PHOTONICS RESEARCH GROUP

GHENT UNIVERSITY

imec
embracing a better life

TUTORIAL:

Programmable Photonics

Wim Bogaerts

OFC 2021 – 8 June 2021

2

ABSTRACT

GHENT UNIVERSITY

imec

We present the new field of programmable photonic circuits. We introduce the evolution from specialized photonic circuits to general-purpose photonic processors, and describe the layers in the technology stack and their challenges.

Wim Bogaerts
Photonics Research Group
Ghent University – IMEC

3

3

Programmable Photonics: What is in a name?

We manipulate light in software on a small scale

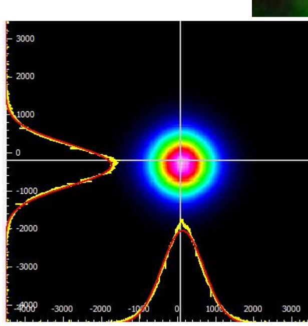
Programmable Photonics

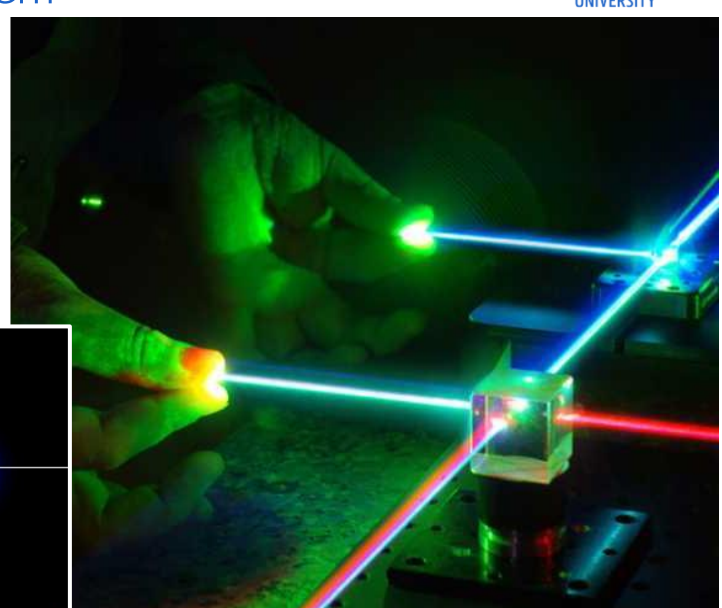
Why?
Because light contains information

Manipulating Beams of Light

Beams of light contain information

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



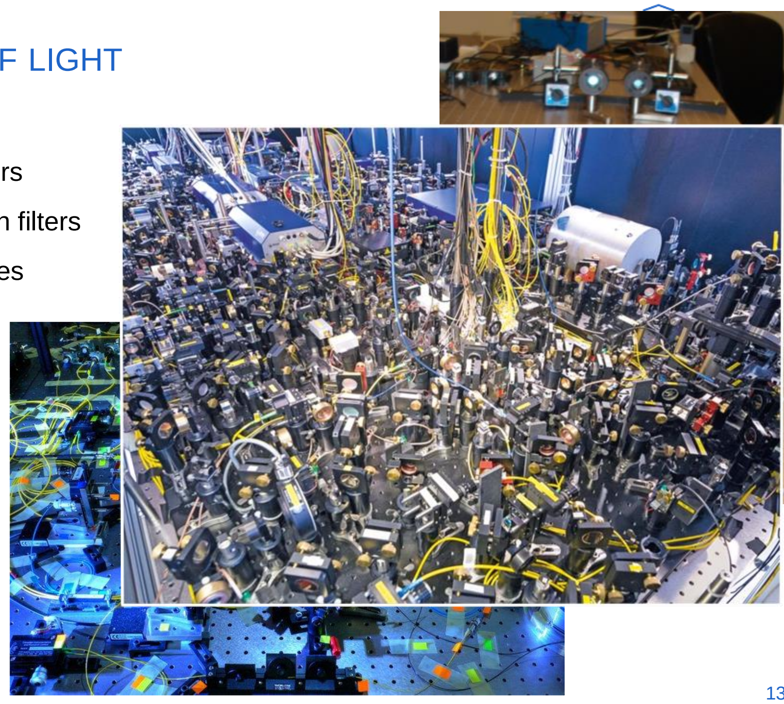


Manipulating Beams of Light

Using optical elements

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

Does not scale very well

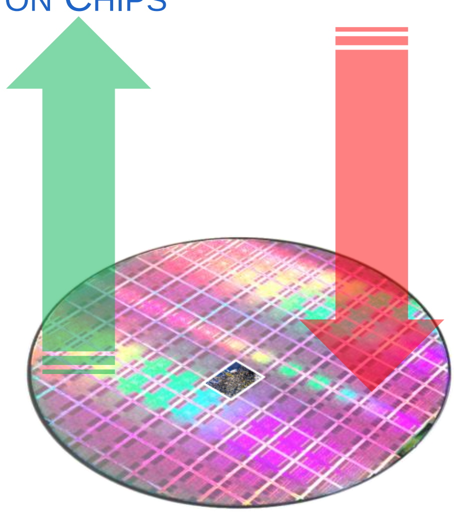


13

13

Manipulating Light on Chips

Complexity
Overall Performance
Reliability
Ergonomy
goes up



Power consumption
Ecological Footprint
Cost
goes down

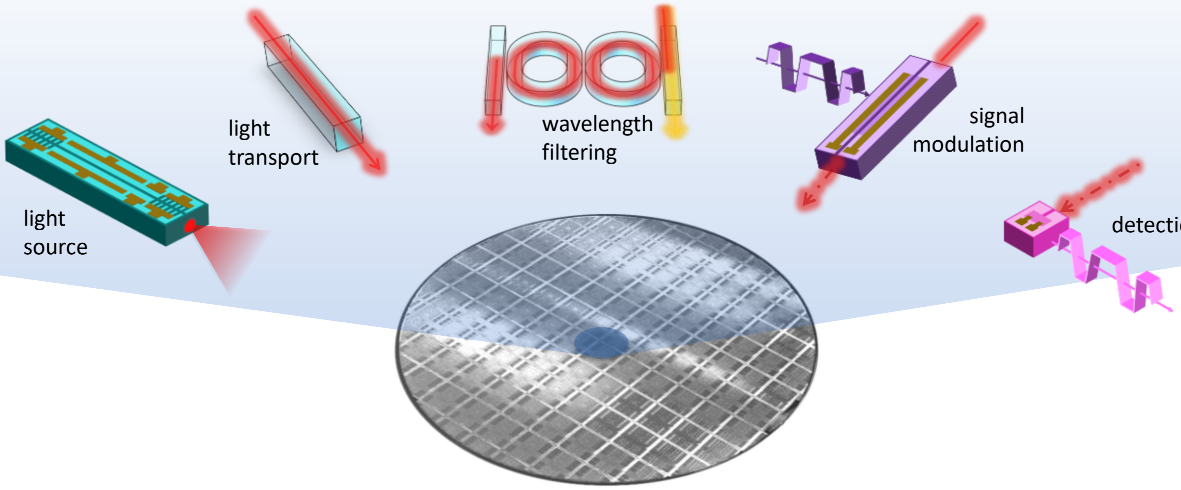
The benefits of scale

14

14

OFC 2021 – Tutorial Programmable Photonics

Photonic Integration: many functions on a chip



Circuits connect elements together with waveguides

15

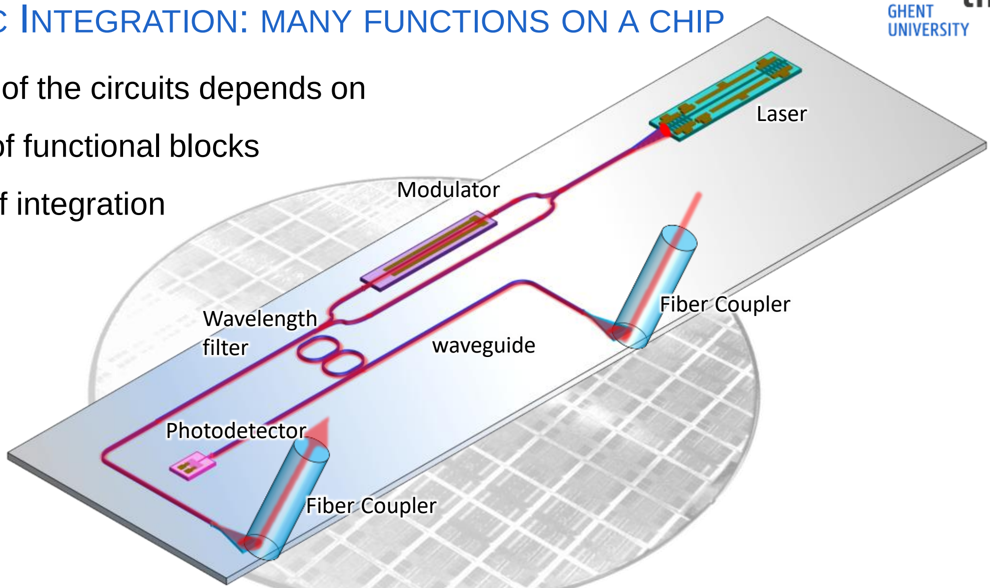
15

OFC 2021 – Tutorial Programmable Photonics

Photonic Integration: many functions on a chip

Complexity of the circuits depends on

- number of functional blocks
- density of integration

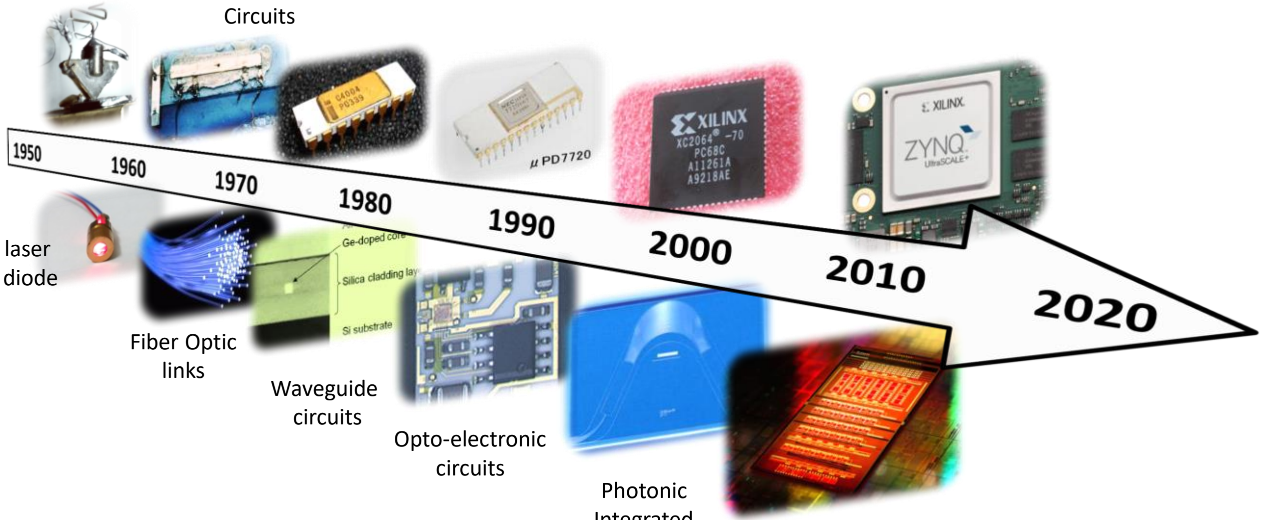


Circuits connect elements together with waveguides

16

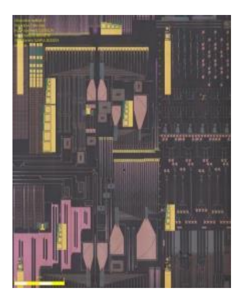
16

The evolution of on-chip integration



Silicon Photonics

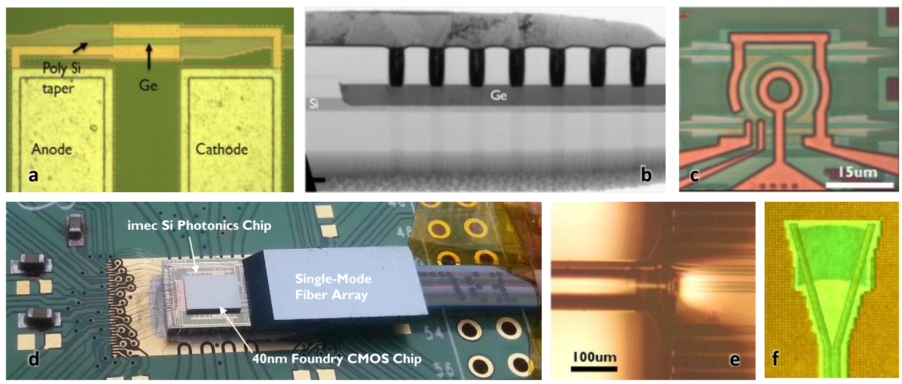
The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab



Complex functionality, compact chips, low cost, high volumes

The IMEC iSiPP50G silicon photonics platform

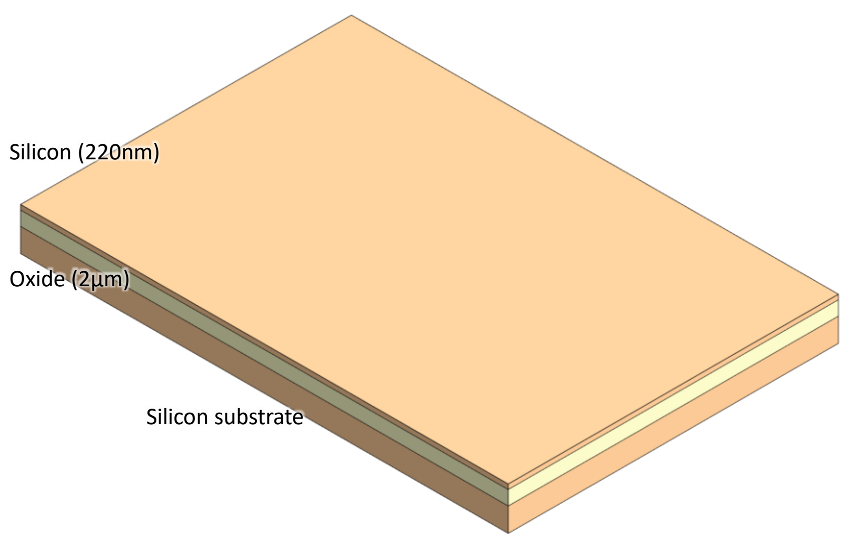
- Passive submicron silicon waveguides
- modulators and germanium photodiodes
- 2 layers of metals
- fiber interfaces



20

20

Bare Silicon-on-Insulator Wafer



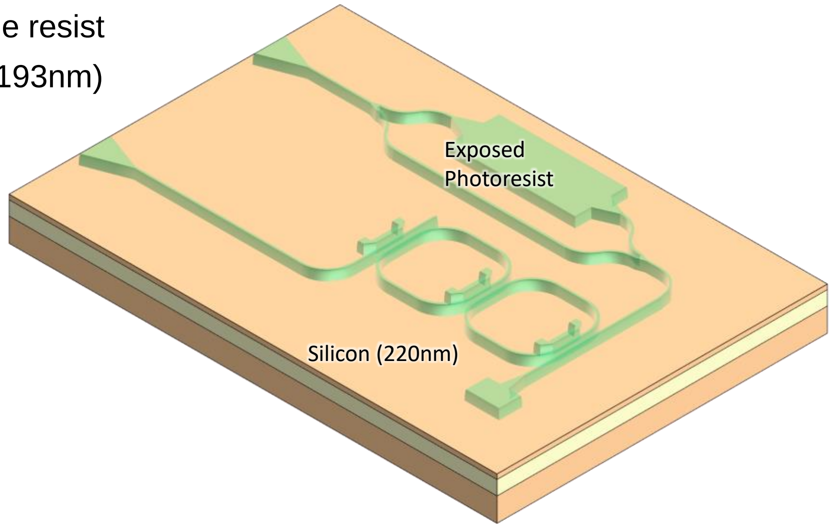
21

21

OFC 2021 – TUTORIAL PROGRAMMABLE PHOTONICS

PHOTOLITHOGRAPHY

1. Spin-coat Photoresist + pre-bake
2. Mask is projected in the resist
   (UV light at 248nm or 193nm)
3. Post-Exposure bake
4. Resist is developed



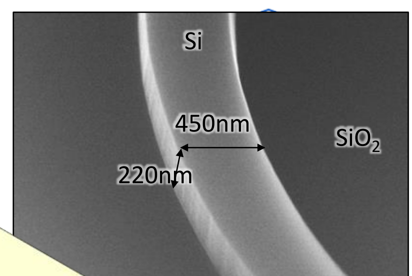
25

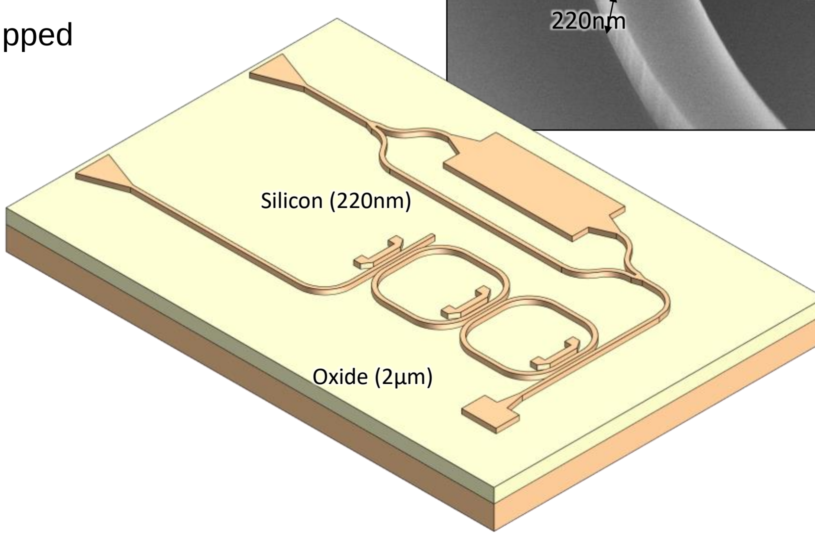
25

OFC 2021 – TUTORIAL PROGRAMMABLE PHOTONICS

SILICON ETCHING

1. Plasma etches the exposed silicon
2. Remaining resist is stripped



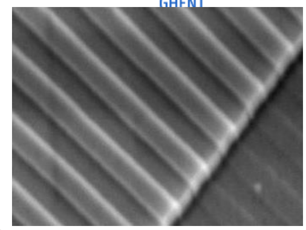


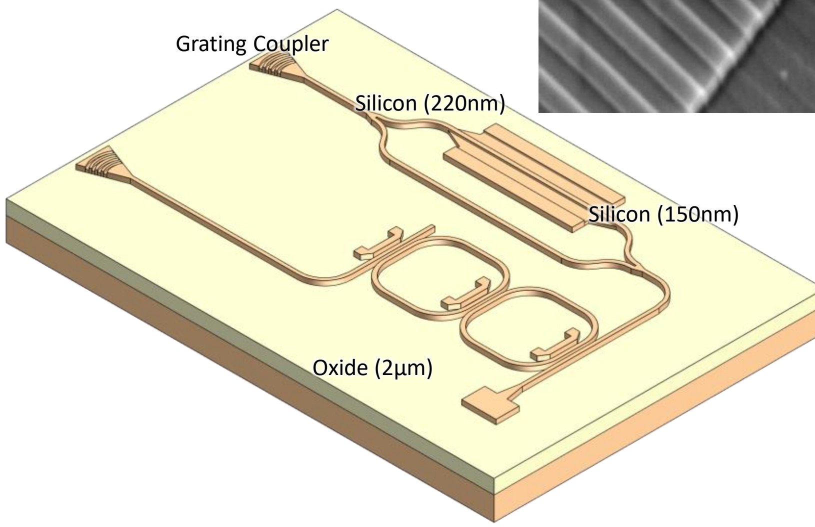
27

27

Partial Silicon Etching

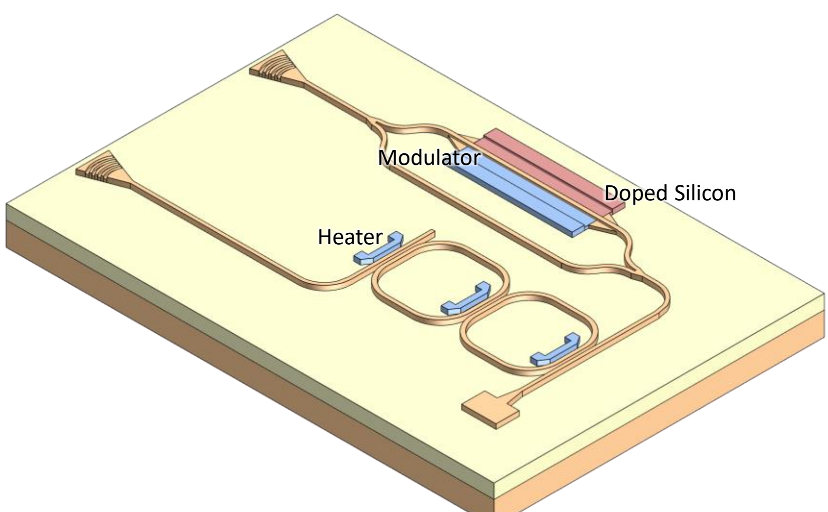
1. Lithography of second layer
2. Plasma etching
3. Resist Stripping





