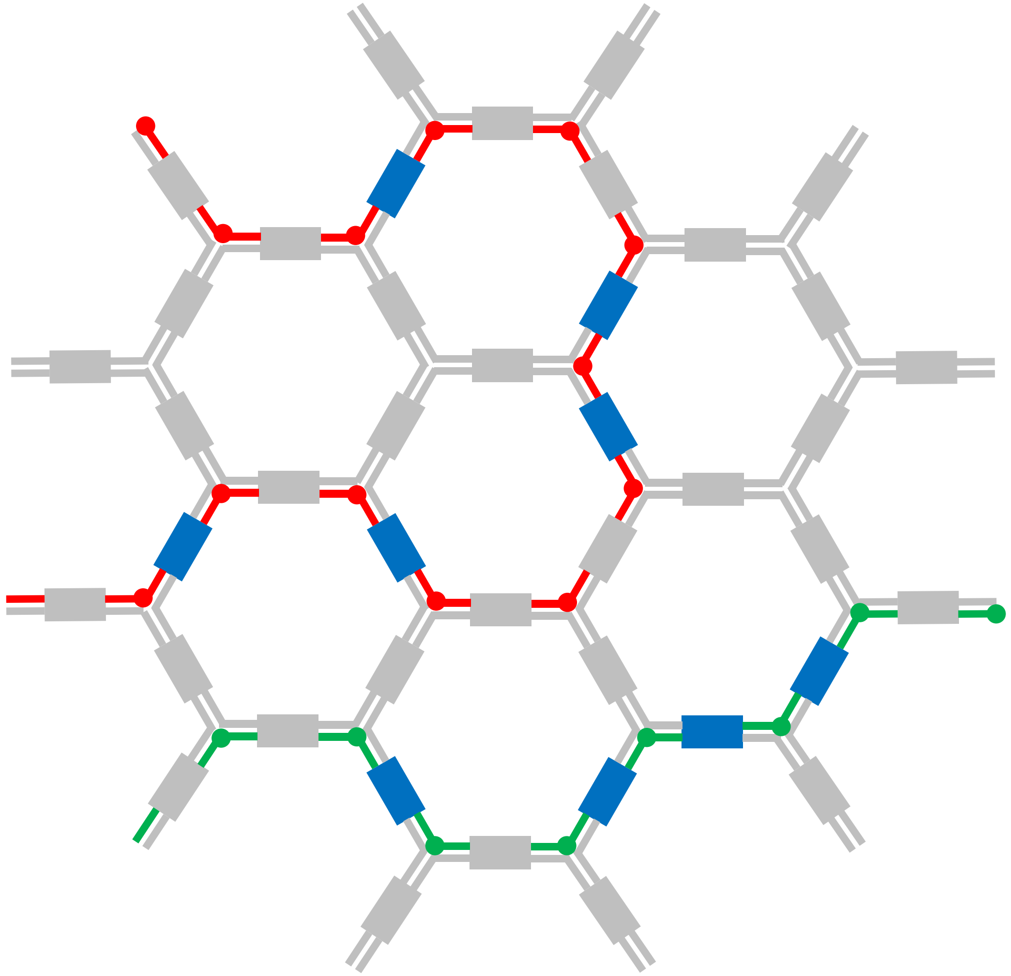


(RE)ROUTING LIGHT

Light can be arbitrarily routed

Multiple routes in the same mesh



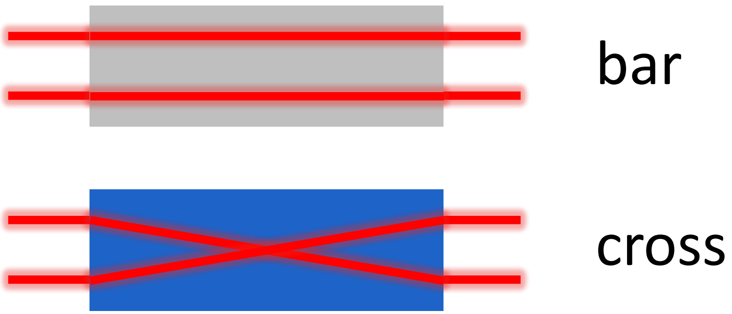


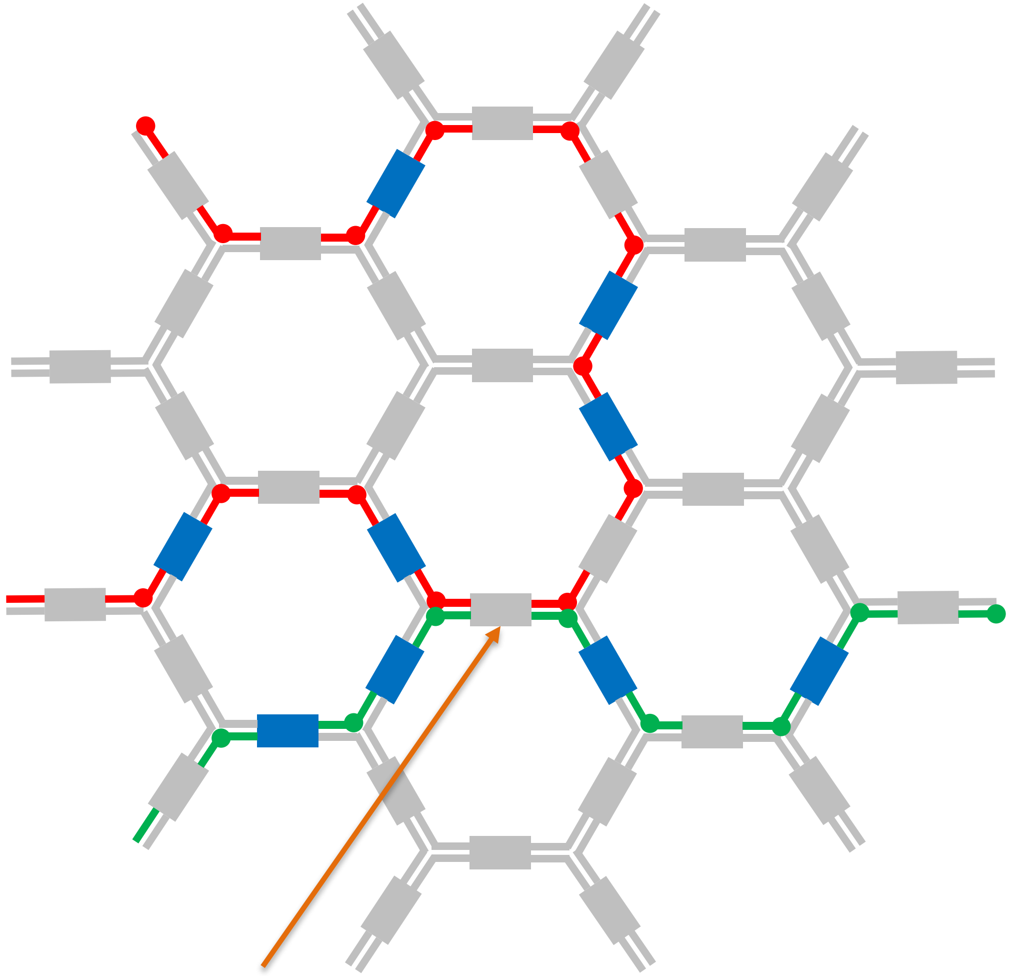
(RE)ROUTING LIGHT

Light can be arbitrarily routed

Multiple routes in the same mesh

Edges can be shared





This coupler is used
by both routes

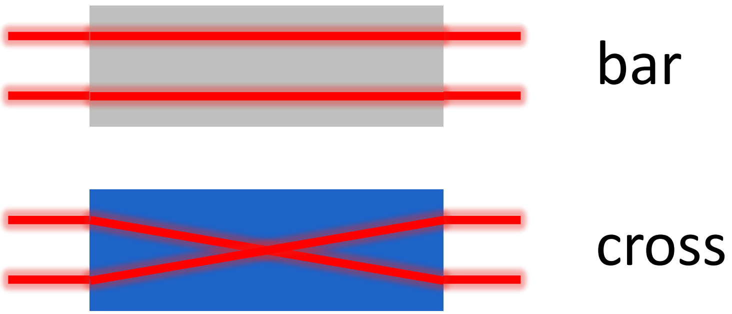
(RE)ROUTING LIGHT

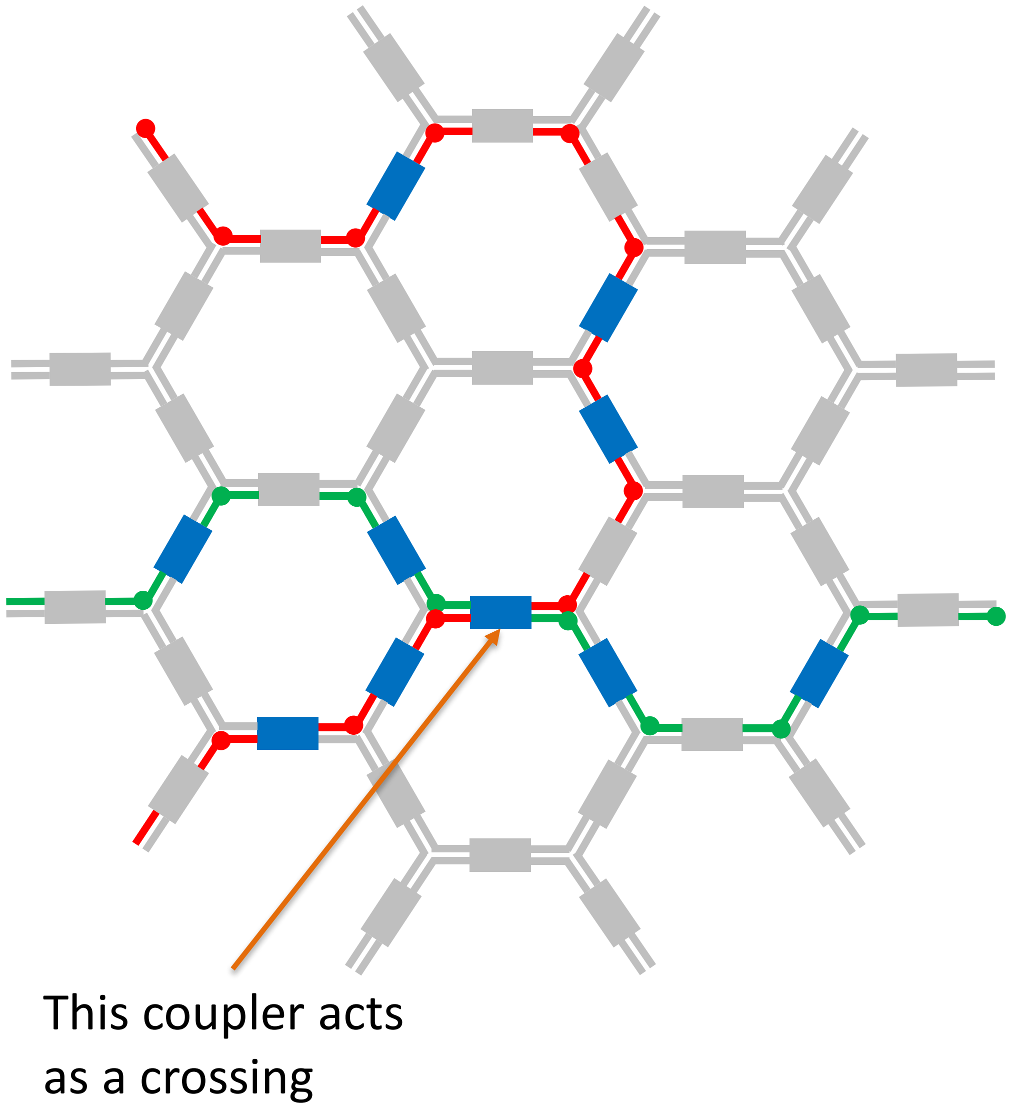
Light can be arbitrarily routed

Multiple routes in the same mesh

Edges can be shared

Crossings are not a problem



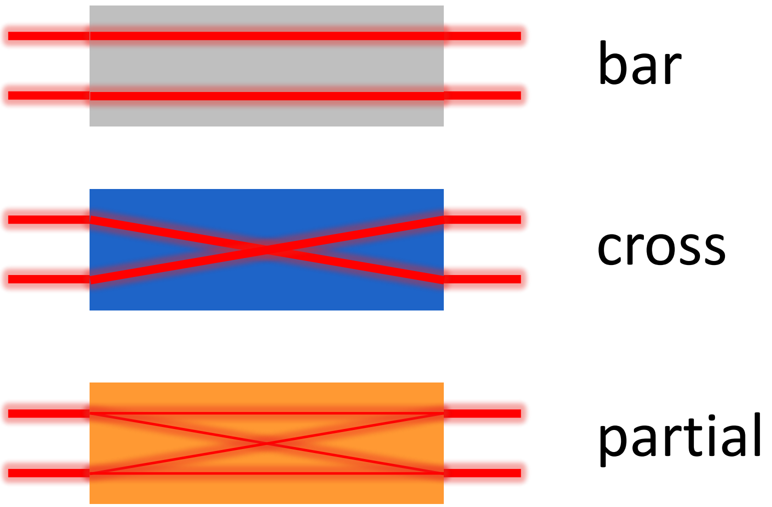


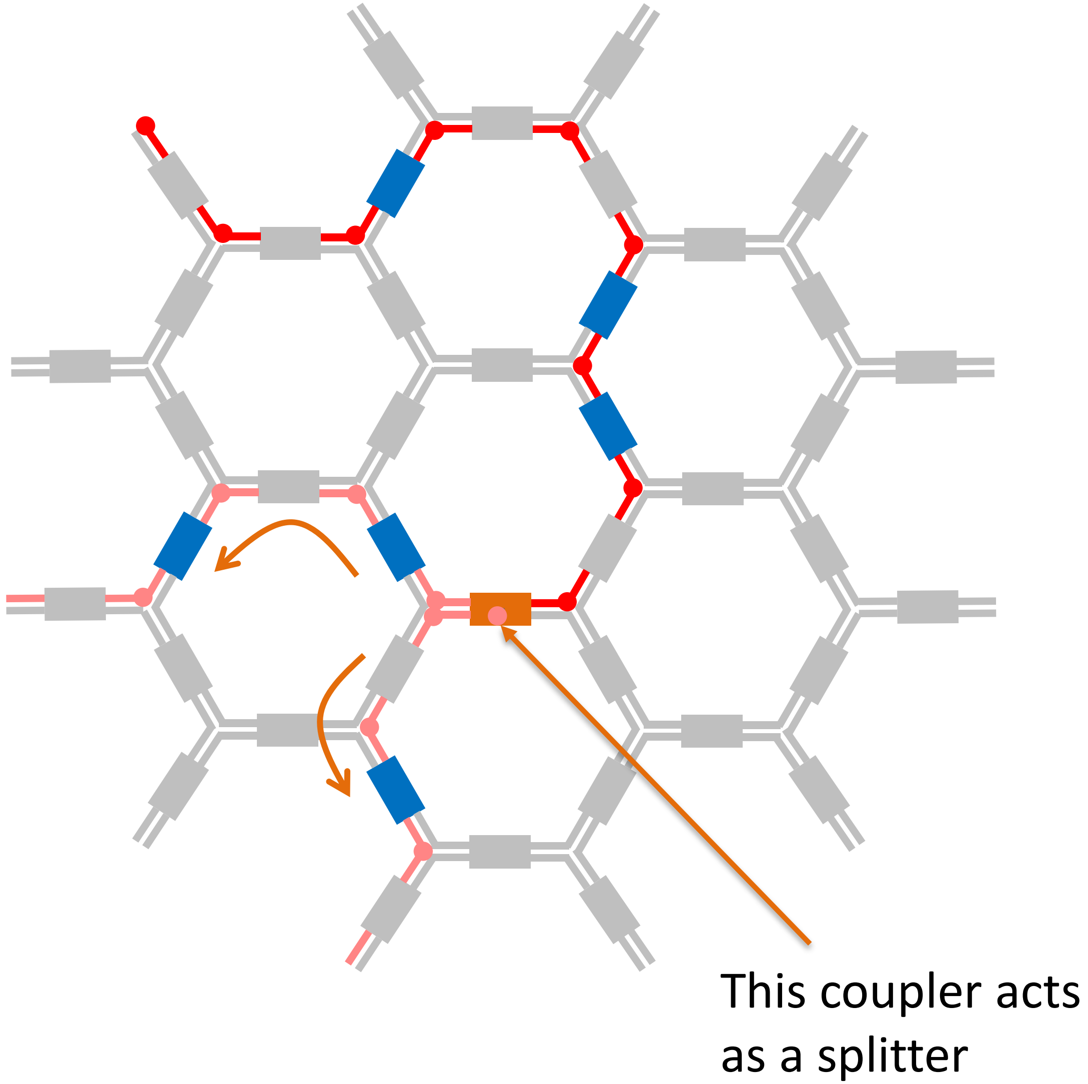
Splitting light

Couplers control arbitrary splitting ratios

Power distribution networks

Multicasting

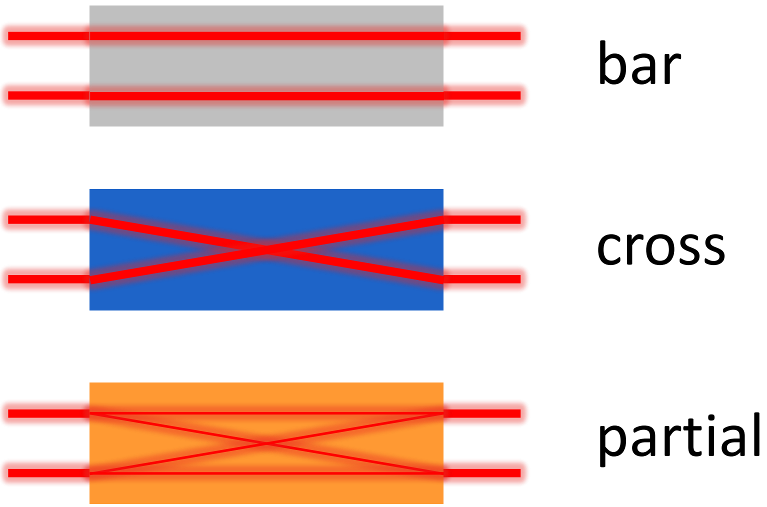


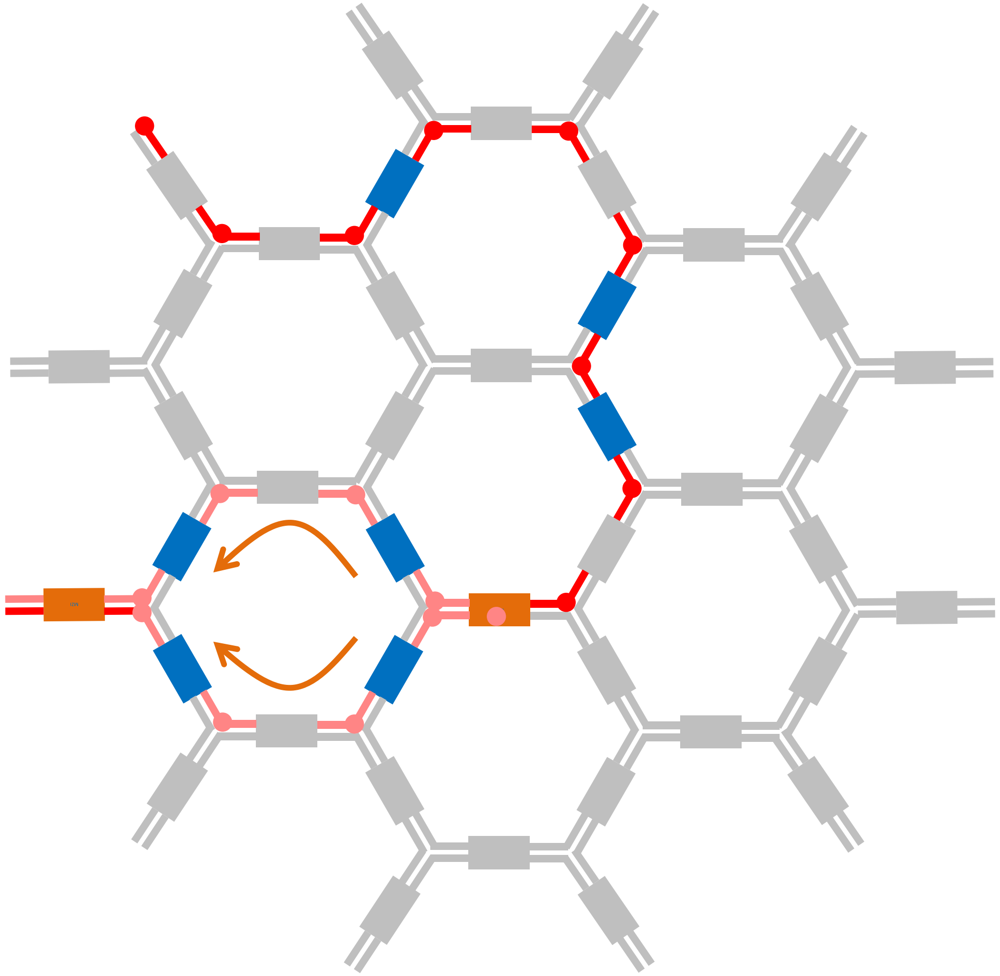


Splitting and Combining Light

Couplers control arbitrary splitting ratios

Phase shifters keep everything in phase

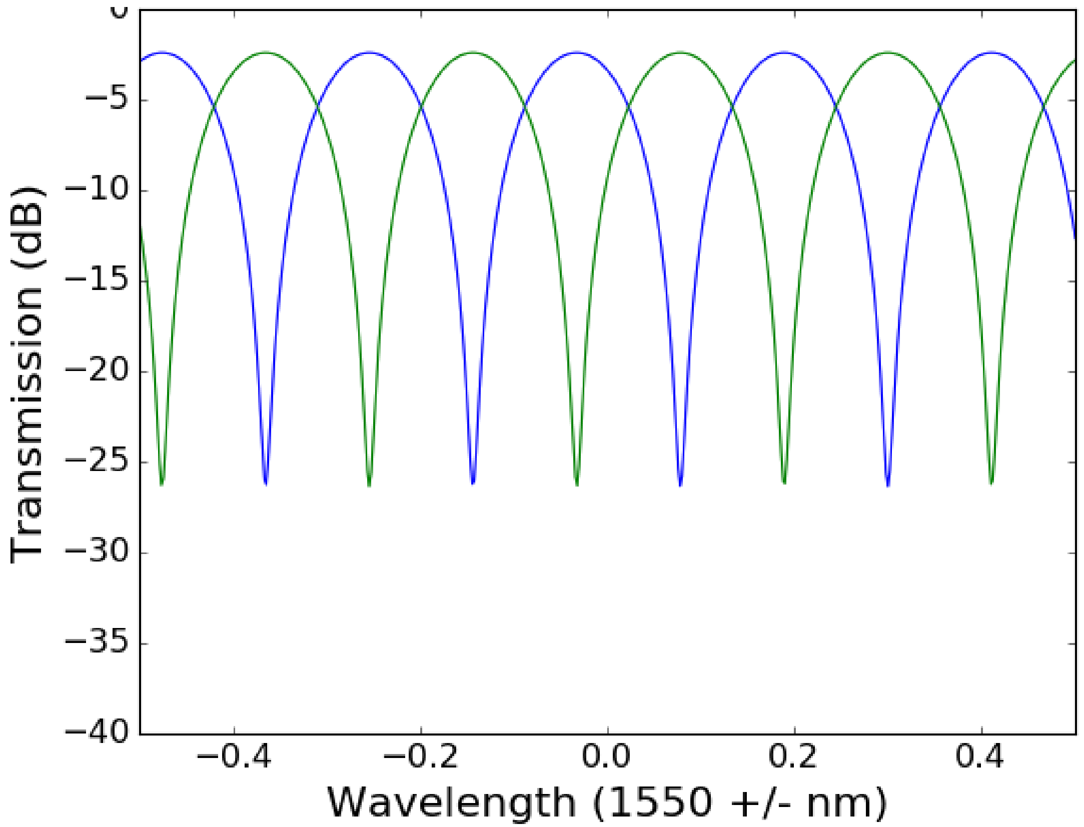




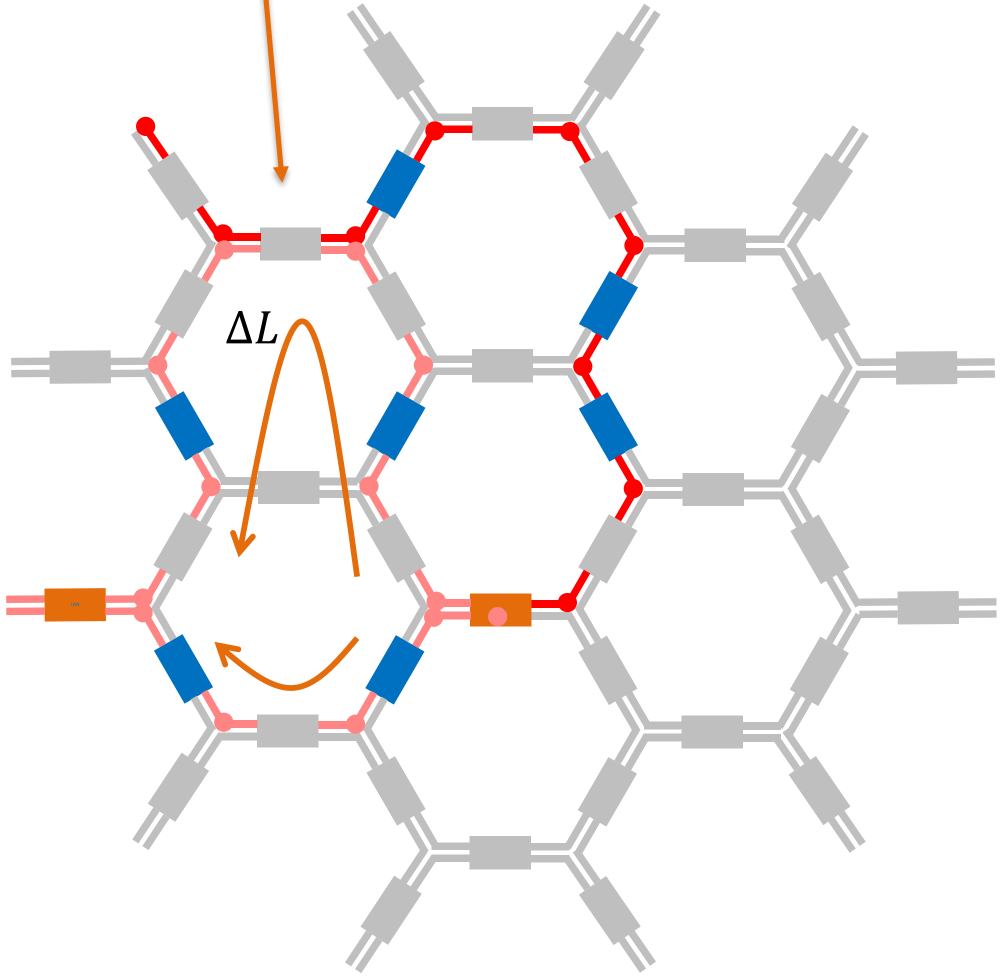
Mach-Zehnder interferometers

Basic building block for FIR filters

Delay can be adjusted per unit lengths



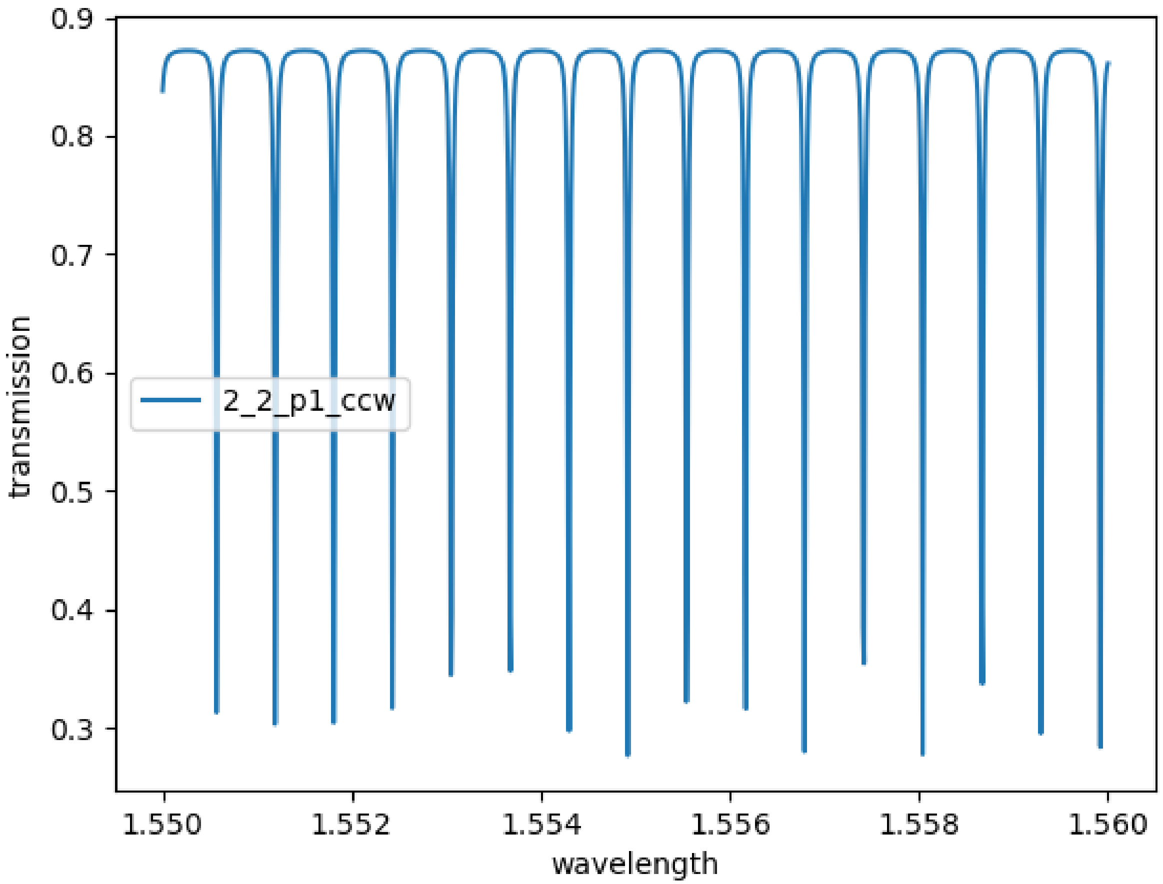
This coupler is used twice

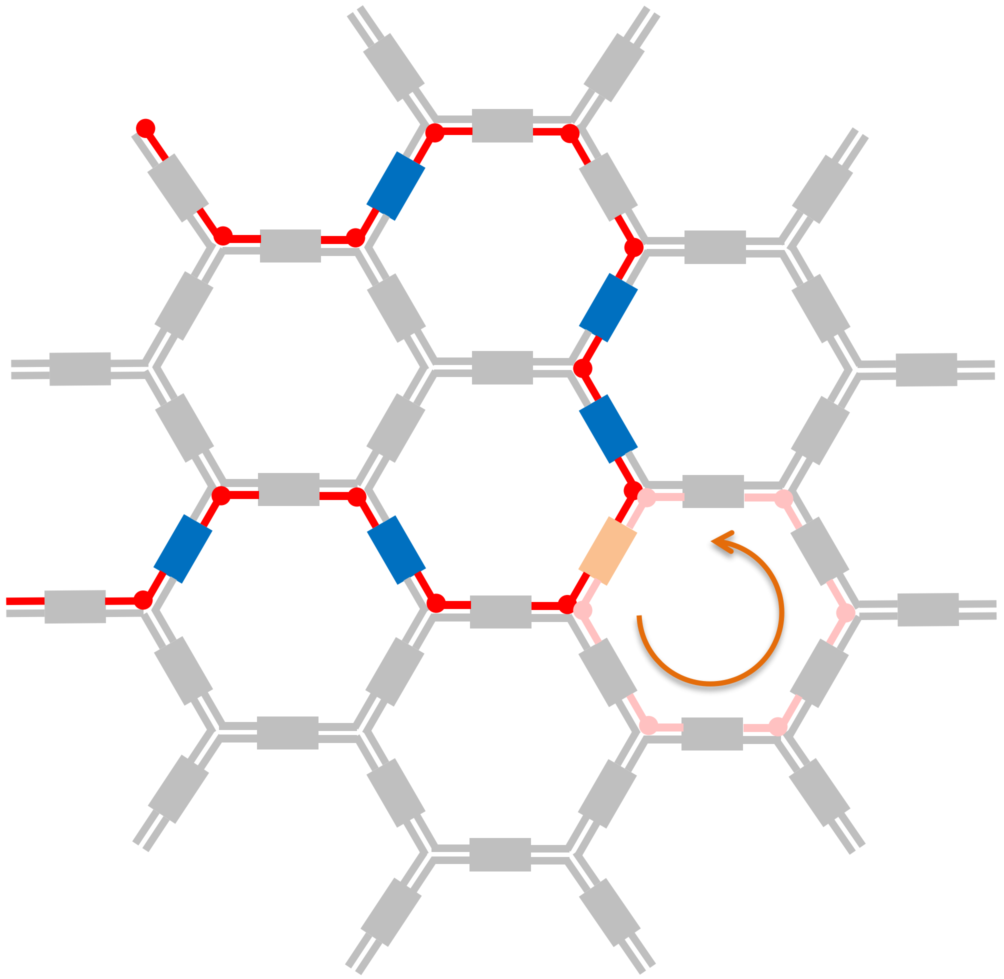


RING RESONATORS

Loop light in itself

Coupler ring resonators together

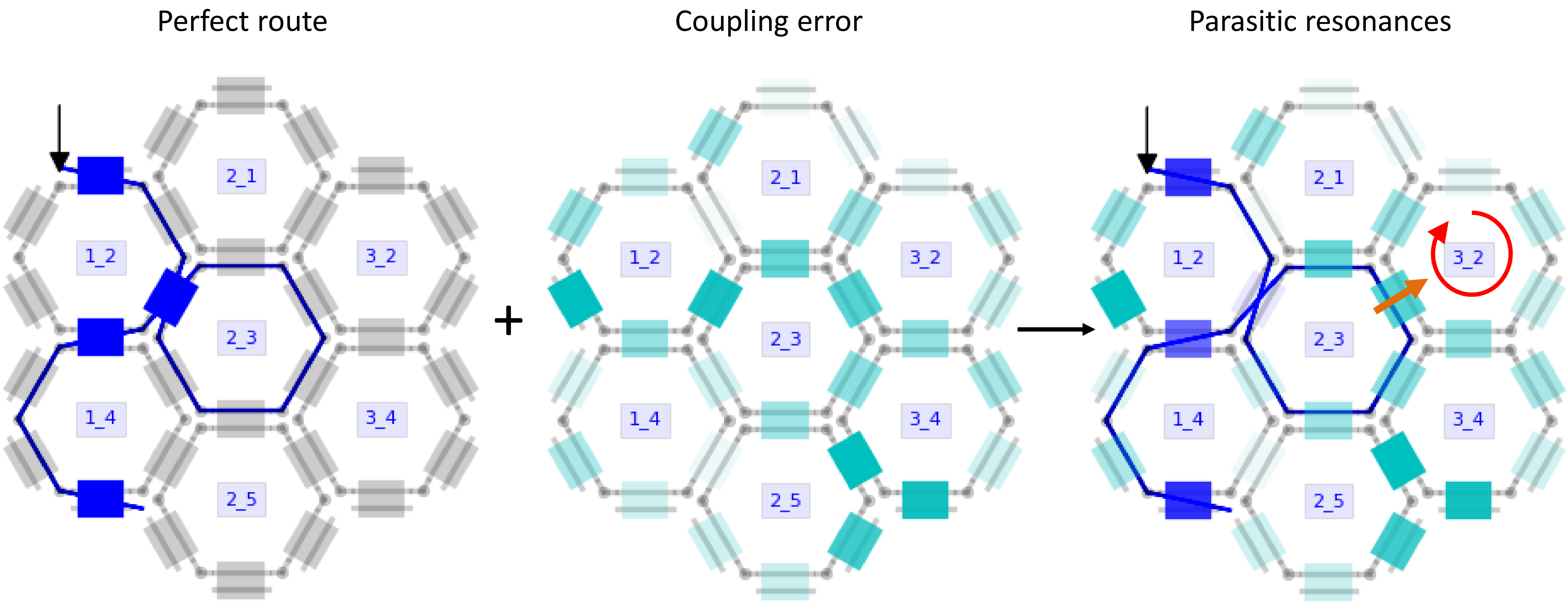




Resonances can be a pain

What if the couplings are not perfect?