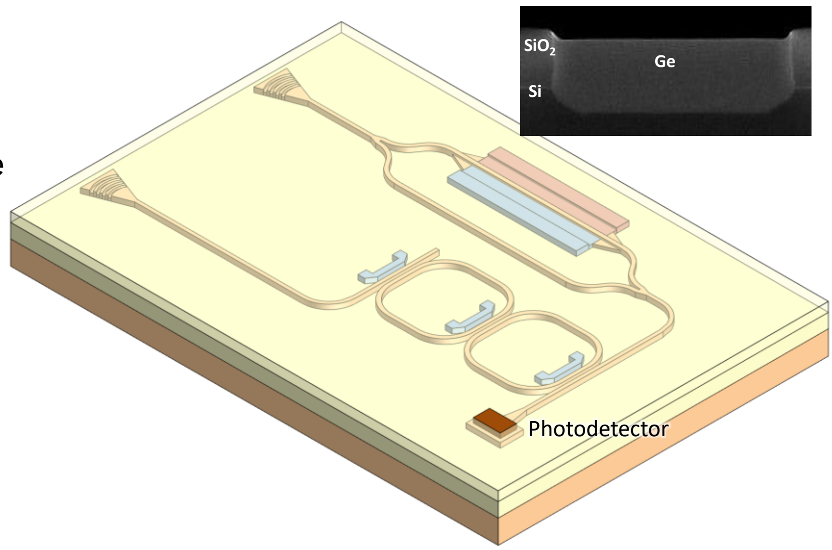
Doped regions for Modulators and Heaters

1. Lithography of windows
2. Ion implantation
3. Resist Stripping



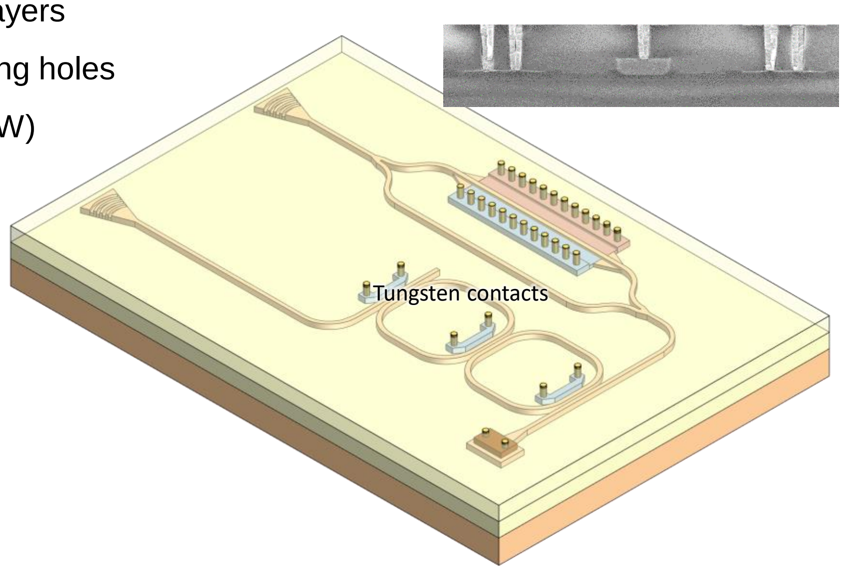
Germanium Photodetectors

1. Oxide cladding
2. Planarization (CMP)
3. Opening of window
4. Epitaxial Growth of Ge
5. Planarization (CMP)



Electrical contacts: Damascene process

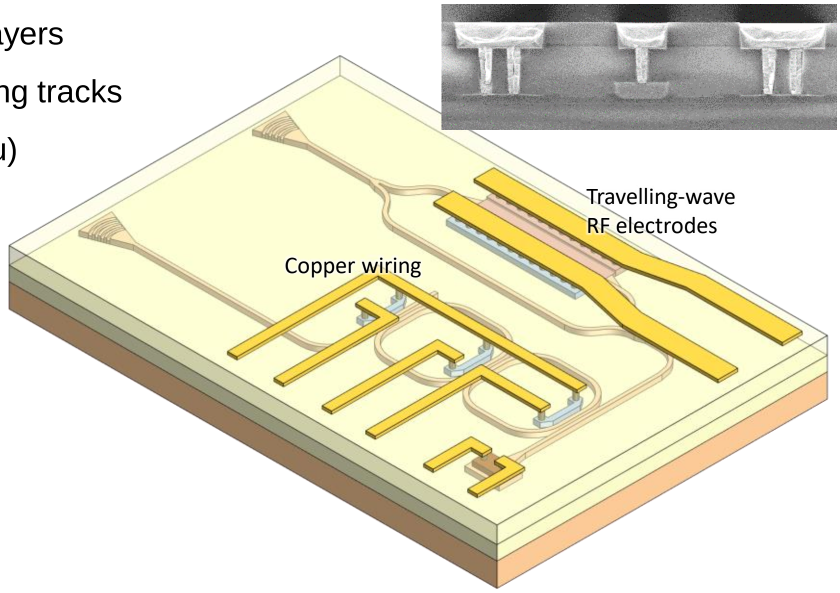
1. Depositing dielectric layers
2. Lithography and Etching holes
3. Filling with Tungsten (W)
4. Planarization (CMP)



Metal Interconnects: Damascene process

1. Depositing dielectric layers
2. Lithography and Etching tracks
3. Filling with Copper (Cu)
4. Planarization (CMP)

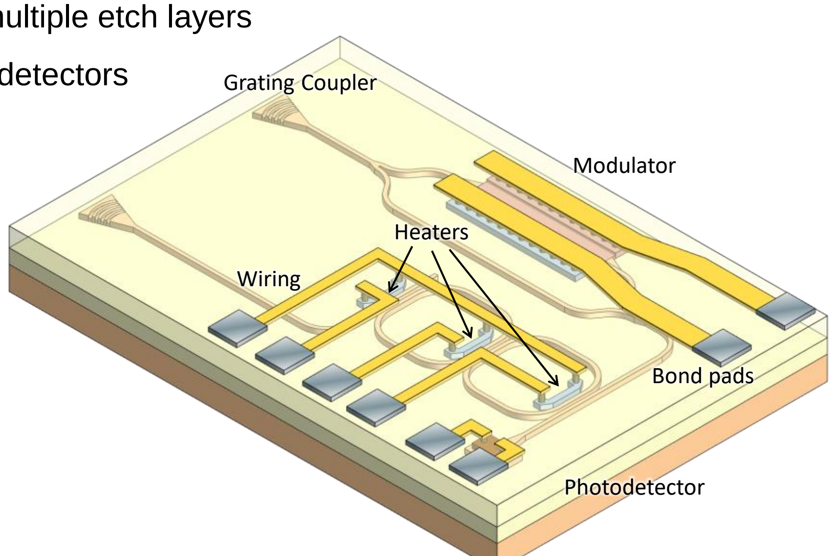
Repeat for more layers



36

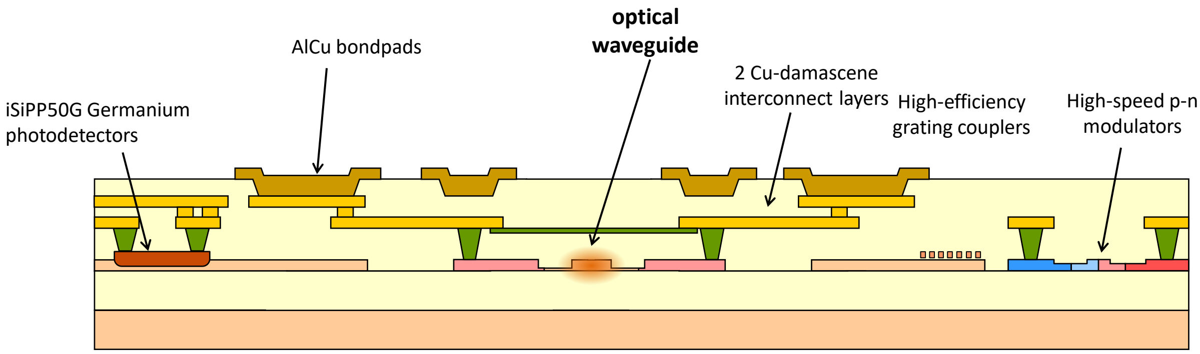
Silicon Photonics Chips

1. Passive circuits with multiple etch layers
2. Modulators and Photodetectors
3. Metal wiring



38

Example: IMEC's iSiPP50G Platform



Low-loss rib and strip waveguides

Multiple types of Integrated heaters

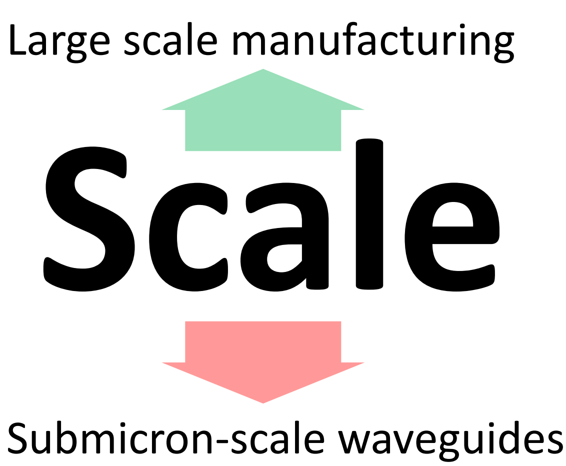
p(i)n junction modulators

Germanium photodetectors

Pantouvaki, JLT 2017 39

39

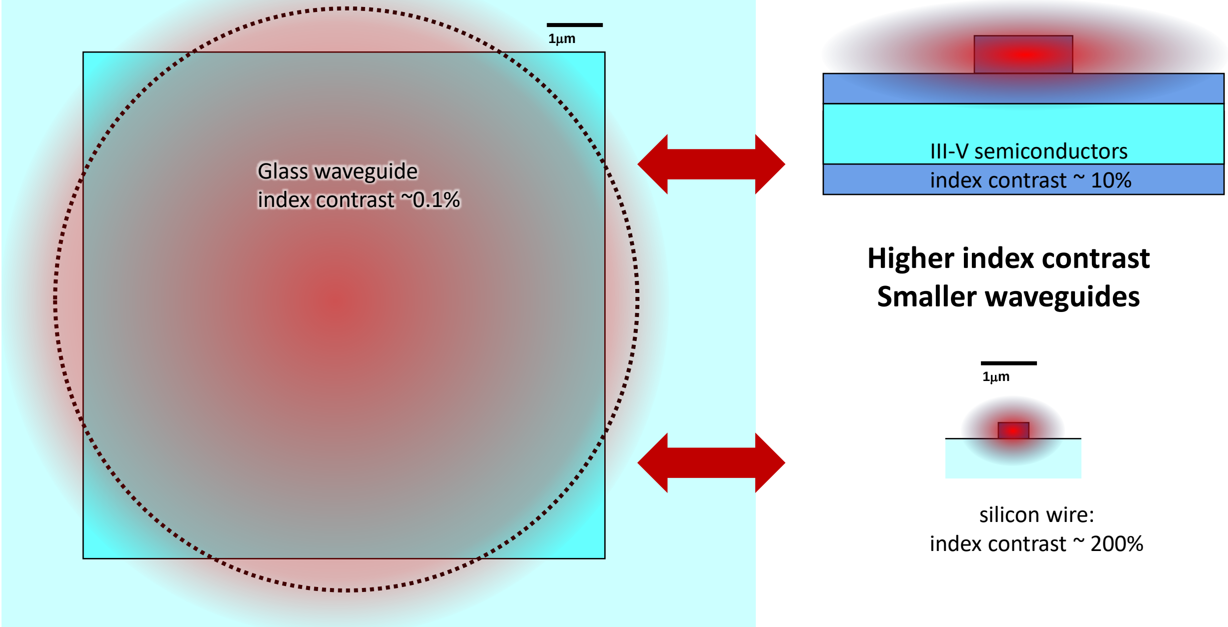
Why silicon photonics?



40

40

Different types of on-chip waveguides



41

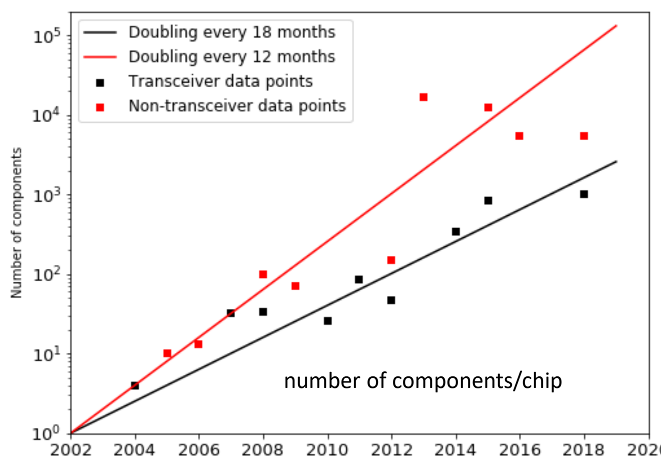
41

OFC 2021 – Tutorial Programmable Photonics

Silicon Photonic Circuit Scaling

Rapidly growing integration

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

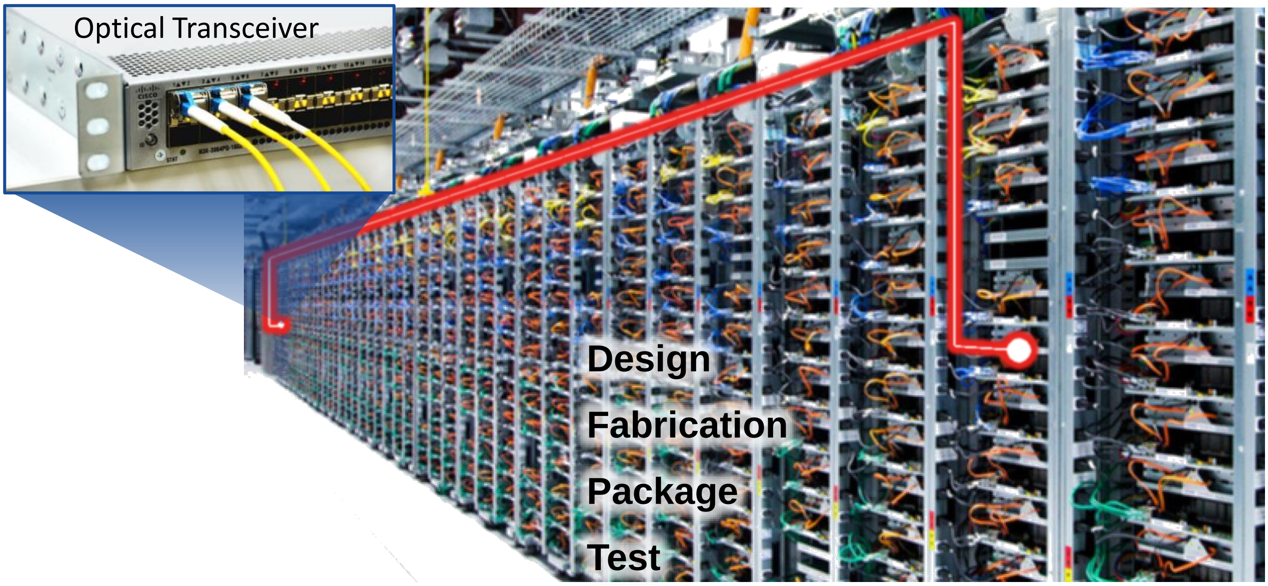


All photonic circuits are ASICs

Khanna et al. 2016 42

42

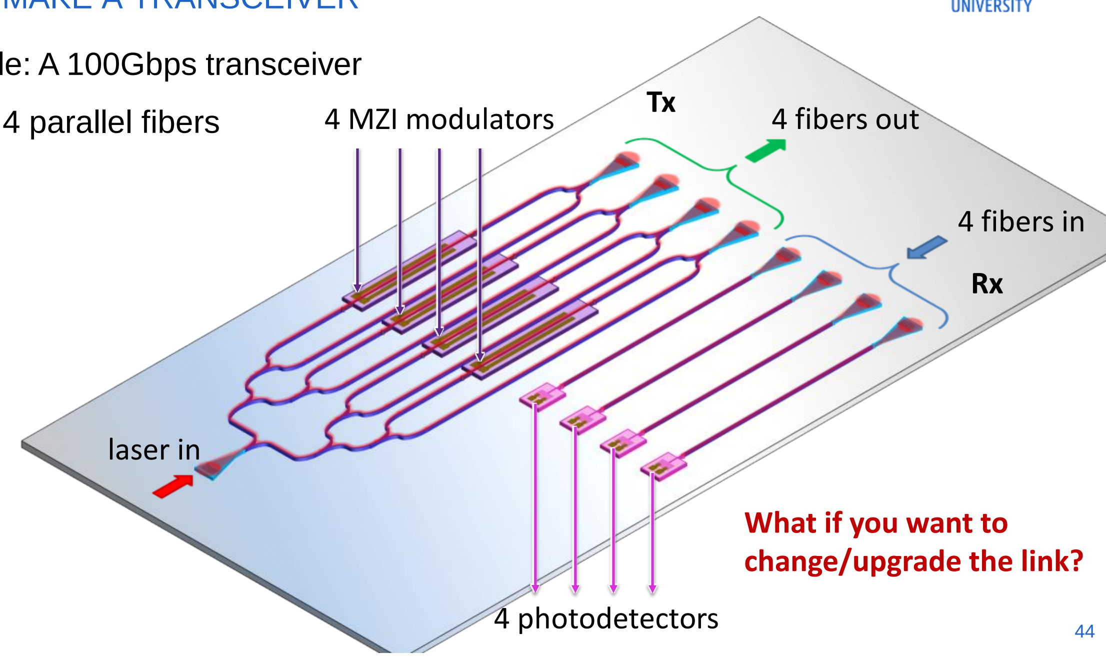
Example: Optical transceivers for datacenter links



Let's make a transceiver

Example: A 100Gbps transceiver

PSM4: 4 parallel fibers

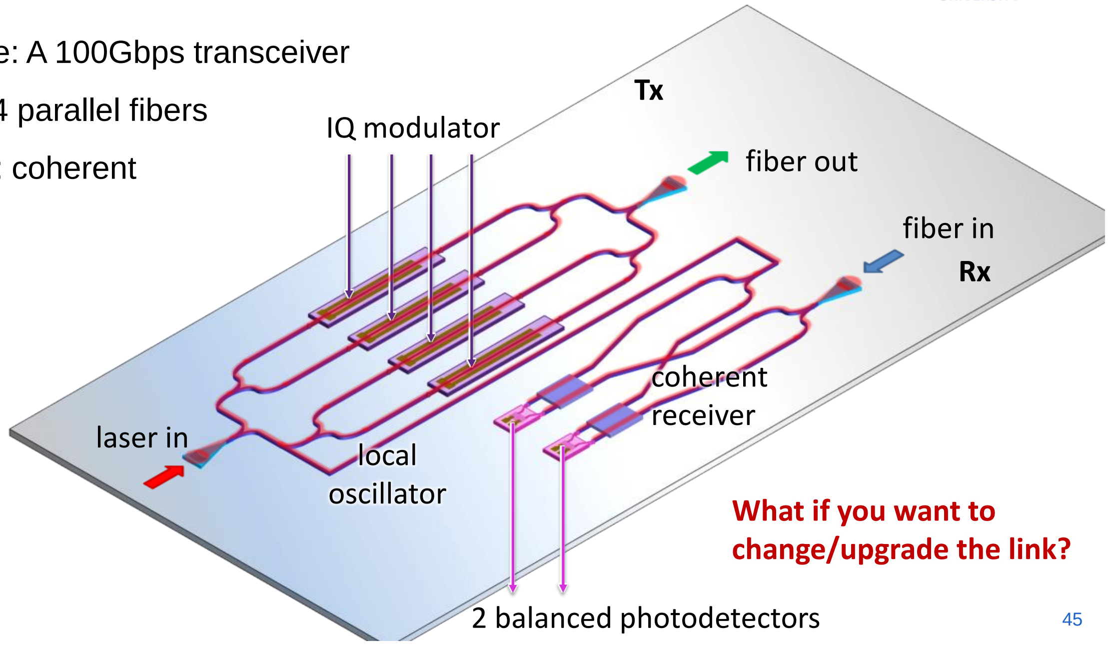


Let's make a transceiver

Example: A 100Gbps transceiver

PSM4: 4 parallel fibers

QAM16: coherent



What if you want to change/upgrade the link?

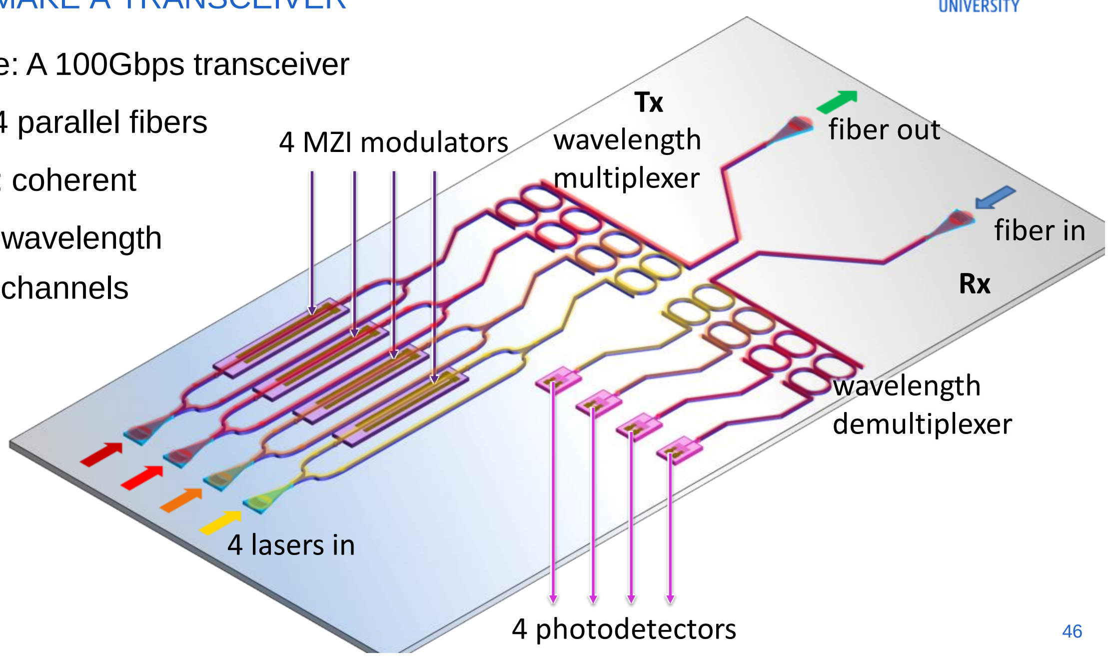
Let's make a transceiver

Example: A 100Gbps transceiver

PSM4: 4 parallel fibers

QAM16: coherent

WDM4: wavelength channels



Prototyping a New (Silicon) Photonic IC

Design (4M)

Fabrication (6M)

Package (1M)

Test (2M)

Then you discover the bugs…

Repeat!