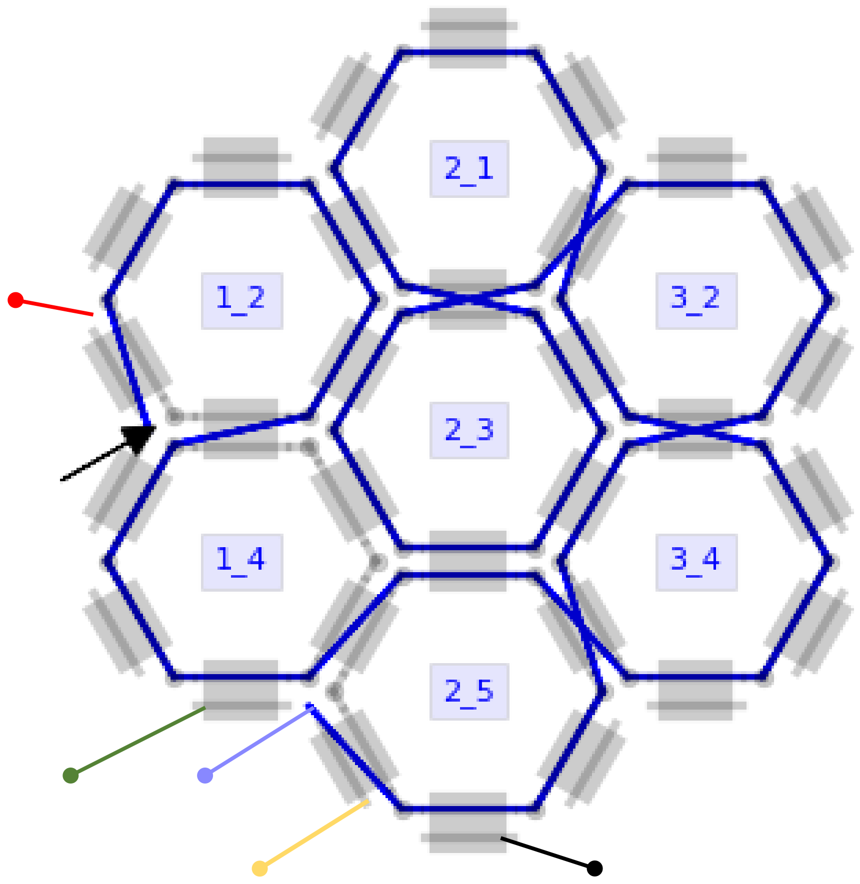
Fabrication errors
Control errors
Digital driving
Temperature gradients

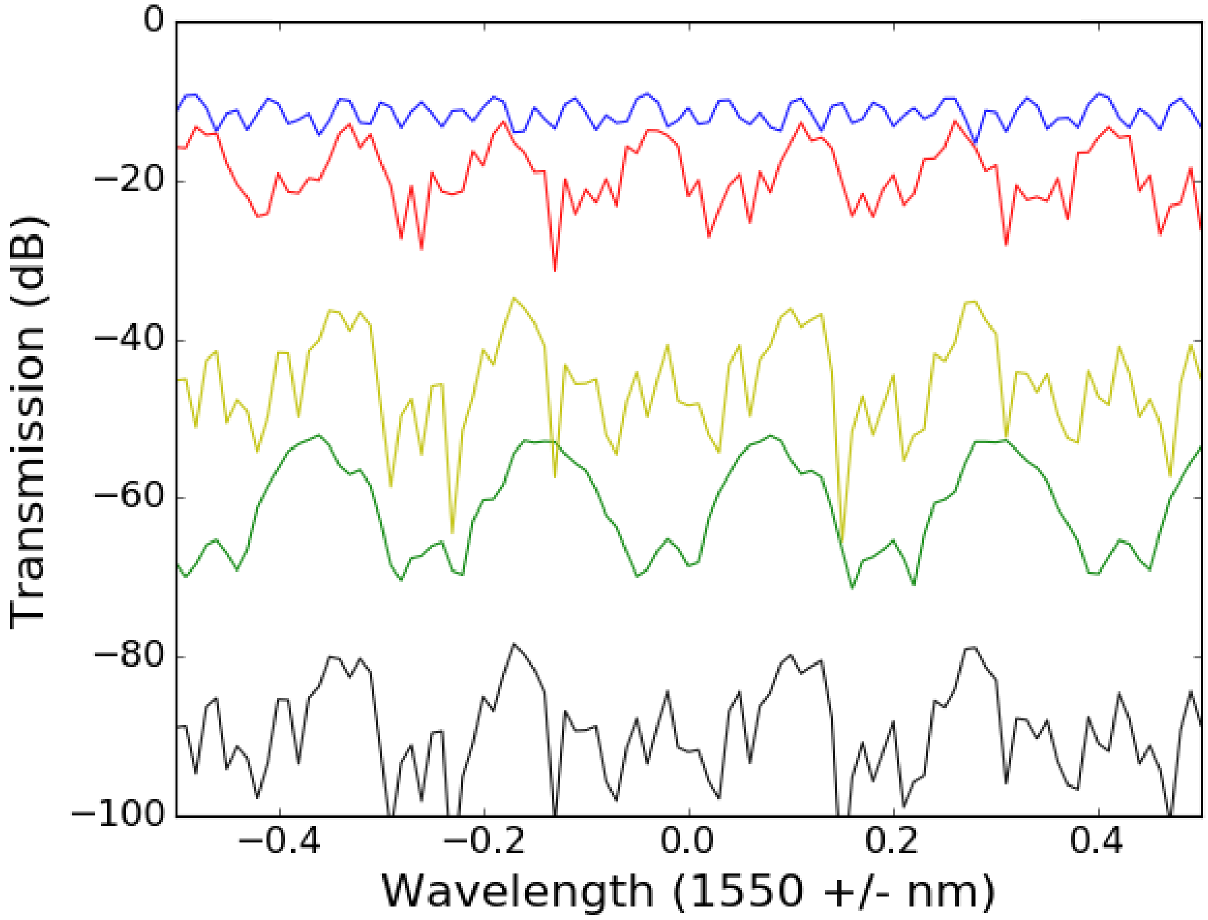


I. Zand, in preparation

Parasitic outputs…

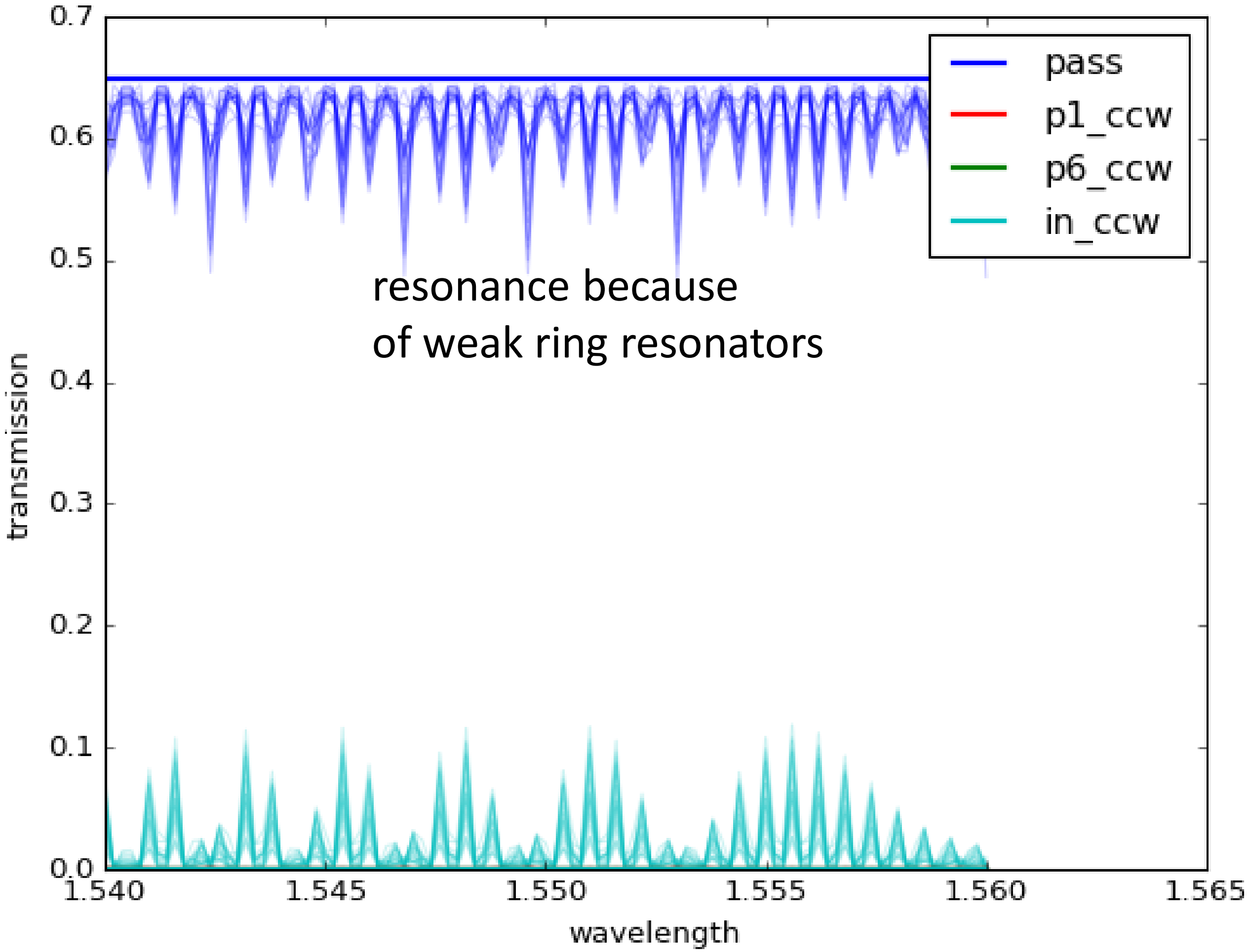
Light goes everywhere it can…

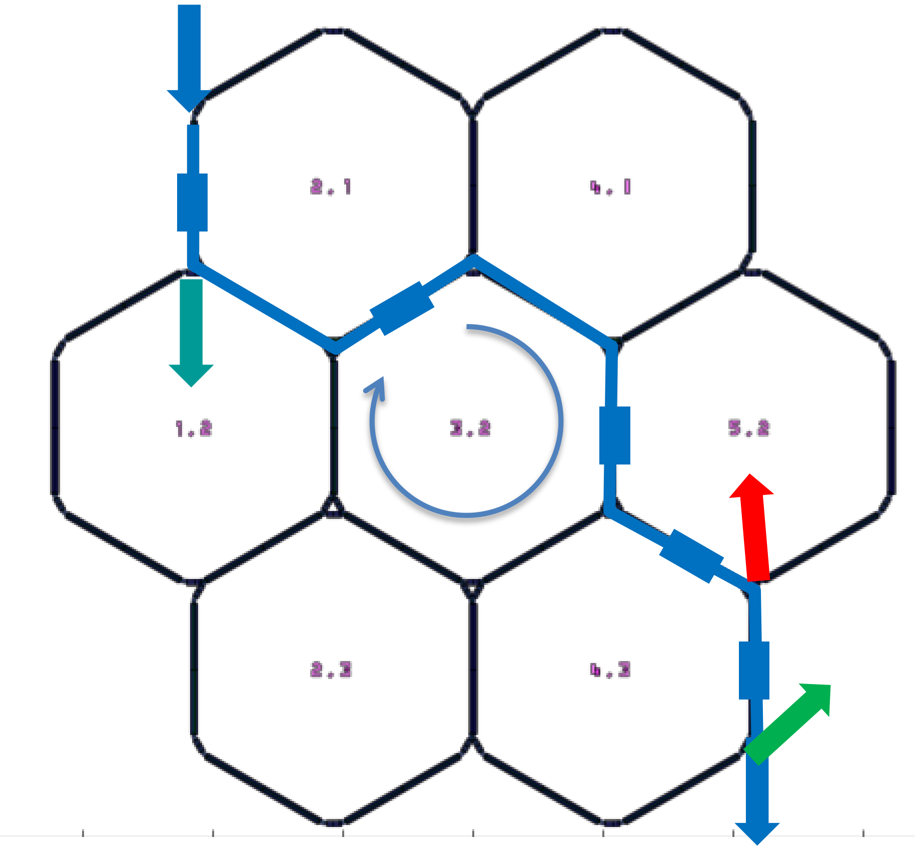




Routing a Path

1% random Variations on the nominal coupling

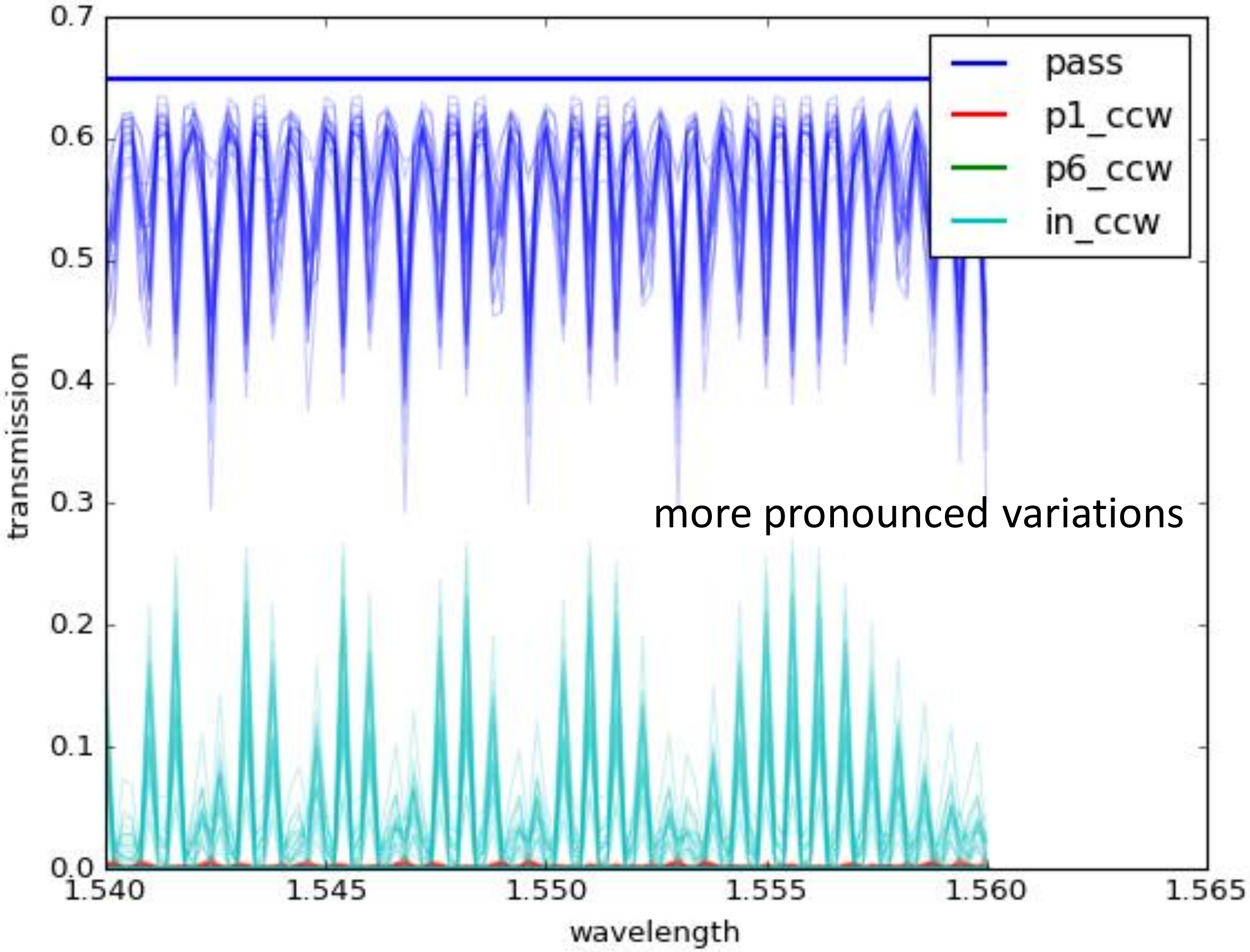


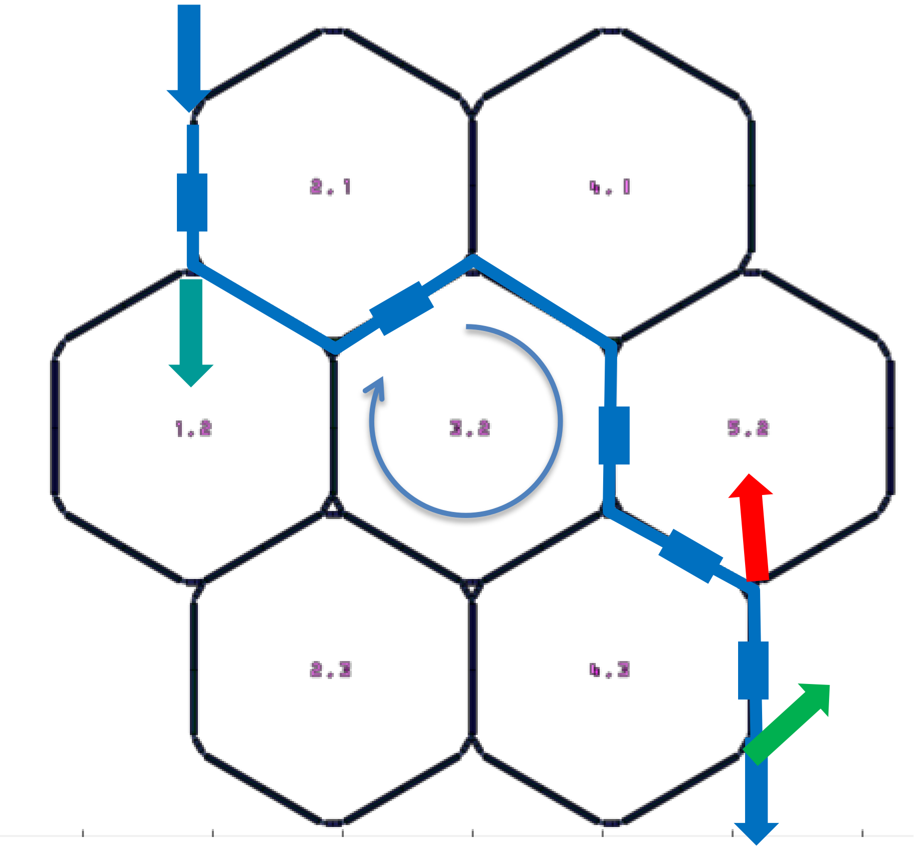


I. Zand, in preparation

Routing a Path

3% random Variations on the nominal coupling

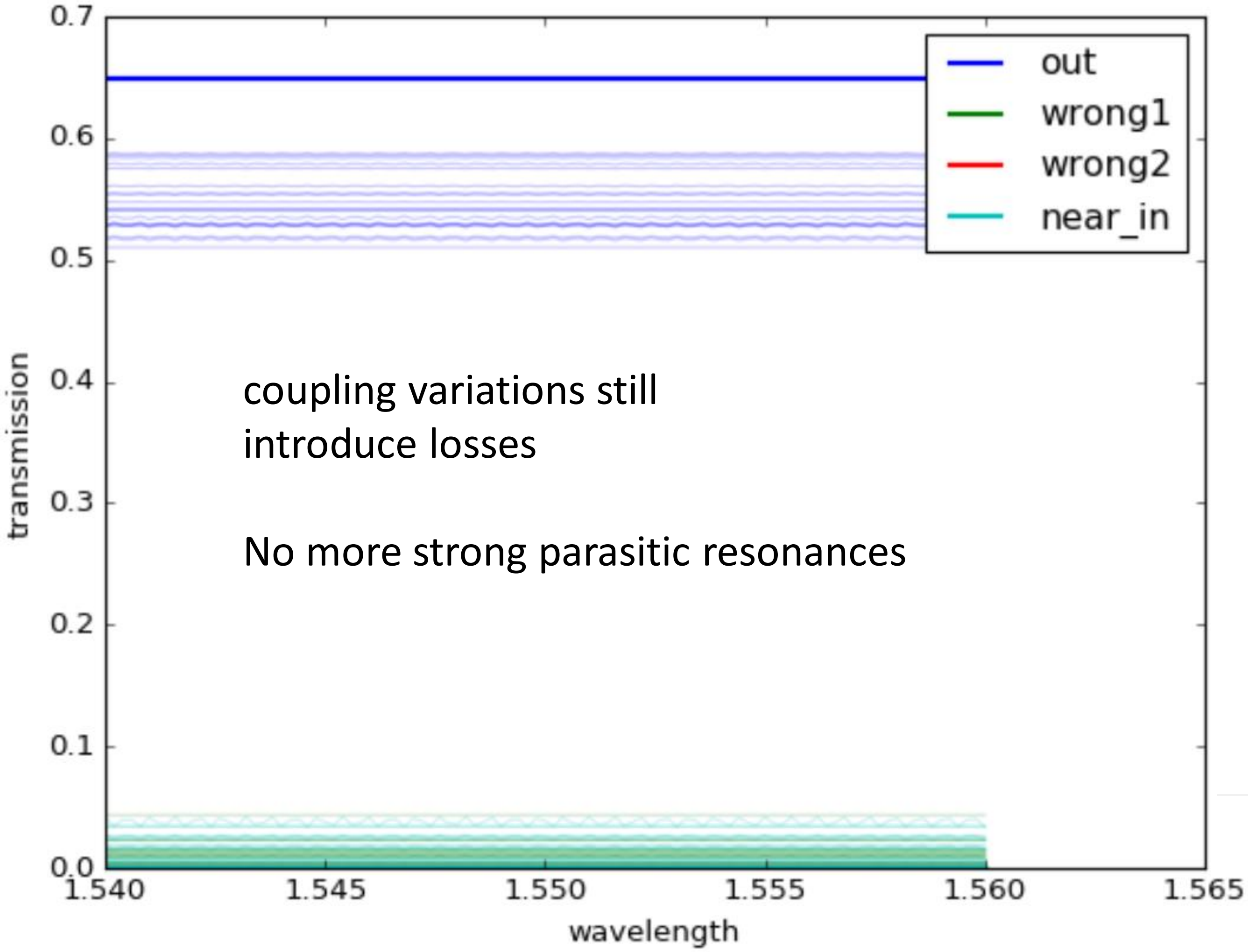


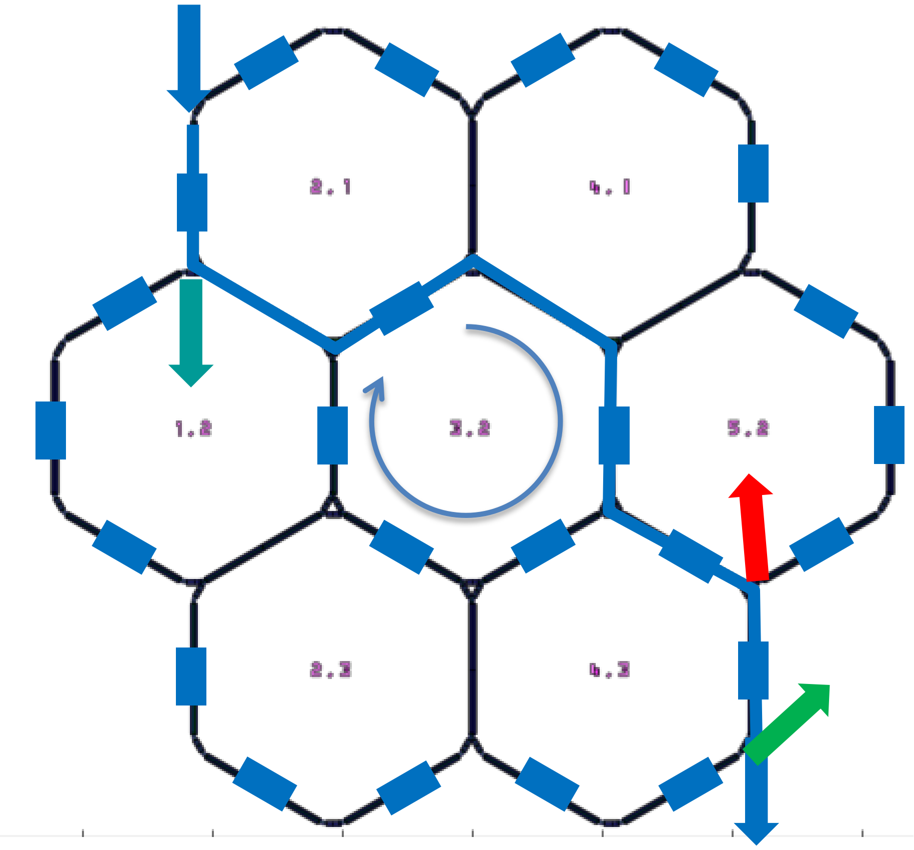


I. Zand, in preparation

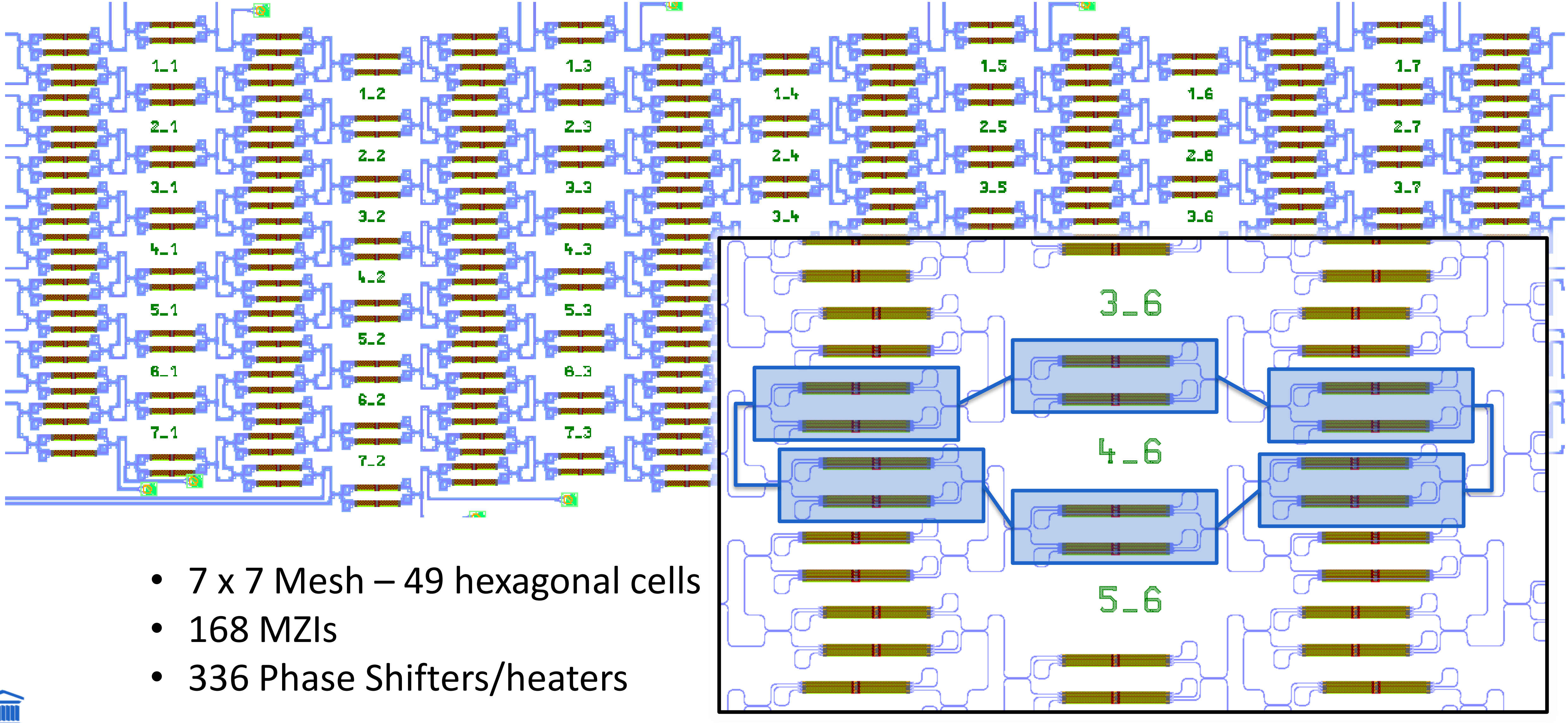
Optimizing the 'unused' couplers

3% random Variations on the nominal coupling





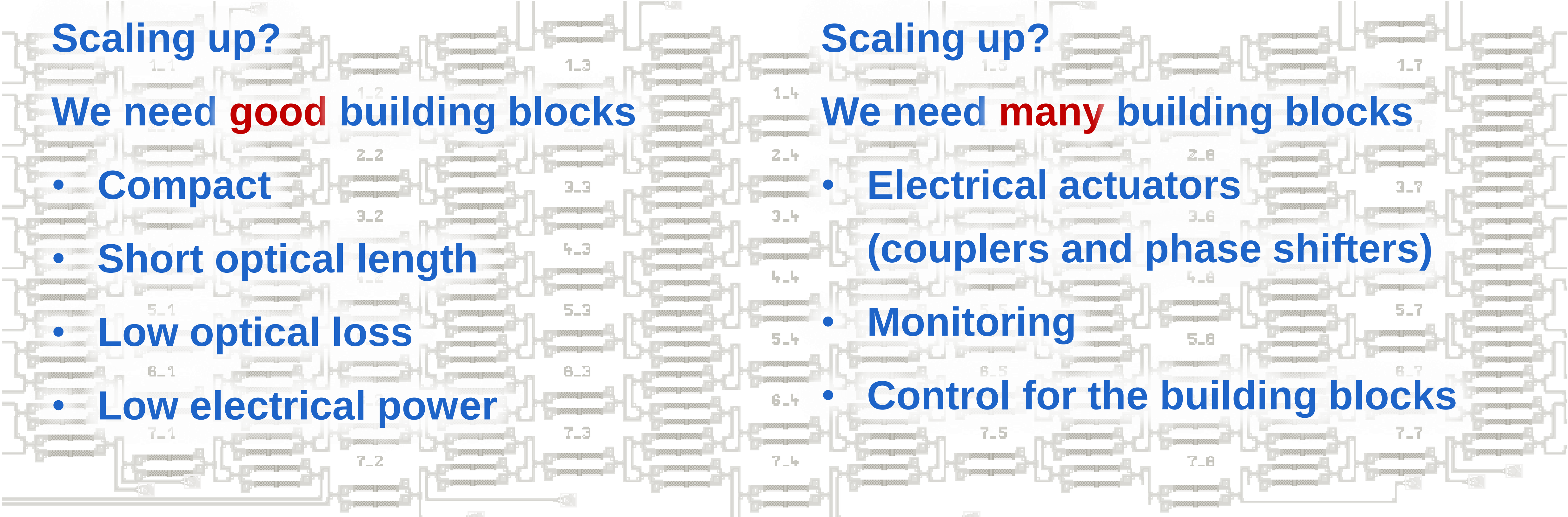
Scaling up the Hexagonal Mesh



- 7 x 7 Mesh – 49 hexagonal cells
- 168 MZIs
- 336 Phase Shifters/heaters

Ribeiro et al., in preparation

LARGE-SCALE OPTICAL MESHES



Scaling up?

We need good building blocks

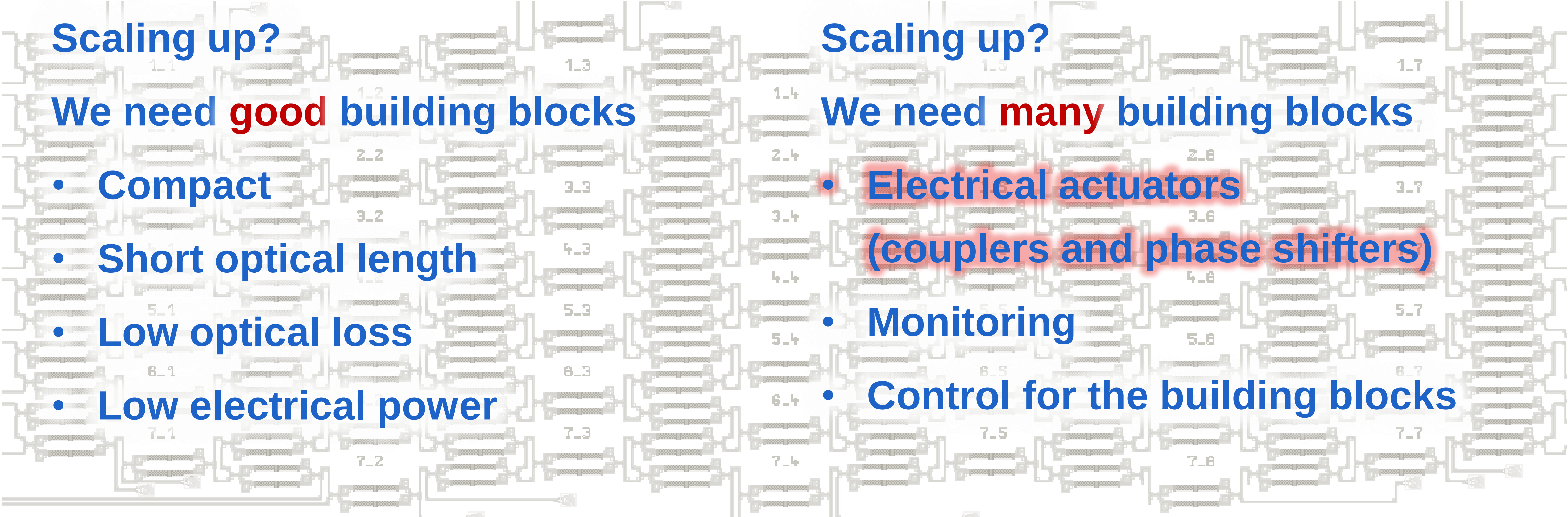
- **Compact**
- **Short optical length**
- **Low optical loss**
- **Low electrical power**

Scaling up?

We need many building blocks

- **Electrical actuators (couplers and phase shifters)**
- **Monitoring**
- **Control for the building blocks**

LARGE-SCALE OPTICAL MESHES



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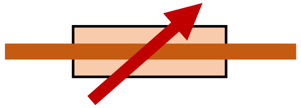
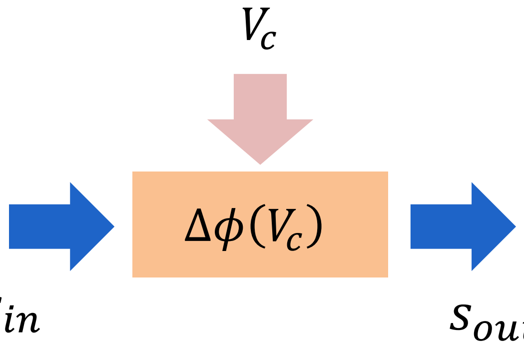
THE ESSENTIAL ACTUATOR BLOCKS

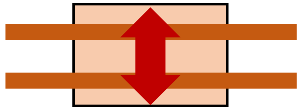
Phase Shifters

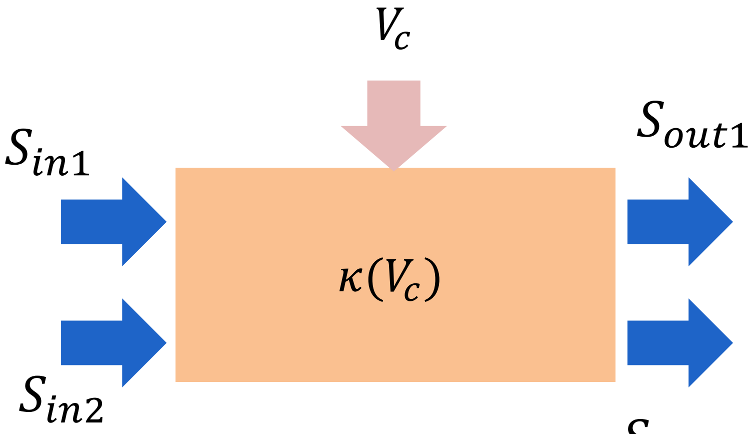




$$s_{out} = s_{in} . e^{j\Delta\phi(V_c)}$$

Tunable Couplers

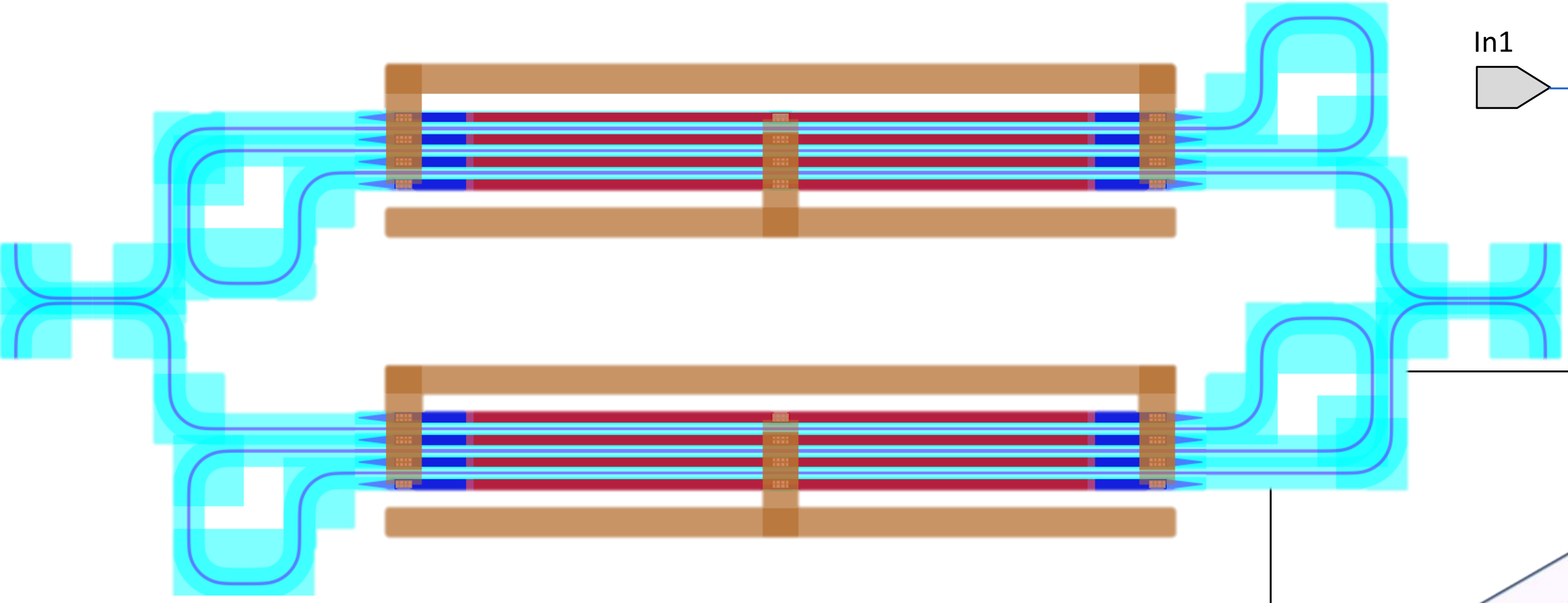


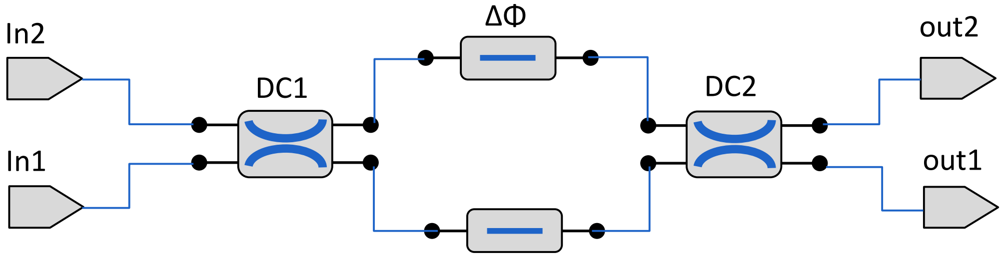


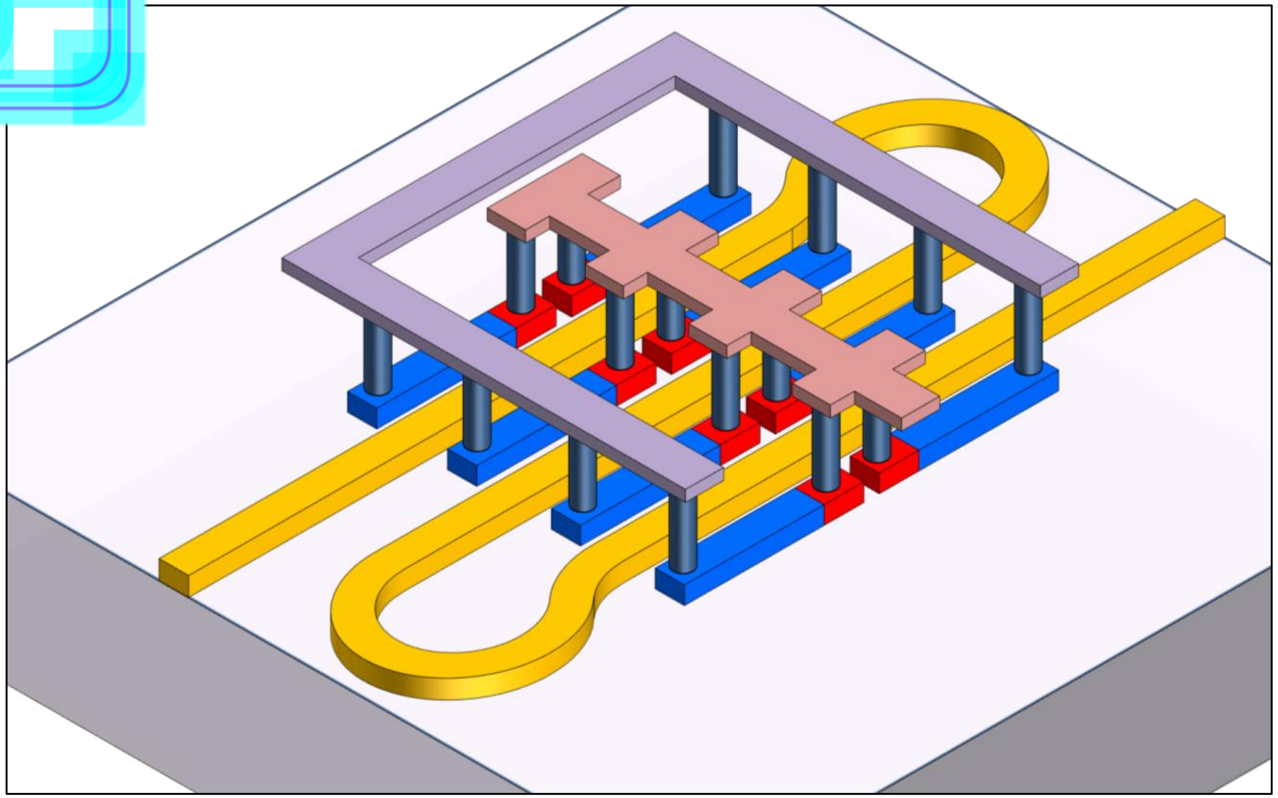
$$S_{out1} = S_{in1}(1-\kappa) + S_{in2}\kappa$$

$$S_{out2} = S_{in1}\kappa + S_{in2}(1-\kappa)$$

Thermal MZI Switch



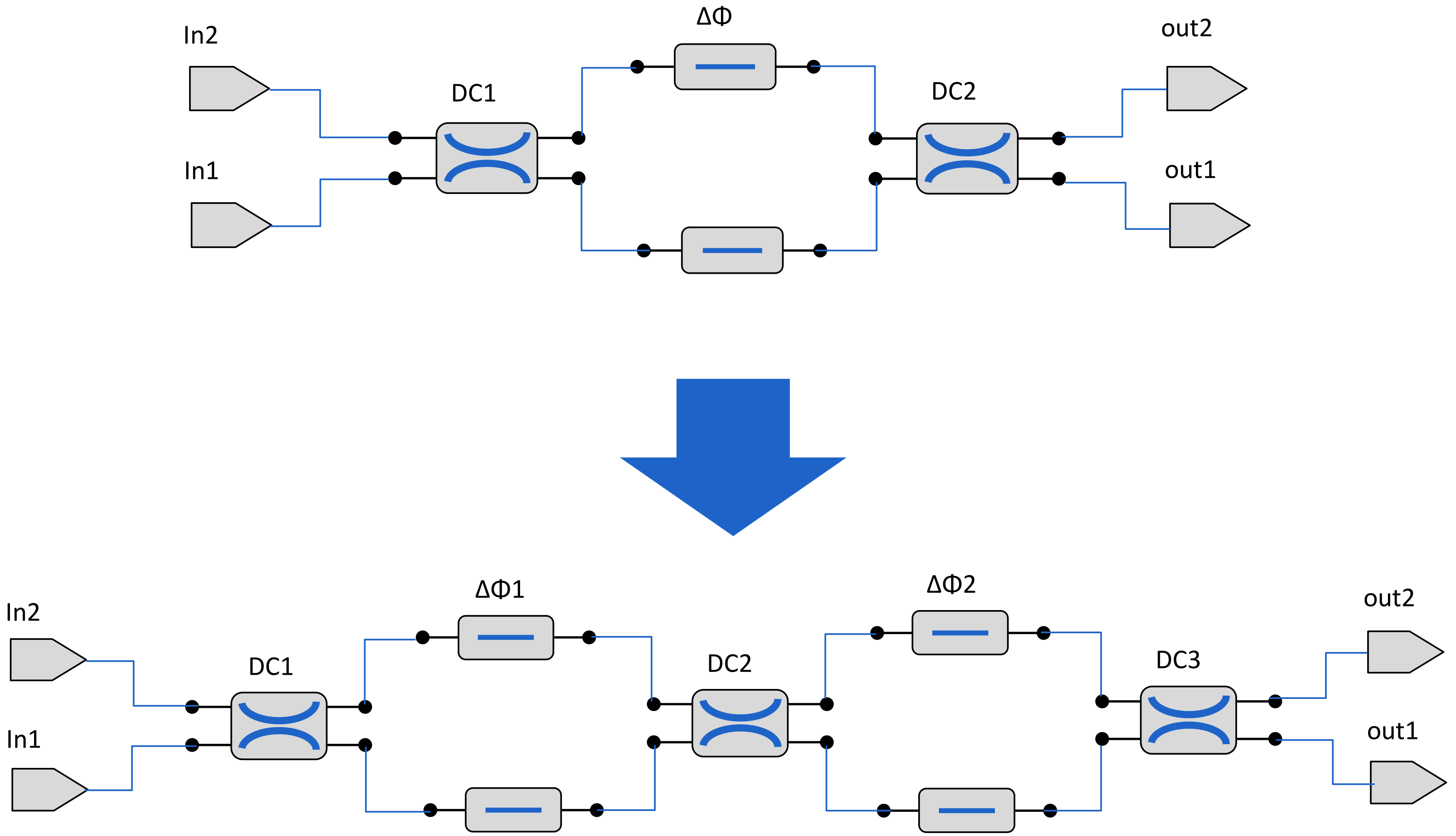




- Symmetric MZI with phase shifter in both arms
- Directional coupler as splitter/combiners
- Side-strip heater with integrated diode as phase shifter

MAKING THE TUNABLE COUPLER BROADBAND AND TOLERANT

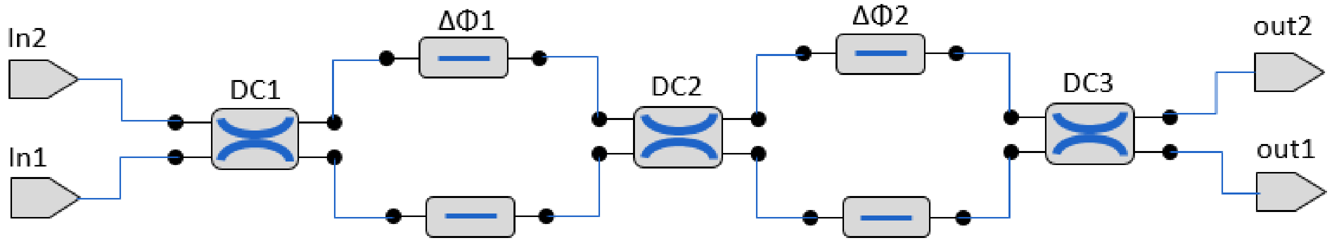
Use two coupler stages

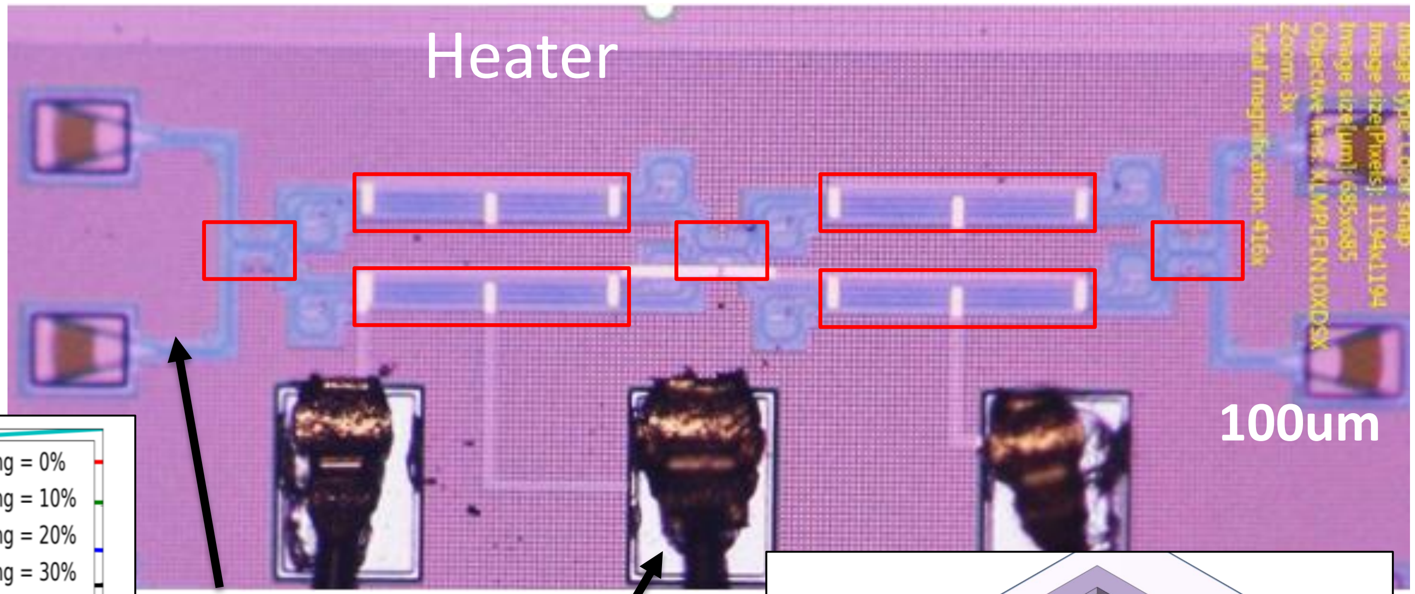


MAKING THE TUNABLE COUPLER BROADBAND AND TOLERANT

Broadband coupling over 50nm

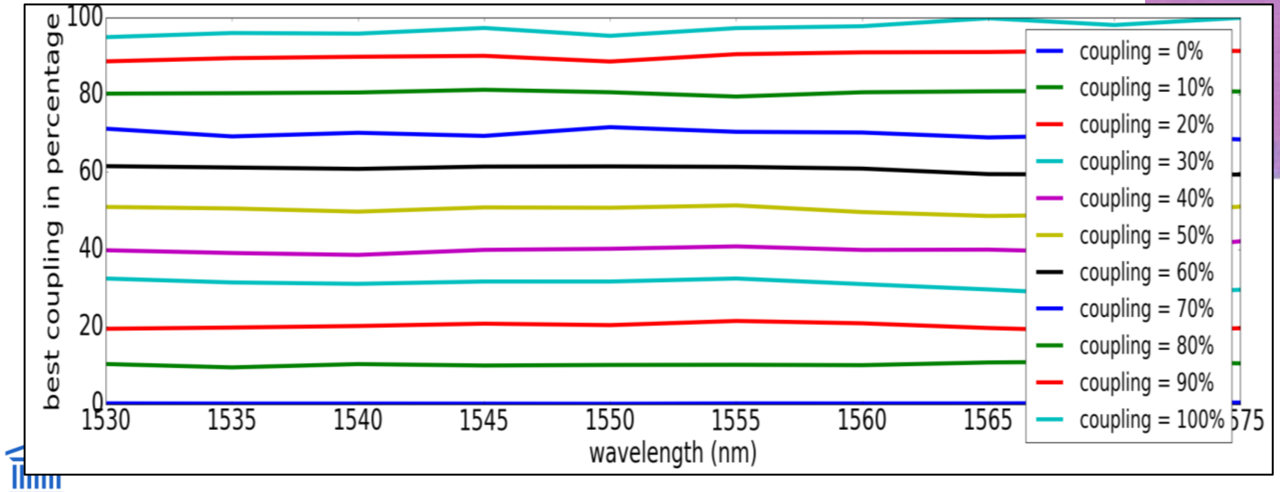
Tolerant to fabrication variations in the directional couplers

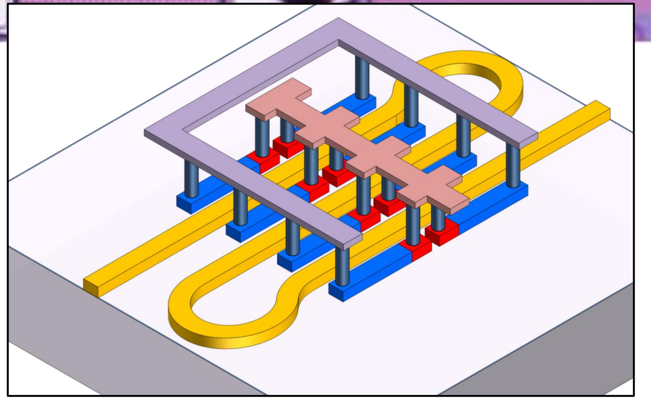




Grating coupler

wirebond





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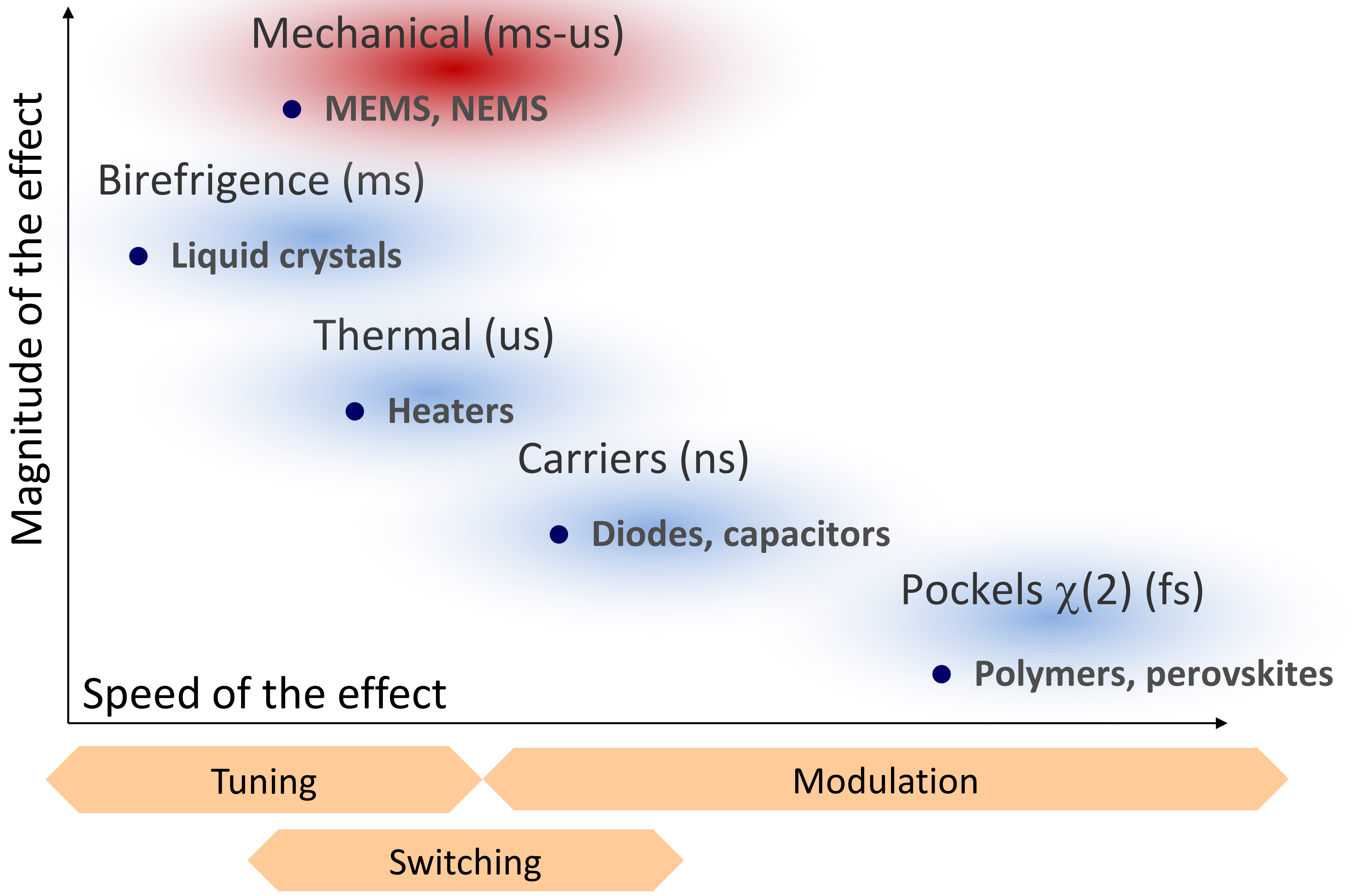
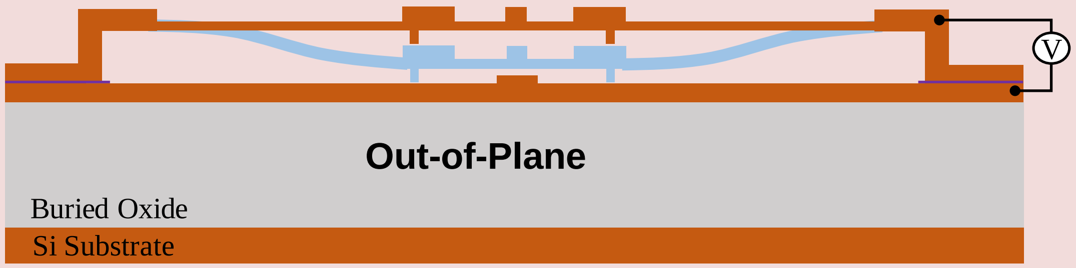
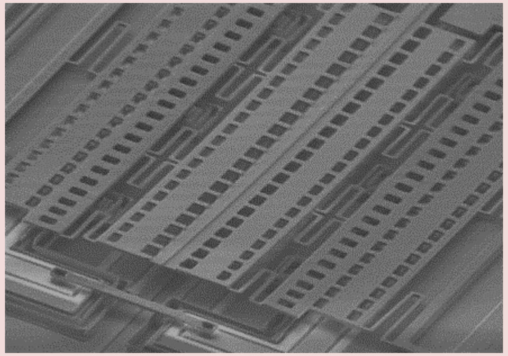
PHOTONIC PHASE SHIFTERS: REDUCE POWER CONSUMPTION?



Movable Waveguide Approaches in Silicon Photonics

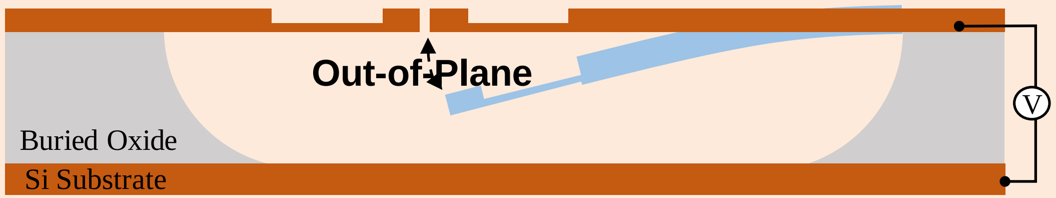
Multi-Layer

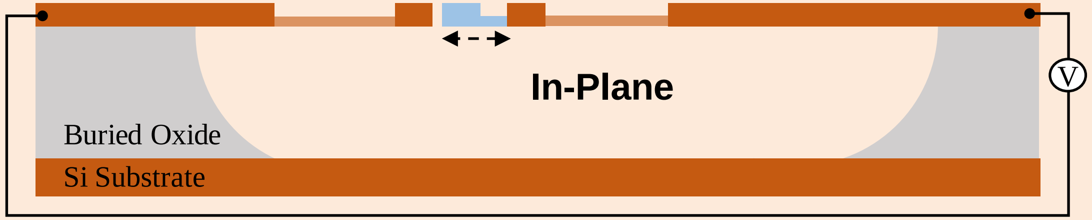


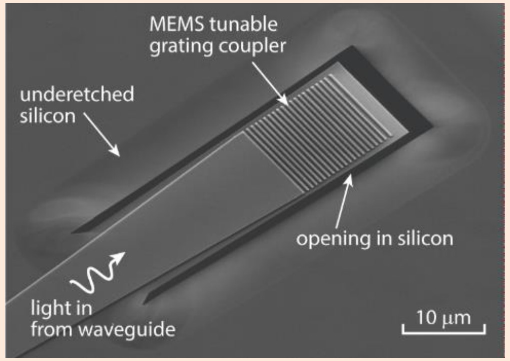


Han et al.,
Optica, 2018

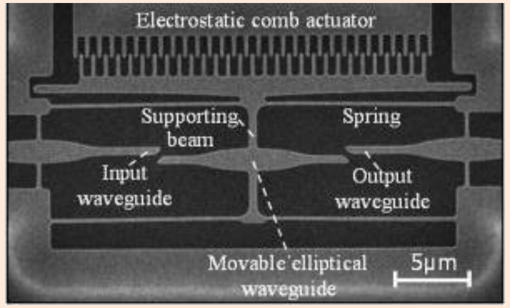
Single-Layer







Errando-Herranz, C., Colangelo, M., Ahmed, S., Björk, J., Gylfason, K B., IEEE MEMS 2017