47

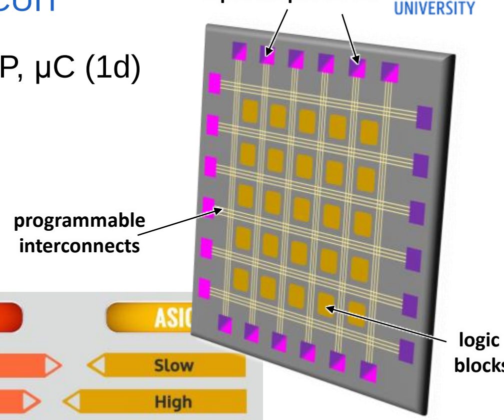
Prototyping a new Electronic Circuit

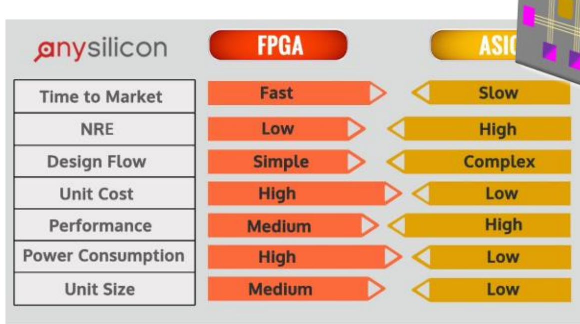
Select a suitable programmable IC: FPGA, DSP, µC (1d)

Program and test the chip (1-4w)

Only then, if needed:

- Design ASIC …





	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

48

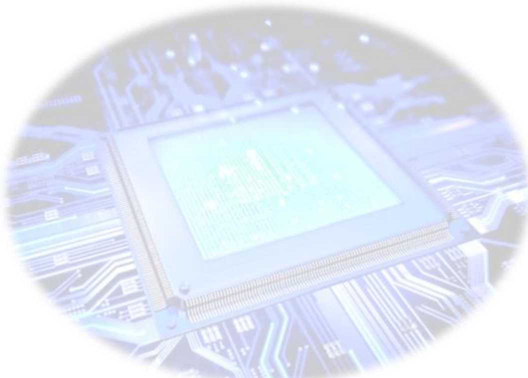
The Photonic FPGAs?

or programmable photonics

reconfigurable photonics

photonic processors

universal photonic circuits …



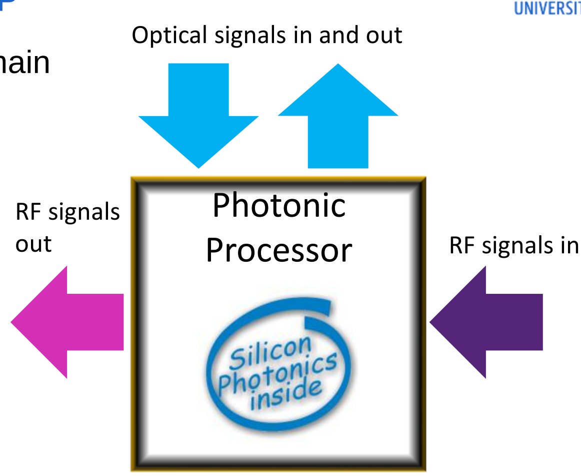
Photonic Integrated Circuits that **can be reconfigured** using **software** to perform **different functions**.

Programmable Photonic Chip

Can process signals in the optical domain

- balancing
- filtering
- transformations

Both on Optical and RF signals



Generic Programmable Photonic Circuit

GHENT UNIVERSITY imec

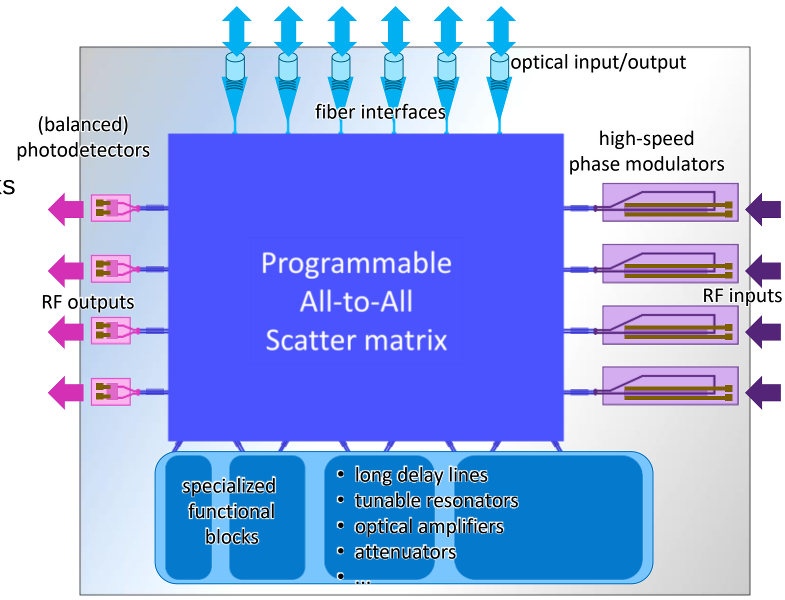
Optical inputs and outputs

RF inputs: modulators

RF outputs: balanced PDs

Specialized high performance blocks

Connected by a programmable linear optical circuit



51

51

Optical Linear Processing

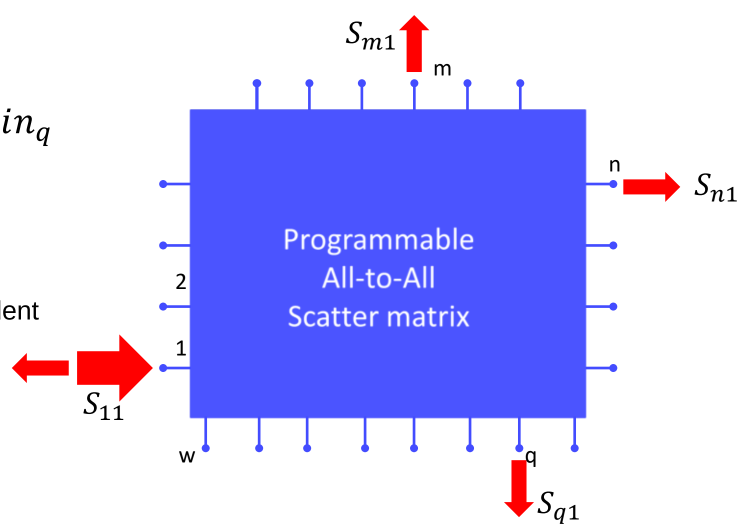
GHENT UNIVERSITY imec

Linear optical circuits

can be described by an

S-matrix $$out_p = \sum_q S_{pq}.in_q$$

- Frequency domain
- Complex numbers
- Wavelength dependent
- Includes reflection
- Reciprocal



IF NO LOSS ⇒ S is unitary

52

52

Optical Linear Processing (forward only)

forward-only (left-to-right) linear optical circuits

is easier to describe by an

Transmission matrix

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

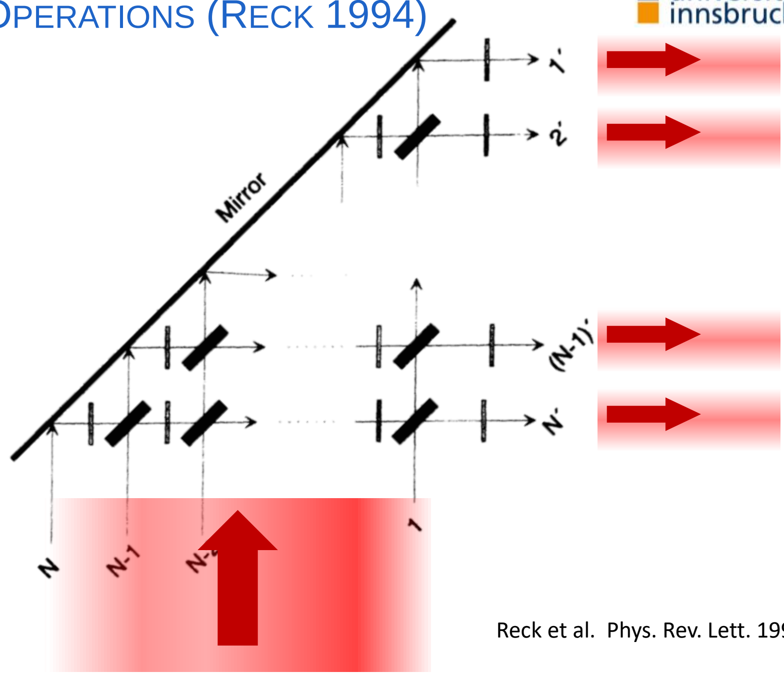
- Frequency domain
- Complex numbers
- Wavelength independent
- **NO REFLECTION**

IF NO LOSS ⇒ T is unitary

Discretized Linear Operations (Reck 1994)

Processing with

- tunable phase shifters
- tunable beam splitters



Reck et al. Phys. Rev. Lett. 1994

Stanford University

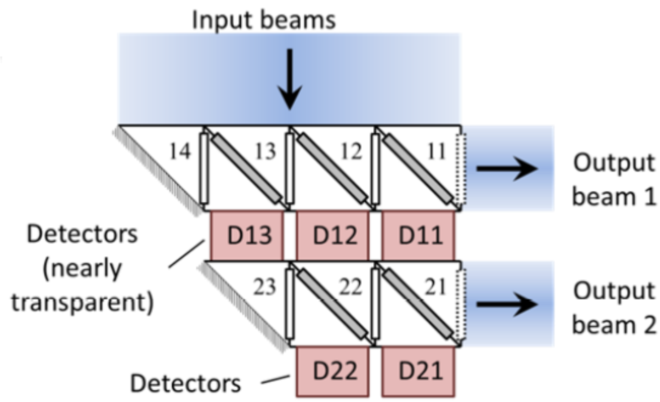
Universal Linear Optics (Miller 2013)

Processing with

- tunable phase shifters
- tunable beam splitters

+ monitor detectors

+ control algorithms



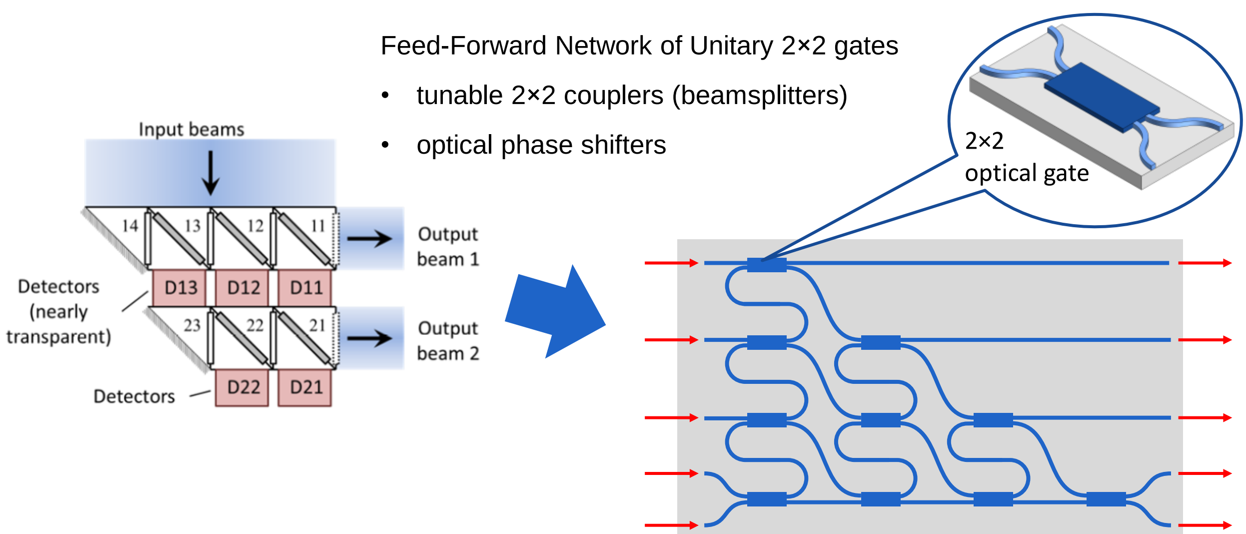
Miller. OpEx. 2013

Stanford University

Universal Interferometric Circuit on a Chip

Feed-Forward Network of Unitary 2×2 gates

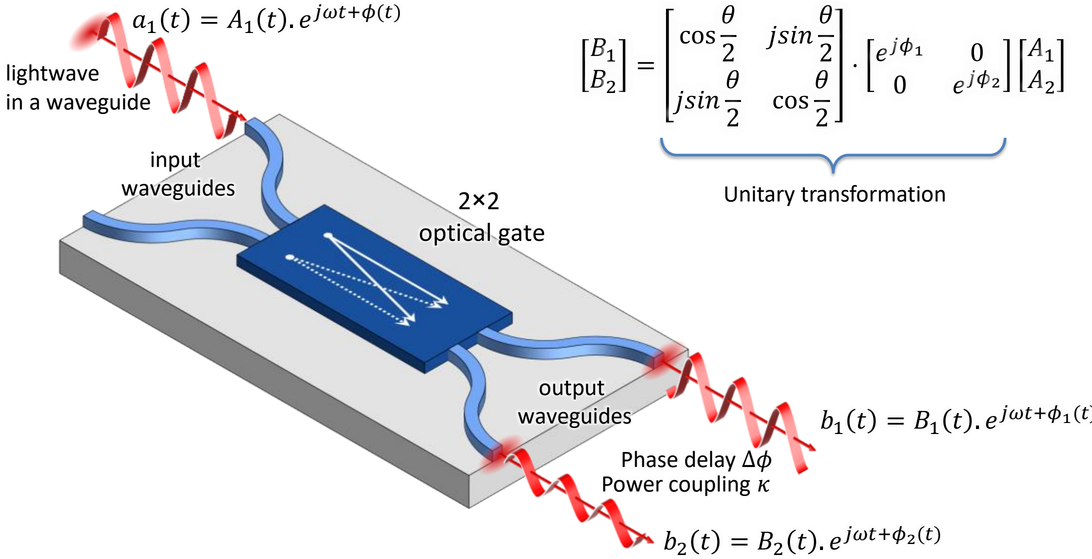
- tunable 2×2 couplers (beamsplitters)
- optical phase shifters



Miller. OpEx. 2013

The basic unit cell: 2×2 Unitary gate

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \cos\frac{\theta}{2} & j\sin\frac{\theta}{2} \\ j\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix} \cdot \begin{bmatrix} e^{j\phi_1} & 0 \\ 0 & e^{j\phi_2} \end{bmatrix}}_{\text{Unitary transformation}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$



Review: Bogaerts et al, Nature 2020 57

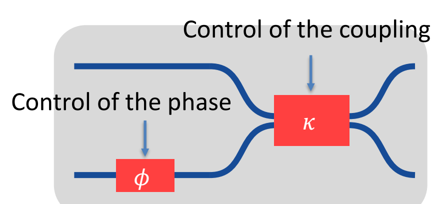
57

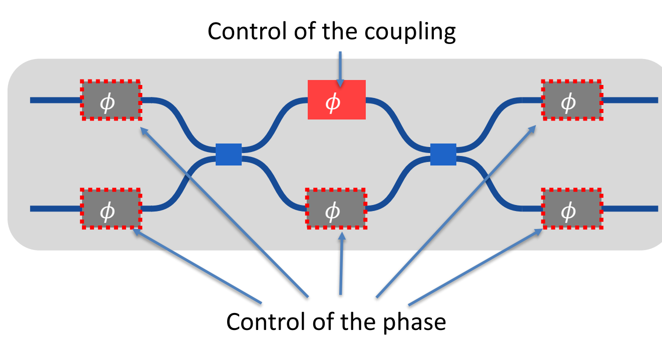
The basic unit cell: 2×2 Unitary gate

On-chip implementations:

at least 2 control points needed

- Phase shifter + Tunable Coupler
- Mach-Zehnder interferometer





58

58

Feedback control with monitors: 2×2 Forward gate

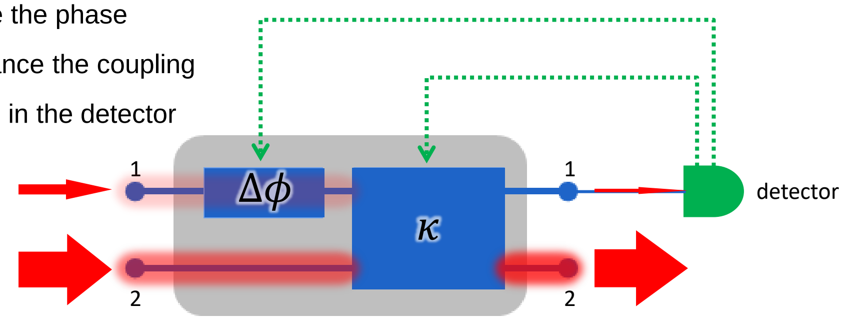
GHENT UNIVERSITY imec

Coupling all light to output 2

Use monitor to tune the phase

Use monitor to balance the coupling

minimize the power in the detector



2x2 optical gate

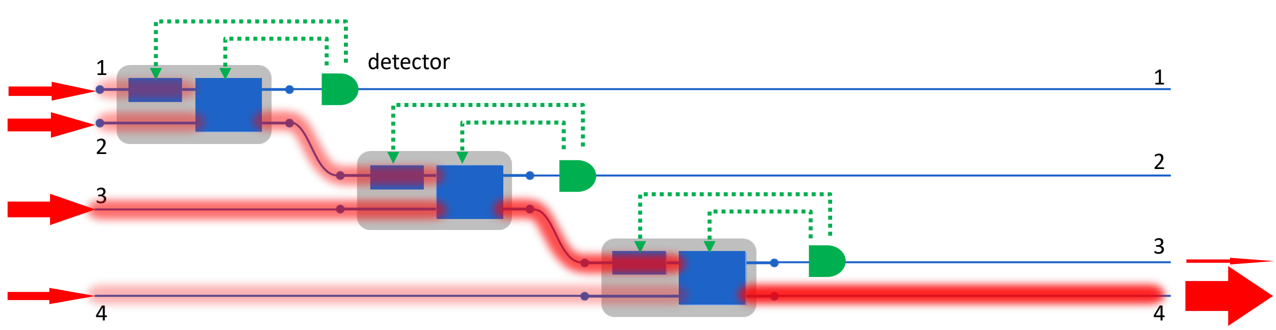
Stanford University Miller, OpEx 2013 61

61

OFC 2021 – Tutorial Programmable Photonics

Feedback control with monitors: Cascaded 2×2 Gates

GHENT UNIVERSITY imec



Cascading gates

Couple all light to output 4

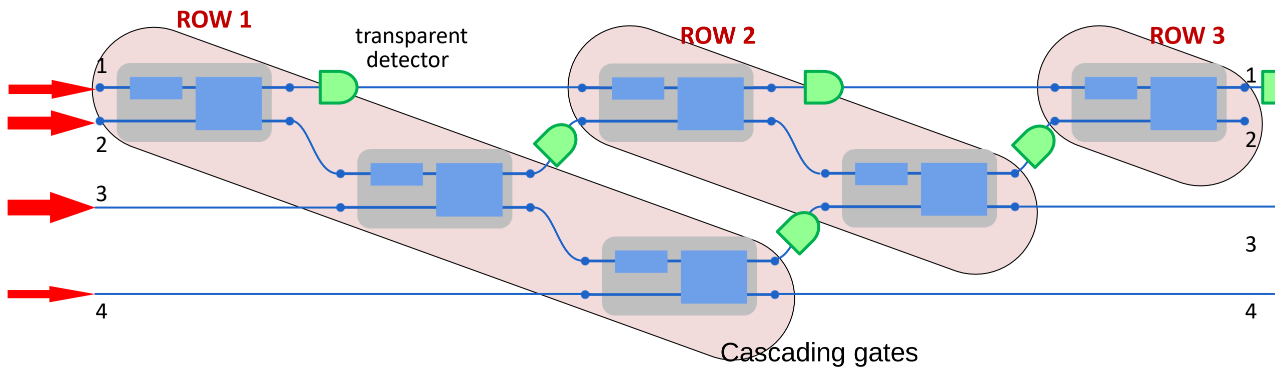
Sequentially optimize 2x2 gates

Stanford University Miller, OpEx 2013 65

65

OFC 2021 – Tutorial Programmable Photonics

Feedback control with monitors: Mesh of 2×2 Gates



Cascading gates

Couple all light to output 4

Sequentially optimize 2x2 gates

Use 'transparent' monitors

Cascade in multiple layers

Stanford University Miller, OpEx 2013 68

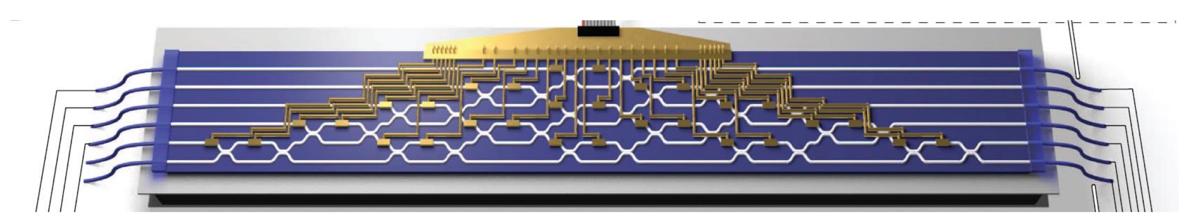
68

OFC 2021 – Tutorial Programmable Photonics

First programmable forward-only matrix circuit

First implementation in silica (low contrast): 2015

6x6 Matrix



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

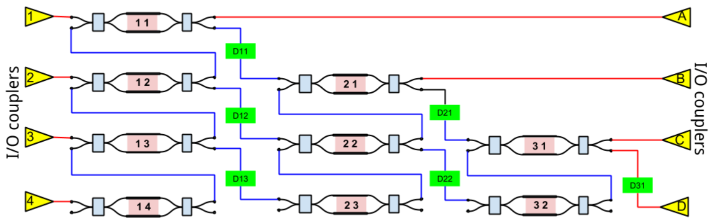
University of BRISTOL

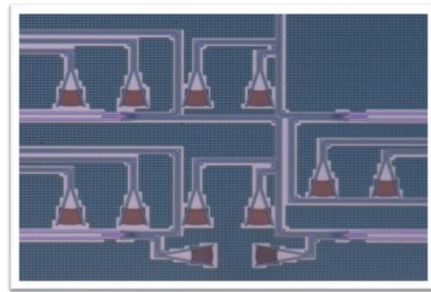
Carolan et al. Science 2015 69

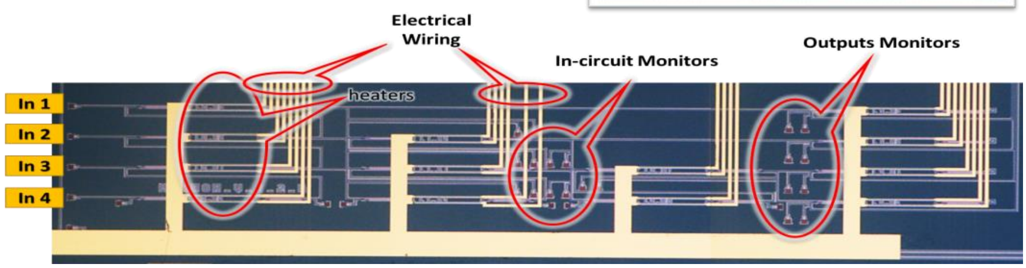
69

First forward-only Matrix circuit in silicon

4x4 circuit: 2.5 x 0.4 mm^2





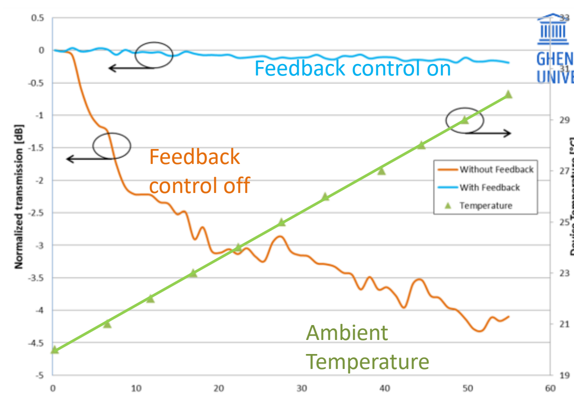


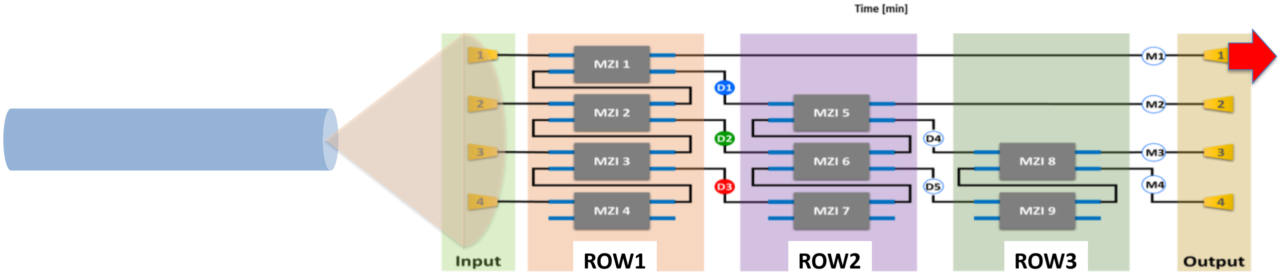
Ribeiro et al, Optica 2016

Adaptive Beam Coupler

Circuit adapts itself to maximize output to a single mode waveguide

Local feedback loops stabilize the entire circuit.



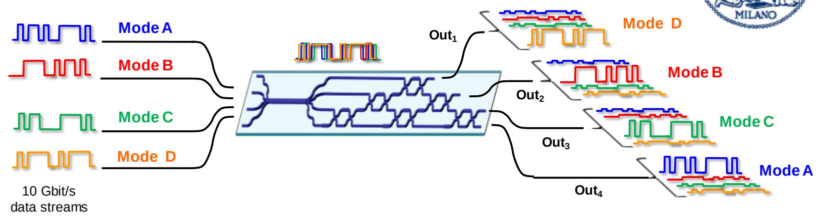


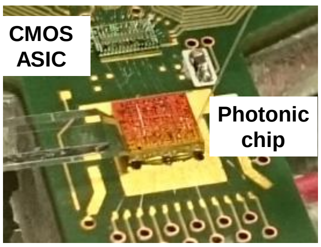
Ribeiro et al, Optica 2016

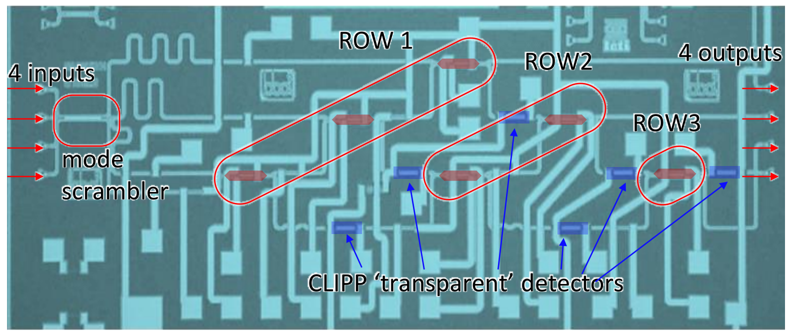
OFC 2021 – Tutorial Programmable Photonics

Adaptive Mode Unscrambler

Input 'states' can be orthogonal modes (e.g. multimode fiber)





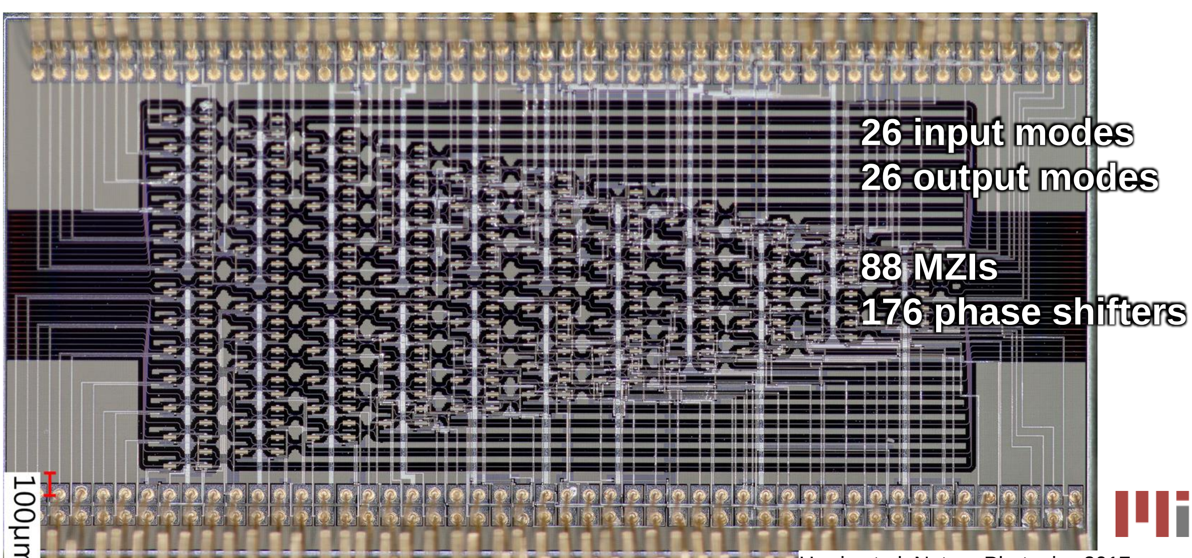


Annoni et al, Light Sci. App. 2017 72

72

OFC 2021 – Tutorial Programmable Photonics

Large-scale Forward-only Matrix Circuit

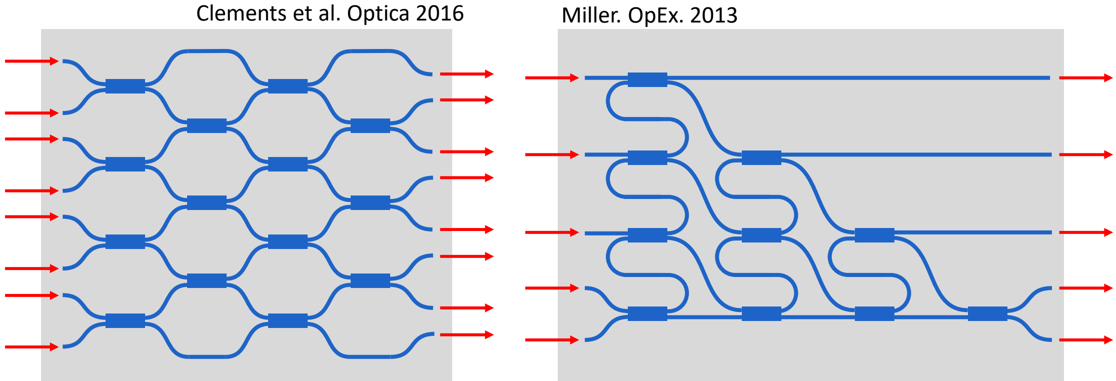


Harris et al, Nature Photonics 2017
Shen, Harris et al, Nature Photonics 2017
Harris et al, Optica 2018 73

73

Forward-only Waveguide meshes

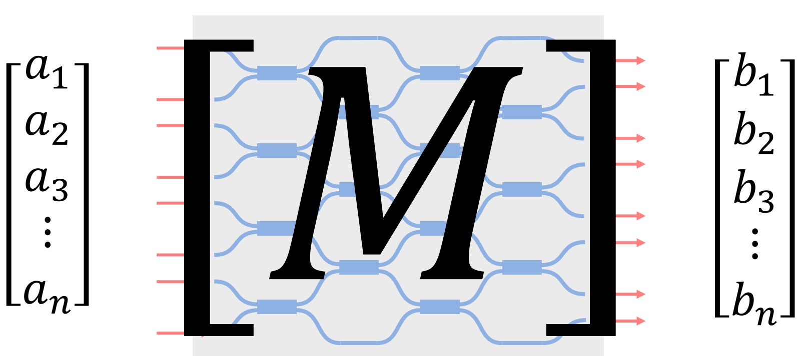
‘layered’ meshes: generalized interferometers



Applications of Forward-Only Meshes

Linear circuit performs real-time matrix-vector product (MAC operation)

$$\boldsymbol{b} = \boldsymbol{M} \cdot \boldsymbol{a}$$



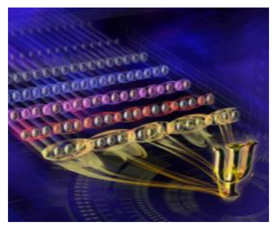
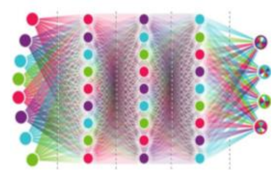
Applications of Forward-Only Meshes

Linear circuit performs real-time matrix-vector product (MAC operation)

Basic operation in

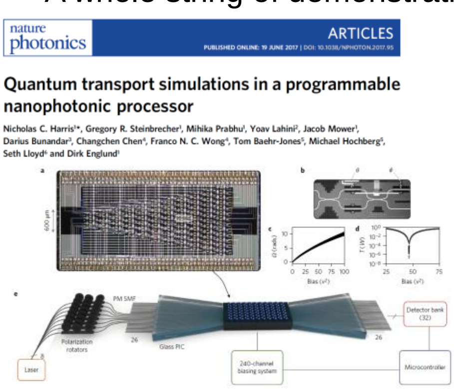
- Pattern Recognition
- Linear Quantum Optics
- Artificial Neural Networks

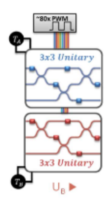
$$\boldsymbol{b} = \boldsymbol{M} \cdot \boldsymbol{a}$$

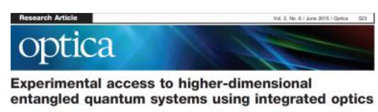




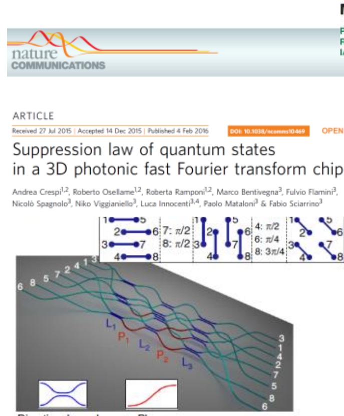
Quantum Photonics Circuits

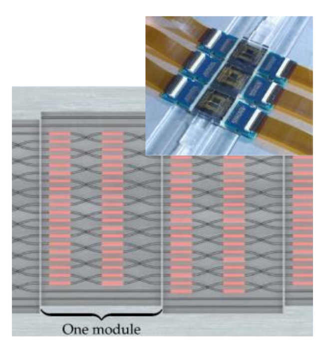
A whole string of demonstrations





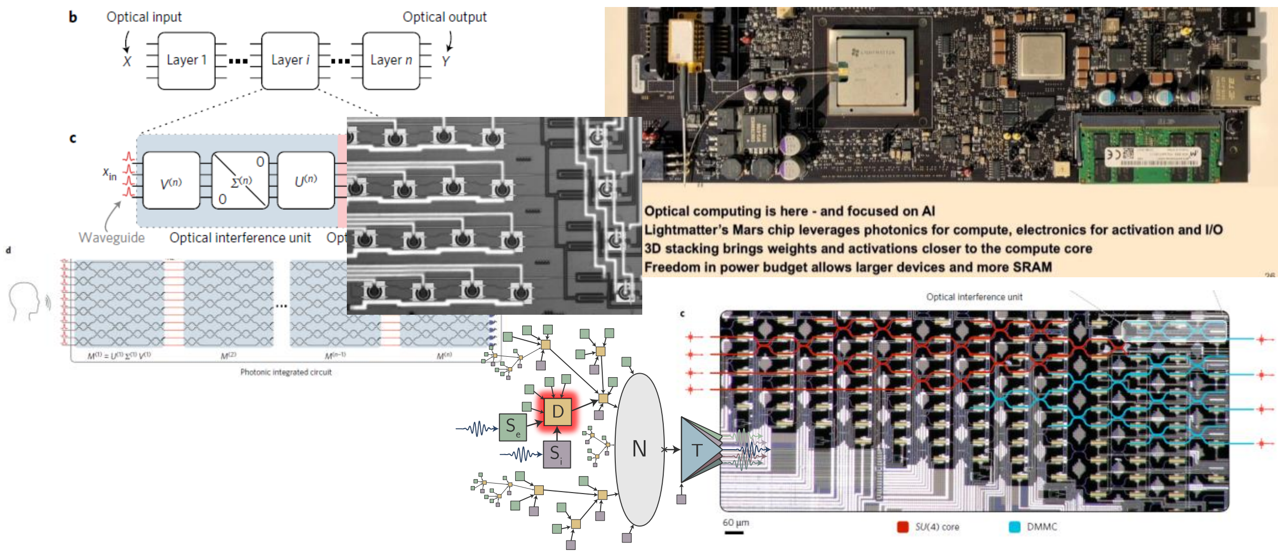






Photonic Accelerators for AI

Neural networks need fast multiplications of large matrices

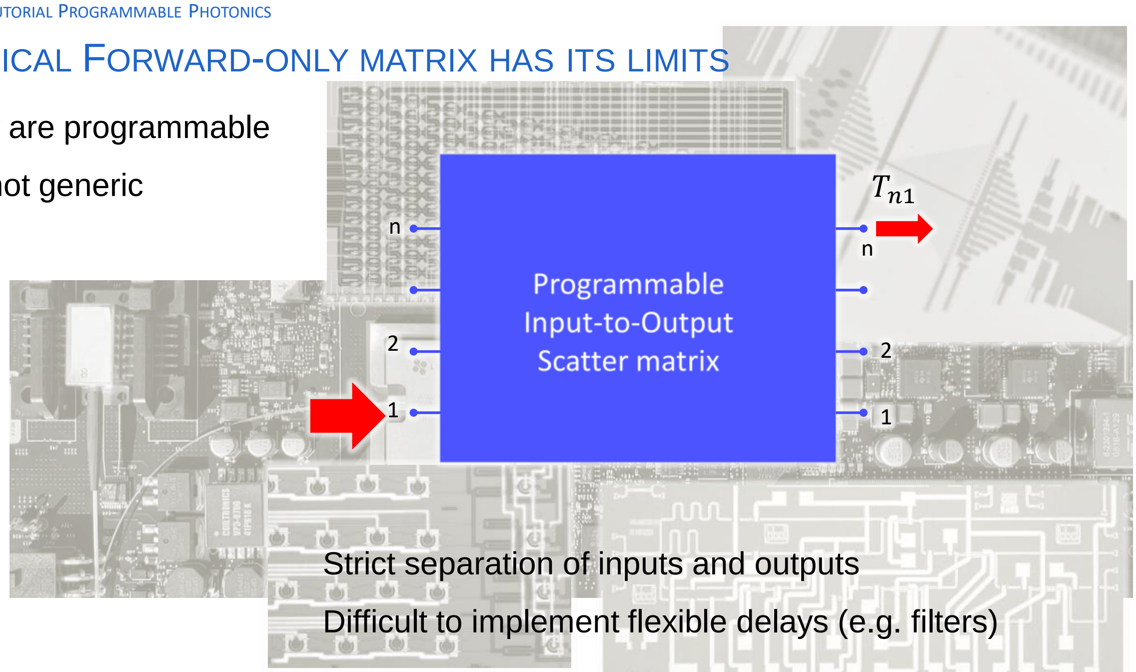


78

Optical Forward-Only Matrix Has Its Limits

They are programmable

But not generic



Strict separation of inputs and outputs

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

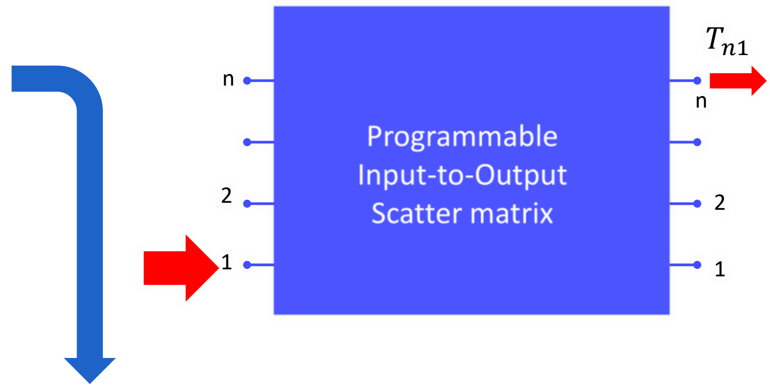
80

80

Optical Forward-only matrix has its limits

What is missing?

- Programmable delays
- Optical feedback
- Wavelength filtering
- Dispersion engineering

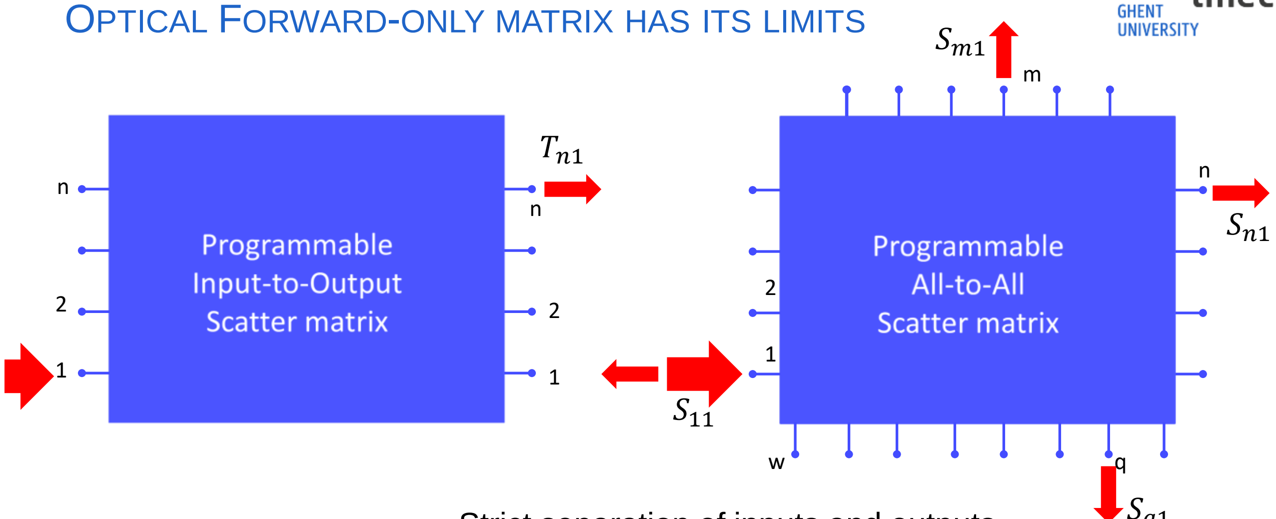


Processing of time signals

Integration / differentiation

Programmable analog signal processing

Optical Forward-only matrix has its limits



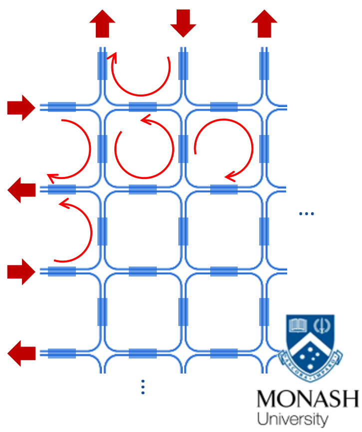
Strict separation of inputs and outputs

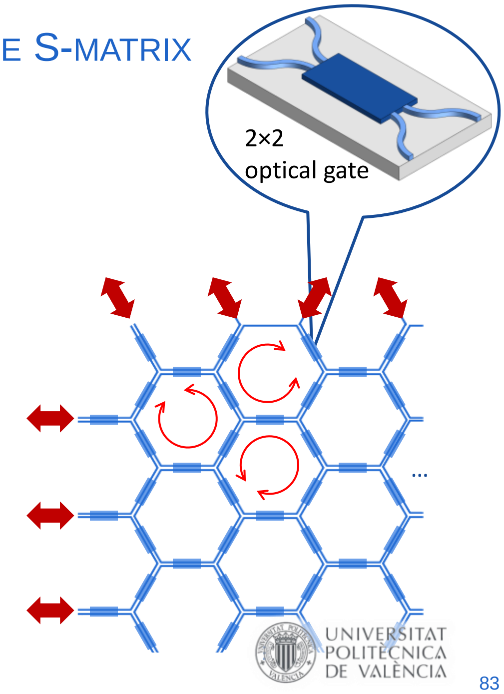
Difficult to implement flexible delays (e.g. filters)