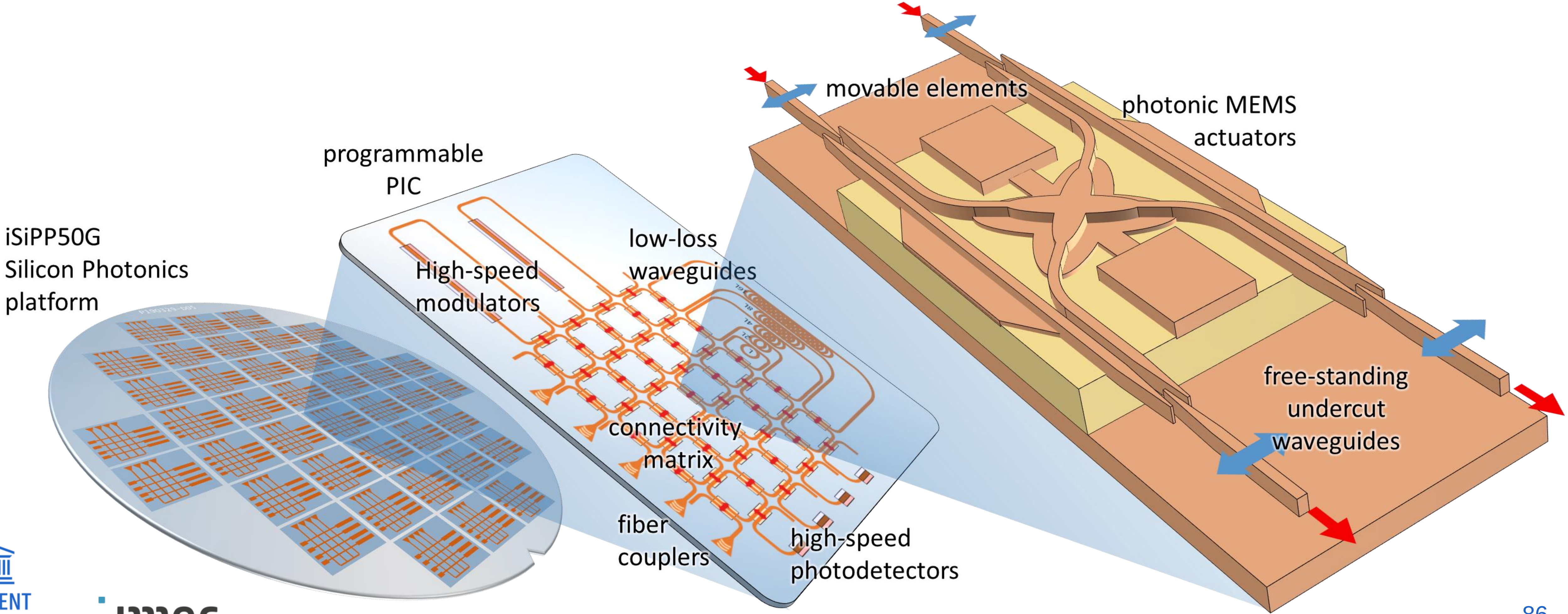


Bulgan, E.; Kanamori, Y., Hane, K.,
Appl. Phys. Lett. 2008, 92, 101110

Courtesy: Niels Quack

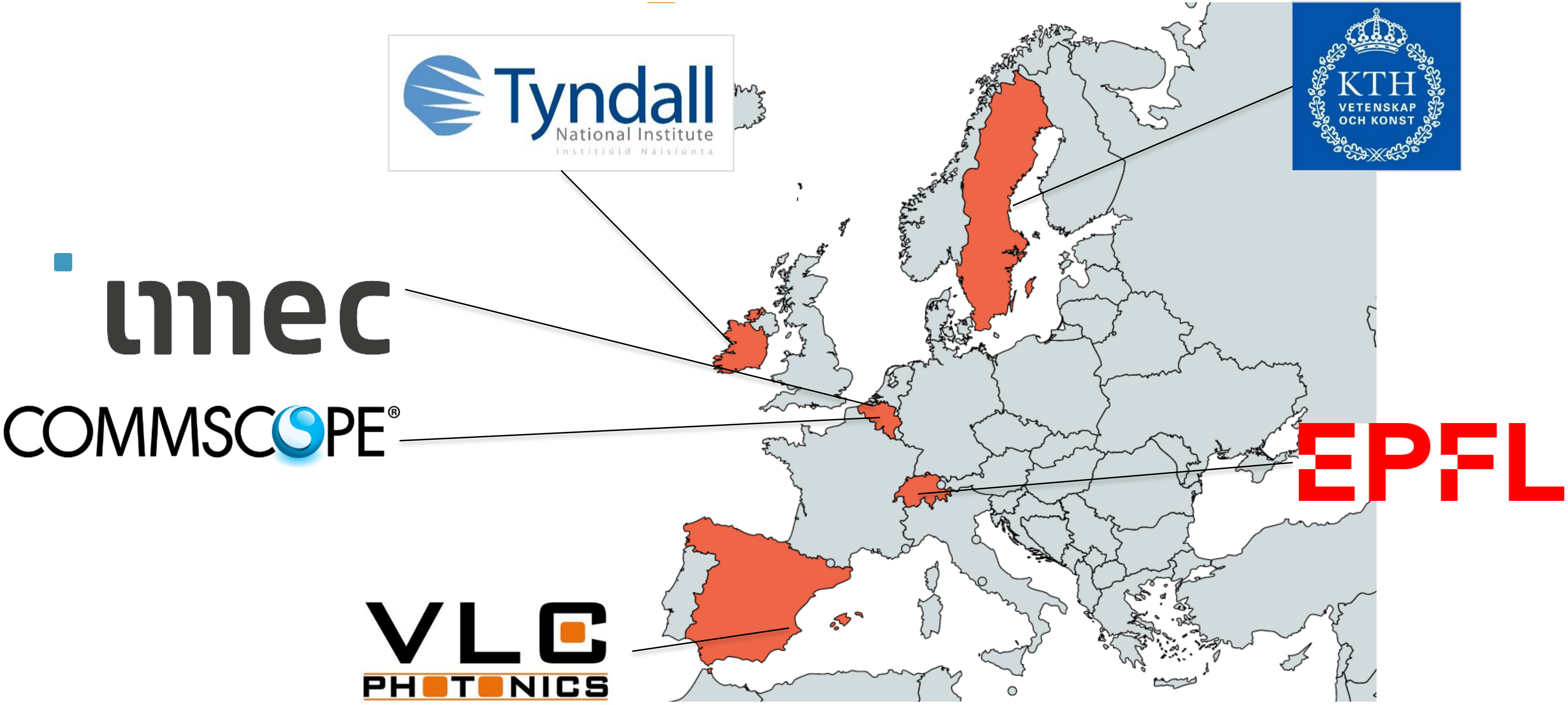
MORPHIC: Photonic MEMS for Programmable Circuits

MEMS enable low (zero) power reprogramming of generic silicon photonics circuitry.



morphic

Mems-based zer**O**-power **R**econfigurable **PH**otonic **IC**s



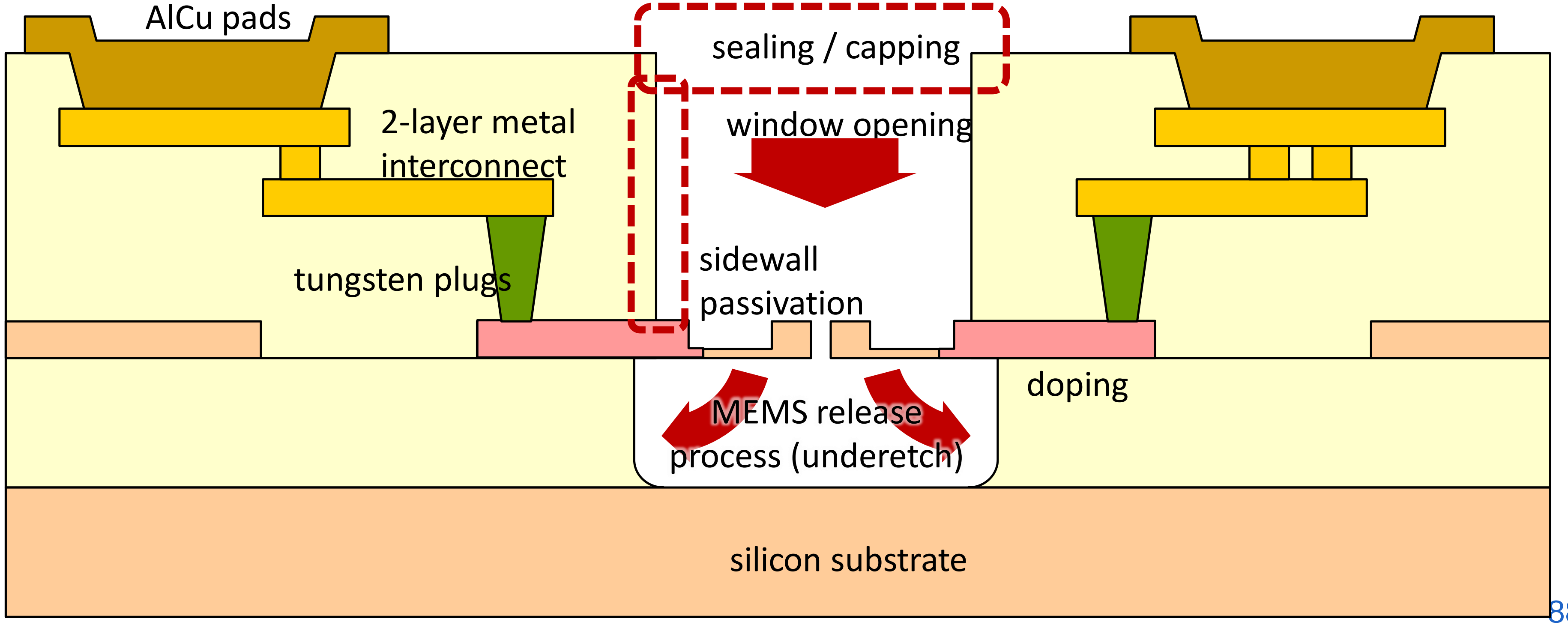
Horizon 2020

SILICON PHOTONICS MEMS PROCESS DEVELOPMENT

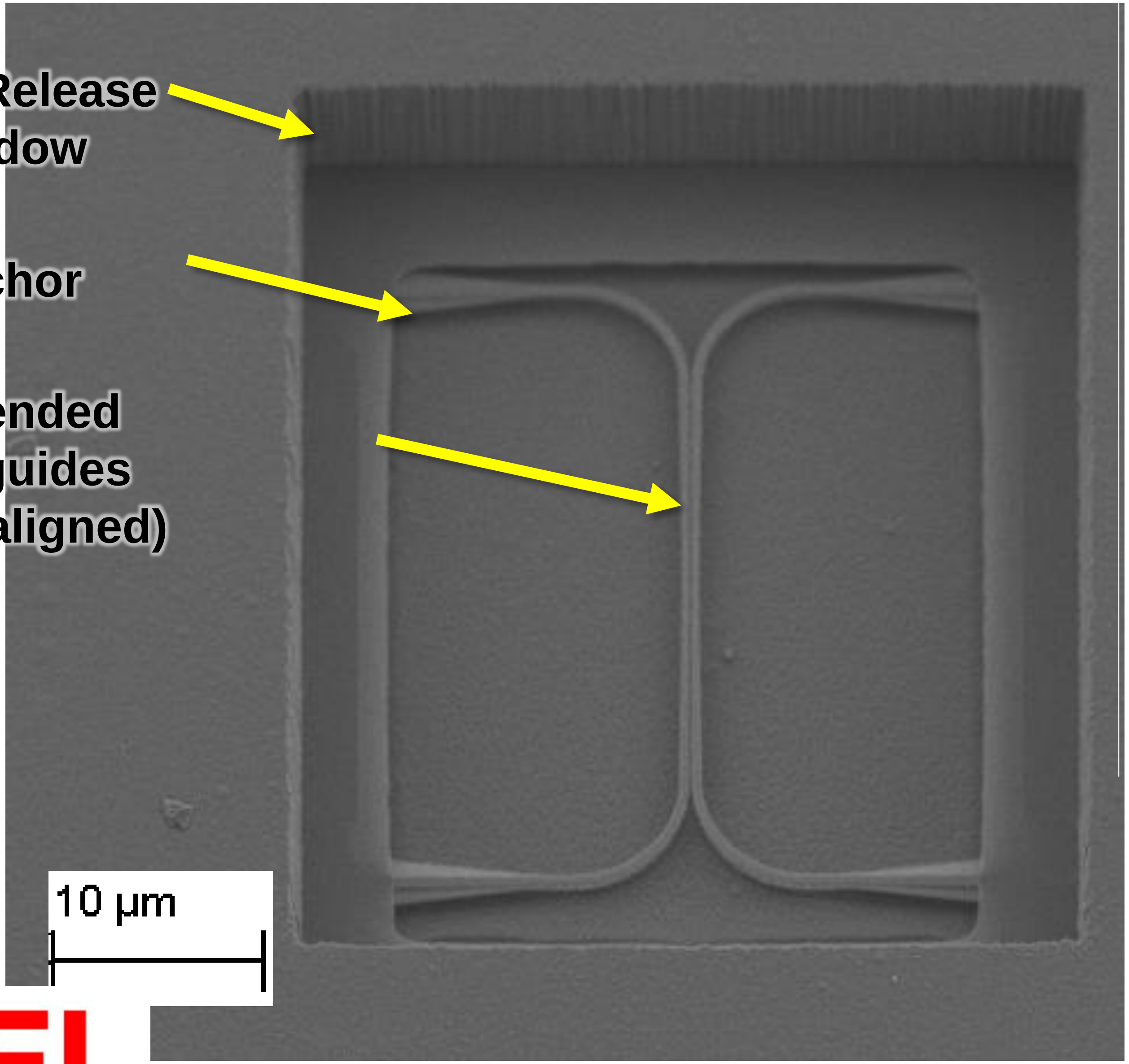
Silicon Photonic MEMS process.

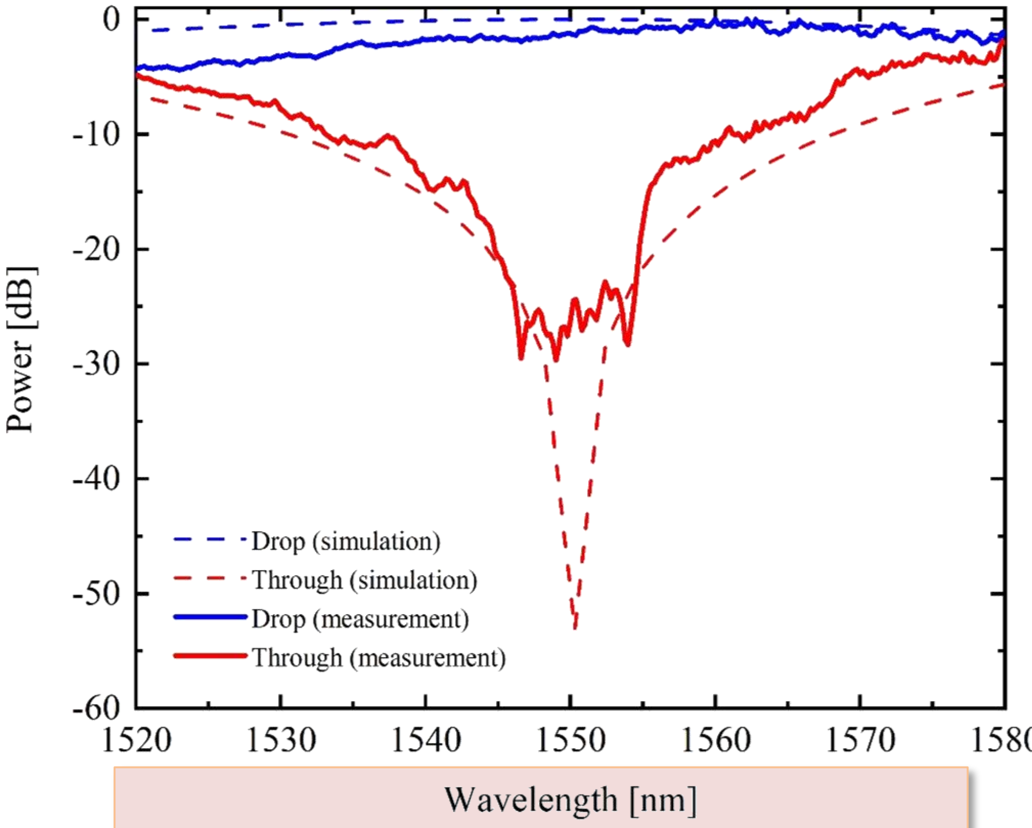
Extend IMEC's wafer-level iSiPP50G process on a die level (EPFL, KTH)

- opening
- passivation
- underetch (release)
- sealing



DEVICE EXAMPLE: FREESTANDING ADIABATIC COUPLER





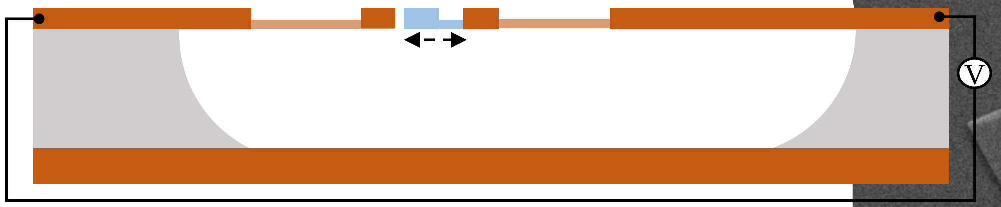
Experimental Data:

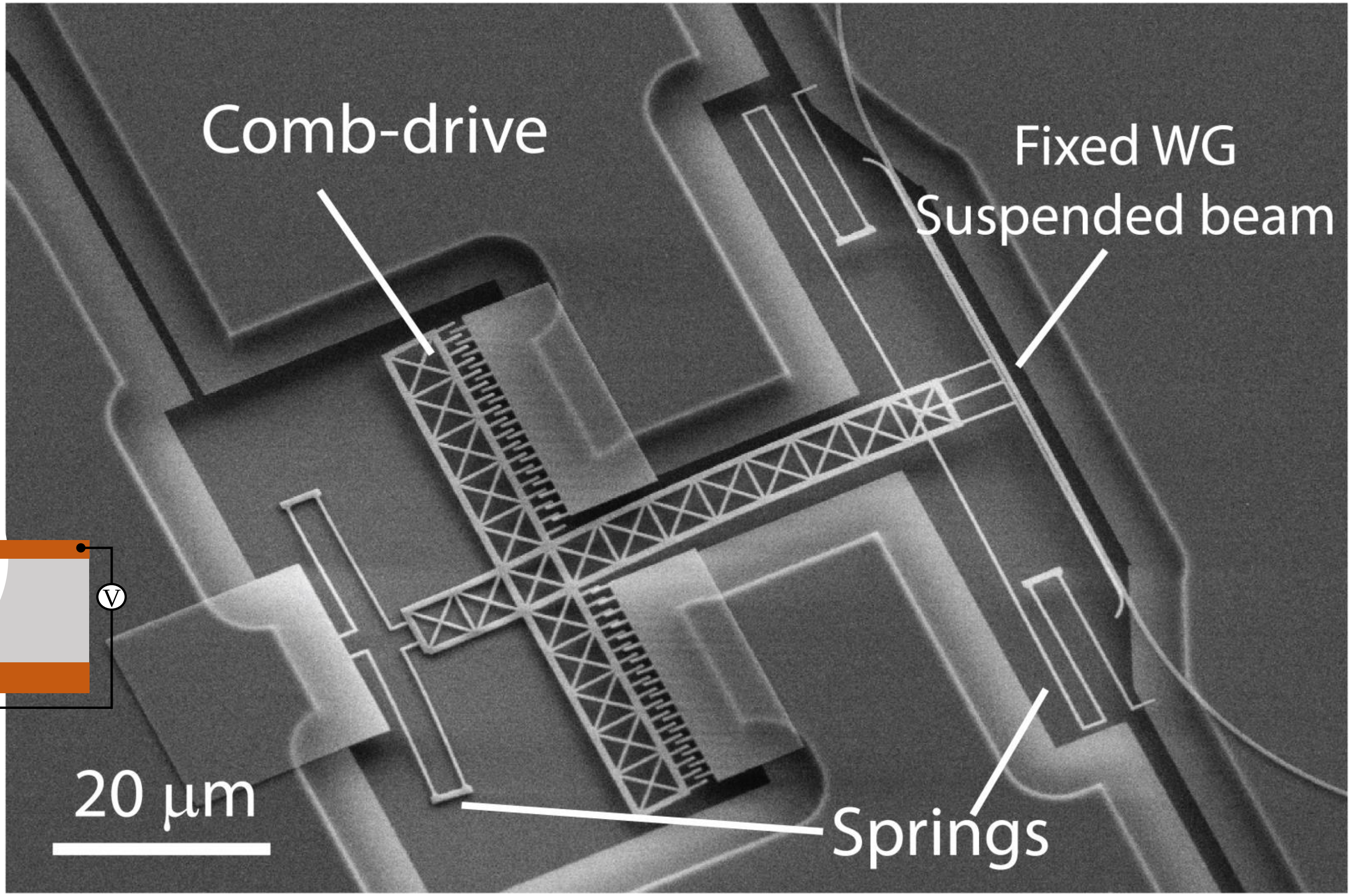
- **Insertion Loss: <0.5dB**
- **1dB Bandwidth: 35nm (@1560nm)**

Sattari et al. (in preparation)

MEMS-based Phase shifter

In-plane actuation with Comb drive



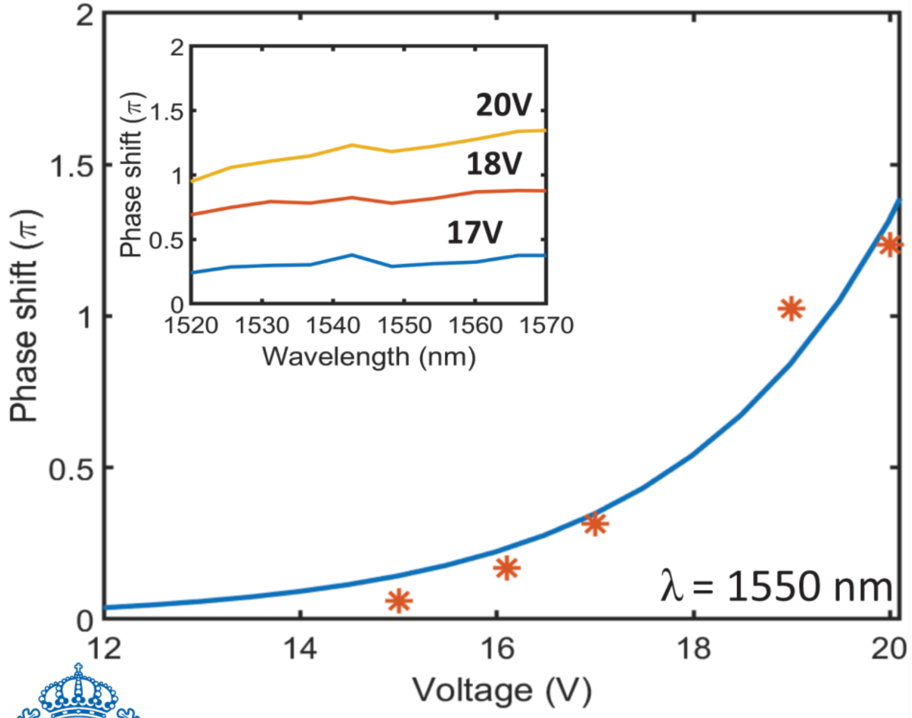


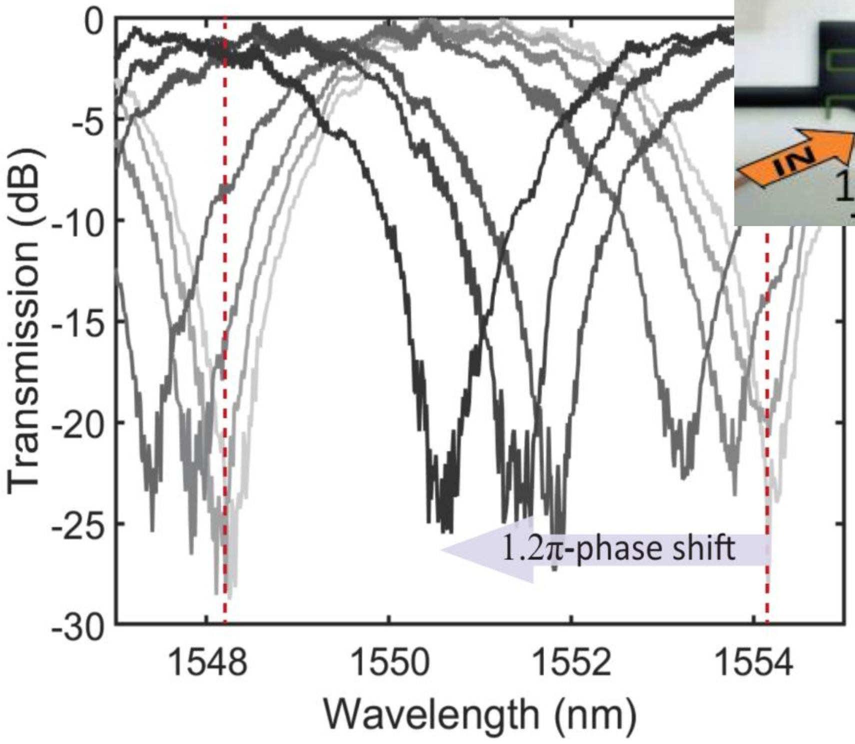
Edinger et al. *Low-loss MEMS phase shifter for large scale reconfigurable silicon photonics*. *32nd IEEE MEMS conference (2019)*

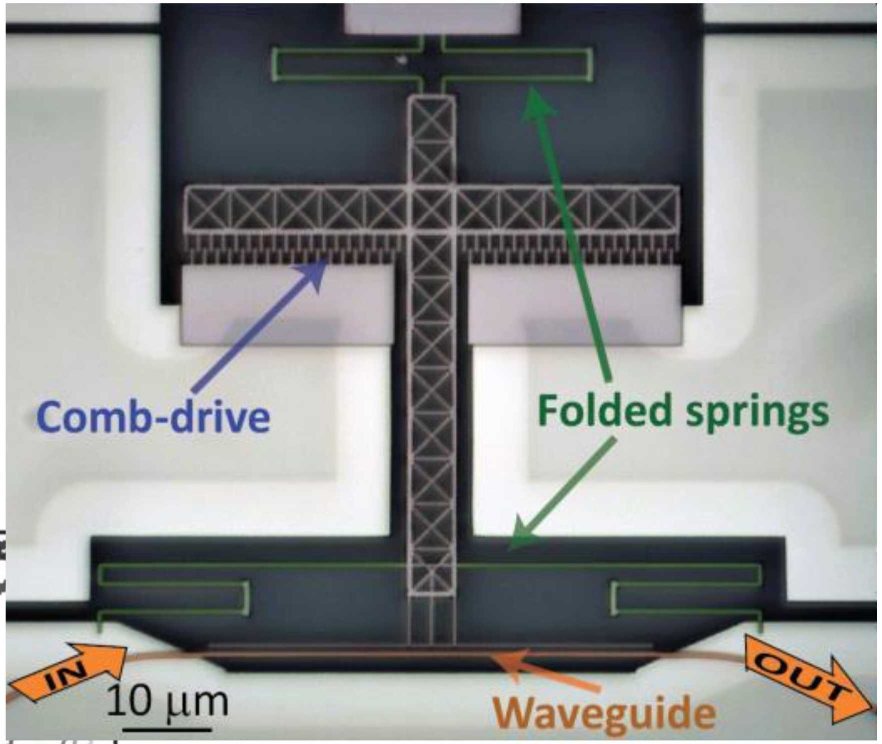
MEMS-based Phase shifter

In-plane actuation with Comb drive

> π phase shift at < 20V

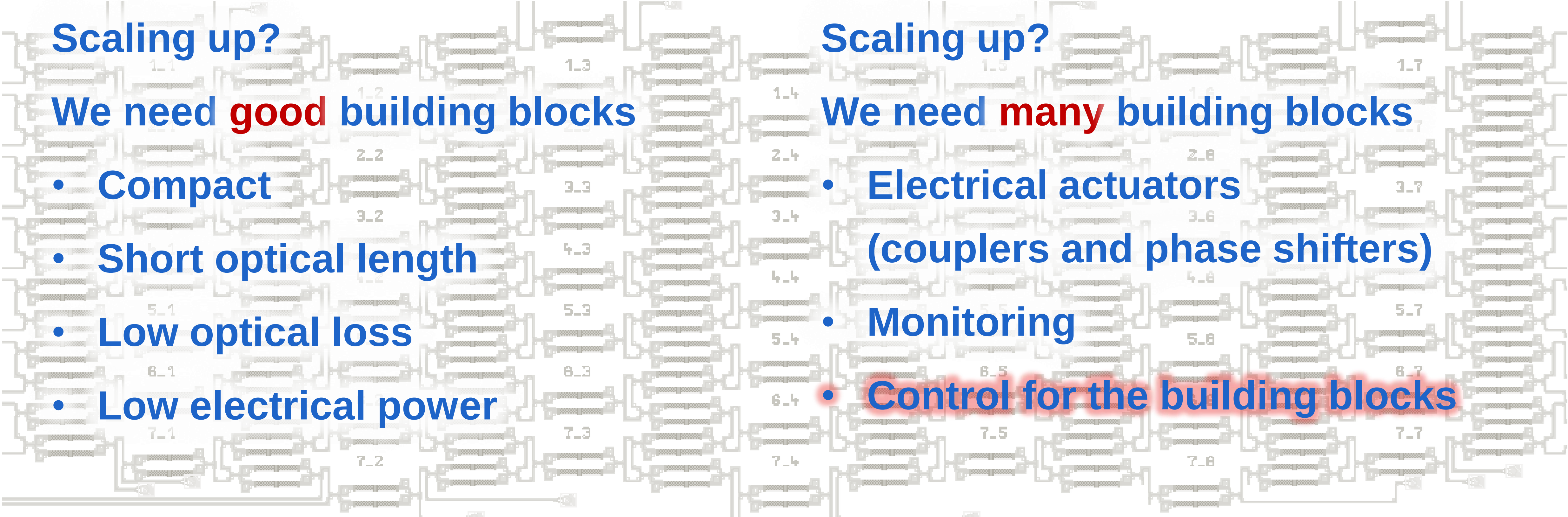






Edinger et al. *Low-loss MEMS phase shifter for large scale reconfigurable silicon photonics*. *32nd IEEE MEMS conference (2019)*

Large-scale Optical Meshes



Scaling up?

We need good building blocks

- **Compact**
- **Short optical length**
- **Low optical loss**
- **Low electrical power**

Scaling up?

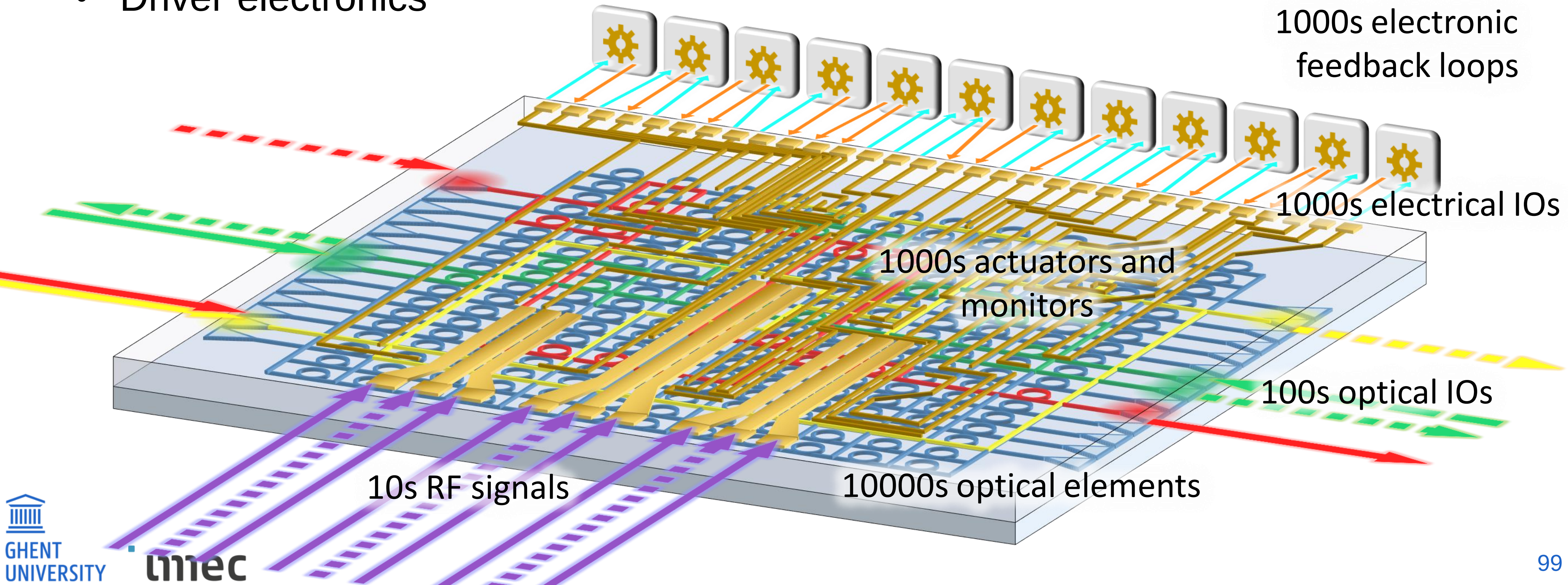
We need many building blocks

- **Electrical actuators (couplers and phase shifters)**
- **Monitoring**
- **Control for the building blocks**

More than just photons

It is not just the optical chip

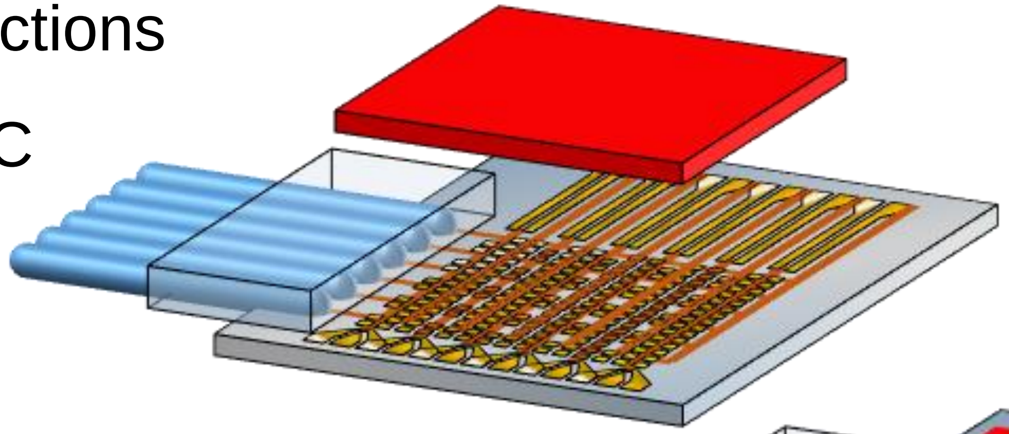
- Packaged interfaces
- Driver electronics