Recirculating Meshes: Programmable S-matrix

Adding feedback (loops)

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





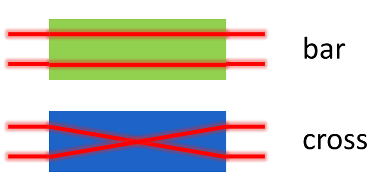
(Re)Routing Light

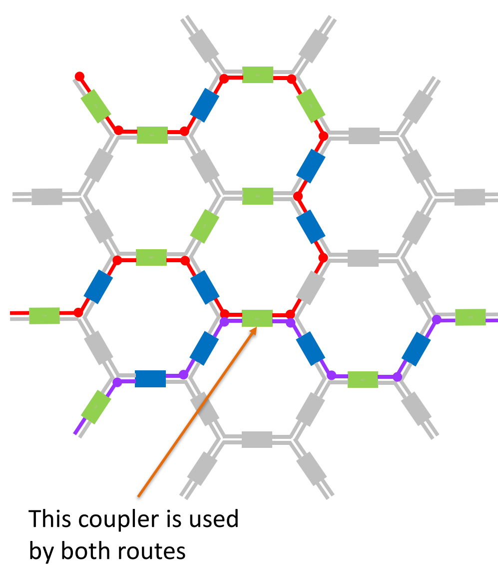
GHENT UNIVERSITY imec

Light can be arbitrarily routed

Multiple routes in the same mesh

Edges can be shared



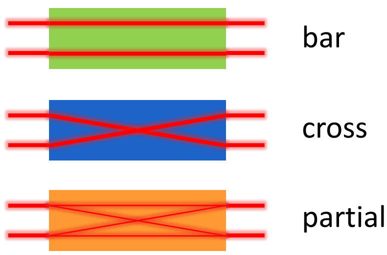


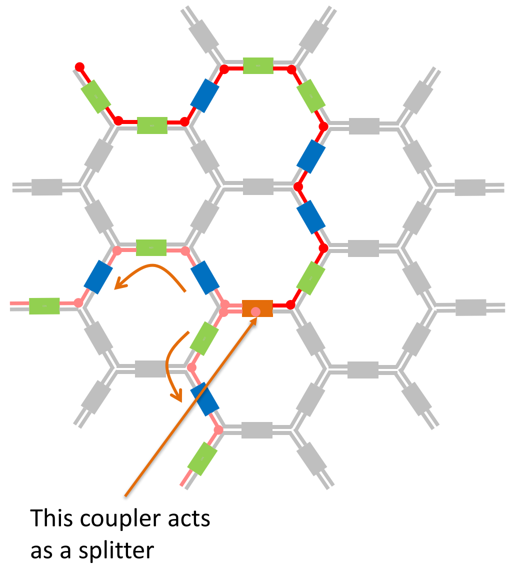
Splitting light

Couplers control arbitrary splitting ratios

Power distribution networks

Multicasting

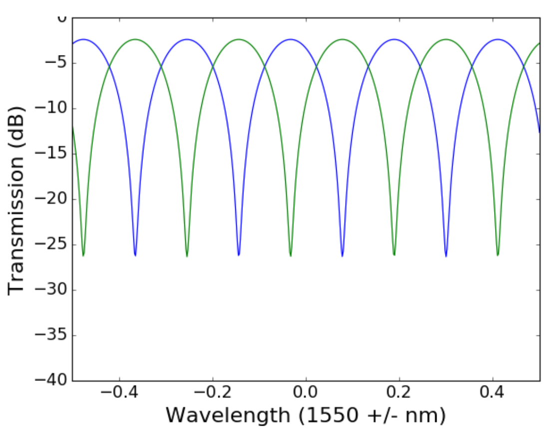


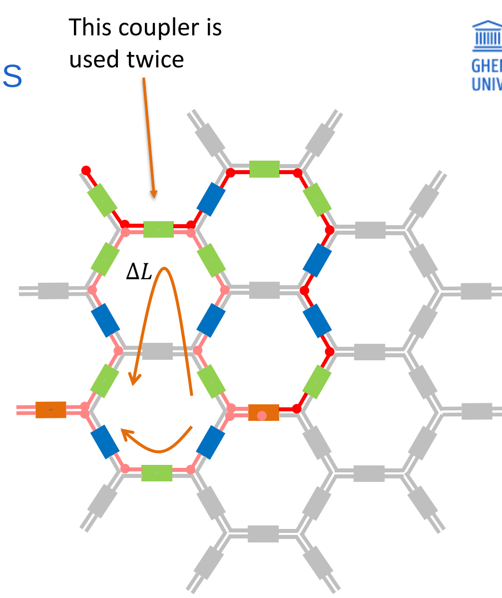


Mach-Zehnder interferometers

Basic building block for FIR filters

Delay can be adjusted per unit lengths

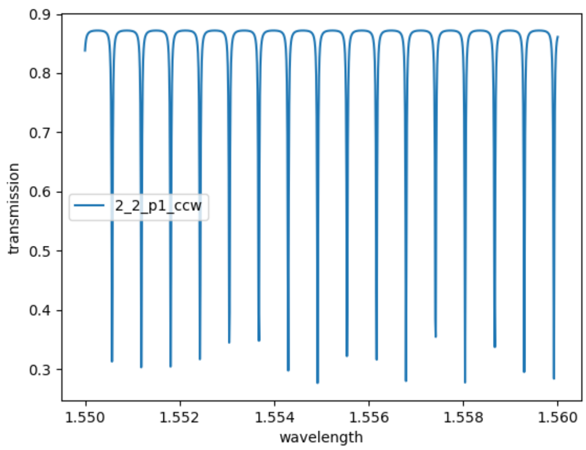


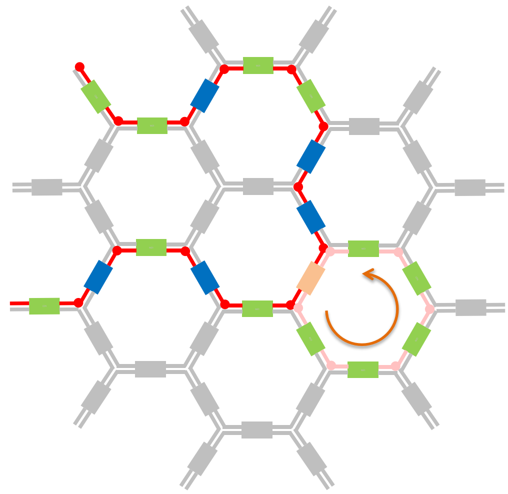


Ring resonators

Loop light in itself

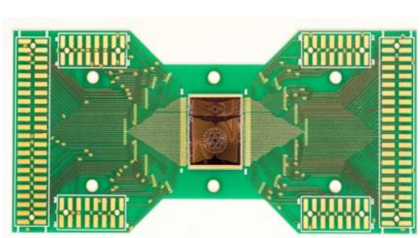
Coupler ring resonators together

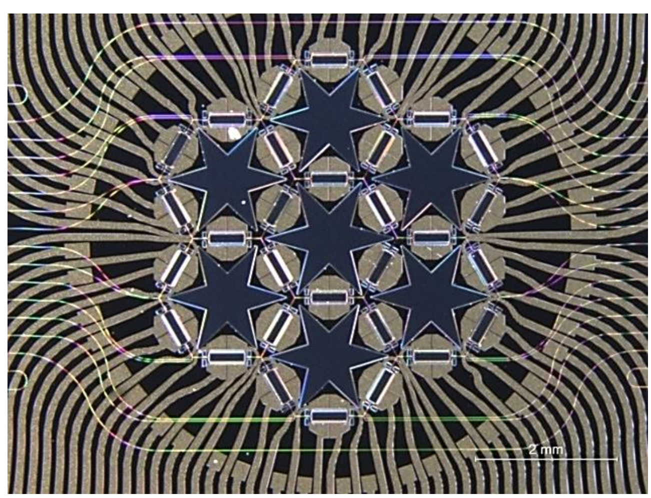




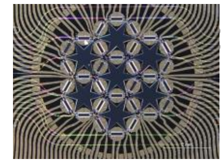
Hexagonal mesh circuit demonstration

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



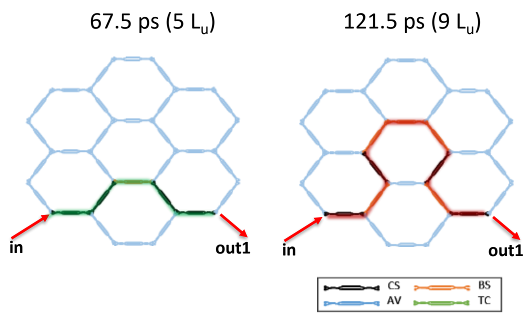


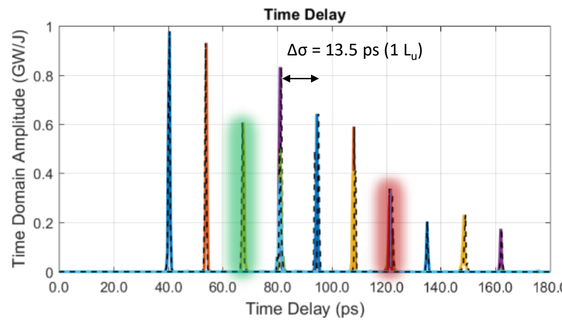
Perez et al, Nature Comm. 2017



Experimental Discrete Delay Lines

Programmable delay lines with discrete steps

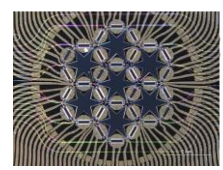




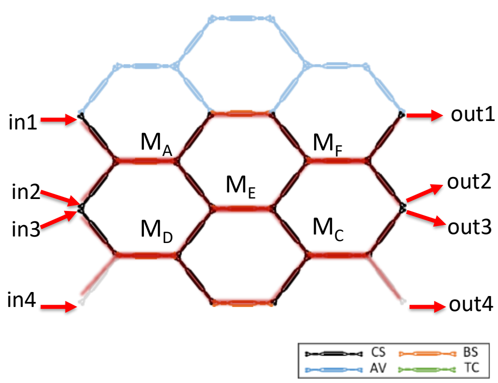
Basic Time Delay: $\sigma=(n_g L_u)/c = 13.5$ ps

Perez et al, JLT 2018

UNIVERSITAT POLITÈCNICA DE VALÈNCIA 95

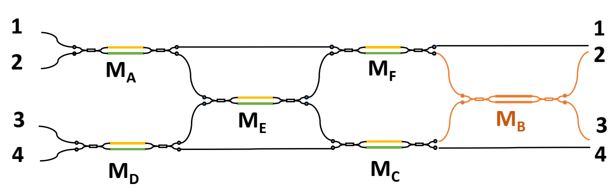


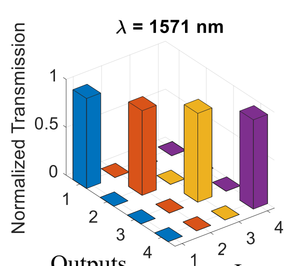
Forward-only interferometers

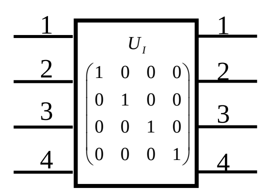


4x4 CNOT transformer

Linear optics M×M Unitary matrix transformers



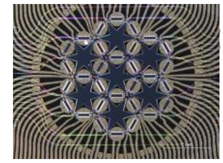




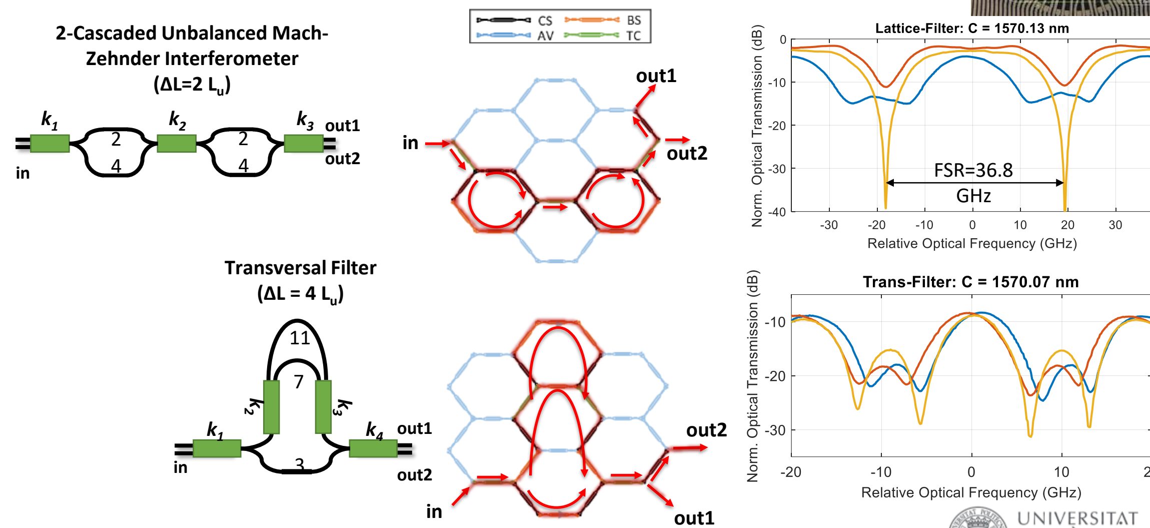
Perez et al, LPR 2017

UNIVERSITAT POLITÈCNICA DE VALÈNCIA 96

Experimental Filters: Finite impulse response (FIR)

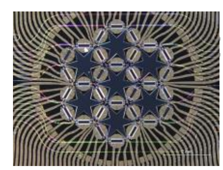


Multi-MZI interferometers

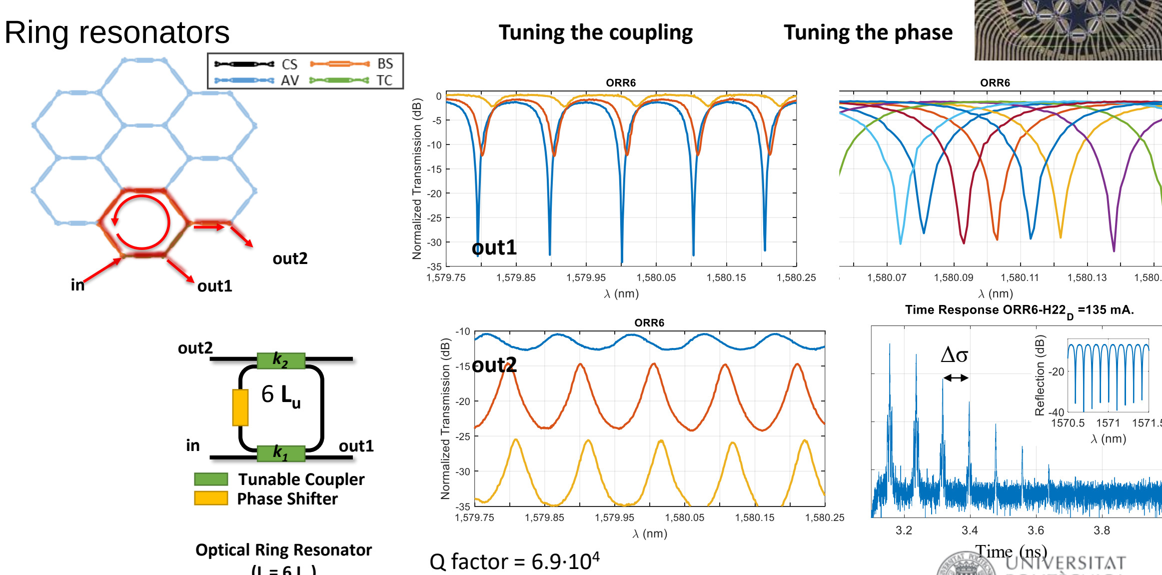


Perez et al, Nature Comm. 2017

Experimental Filters: Infinite impulse response (IIR)



Ring resonators



Q factor = $6.9 \cdot 10^4$
Finesse = 4.3

Perez et al, Nature Comm. 2017

Filters in a Hexagonal Mesh

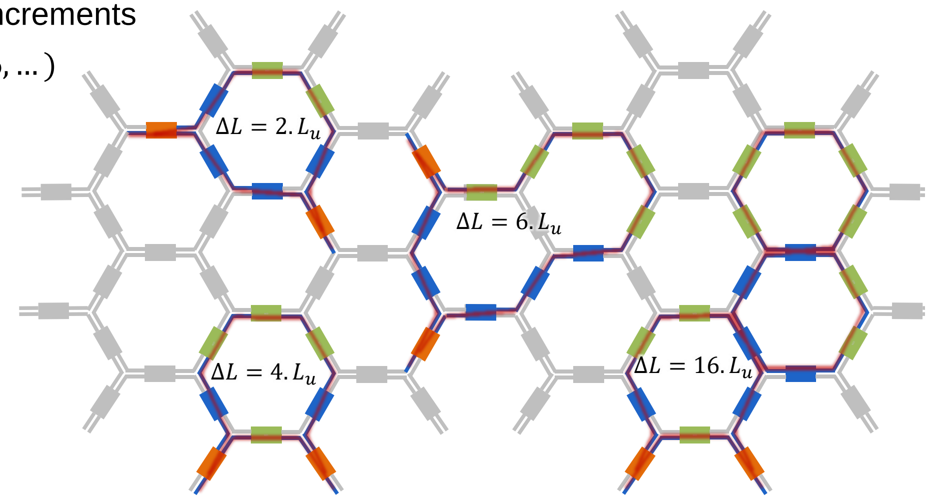
Mach-Zehnder filters:

only discrete delay increments

$\Delta L = n.L_u \;\; (n = 2,4,6,\ldots)$

→ limits the FSR

$$FSR = \frac{\lambda_0^2}{n_g.\Delta L}$$



Filters in a Hexagonal Mesh

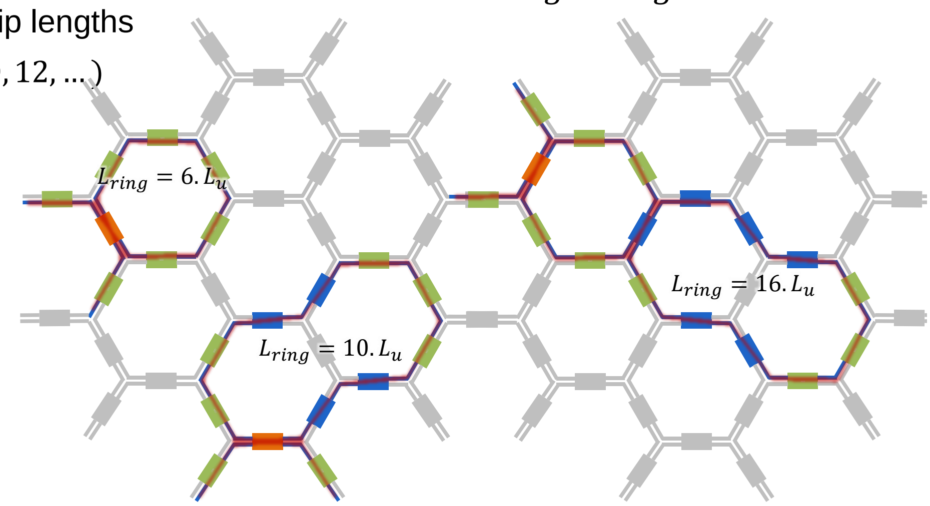
Ring Filters:

only discrete roundtrip lengths

$\Delta L = n.L_u \;\; (n = 6, 10, 12, \ldots)$

→ limits the FSR

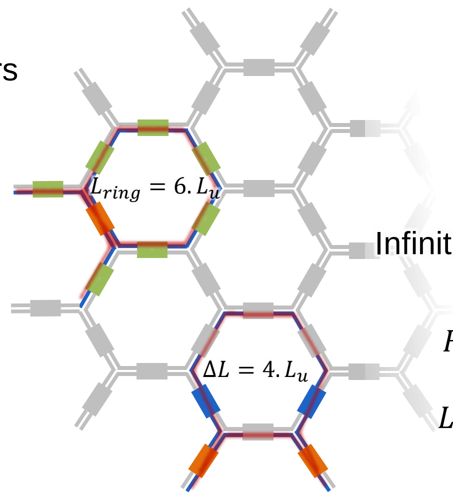
$$FSR = \frac{\lambda_0^2}{n_g.L_{ring}}$$



Filters with Large Free Spectral Range

Large FSR requires short edge L_u

- Sharp bends
- Short phase shifters
- Compact splitters
- Dense packing



Finite impulse response:

$$FSR = \frac{\lambda_0^2}{n_g.\Delta L}$$

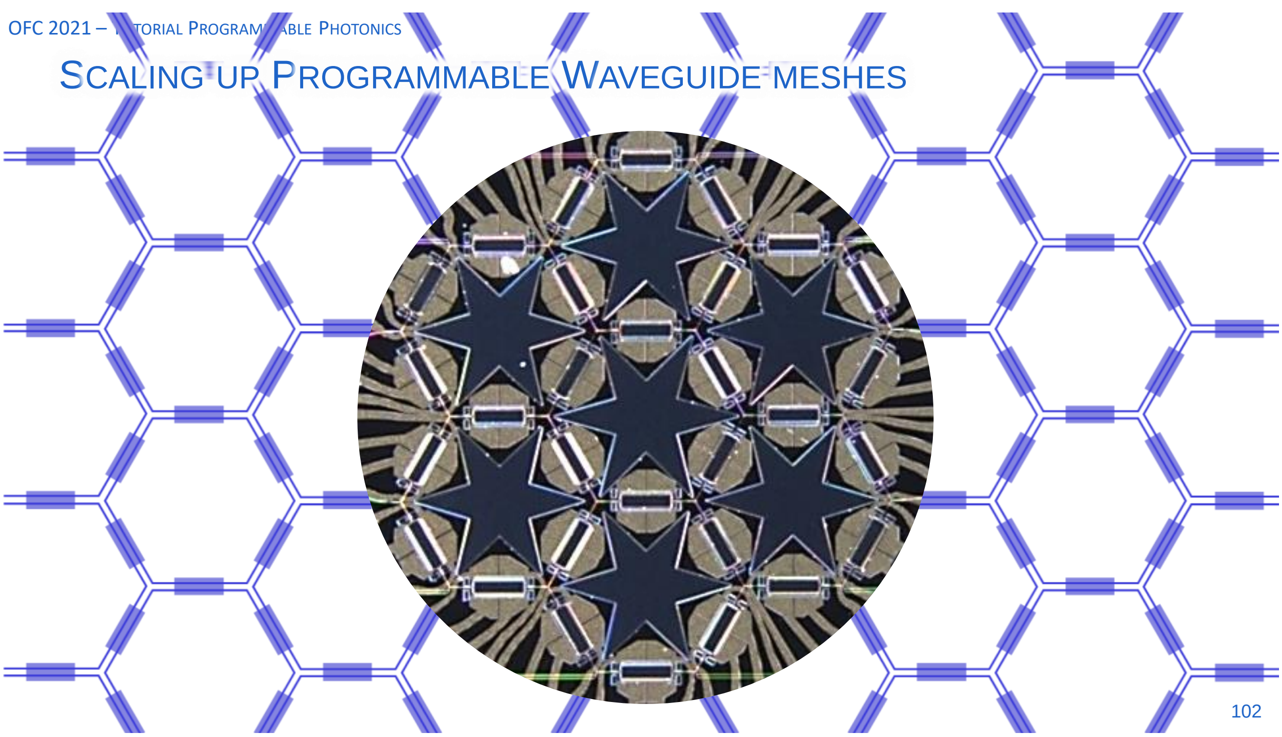
$$\Delta L = n.L_u \ \ (n = 2,4,6,\ldots)$$

Infinite impulse response

$$FSR = \frac{\lambda_0^2}{n_g.L_{ring}}$$

$$L_{ring} = n.L_u \ \ (n = 6, 10, 12, \ldots)$$

Scaling up Programmable Waveguide meshes



SCALING UP PROGRAMMABLE WAVEGUIDE MESHES

Scaling up?