CONTROLLING MANY ELECTRO-OPTICAL ELEMENTS

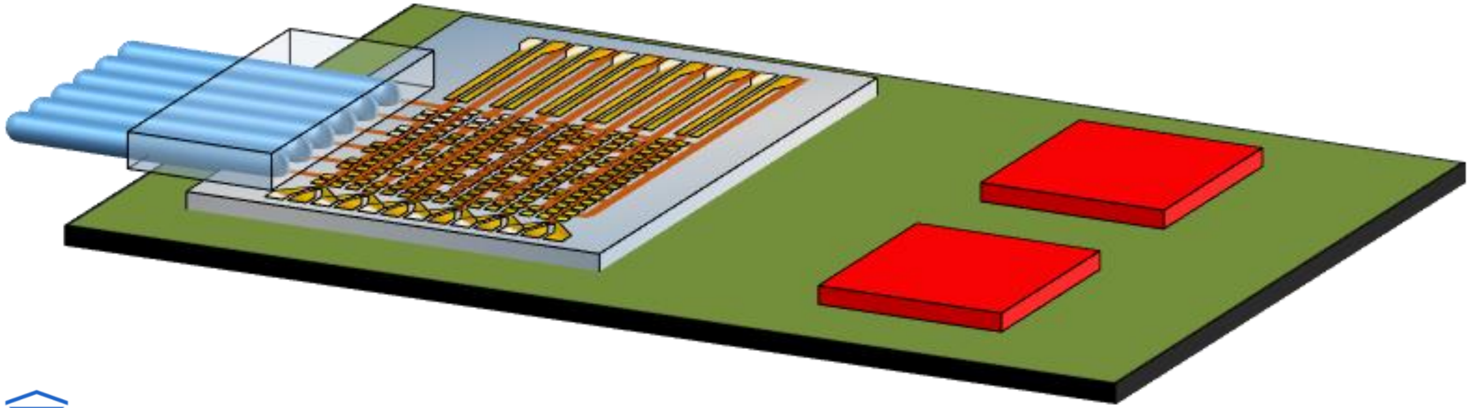
Flip-chip / 3D stacking

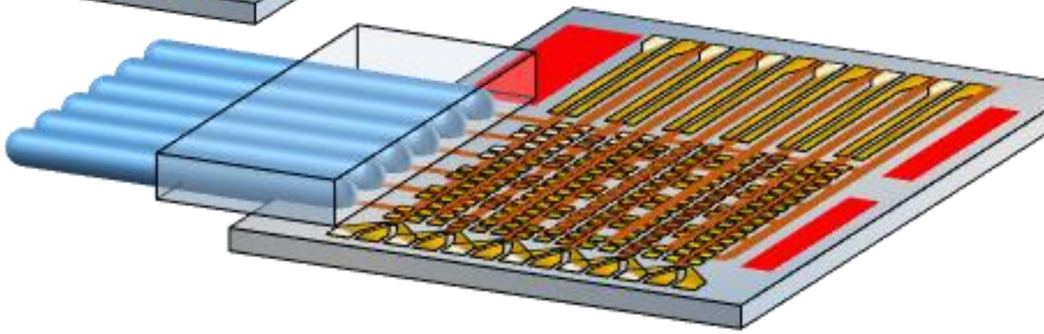
- Many connections
- Custom ASIC



Wire-bonding

- flexible
- limited connections





Monolithic:

- Very powerful
- Complex process/design

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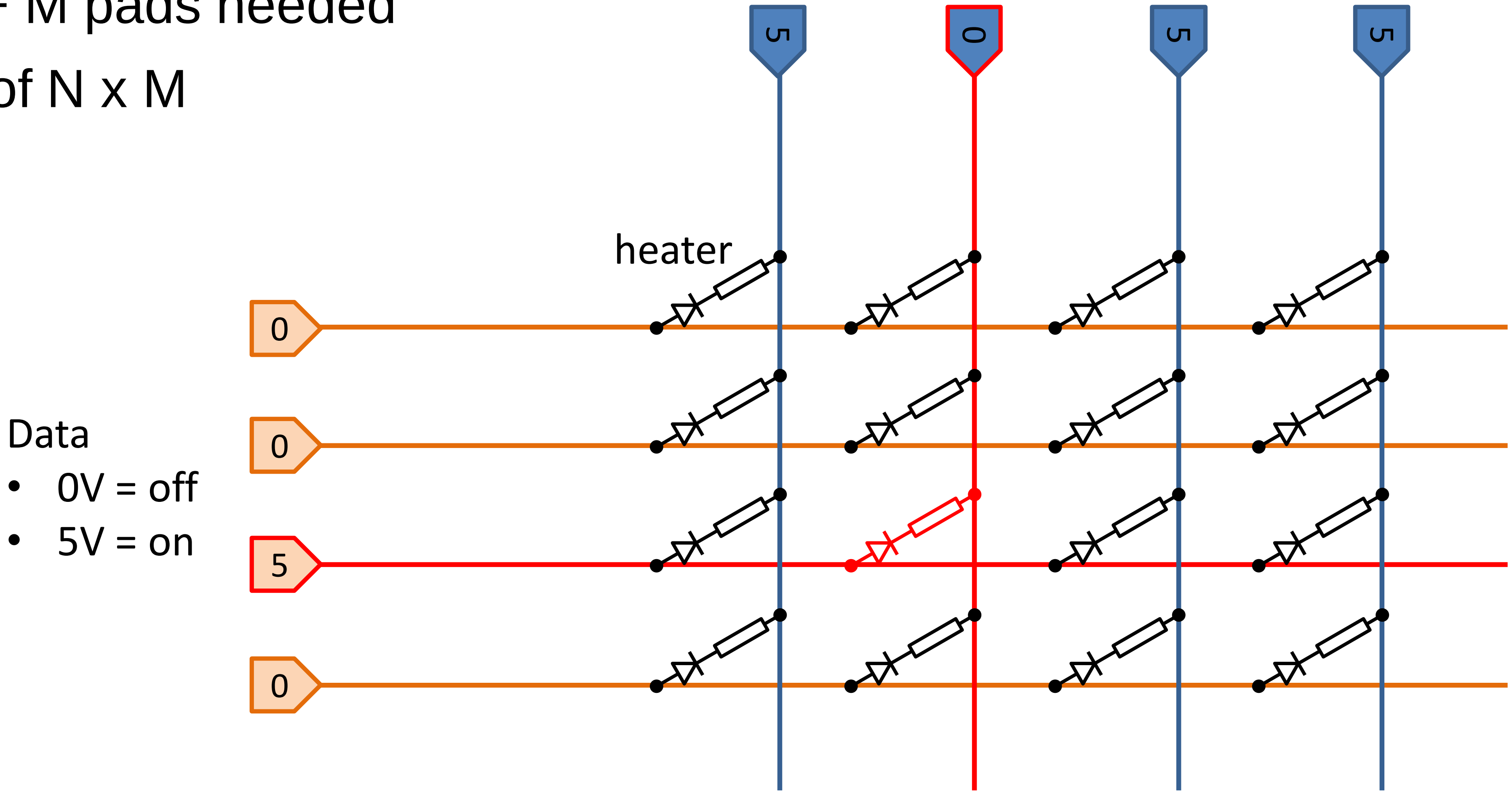
MATRIX ADDRESSING OF HEATERS WITH DIODES

Diodes enable Matrix addressing

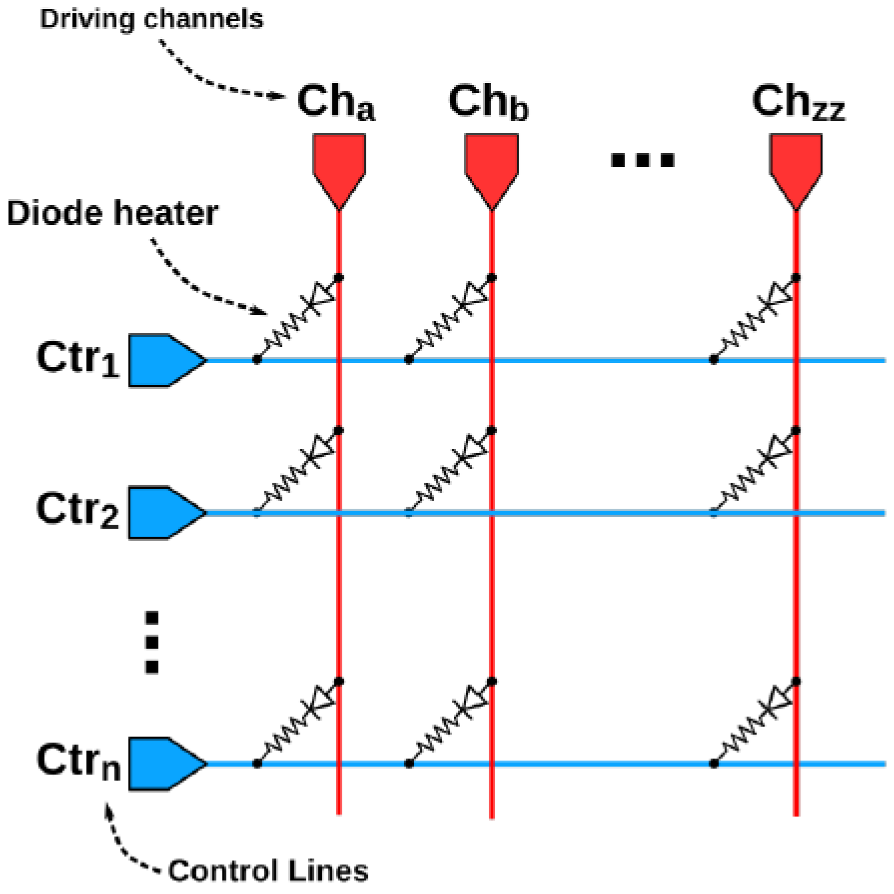
- Only N + M pads needed
  instead of N x M

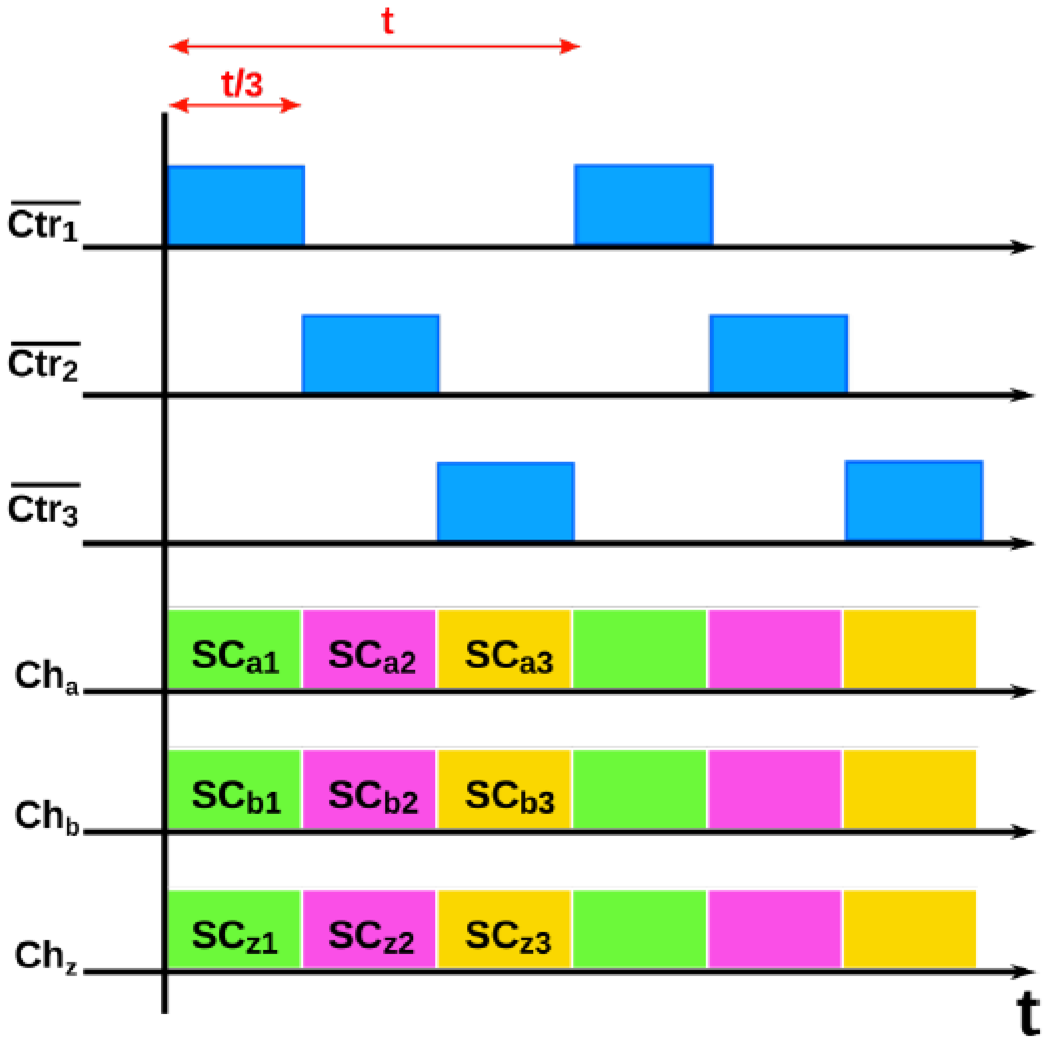


A. Ribeiro, in preparation

Matrix Addressing of heaters with diodes

Time-multiplexing the control





More than just photons

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- Packaged interfaces
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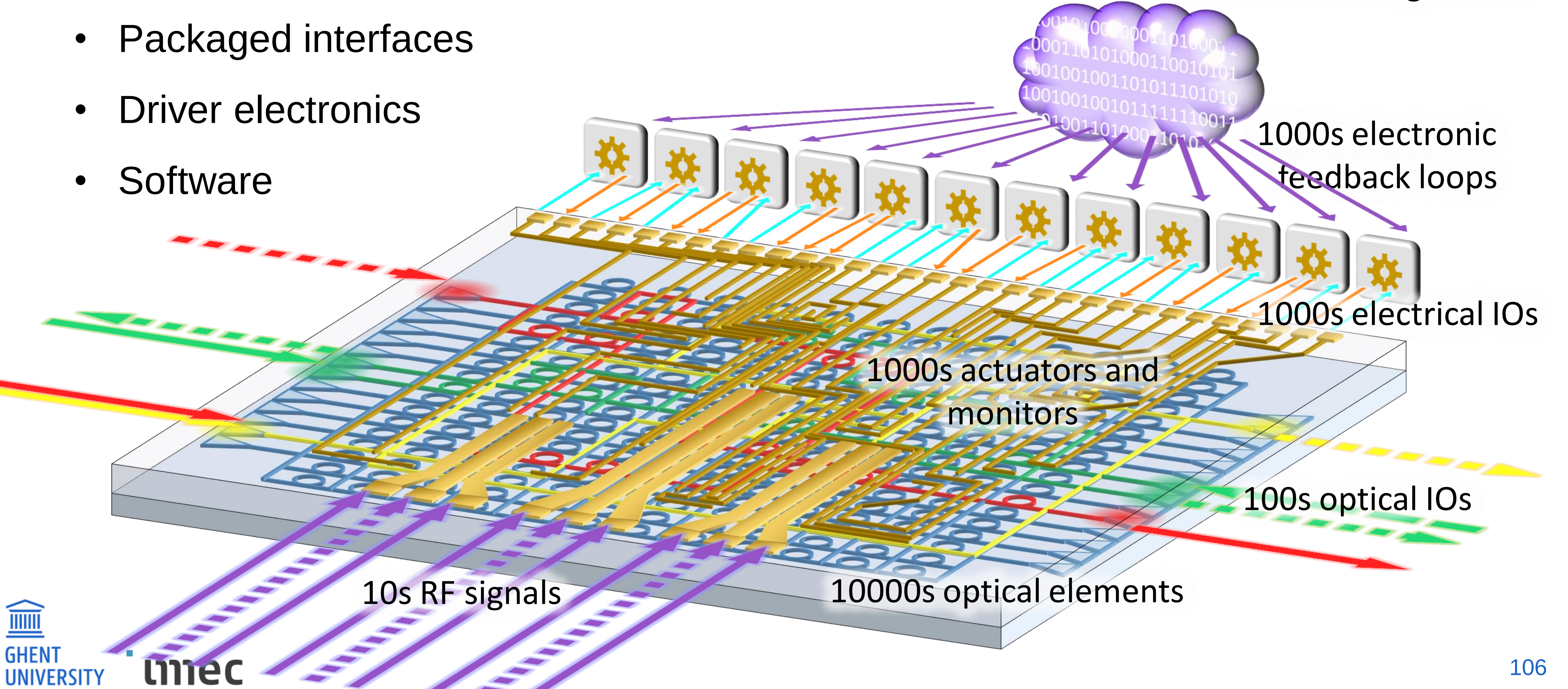
- Software

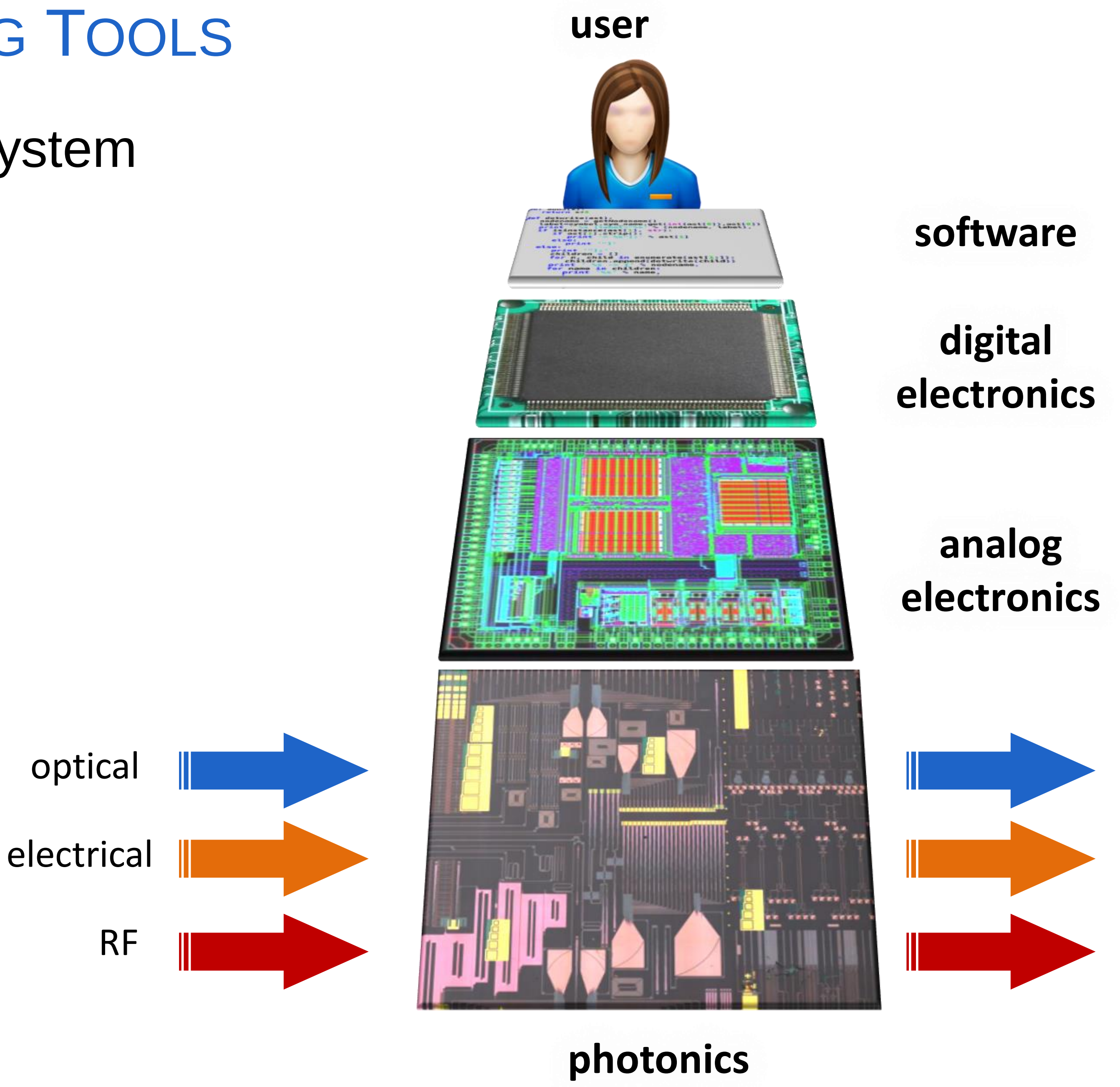


INTERFACES AND PROGRAMMING TOOLS

Programmable circuits are part of a system

- Photonics
- Electronics
- Software
- Optical interfaces
- Electrical and RF interfaces

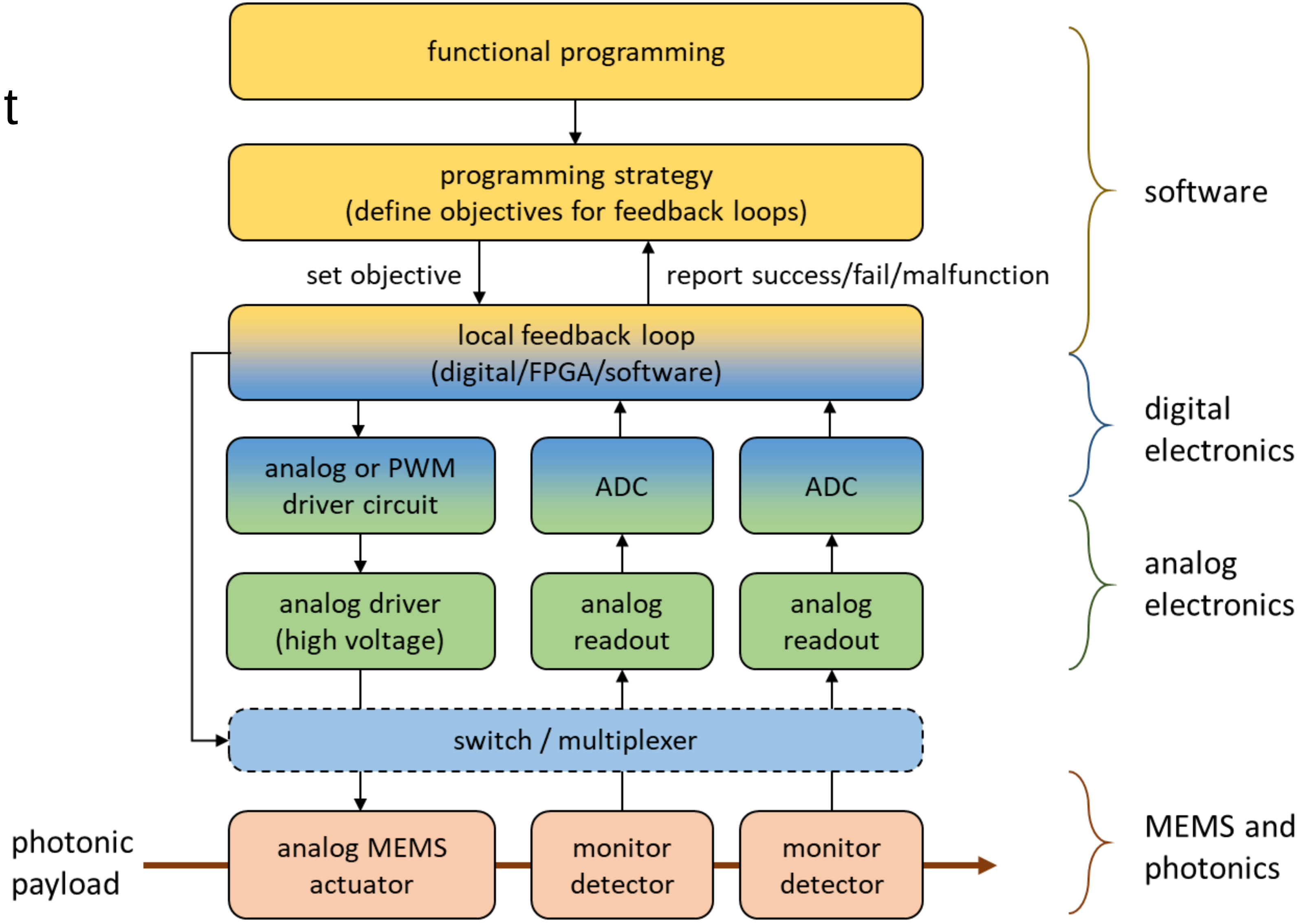
Develop packaging
and programming tools



Programmable Circuits: The logic stack

Control system

- Electronic driver / readout
- Digital control
- Local feedback loops
- Software control
- High-level programming



FROM IDEA TO PROGRAMMABLE CIRCUIT

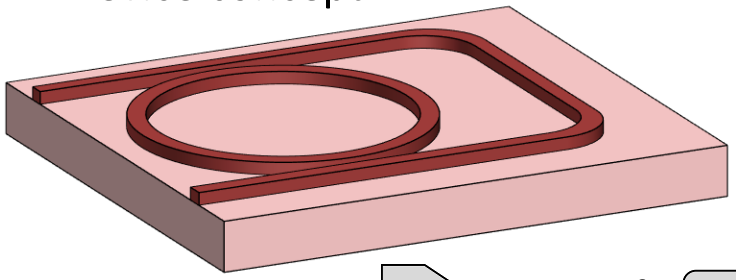
How to program functionality?

- translate specifications to programming code for control circuit
- sequential programming strategies
- trade-off for different metrics (loss, phase errors, balance)

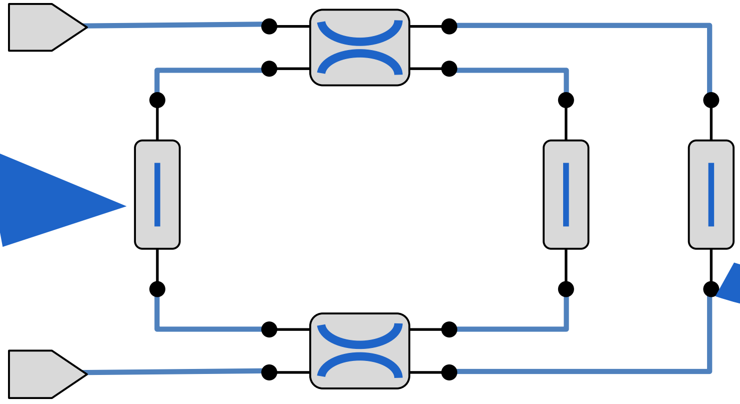
Programming code

```
for k in range(N):
    set_current(k, I)
    read_monitor(k, 1)
    read_monitor(k, 2)
    set_current(k+1, 0.9*I)
    set_current(k-1, 1.1*I)
    read_monitor(k-1, 1)
    read_monitor(k+1, 2)
```

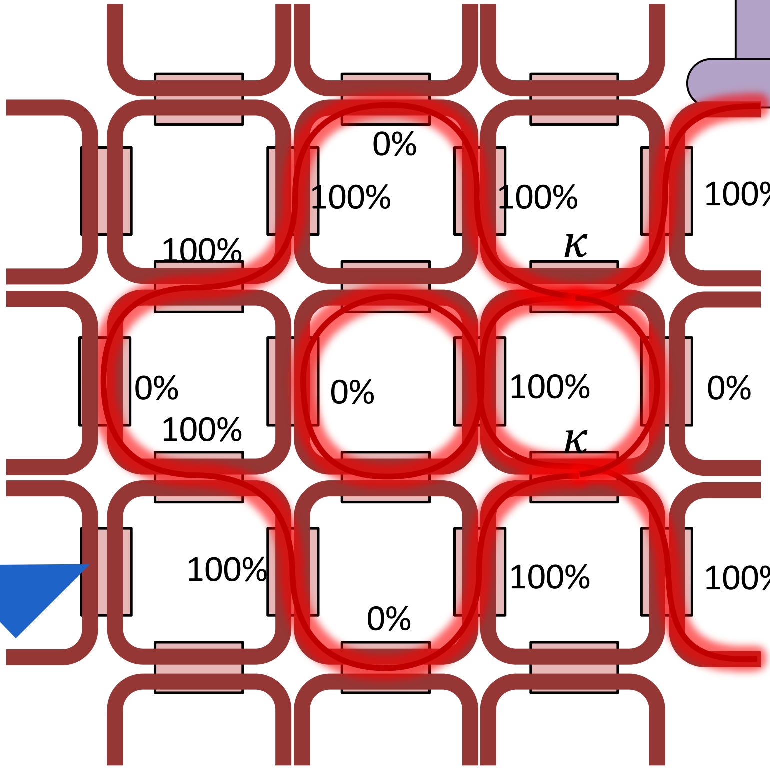
Device concept



Equivalent circuit

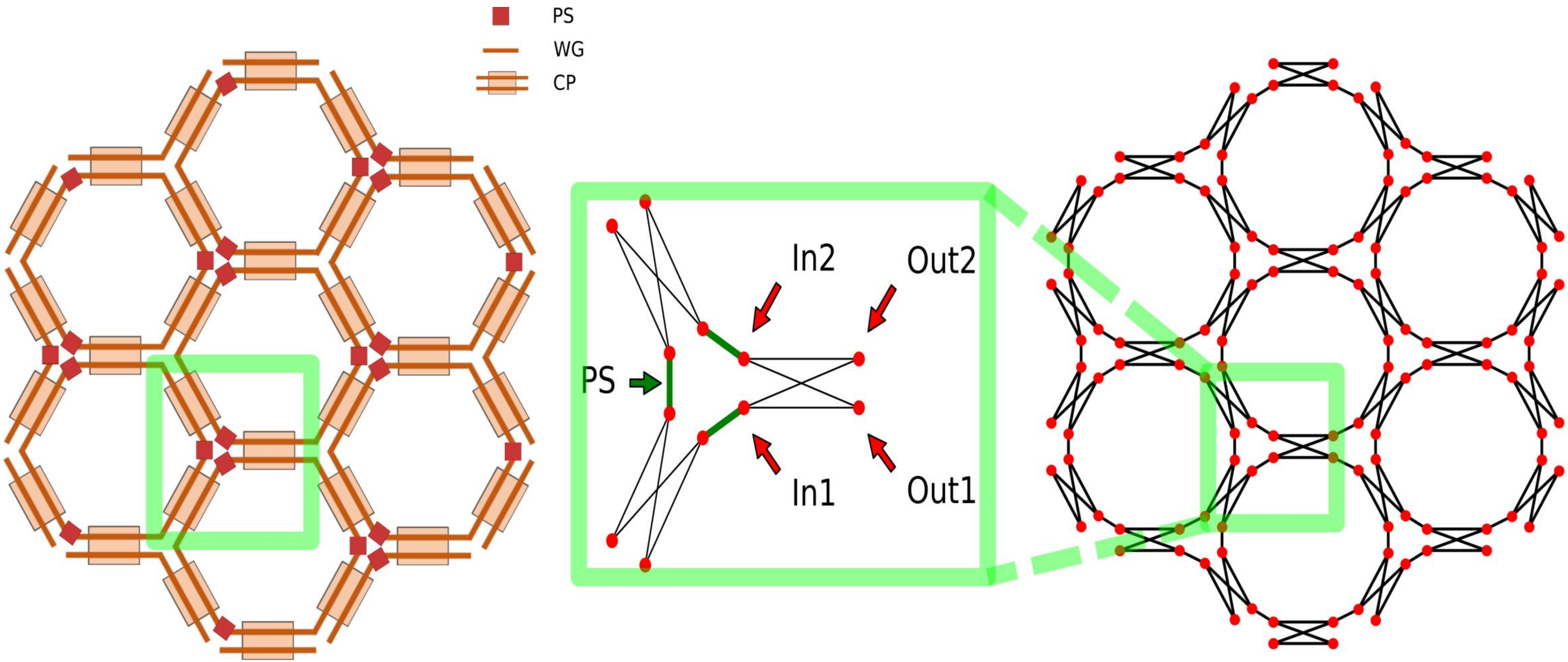


Connectivity Matrix



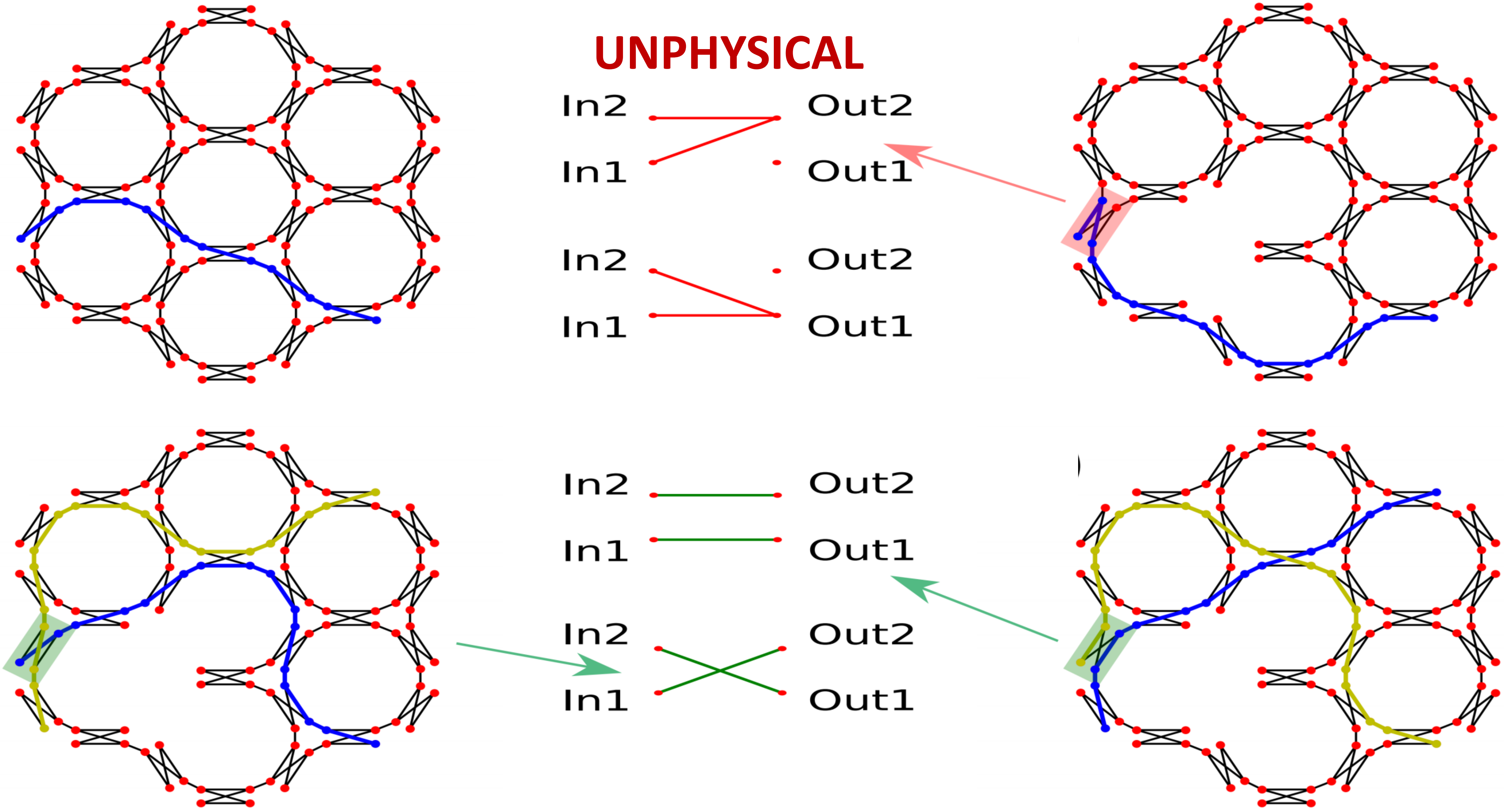
USING GRAPH ALGORITHMS TO ROUTE IN PROGRAMMABLE MESHES

Translate circuit into "photonic graph"



X. Chen, in preparation

EMBEDDING PHOTONIC RULES IS NOT TRIVIAL



X. Chen, in preparation

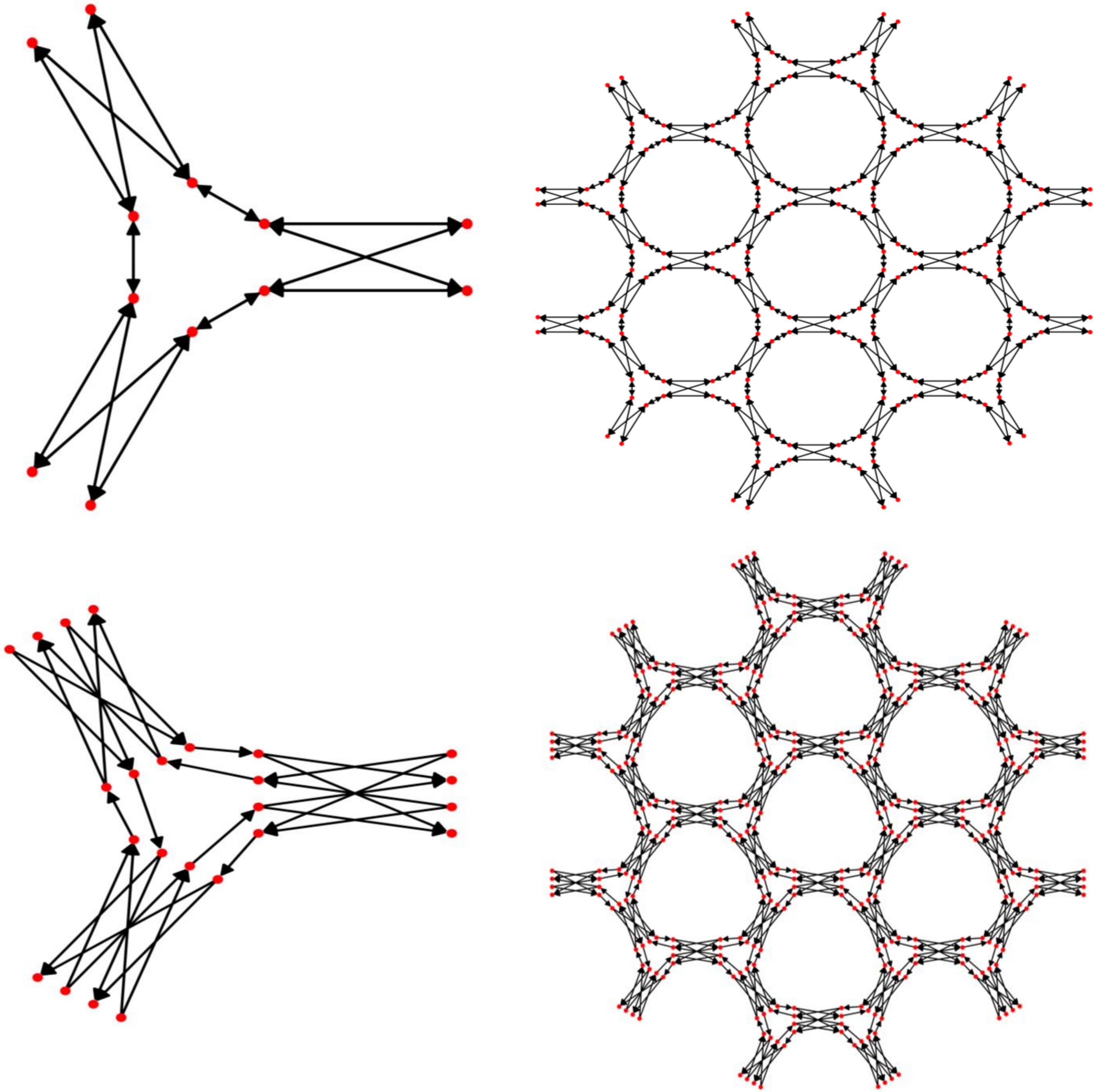
Graph mapping

Directed or undirected

Weighted or unweighted

Introduce artificial nodes

Compatible with existing algorithms?