We need good 2 × 2 gates

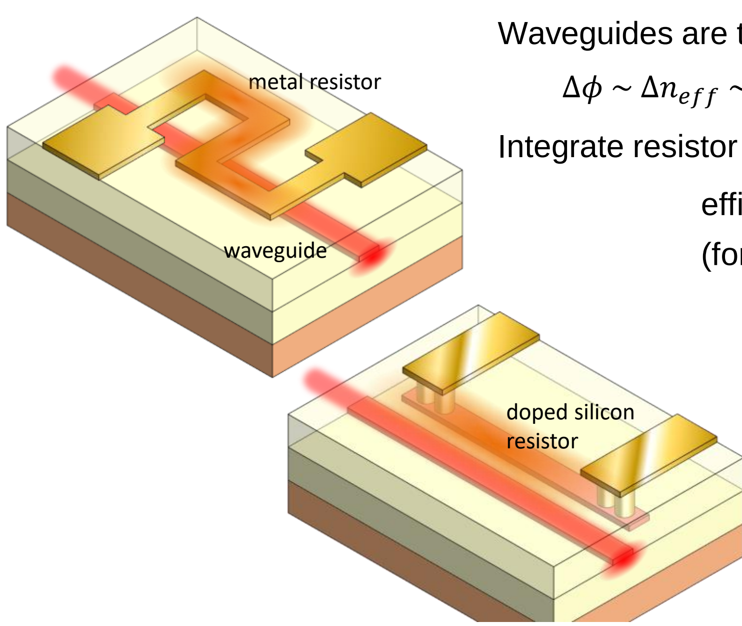
- **Compact**
- **Short optical length**
- **Low optical loss**
- **Low electrical power**

Scaling up?

We need many 2 × 2 gates

- **Optical and electrical interfaces**
- **Electrical driving circuits**
- **On-chip Monitoring**
- **Control for the building blocks**

THE BASIC OPTICAL PHASE SHIFTER: A HEATER



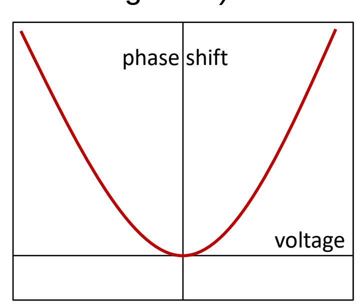
Waveguides are thermally sensitive:

$$\Delta\phi \sim \Delta n_{eff} \sim T \sim P_{elec} \sim V^2 \sim I^2$$

Integrate resistor close to the waveguide

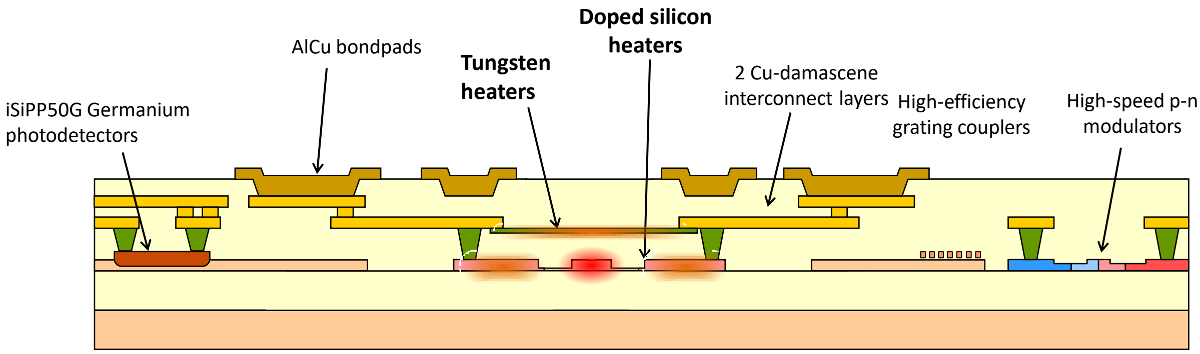
efficiency: $P_\pi \approx 5 - 30mW$

(for silicon waveguides)



OFC 2021 – Tutorial Programmable Photonics

Heaters in the IMEC's iSiPP50G Platform



Doped Silicon Heaters

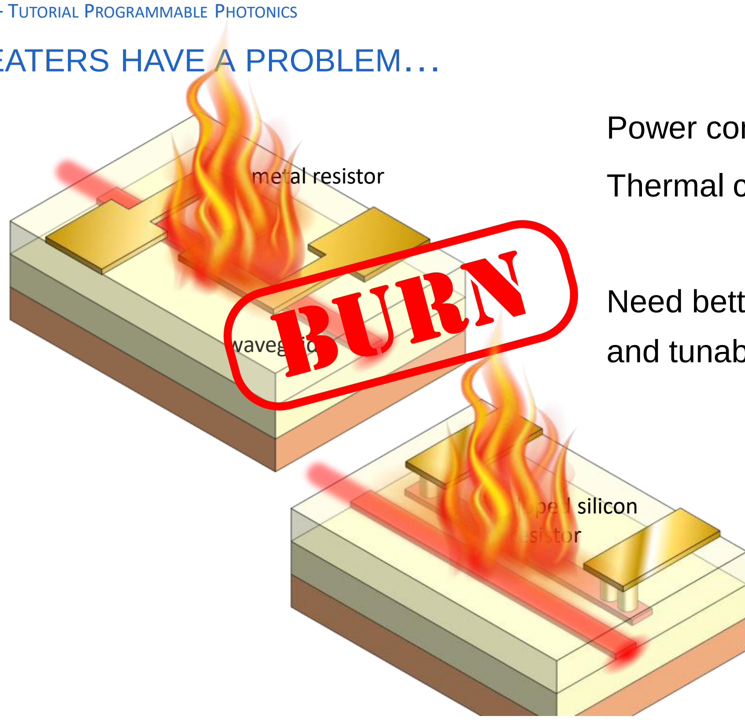
Tungsten overhead heaters

Pantouvaki, JLT 2017

105

OFC 2021 – Tutorial Programmable Photonics

Heaters have a problem…



Power consumption

Thermal crosstalk

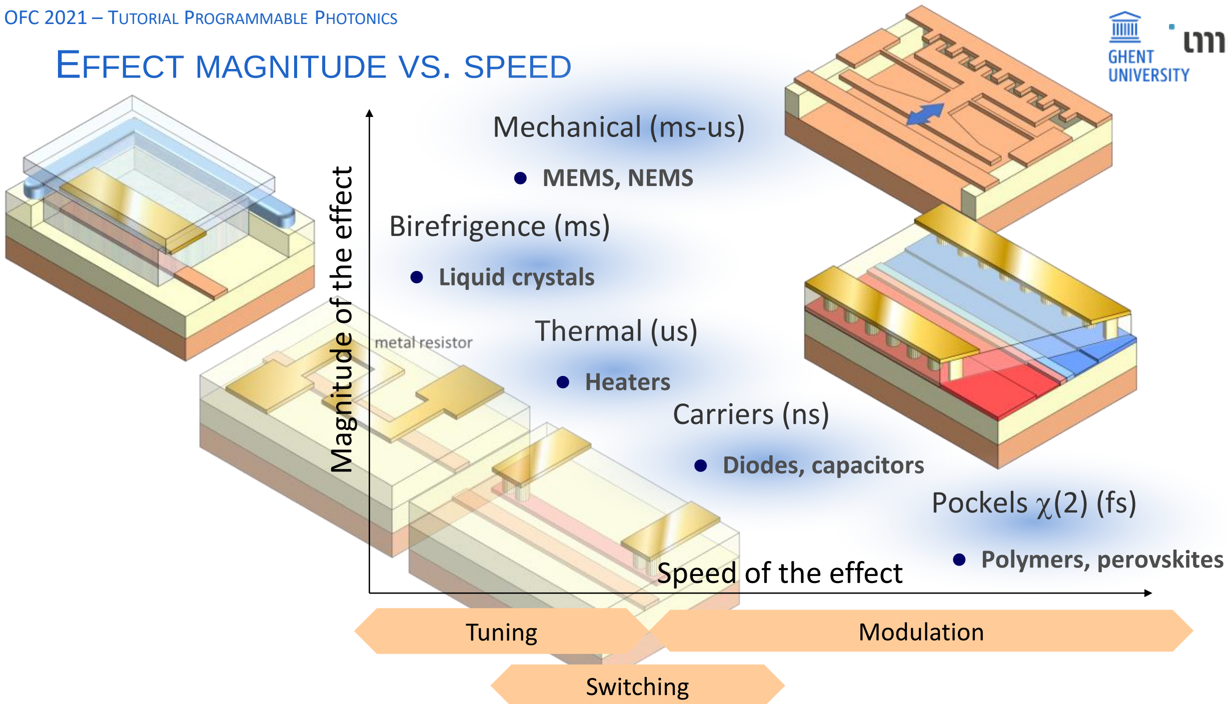
Need better phase shifters

and tunable couplers

106

OFC 2021 – Tutorial Programmable Photonics

Effect magnitude vs. speed



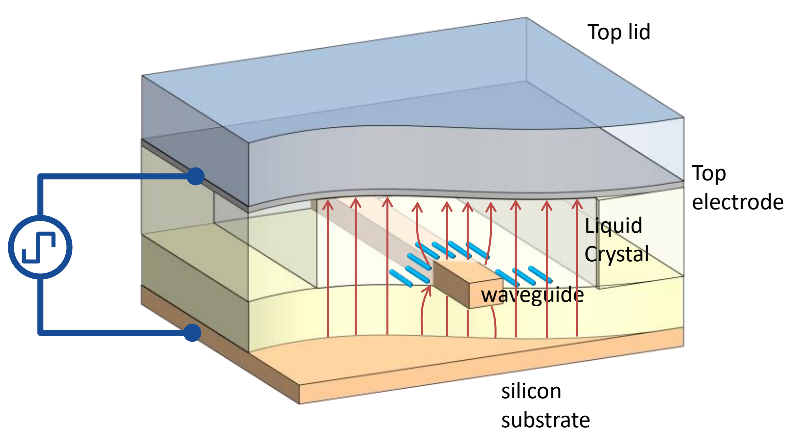
107

107

OFC 2021 – Tutorial Programmable Photonics

Liquid Crystal Actuation with Top Electrode

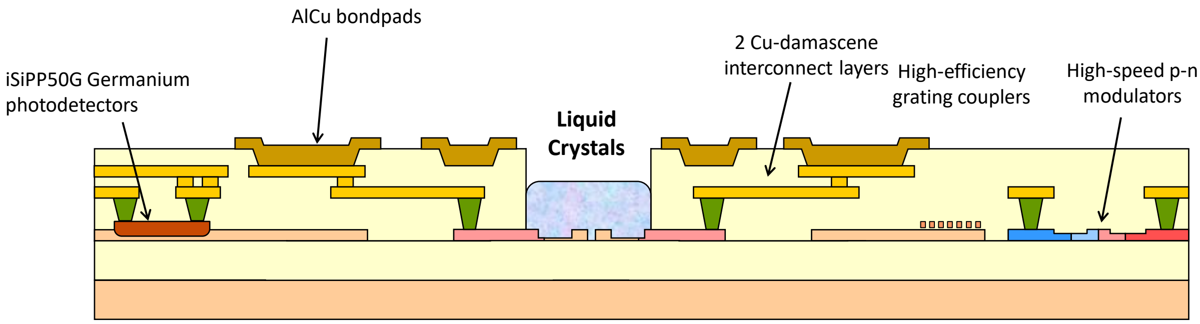
Vertical actuation of a liquid crystal cladding



108

108

Liquid Crystals in IMEC's iSiPP50G process



Open metal/dielectric stack

Expose waveguides

Infiltrate liquid crystals

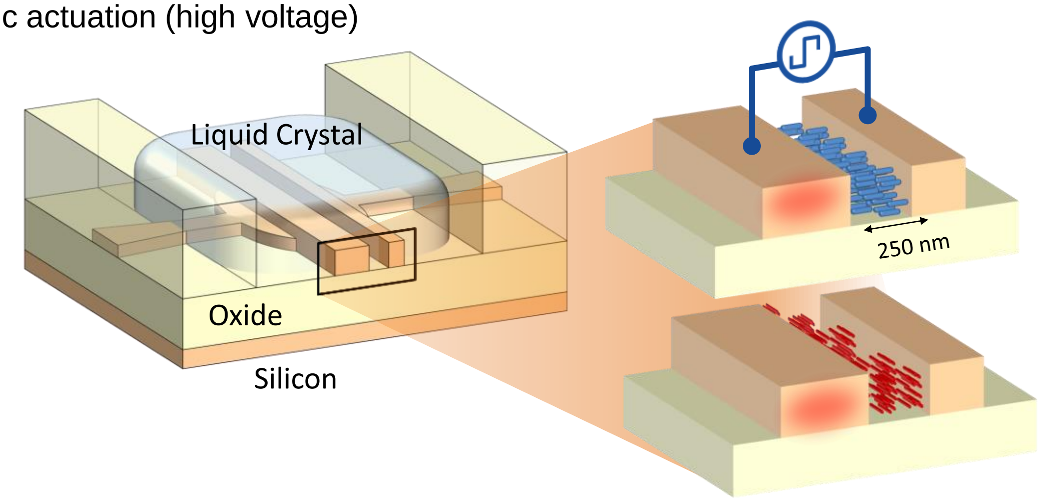
Van Iseghem, ECIO 2020 109

109

Liquid Crystal Tuning

Reorienting molecules

Electrostatic actuation (high voltage)

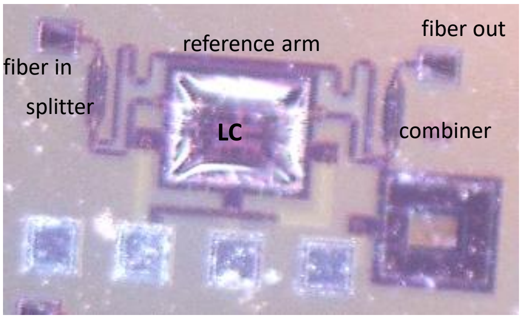


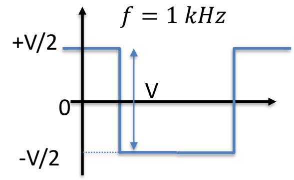
Van Iseghem, ECIO 2020 110

110

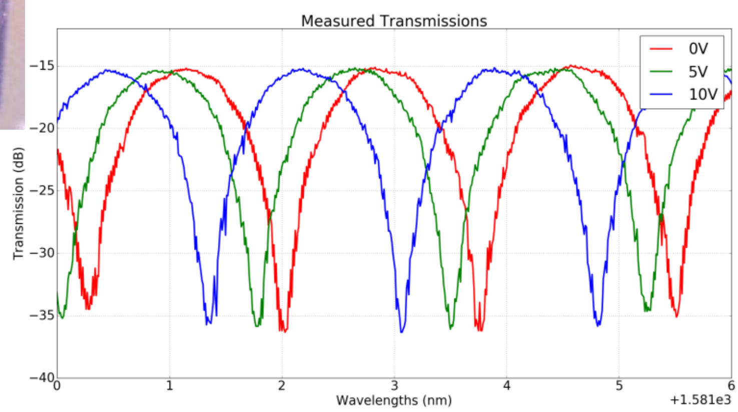
OFC 2021 – Tutorial Programmable Photonics

Liquid Crystal Tuner





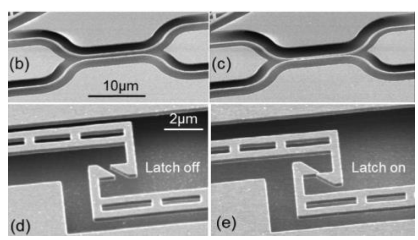
0.8π for 50µm

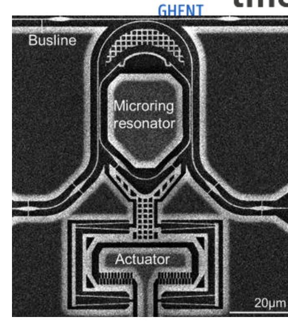


111

OFC 2021 – Tutorial Programmable Photonics

MEMS in Photonics

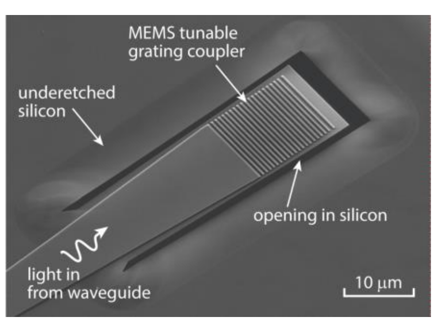


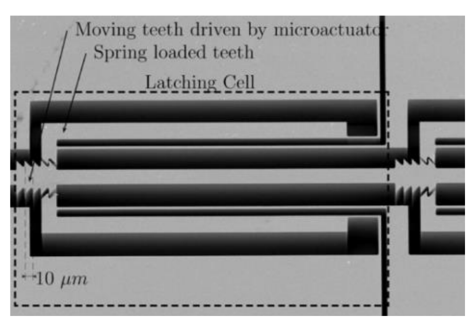


Mechanical effect: very strong

Electrostatic actuation: low-power

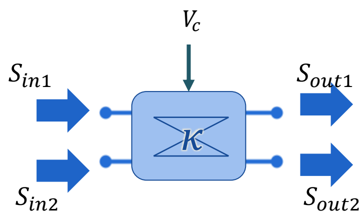
Mechanical latching: non-volatile operation



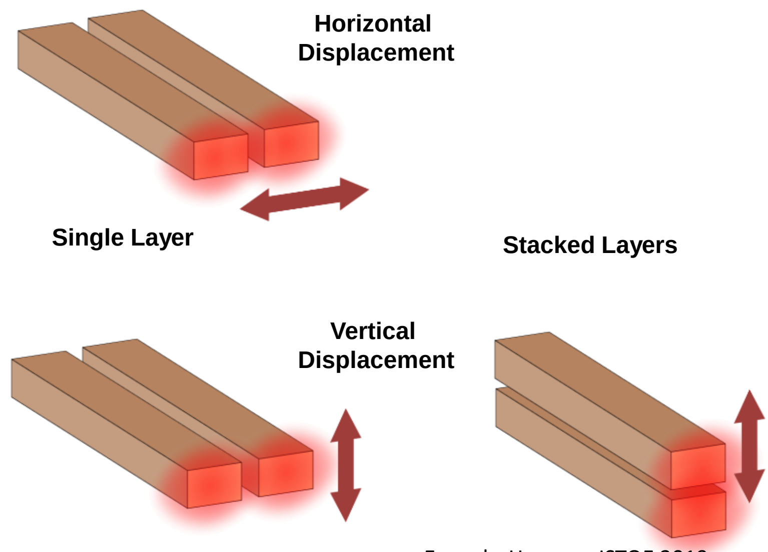


112

Mechanical Tunable Waveguide Couplers

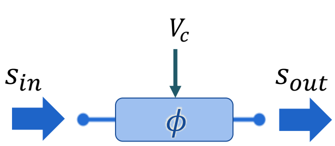


$$S_{out1} = S_{in1}(1-\kappa) + S_{in2}\kappa$$
$$S_{out2} = S_{in1}\kappa + S_{in2}(1-\kappa)$$