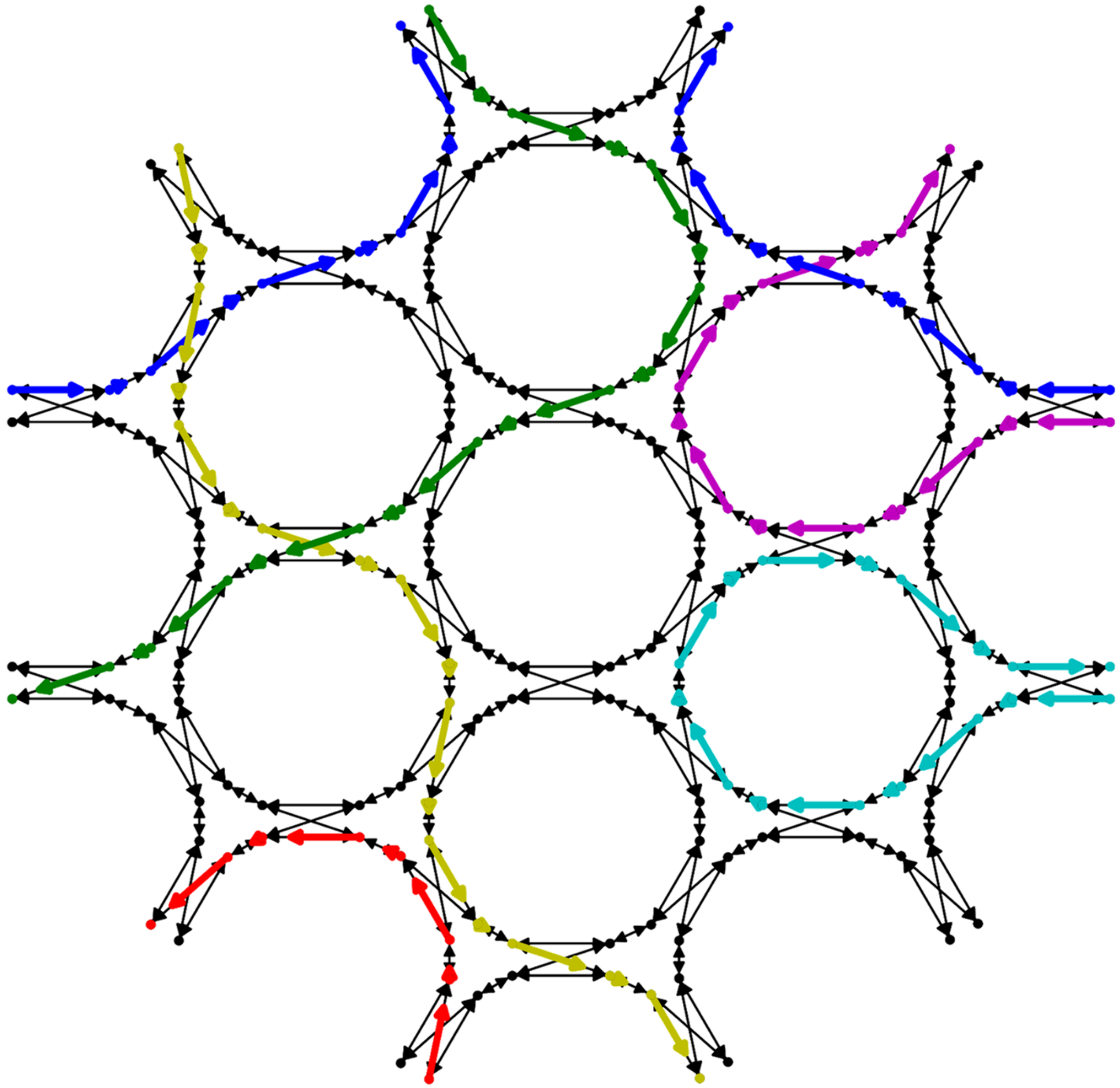
DIFFERENT ALGORITHMS

Example: Multi-path routing with congestion negotiation

Many routing problems are NP

Different algorithms

- Integer Linear Programming (small systems)
- Multi-commodity flow algorithms
- Heuristics



X. Chen, in preparation

History

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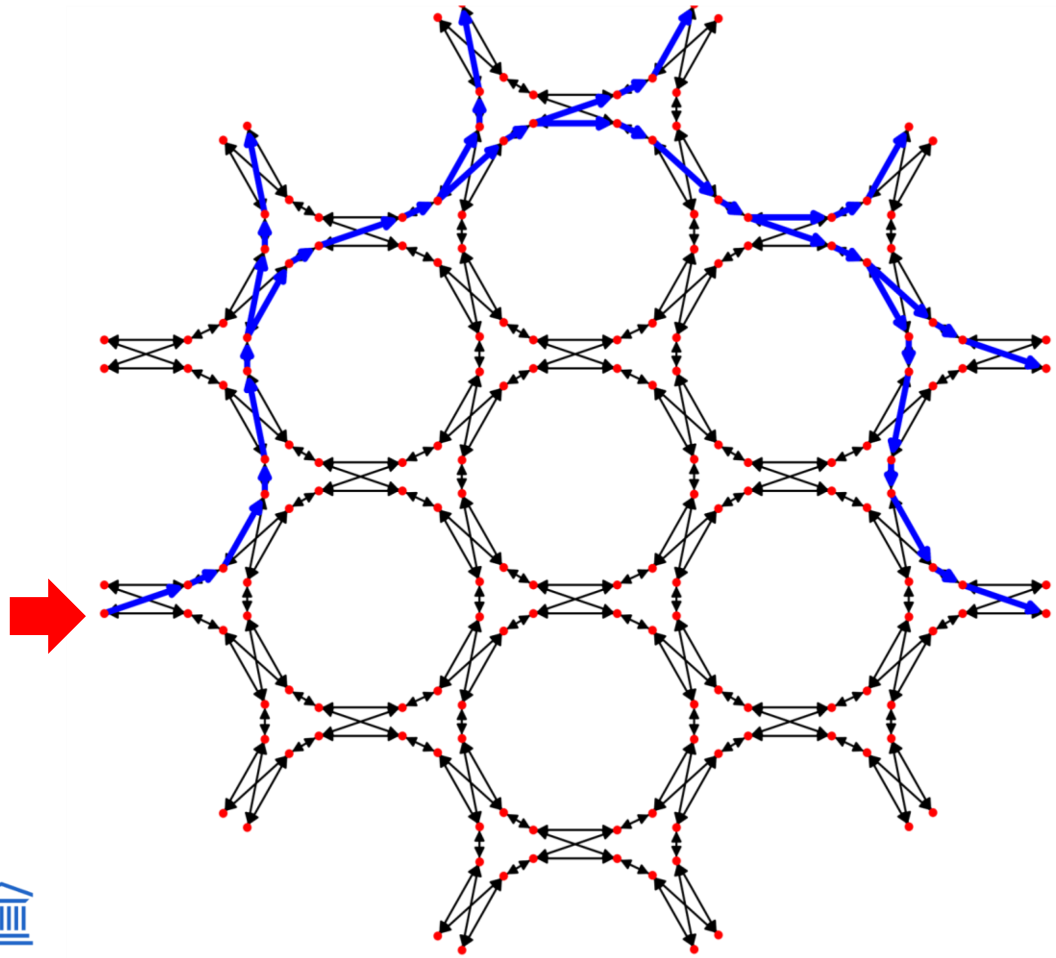
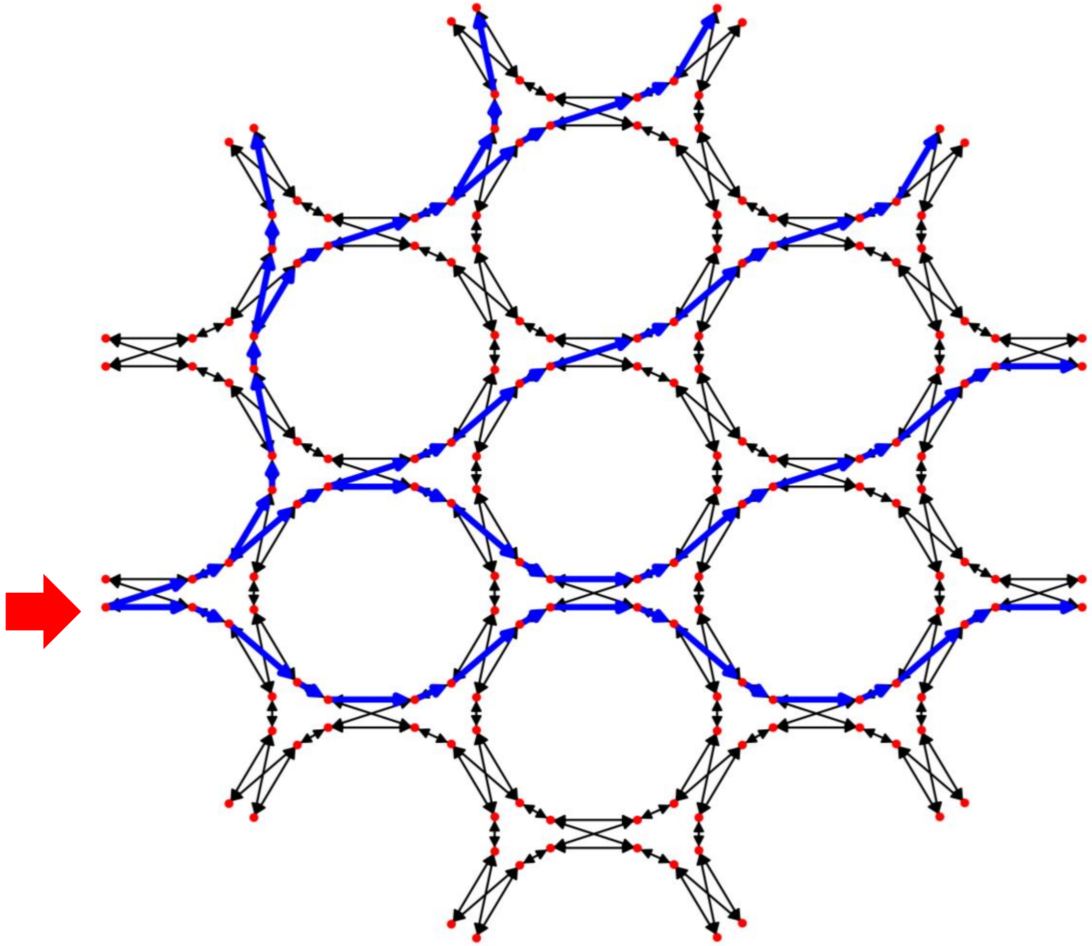
DISTRIBUTION PROBLEMS

Without congestion cost



With congestion cost

(e.g. nonlinear losses, TPA)

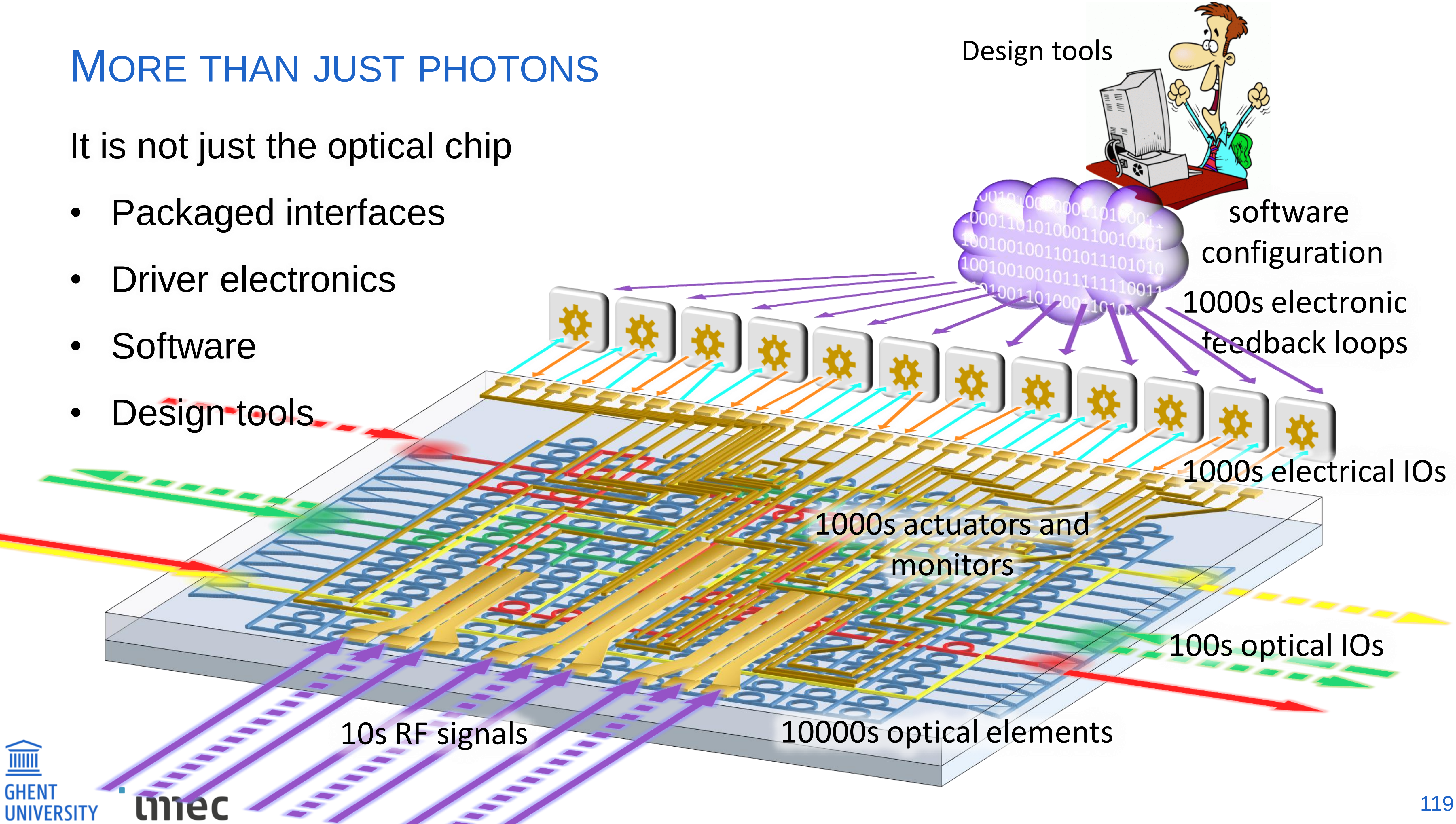


X. Chen, in preparation

More than just photons

It is not just the optical chip

- Packaged interfaces
- Driver electronics
- Software
- Design tools



Large-Scale Optical Meshes

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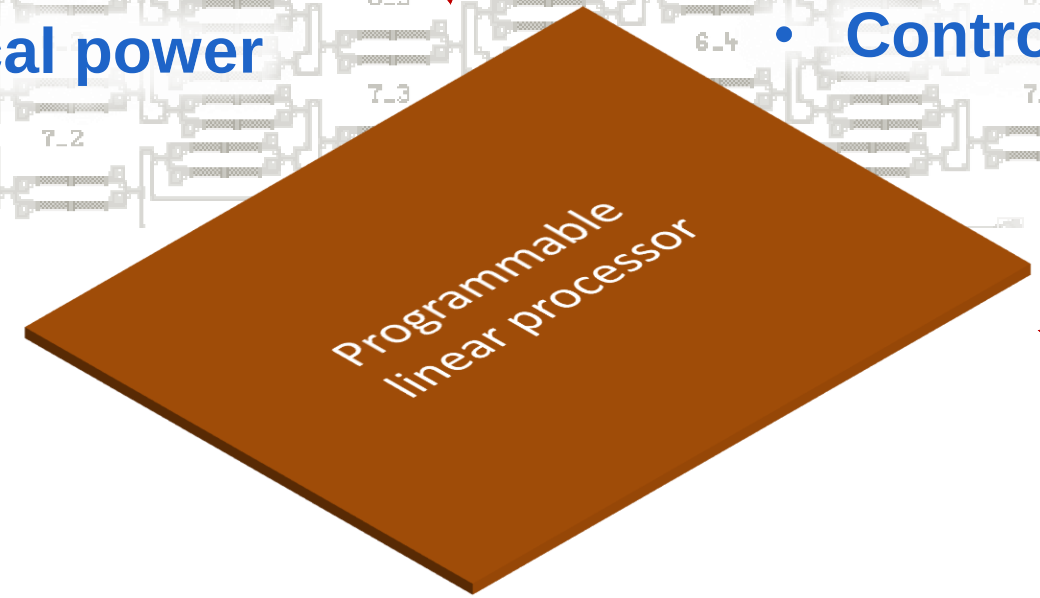

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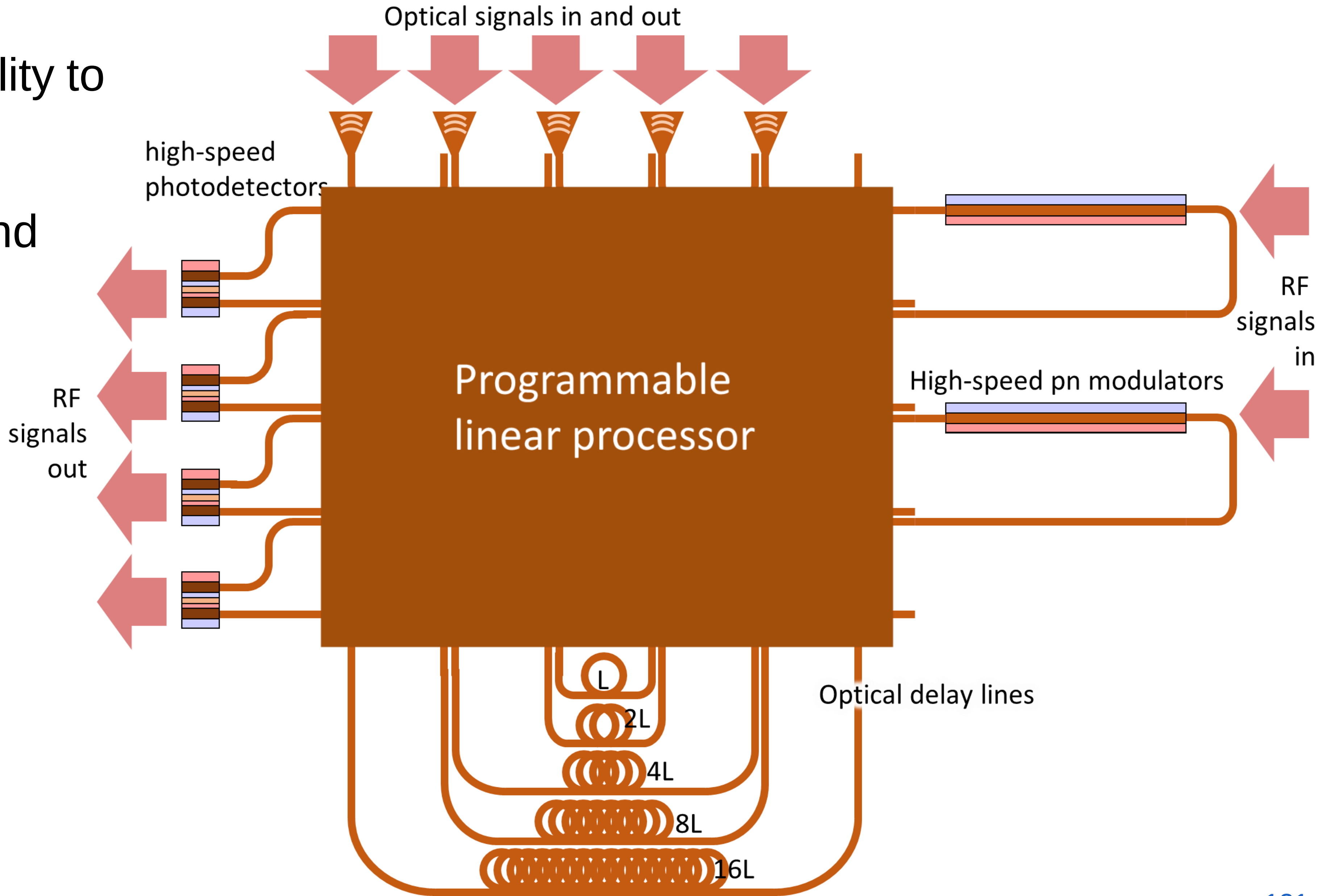
GENERIC PROGRAMMABLE OPTICAL PROCESSOR

Add optical functionality to the linear circuit

- Fast modulation and photodetectors for RF input/output
- Light sources
- Amplifiers
- Fiber input/output
- Long delay lines



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Generic Programmable Optical Processor

Add optical functionality to the linear circuit

- Fast modulation and photodetectors for RF input/output
- Light sources
- Amplifiers
- Fiber input/output
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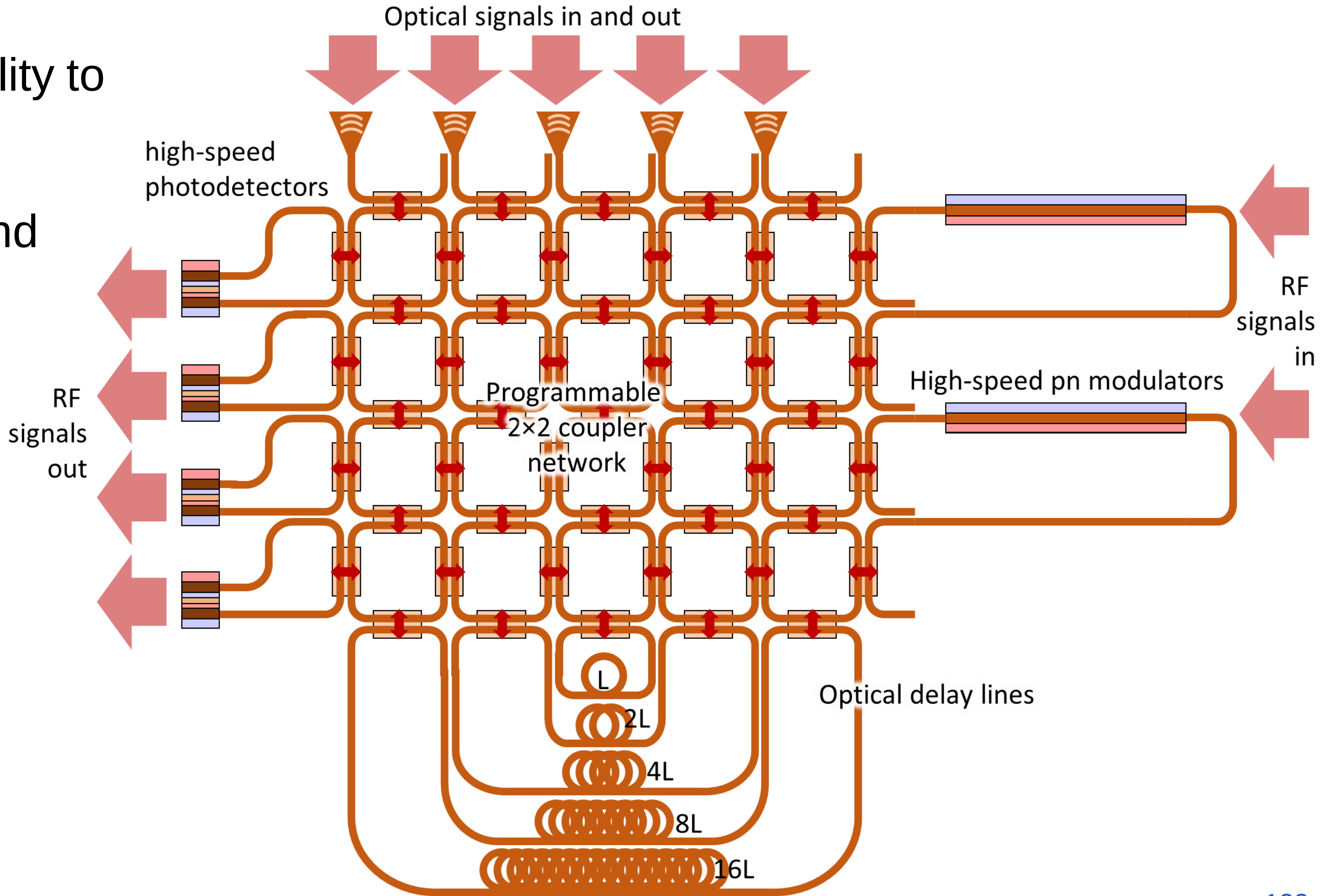
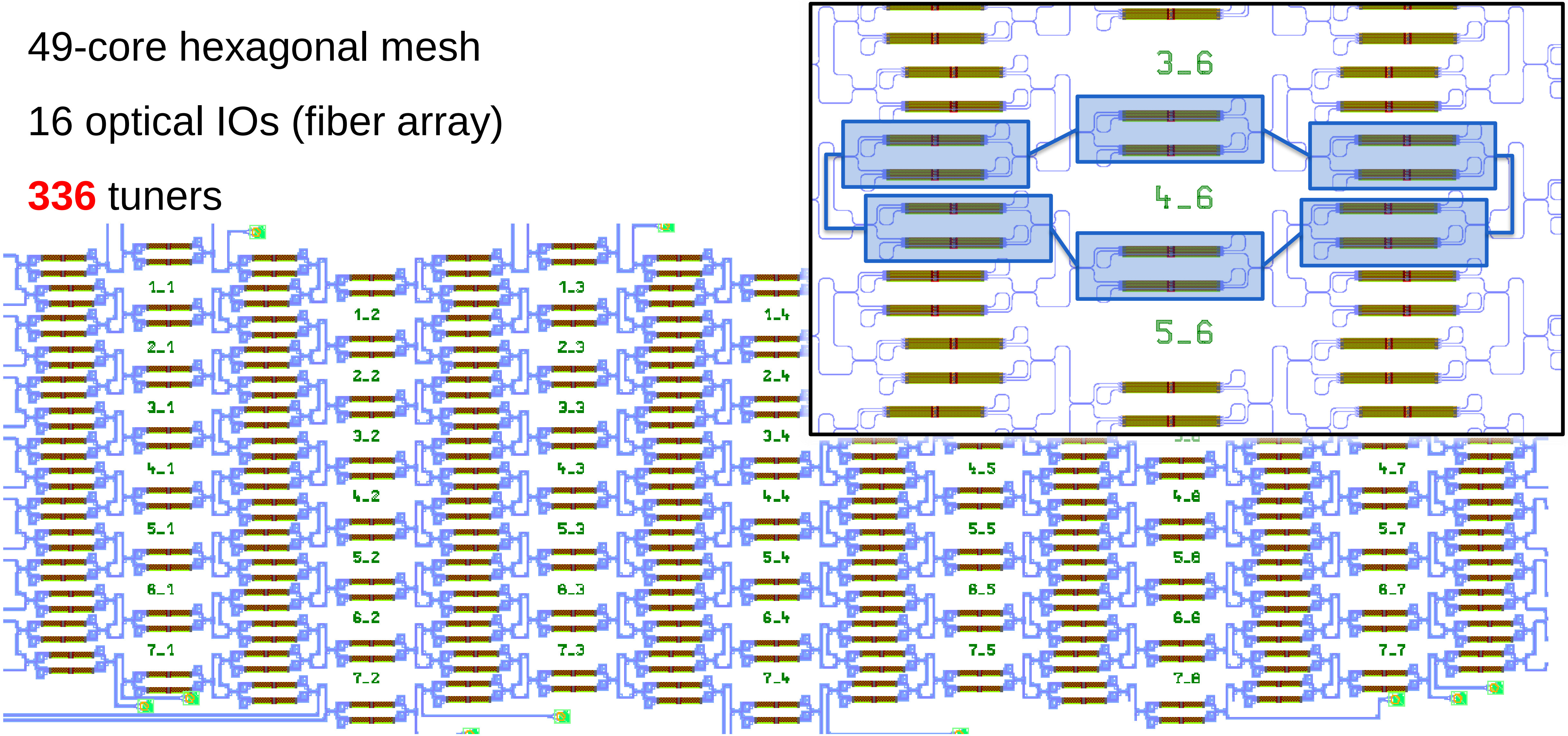


HIVE: Our Next-Generation Programmable PIC

49-core hexagonal mesh

16 optical IOs (fiber array)