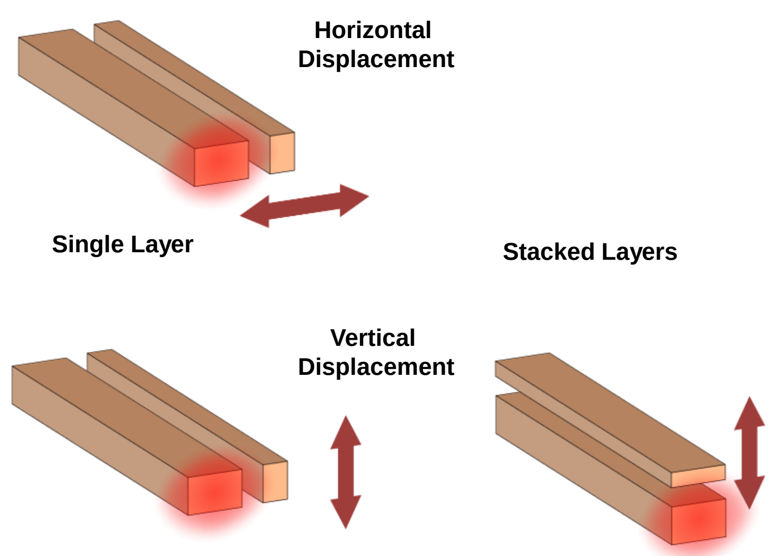


Errando-Herranz, JSTQE 2019

Mechanical Optical Phase Shifters



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

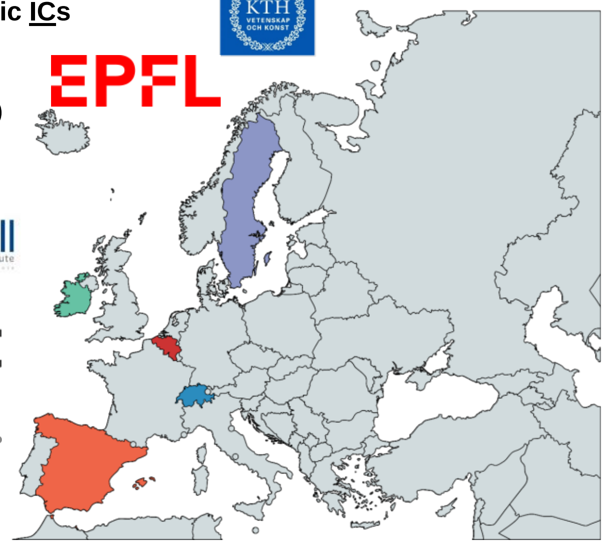


Errando-Herranz, JSTQE 2019

MORPHIC

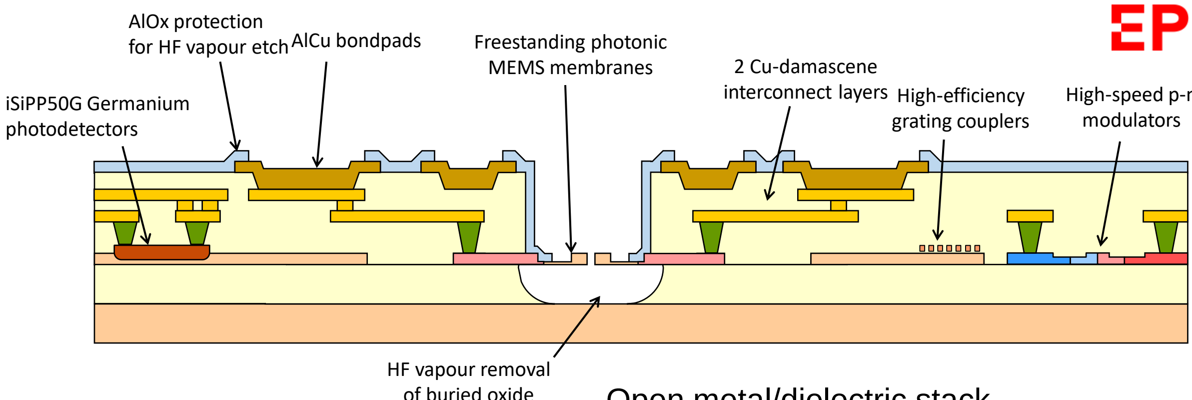
Mems-based zerO-power Reconfigurable PHotonic ICs

- Extend Silicon Photonics with MEMS
- Non-volatile actuations (zero-power consumption)
- Programmable circuit topologies and control
- Demonstrate different applications



Duration: 01/2018 – 12/2021

MEMS integrated with iSiPP50G

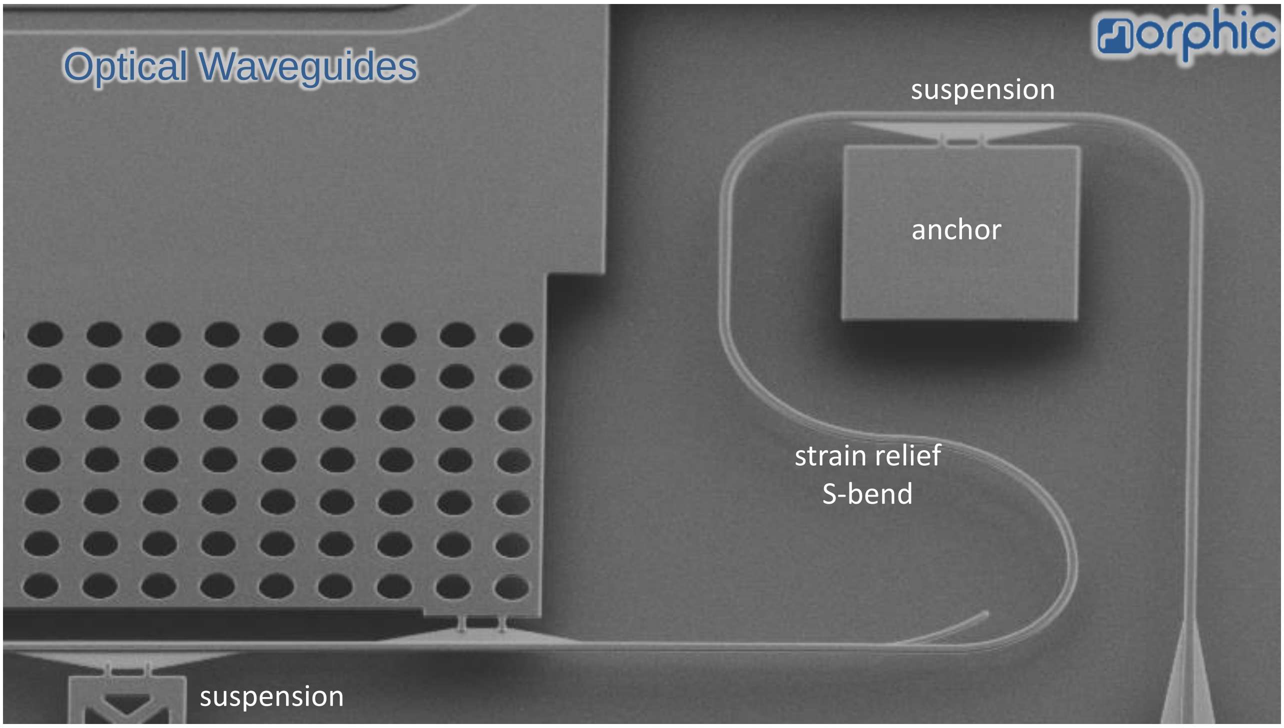


Open metal/dielectric stack

Expose waveguides

AlOx protection layer

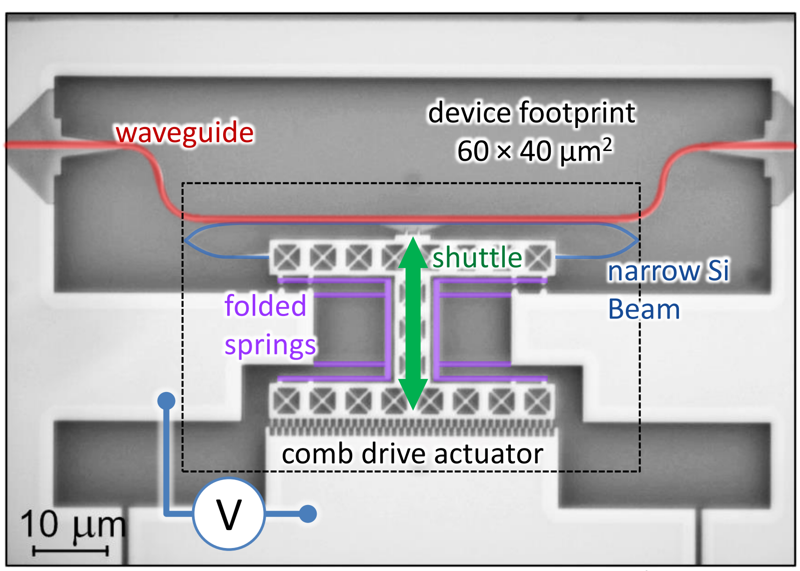
Vapout HF underetching



119

OFC 2021 – TUTORIAL PROGRAMMABLE PHOTONICS

MEMS PHASE SHIFTER

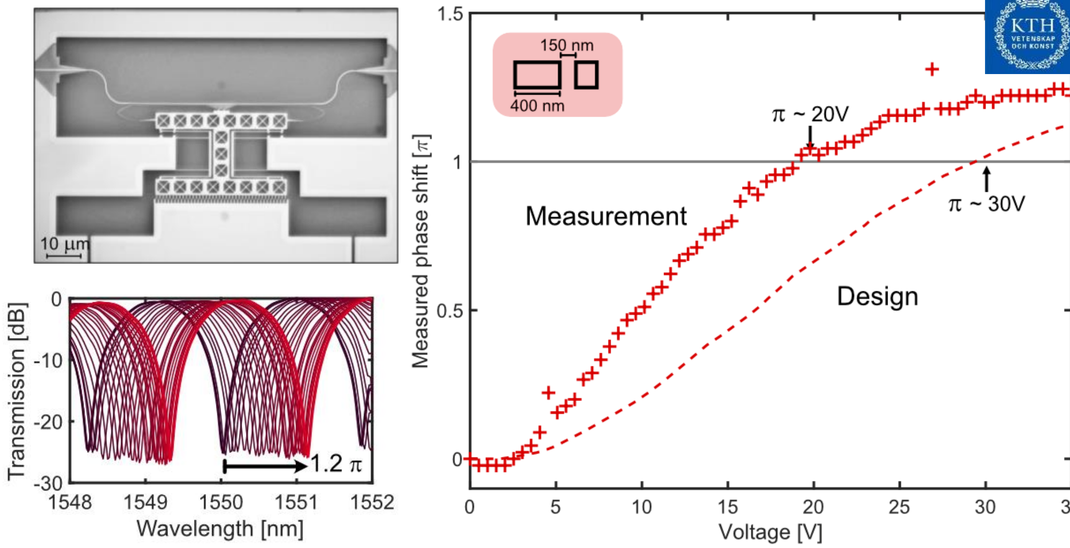


Edinger, CLEO 2021 120

120

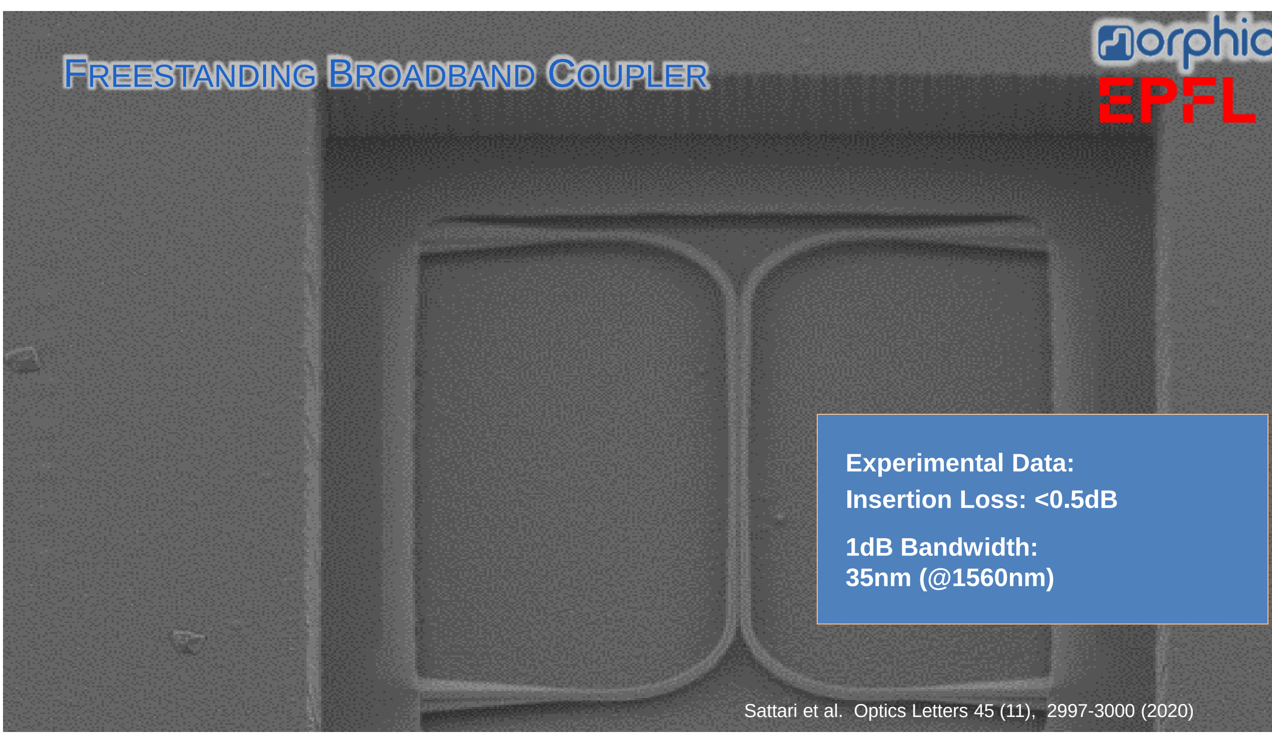
OFC 2021 – Tutorial Programmable Photonics

MEMS phase shifter



Edinger, CLEO 2021 121

121



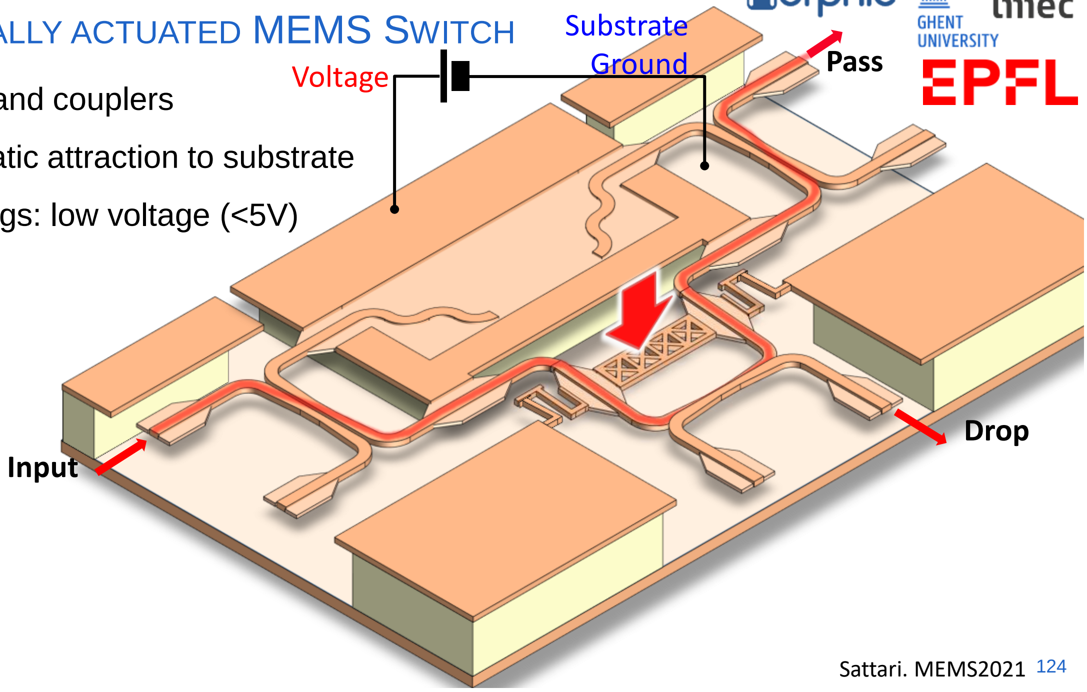
122

Vertically actuated MEMS Switch

3 broadband couplers

Electrostatic attraction to substrate

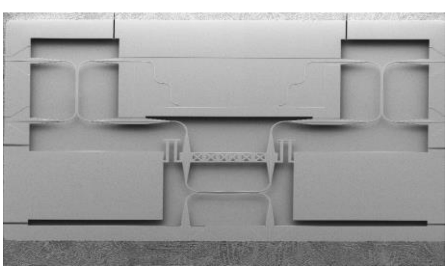
Soft springs: low voltage (<5V)



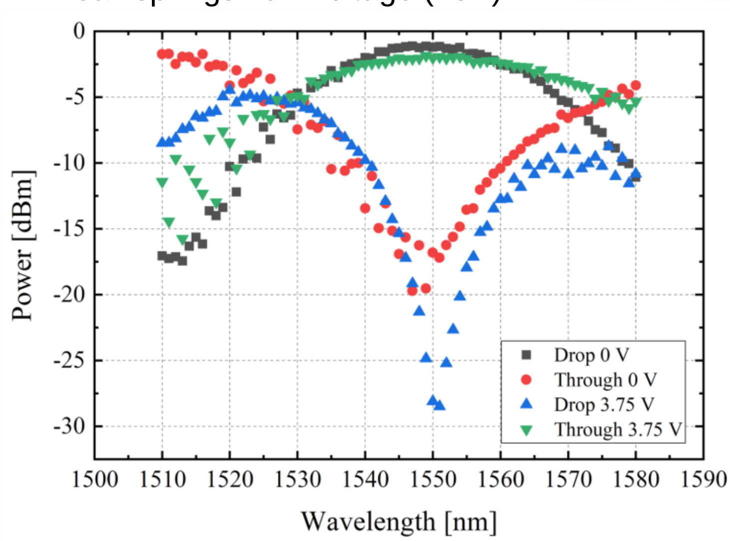
Sattari. MEMS2021 124

124

Vertically actuated MEMS Switch



Weak springs: low voltage (<5V)

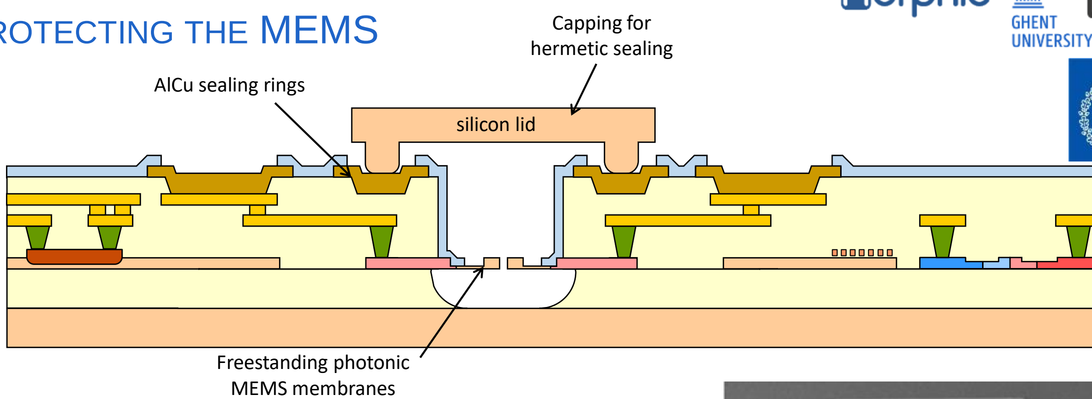


Sattari. MEMS2021 126

126

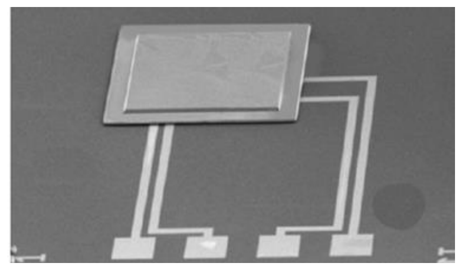
OFC 2021 – Tutorial Programmable Photonics

Protecting the MEMS



Need for hermetic sealing

Wafer-level silicon capping



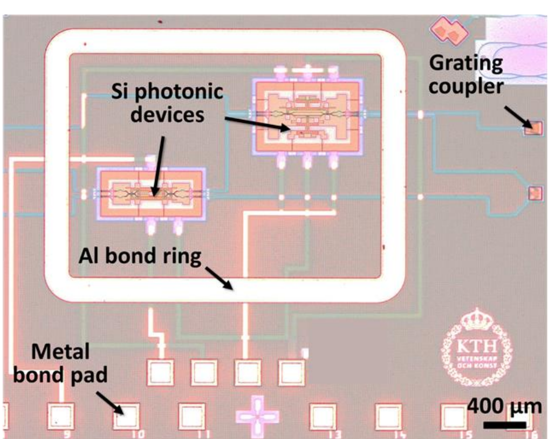
G. Jo, SPIE Phot. West. 2021

127

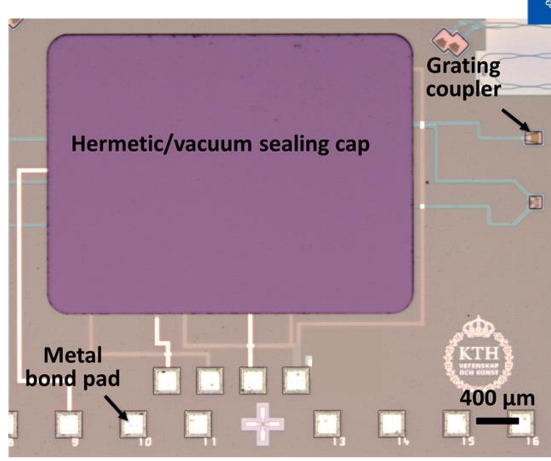
127

OFC 2021 – Tutorial Programmable Photonics

Vacuum Packaging of iSiPP50G Foundry Wafer



Before packaging



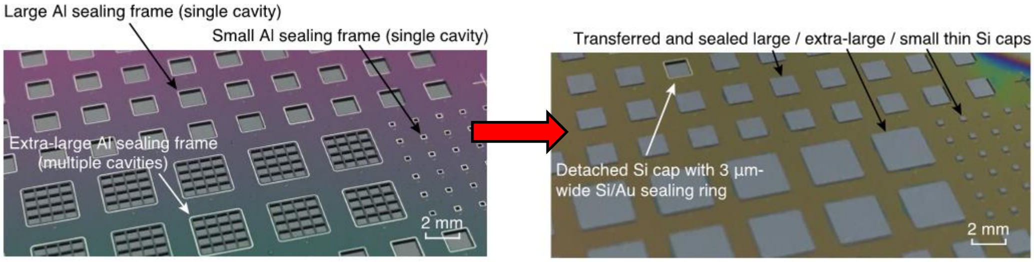
After packaging

G. Jo, SPIE Phot. West. 2021

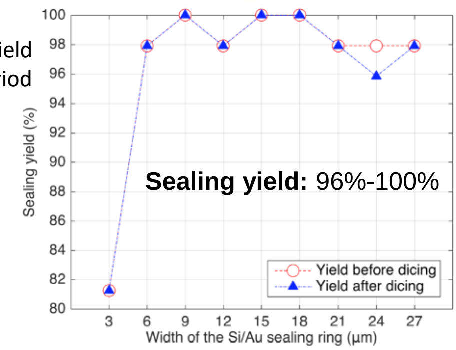
128

128

MEMS hermetic sealing



wafer-scale sealing yield after two month period



X. Wang, J. MEMS 2019

Scaling up Programmable Waveguide meshes

Scaling up?