336 tuners



HIVE: Our Next-Generation Programmable PIC

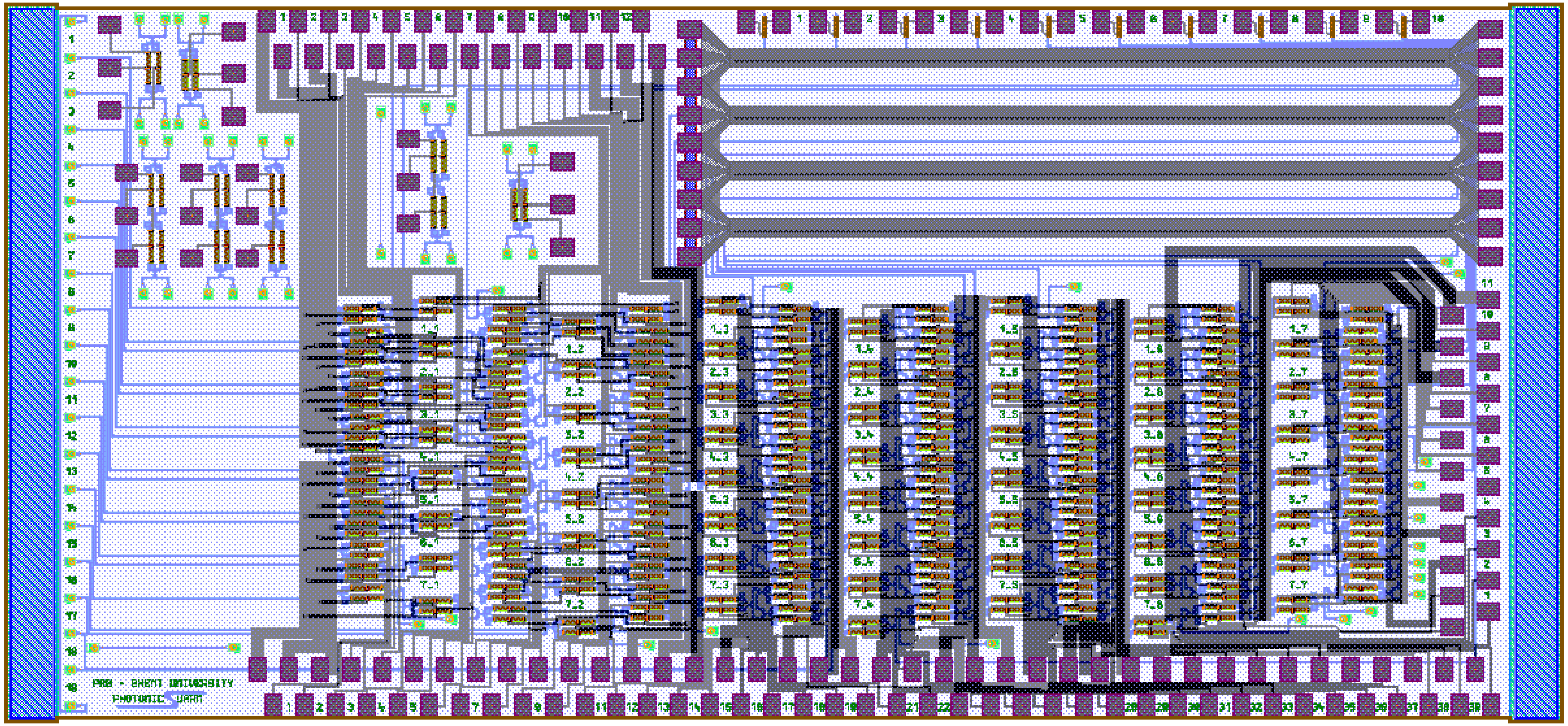
49-core hexagonal mesh

16 optical IOs (fiber array)

336 tuners

4 RF phase modulators

10 RF detectors



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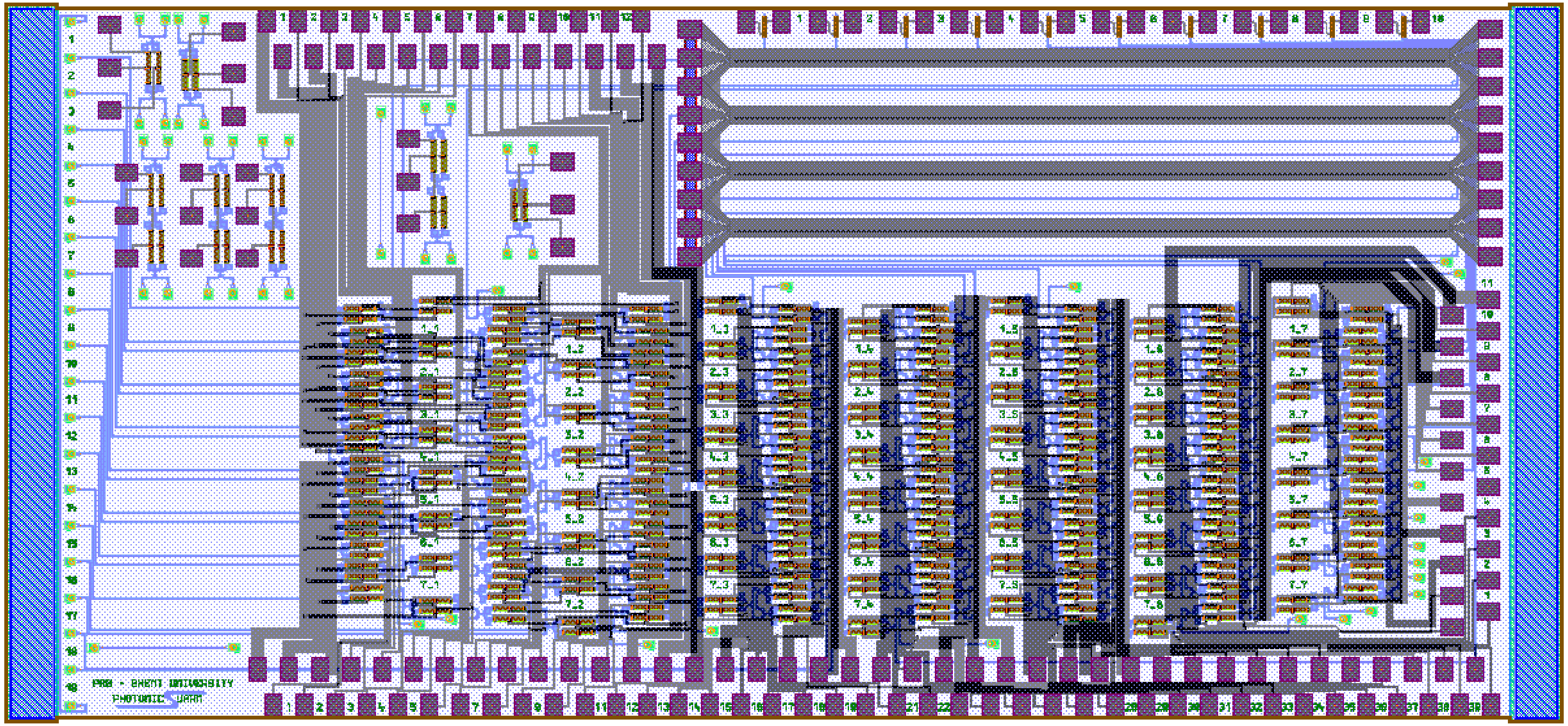
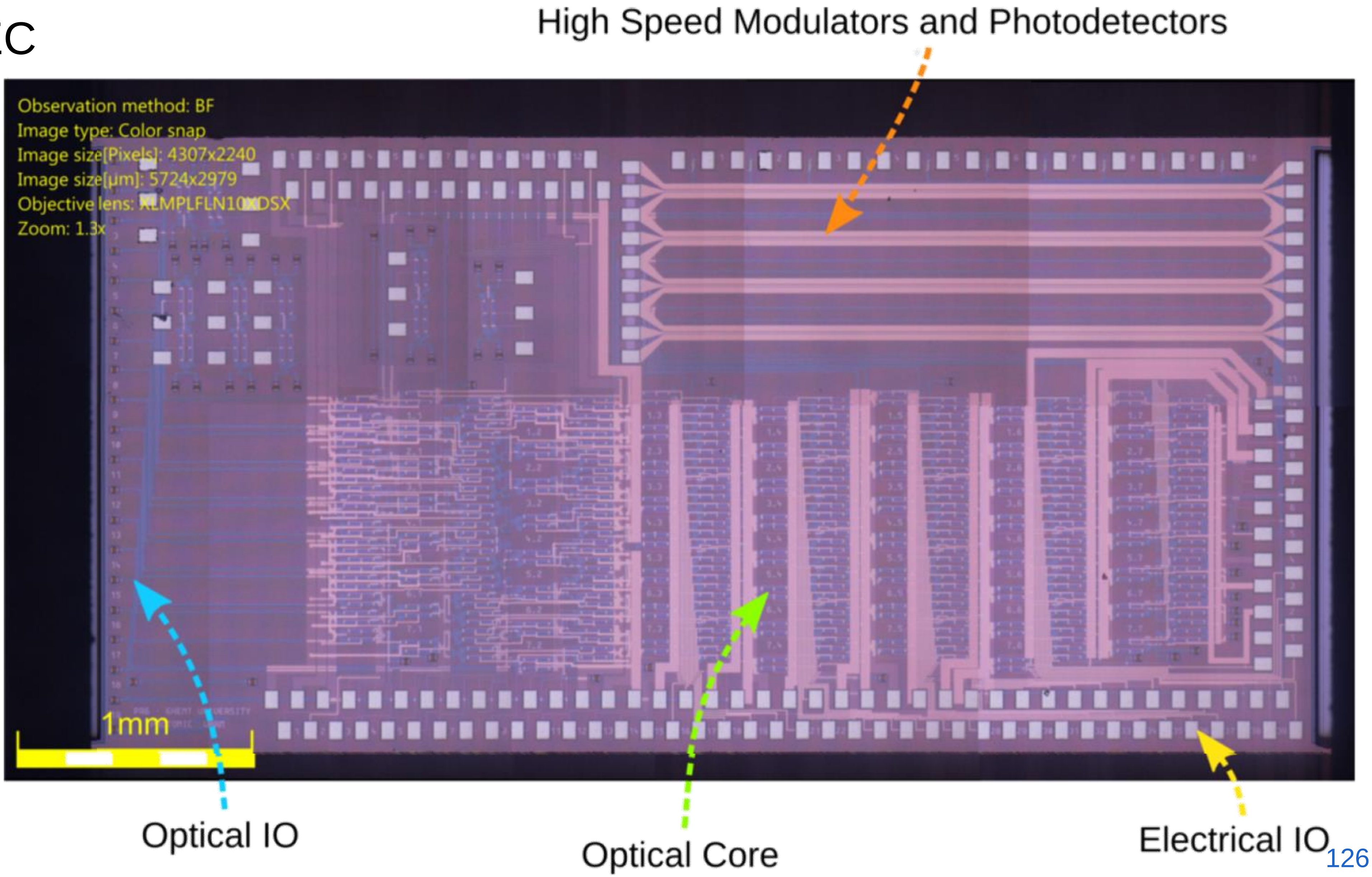


HIVE: Our Next-Generation Programmable PIC

Fabricated in IMEC



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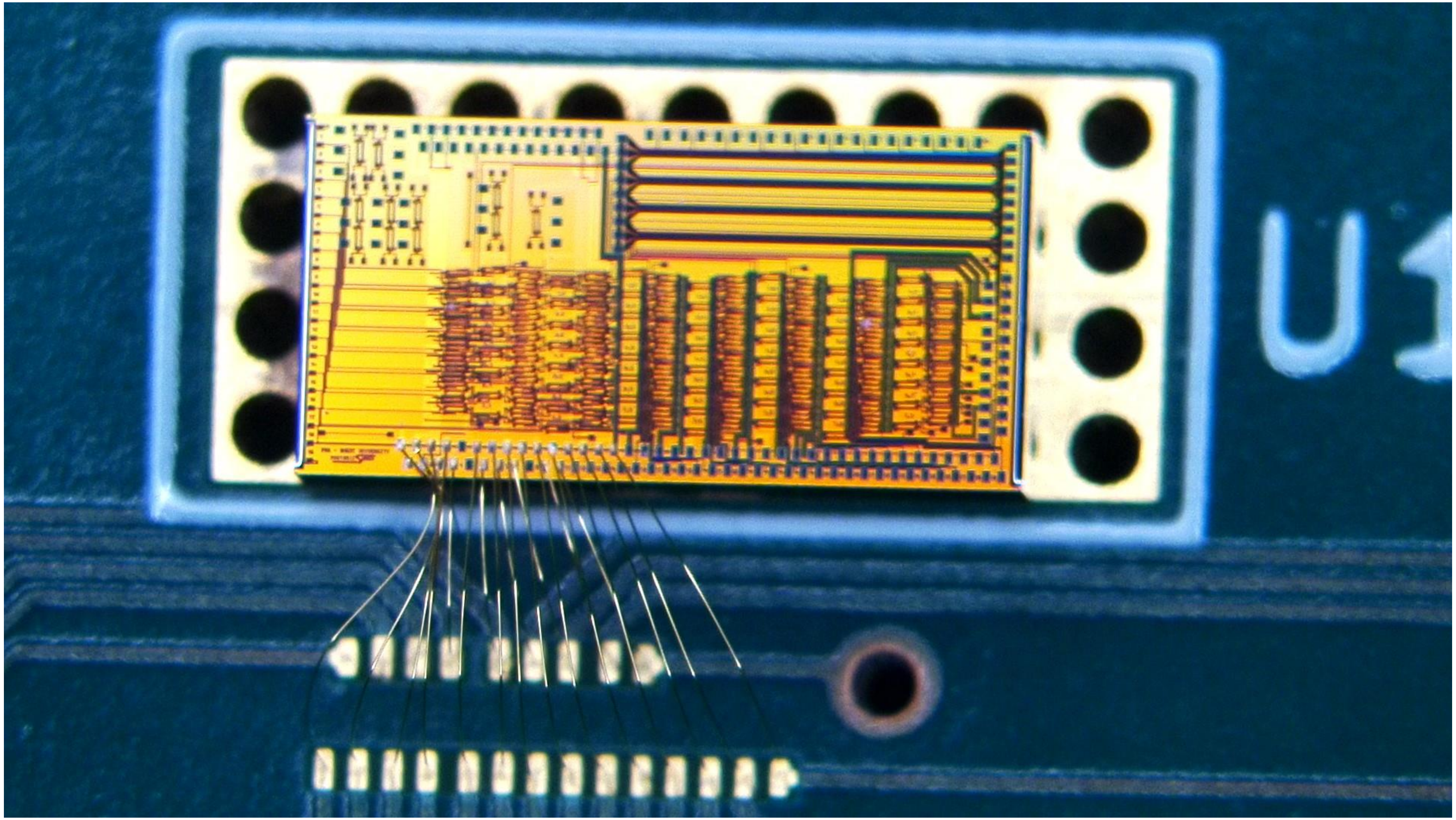
HIVE: Our Next-Generation Programmable PIC

Partially wire-bonded (miniBee)

6 hex cells

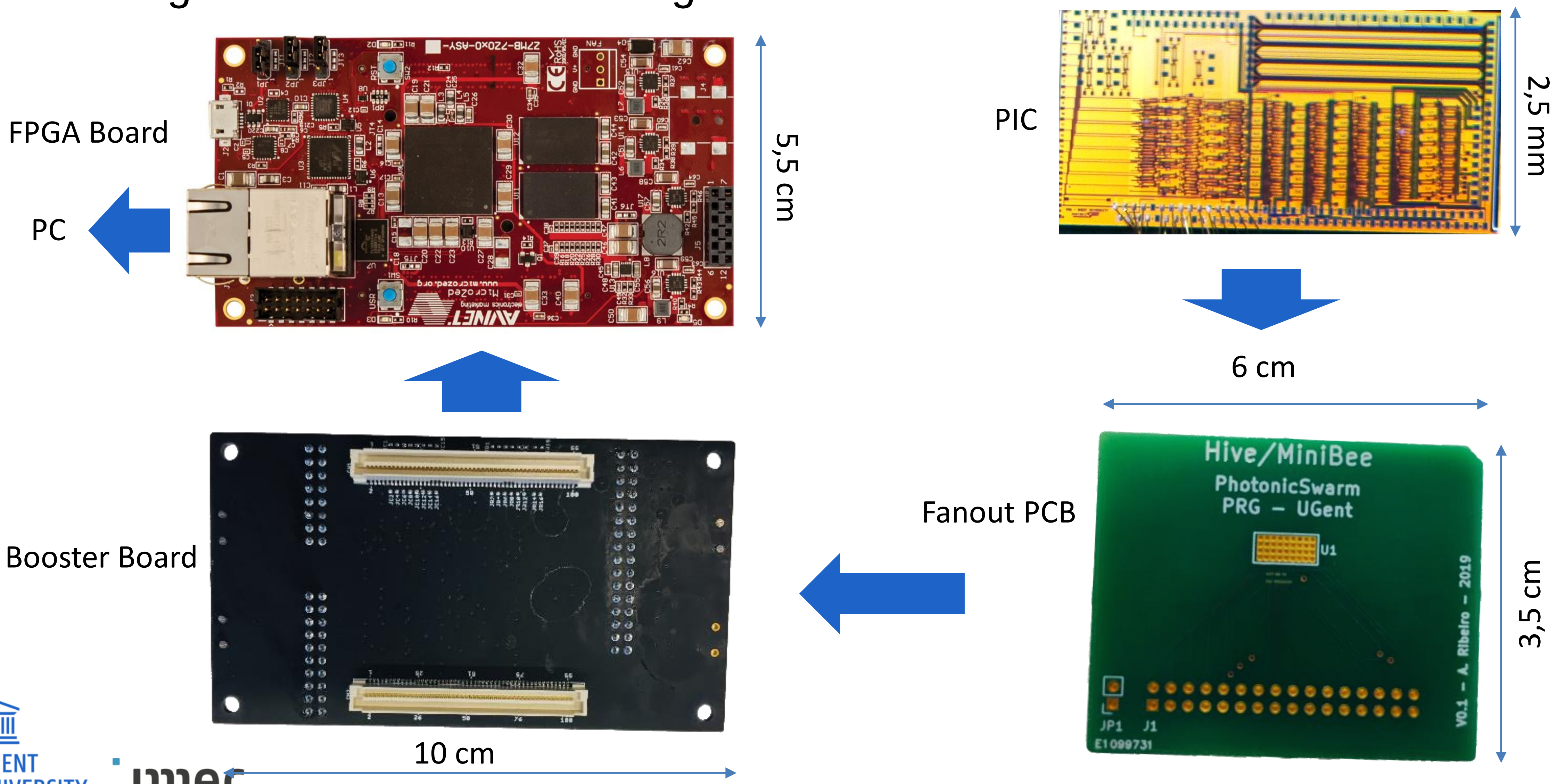
2 address

matrices of 3x10



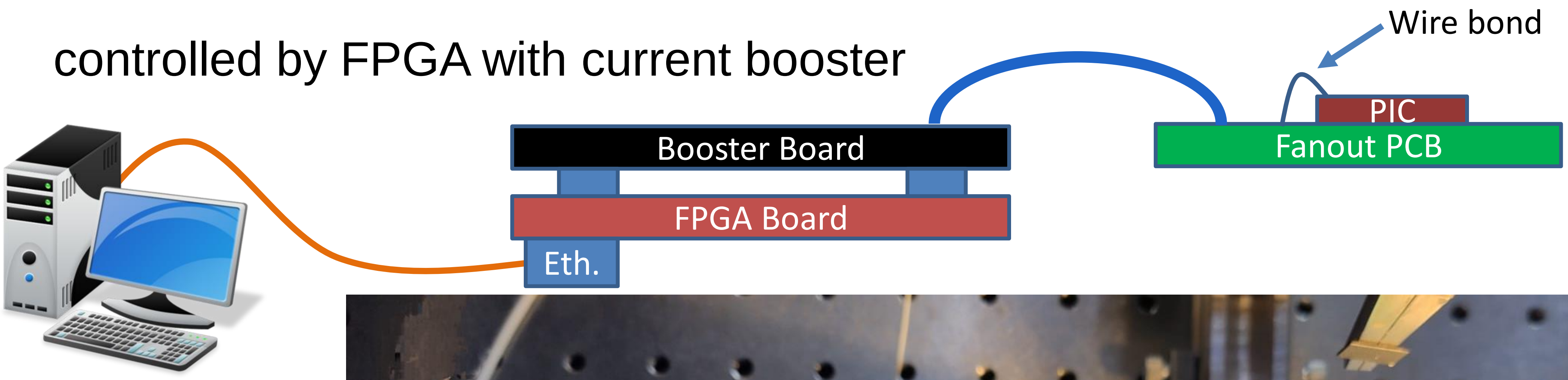
HIVE: Our Next-Generation Programmable PIC

Adding electrical control: starting small

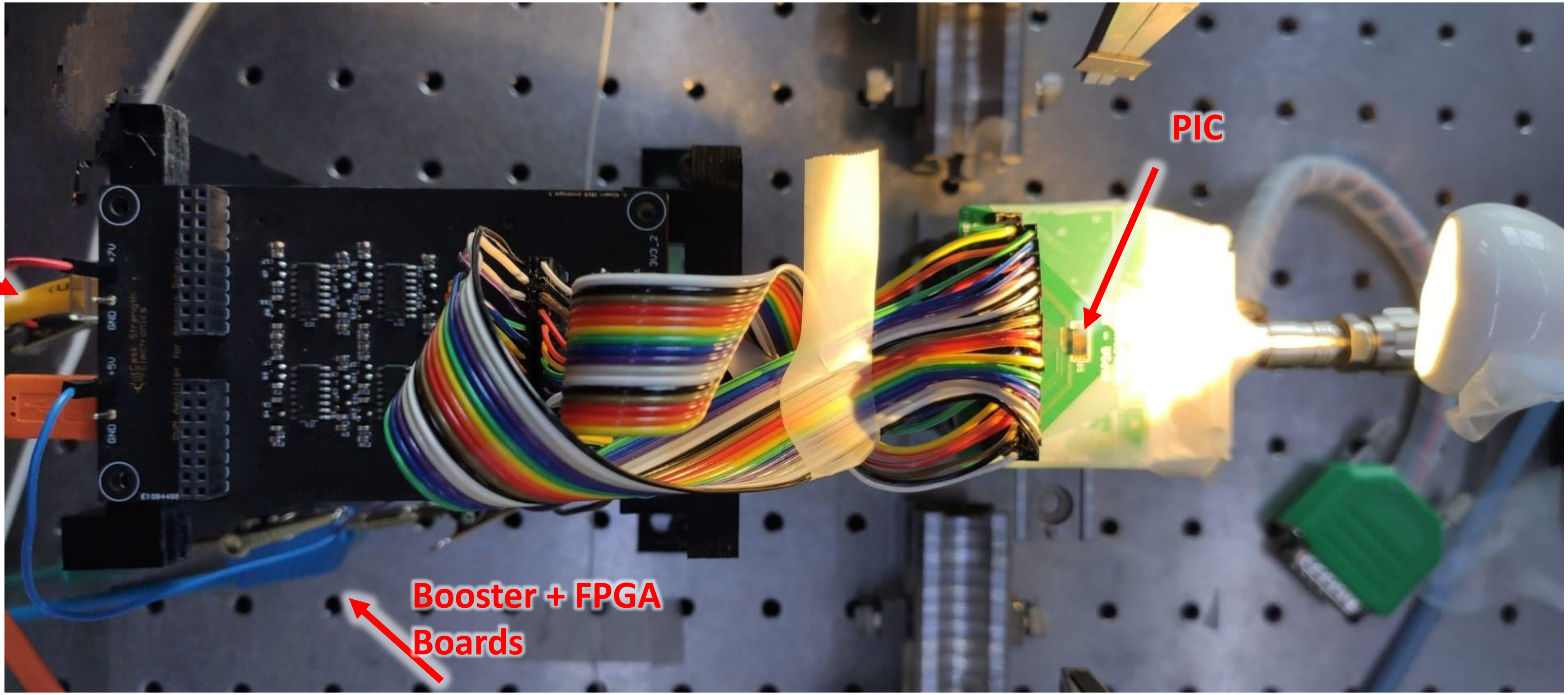


HIVE: Our Next-Generation Programmable PIC

controlled by FPGA with current booster



Ethernet Cable



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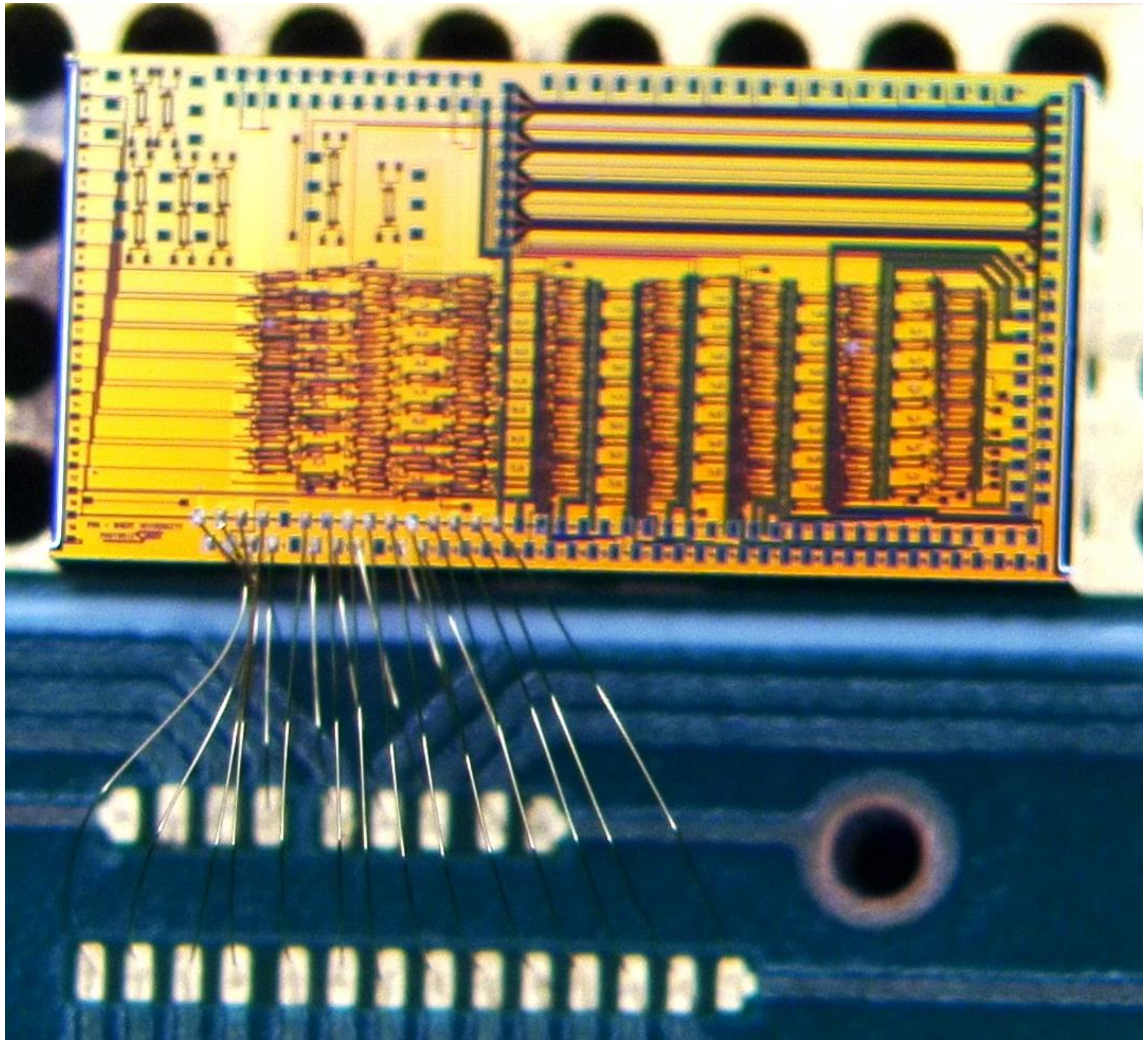
HIVE: Our Next-Generation Programmable PIC

What is next?

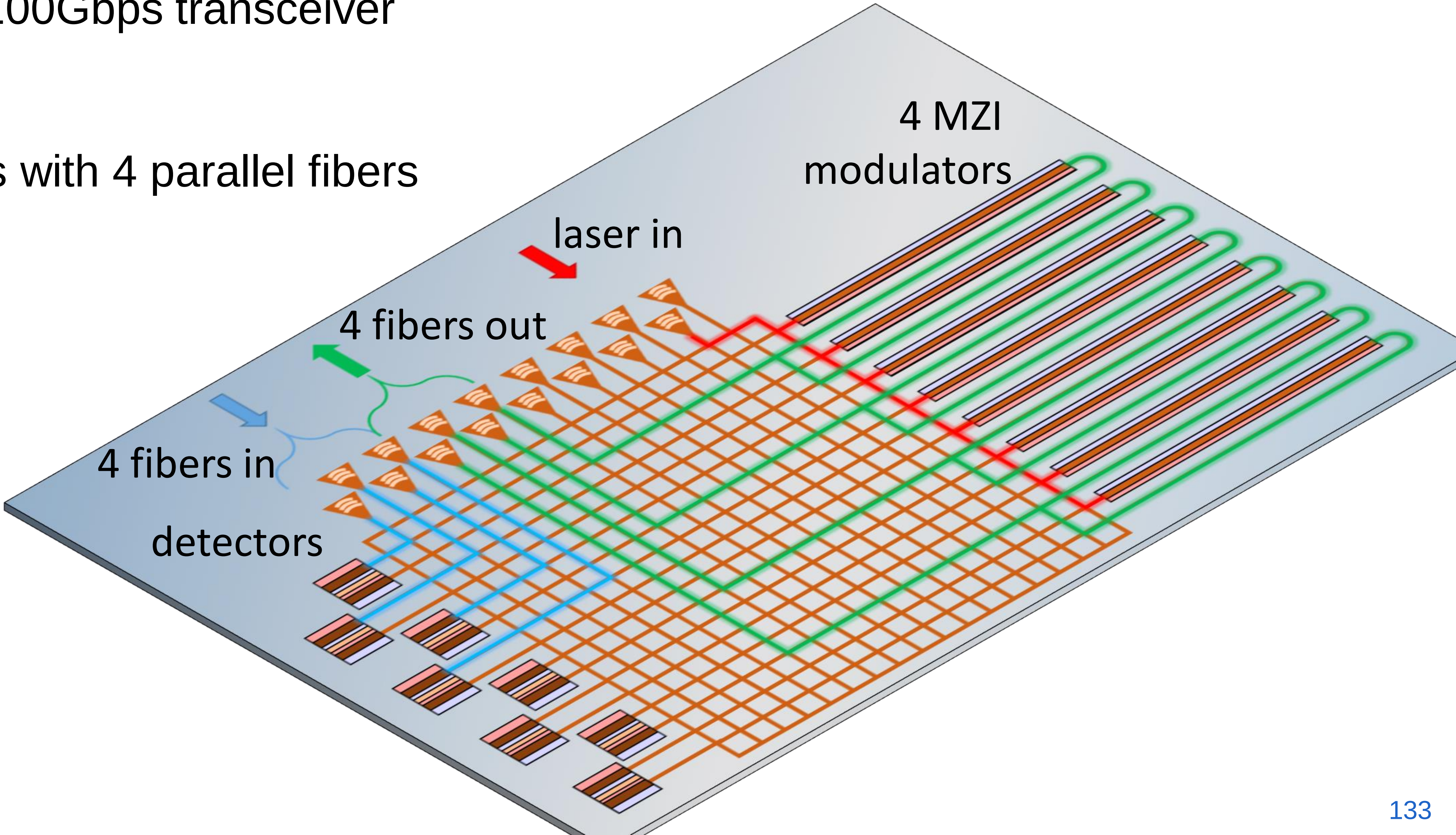
- Programming simple wavelength filters
- Connecting all 336 phase shifters
- Interfacing the RF elements (packaging with Tyndall)
- Application demonstrations
    - microwave processing
    - filtering
    - spectrometers
    - transceivers



Programmable Transceiver

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers

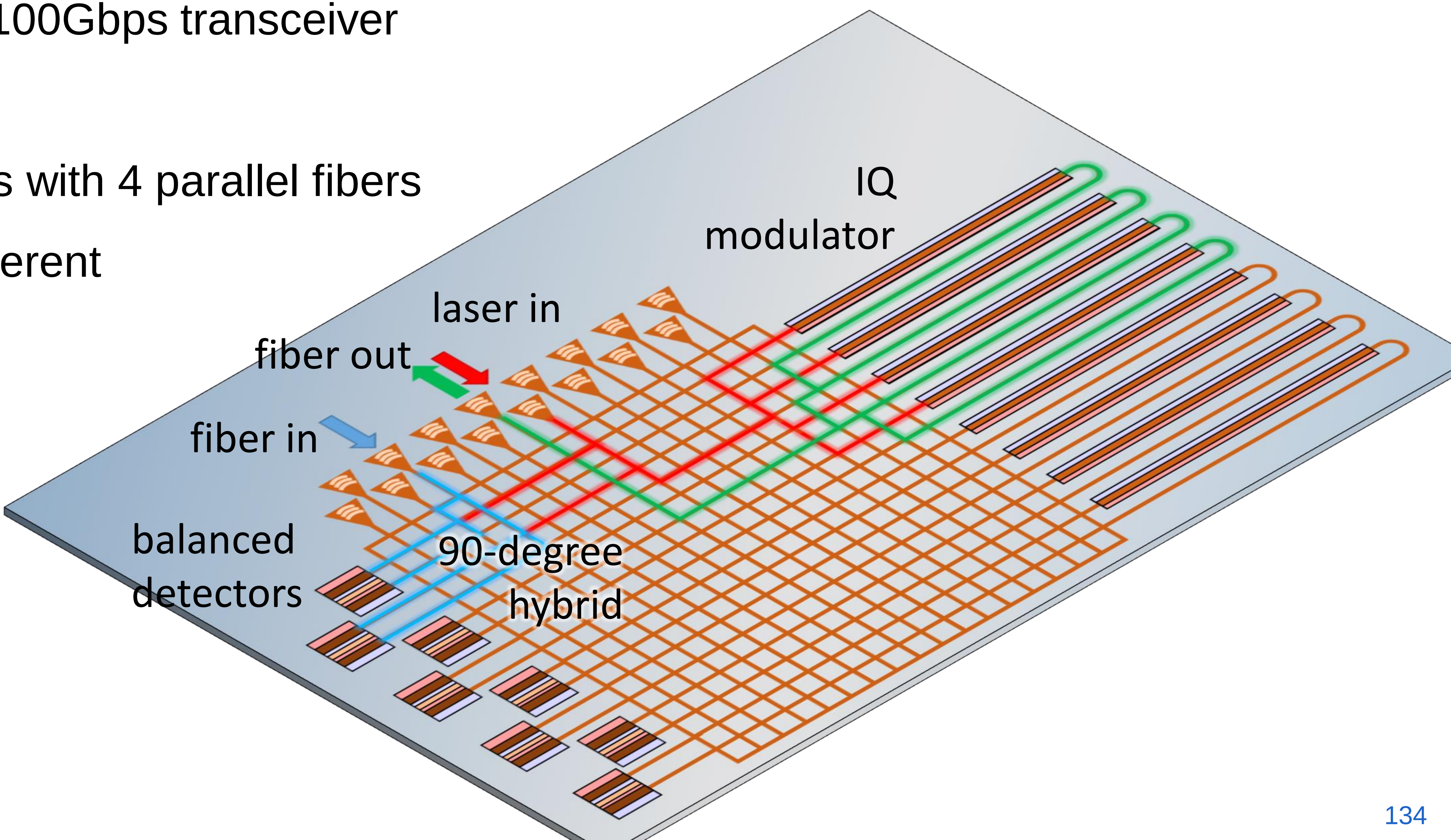


Programmable Transceiver

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers

QAM16: coherent



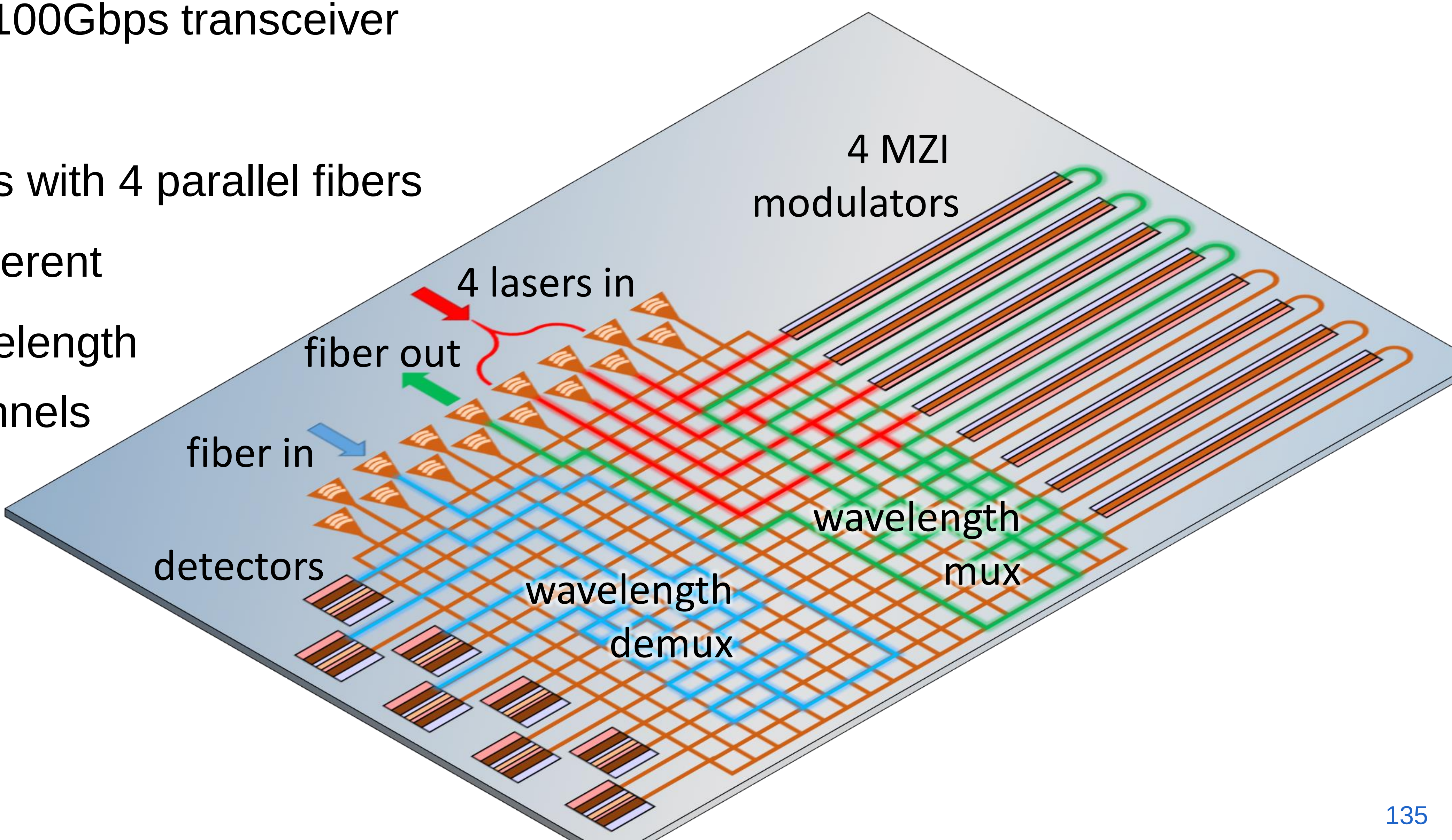
TODAY'S PHOTONIC CHIP: DESIGNED FOR ONE PURPOSE

Example: A 100Gbps transceiver

PSM4: works with 4 parallel fibers

QAM16: coherent

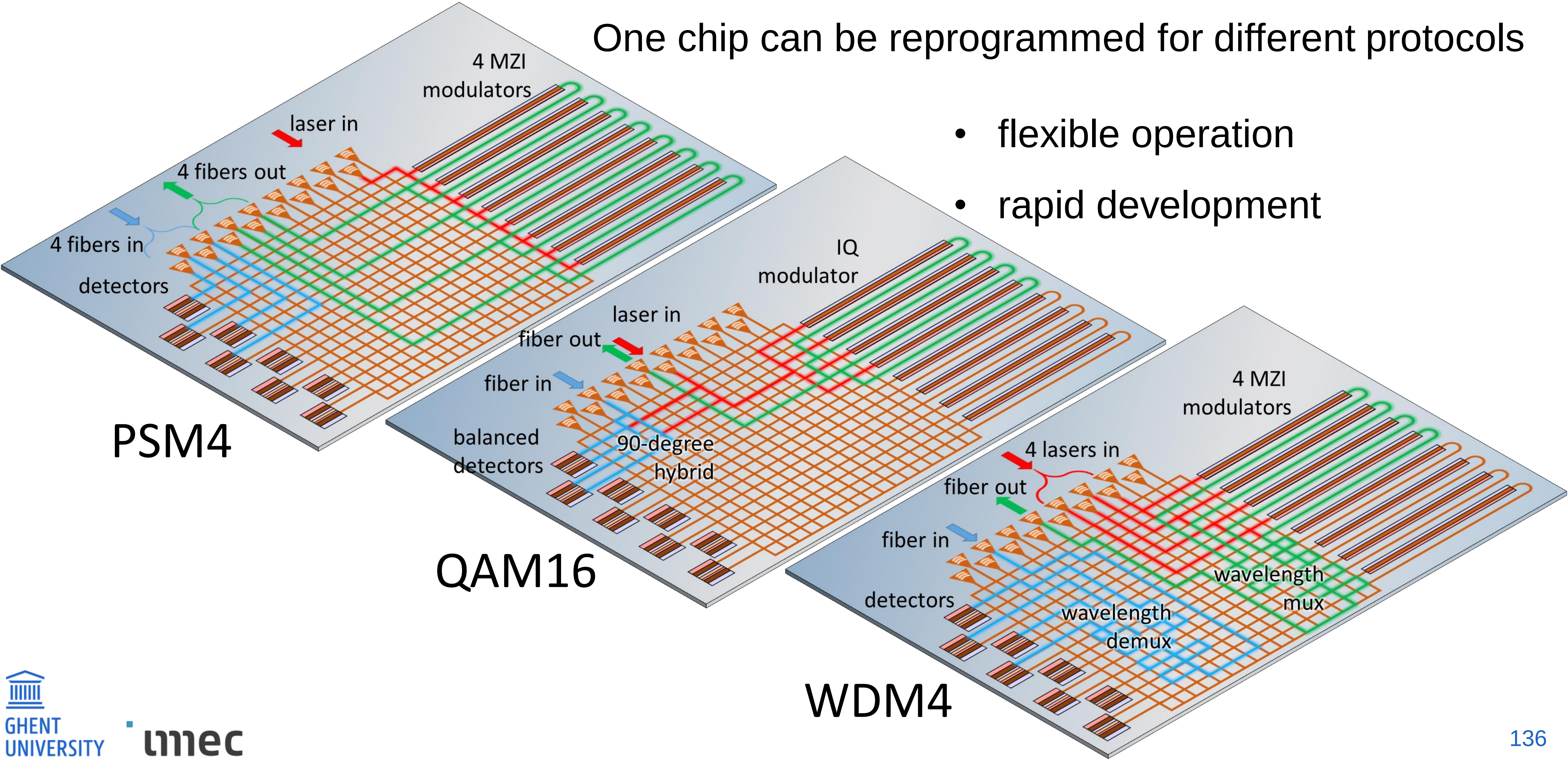
WDM4: wavelength channels



PROGRAMMABLE TRANSCEIVERS

One chip can be reprogrammed for different protocols

- flexible operation
- rapid development



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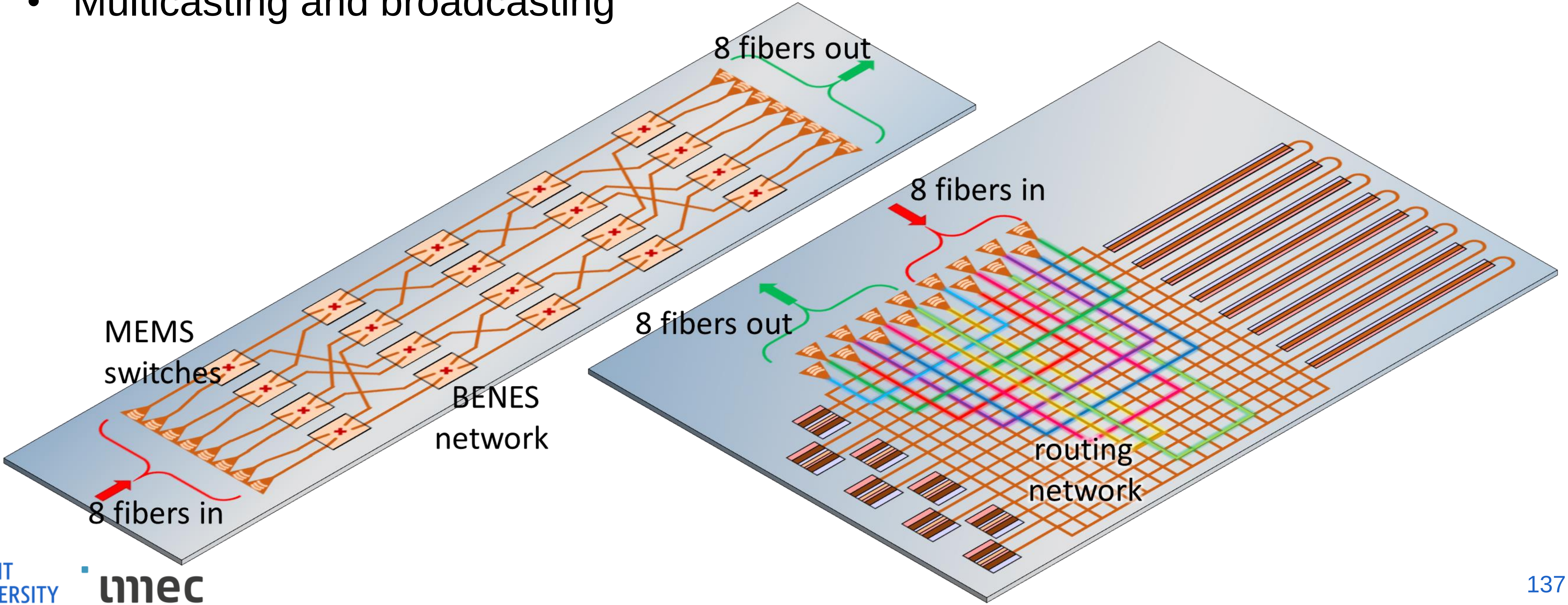
EXAMPLE: SWITCH MATRIX

Switching network

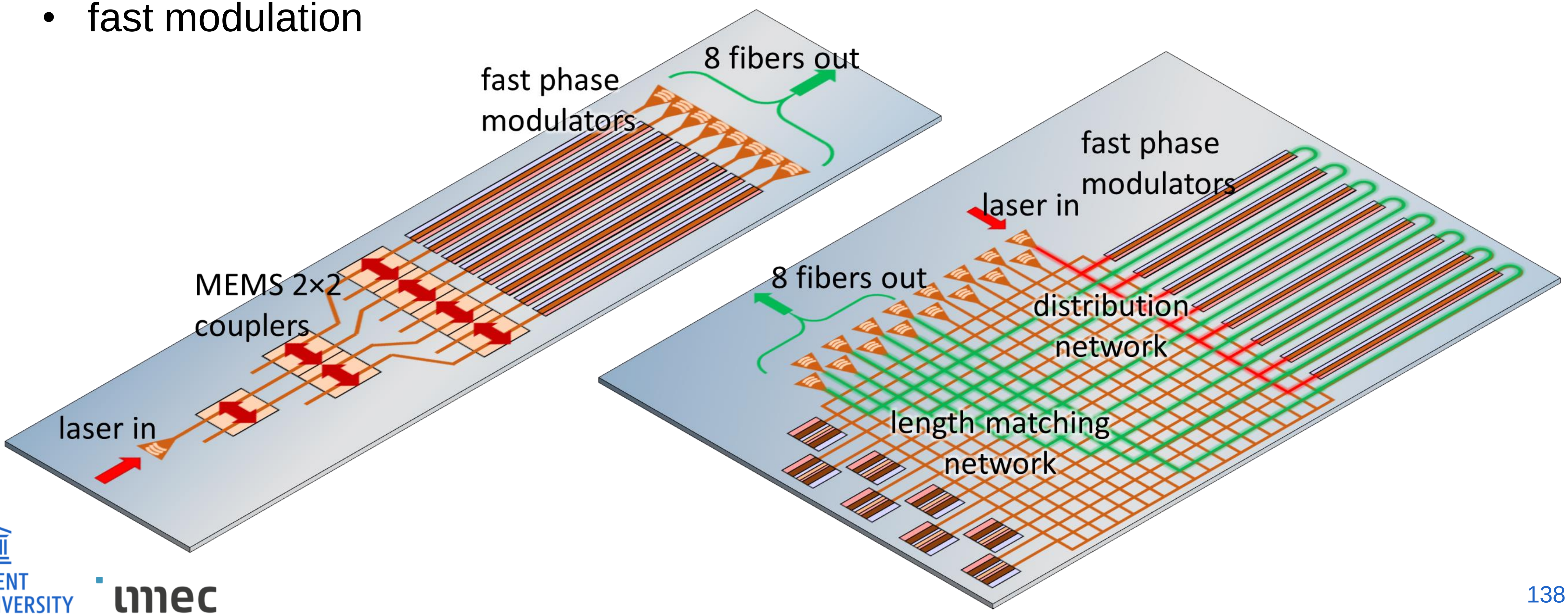
- Different switch architectures possible
- Multicasting and broadcasting



EXAMPLE: OPTICAL BEAM FORMING

Fast beam-forming network

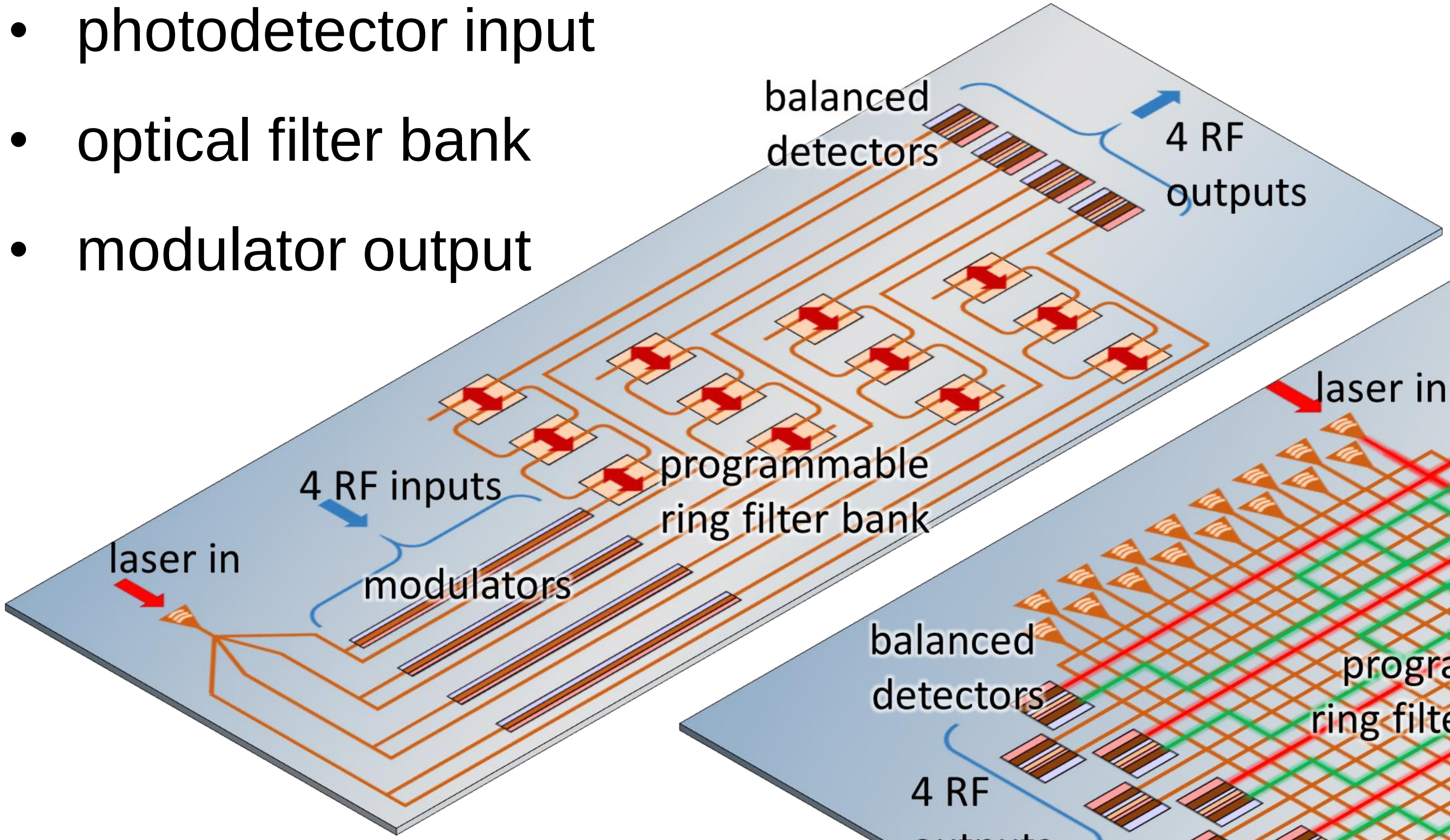
- distribution network (phase and amplitude)
- fast modulation

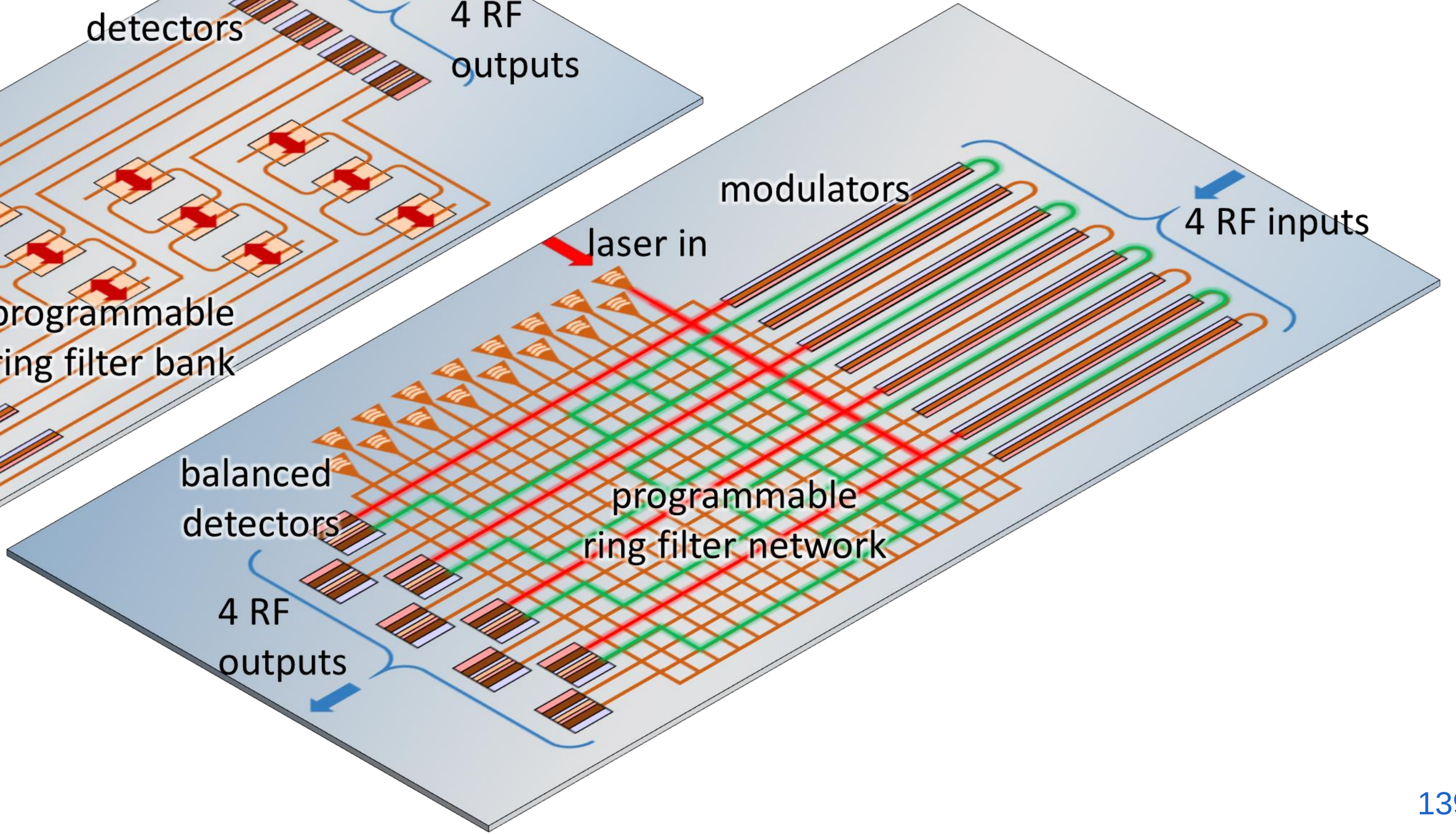


EXAMPLE: MICROWAVE PHOTONICS

multi-channel programmable microwave filter

- photodetector input
- optical filter bank
- modulator output





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CHANGING THE ECOSYSTEM

Larger chip manufacturing volumes

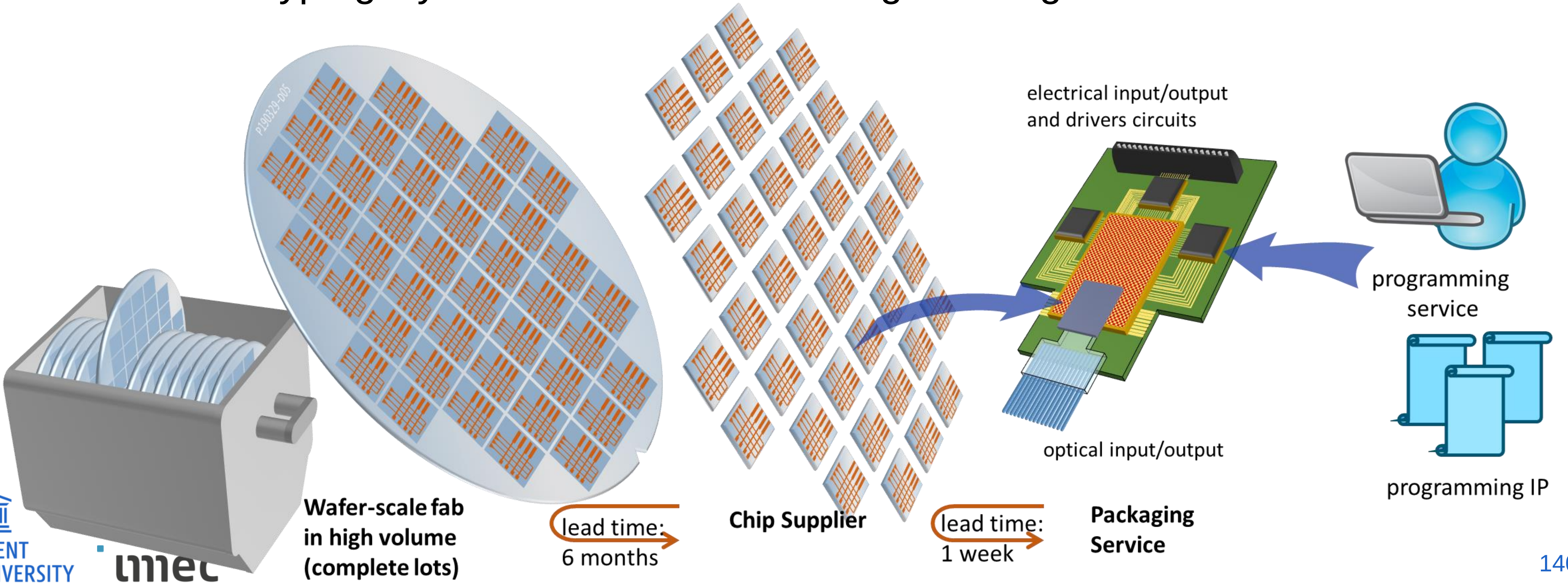
Smaller end-user purchase volumes

Faster Prototyping Cycle

New role for chip suppliers

Specialized Packaging

Programming services and IP creation



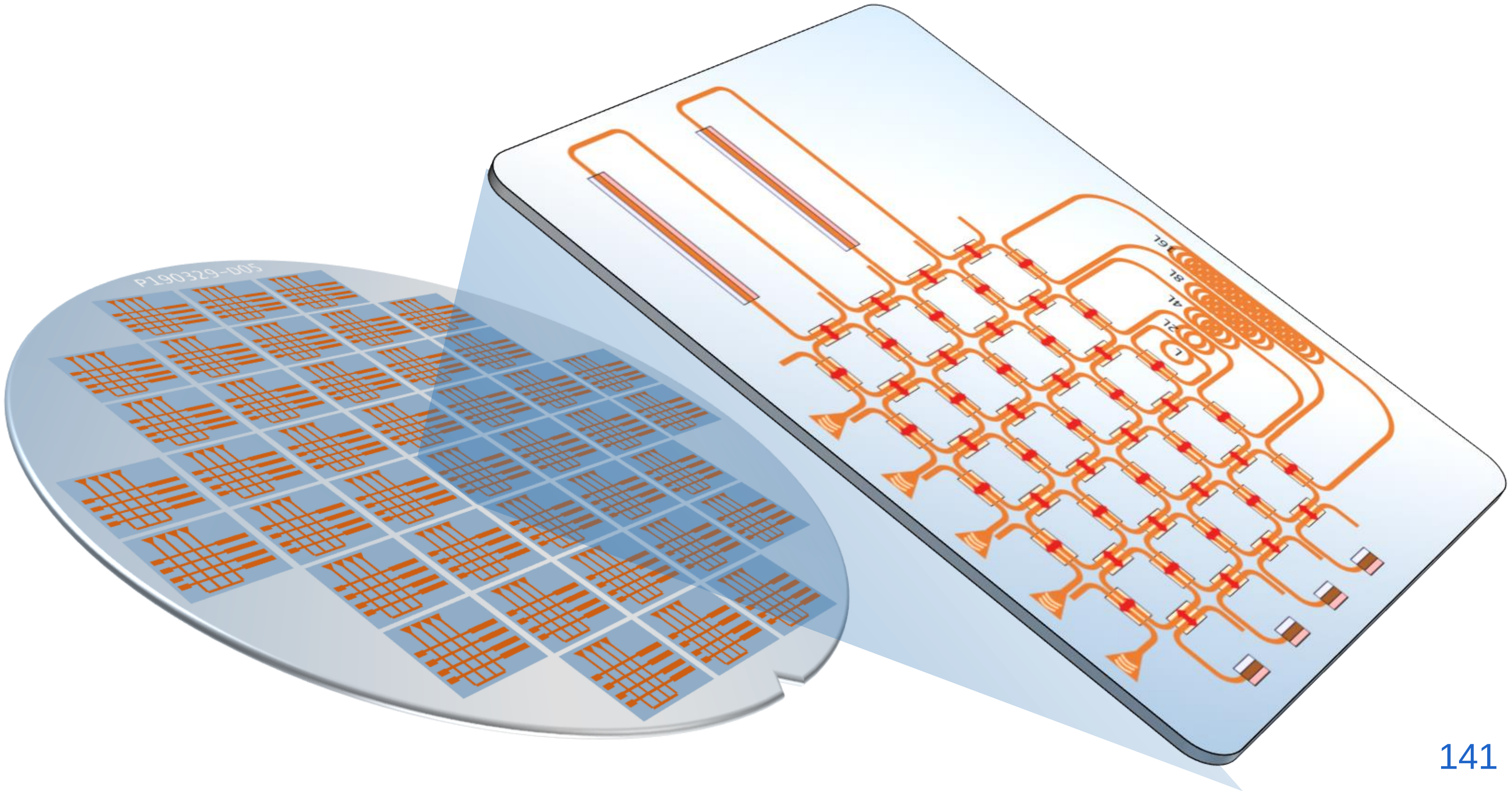
SUMMARY: PROGRAMMABLE PICS

Programmable PICs can become a game-changer:

- Rapid prototyping and development
- High performance
- Different applications

Scaling exposes new challenges

- power consumption
- accumulated loss/parasitics
- control
- packaging
- programming algorithms



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Thanks to the team

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Iman Zand

Xiangfeng Chen

Yinghao Ye

Antonio Ribeiro

Umar Khan

Abdul Rahim

Banafsheh Abasahl

Morphic

Collaborators at IMEC, EPFL, KTH, Tyndall, Commscope and VLC

Source Material

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Dirk Englund (MIT)

Hasitha Jayatilleka (UBC)

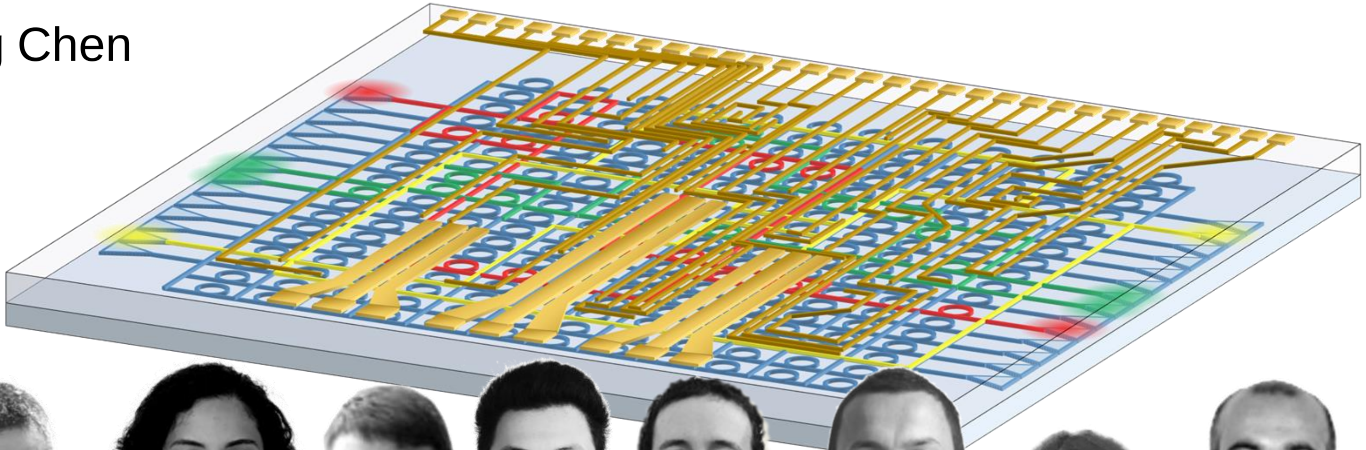
Andrea Melloni (Poli. di Milano)

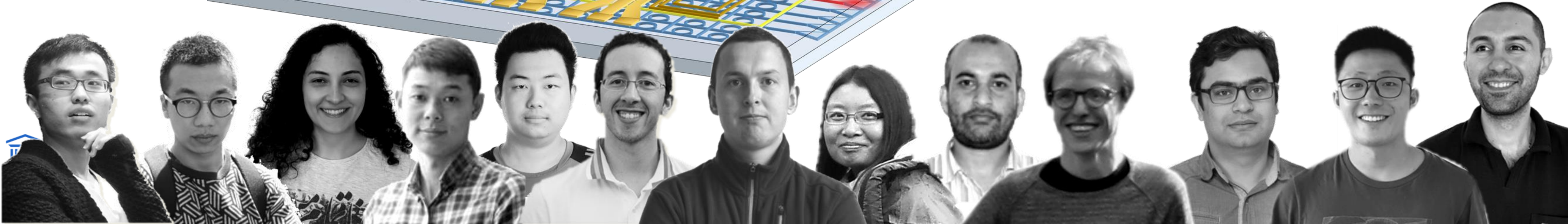
David A.B. Miller (Stanford)

Niels Quack (EPFL)

Graham Reed (U. Southampton)

Josh Silverstone (U. Bristol)





PHOTONICS RESEARCH GROUP

PHOTONICS[21] PHOTONICS PUBLIC PRIVATE PARTNERSHIP

OSA Traveling Lecturer Program

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PhotonICSWARM morphic

www.photonics.intec.ugent.be

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