We need good 2 × 2 gates

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

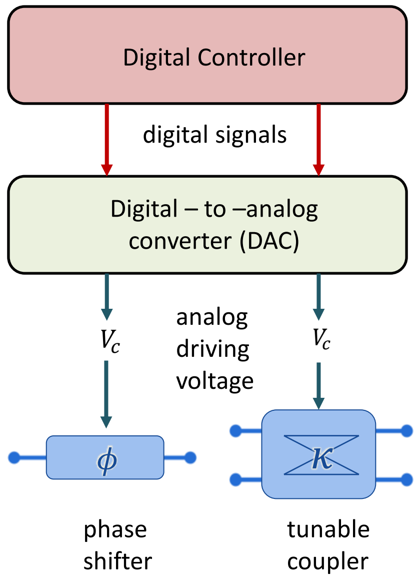
Scaling up?

We need many 2 × 2 gates

- **Optical and electrical interfaces**
- **Electrical driving circuits**
- **On-chip Monitoring**
- **Control for the building blocks**

Electronic Drivers

Analog controls needed for photonic actuators



Important questions

- Supply voltage
- Driving schemes
- Time constants
- Power consumption
- Heat generation
- connections between photonics and electronics

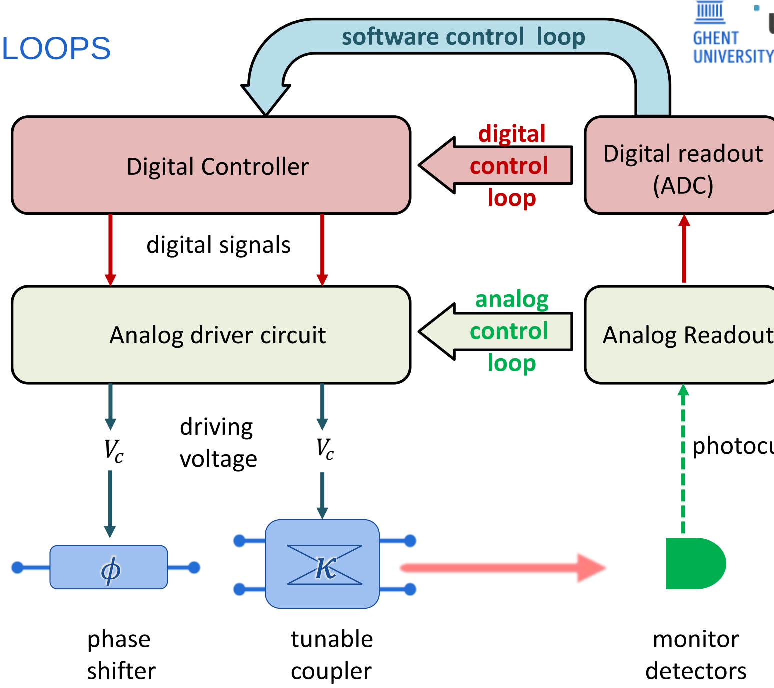
Scaling!

Feedback Control Loops

Monitoring optical signals

- amplitude
- phase
- direction

feedback to the actuators

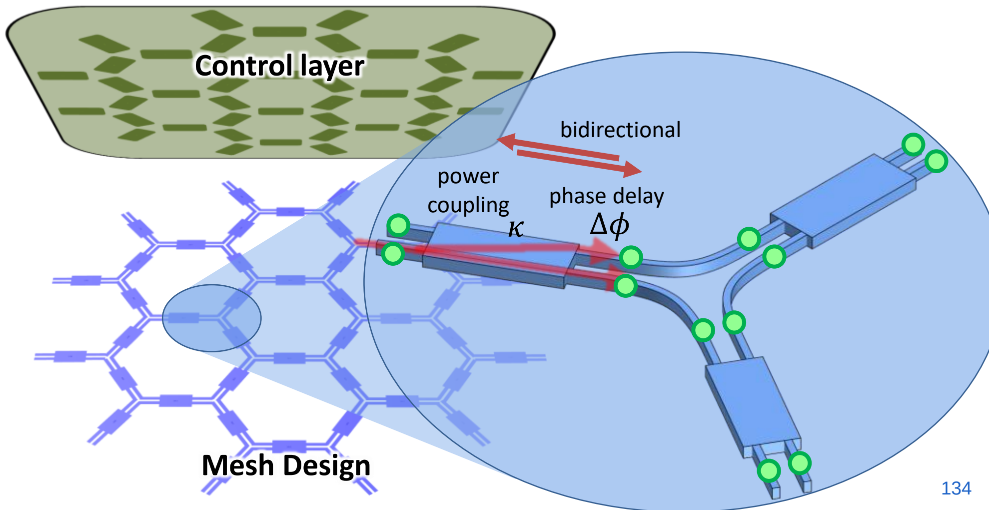


Control in a Recirculating Mesh

More complicated

- bidirectional flow of light
- resonances

Where to insert 'transparent' monitors?

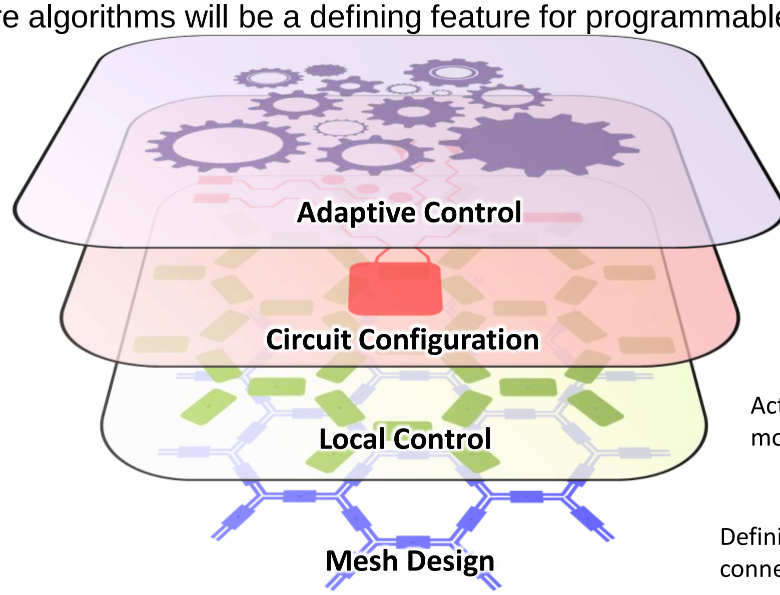


134

134

Software and Control Layers

Software algorithms will be a defining feature for programmable photonics



Error detection, redundancy
self-optimization, healing
drift/aging compensation

Defining logical connectivity
Routing, distribution
Filter synthesis

Actuation curves, calibration
monitor readout, local feedback

Defining the hardware
connectivity and topology

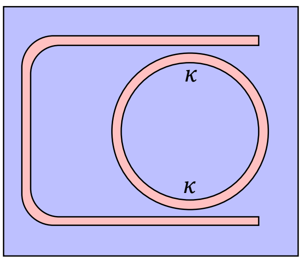
135

135

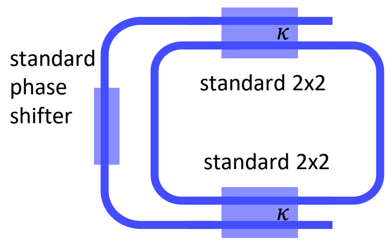
A New way of Designing Functionality

Full Custom design

geometry design

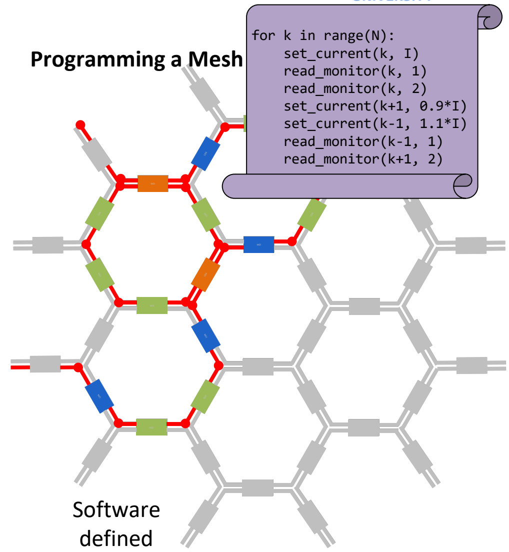


PDK-based Circuit Design



Custom circuit design with standard tunable couplers and phase shifters

Programming a Mesh



Software defined functionality

136

136

New types of IP

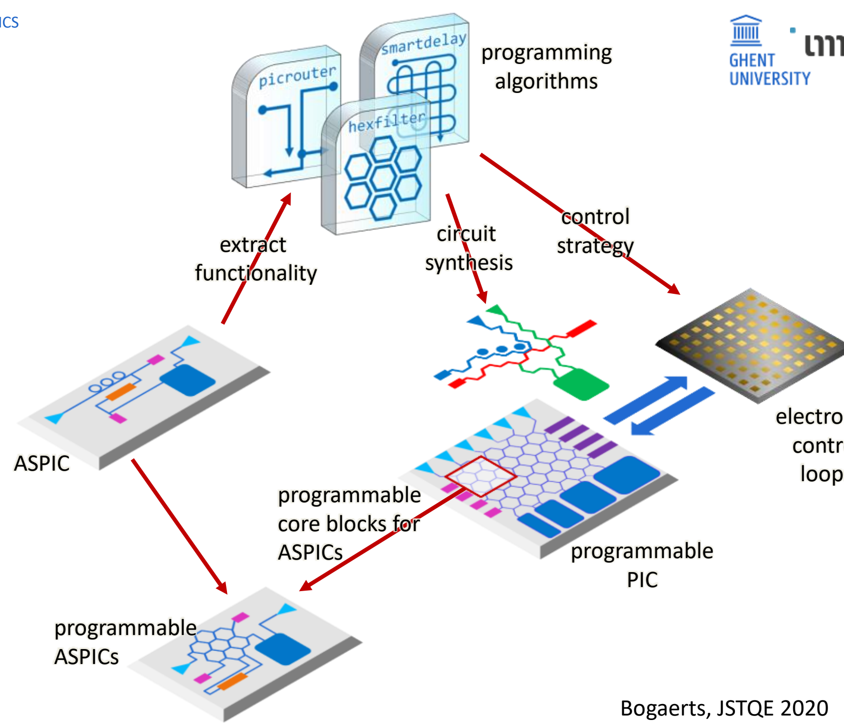
Programming routines

Circuit synthesis

Control strategies

Pluggable design IP

- linear cores
- electronic controls

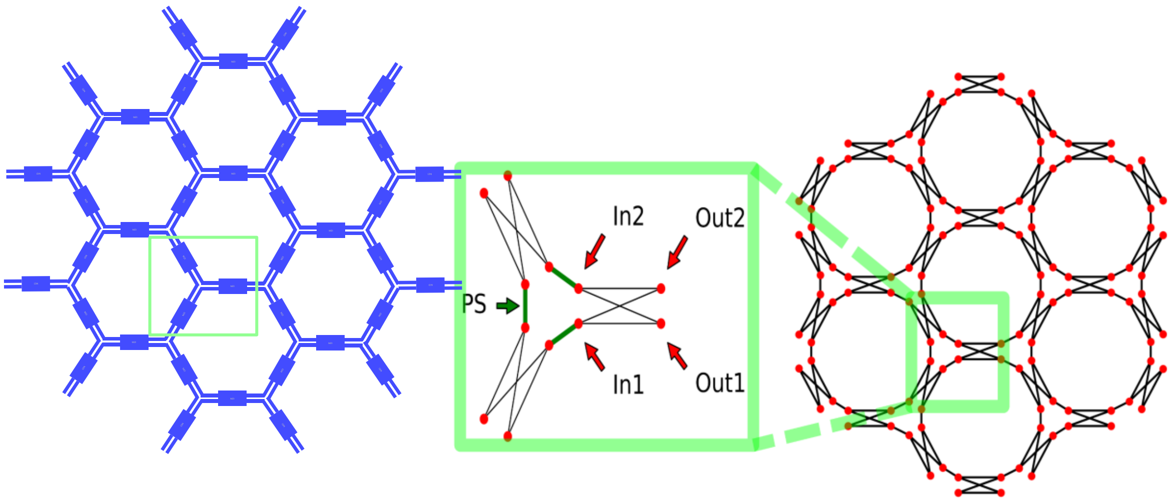


Bogaerts, JSTQE 2020 137

137

Graph Algorithms to Route in Programmable Meshes

Translate circuit into "photonic graph"



Chen et al, JLT 2020 138

138

Graph Mapping

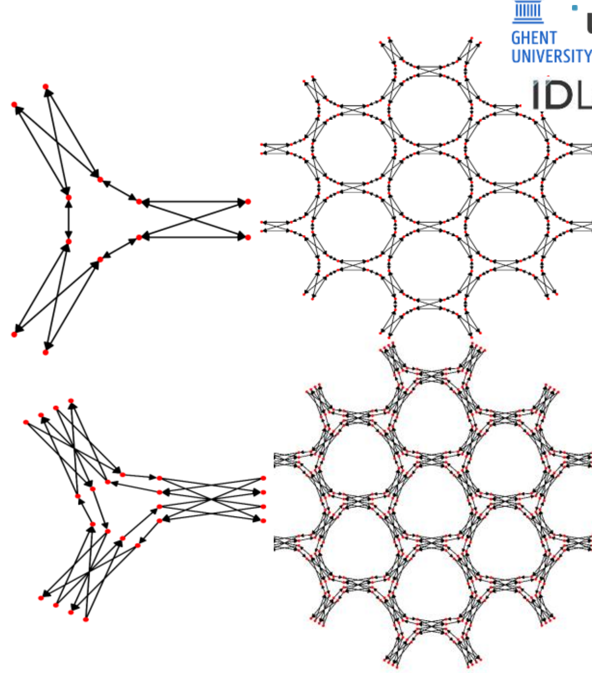
Directed or undirected

Weighted or unweighted

Introduce artificial nodes

Compatible with existing algorithms?

Respect the physics of waveguides



Chen et al, JLT 2020 139

139

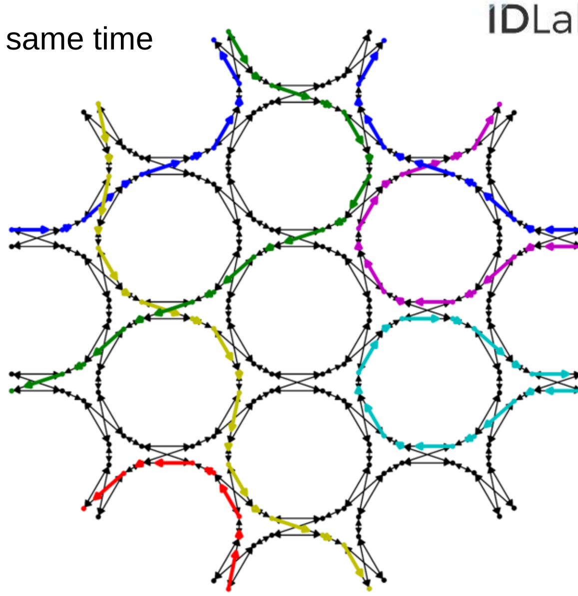
Graph-Based Routing Algorithms

Routing multiple routes at the same time
- congestion negotiation
- path balancing

Distribution trees

Avoiding defective elements

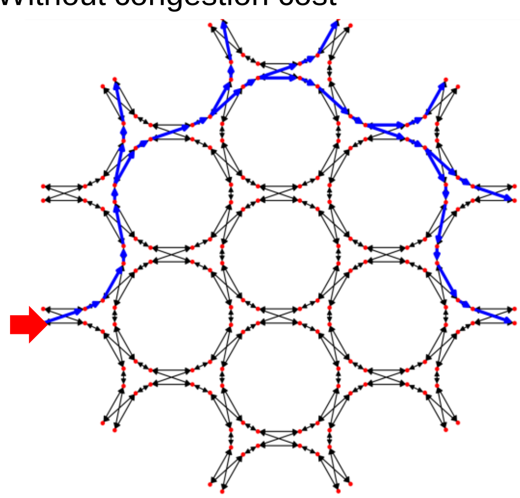
Spreading load and wear



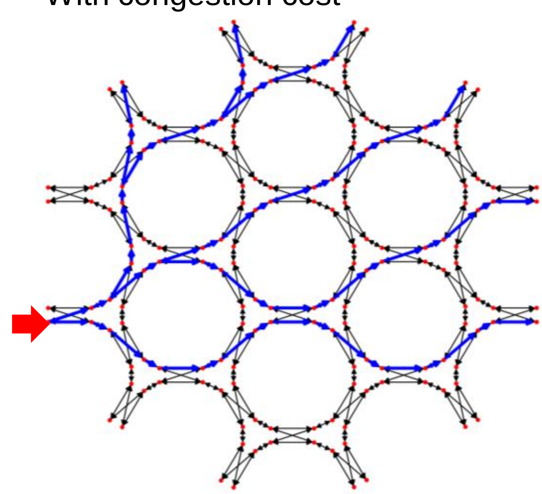
Chen et al, JLT 2020 140

Distribution problems

Without congestion cost



With congestion cost



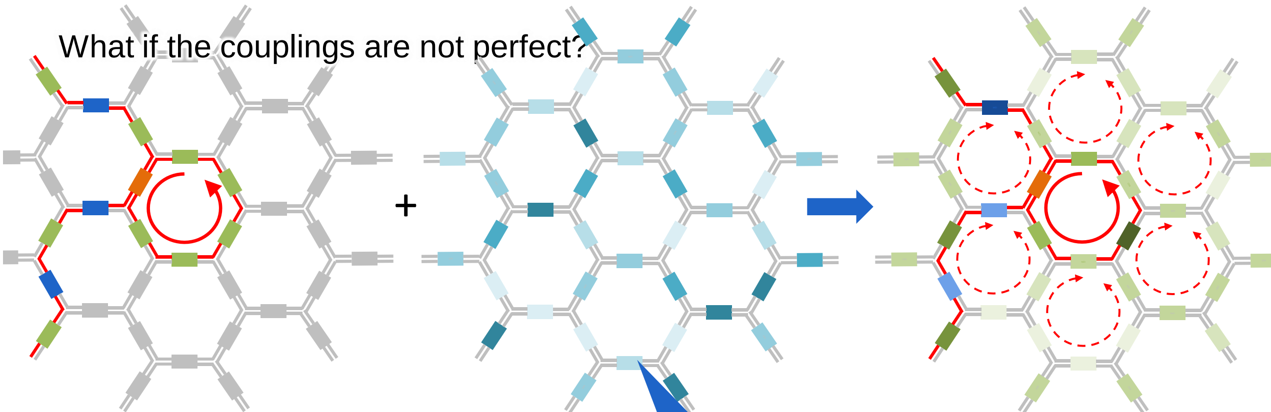
(e.g. nonlinear losses, TPA)

Chen et al, JLT 2020 141

GHENT UNIVERSITY imec

Imperfect control is a problem

What if the couplings are not perfect?



Fabrication errors
Control errors
Digital driving
Temperature gradients

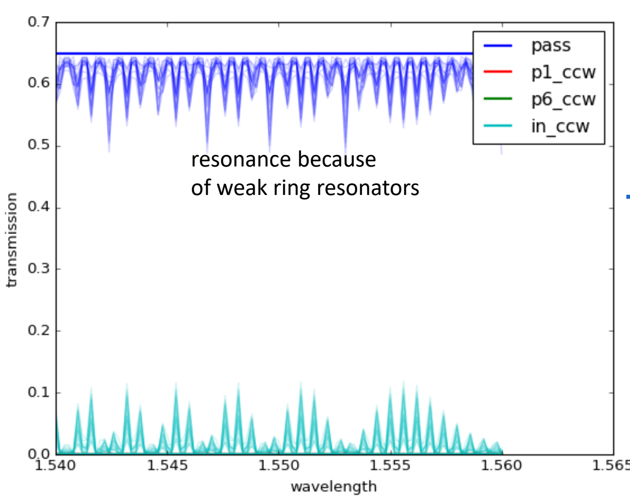
I. Zand, Photon.Res. 2020 142

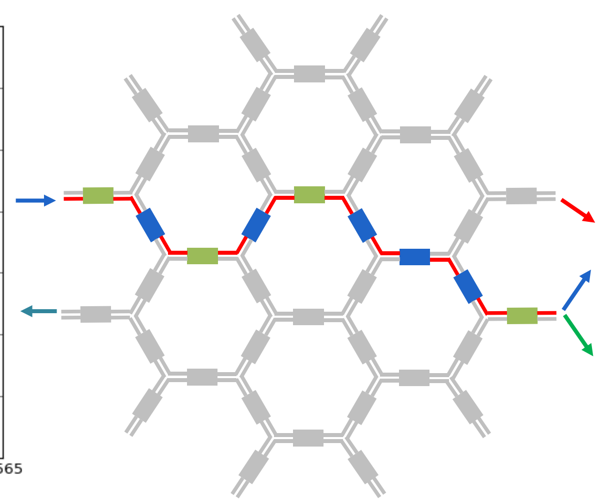
142

GHENT UNIVERSITY imec

Routing a Path

1% random Variations on the nominal coupling



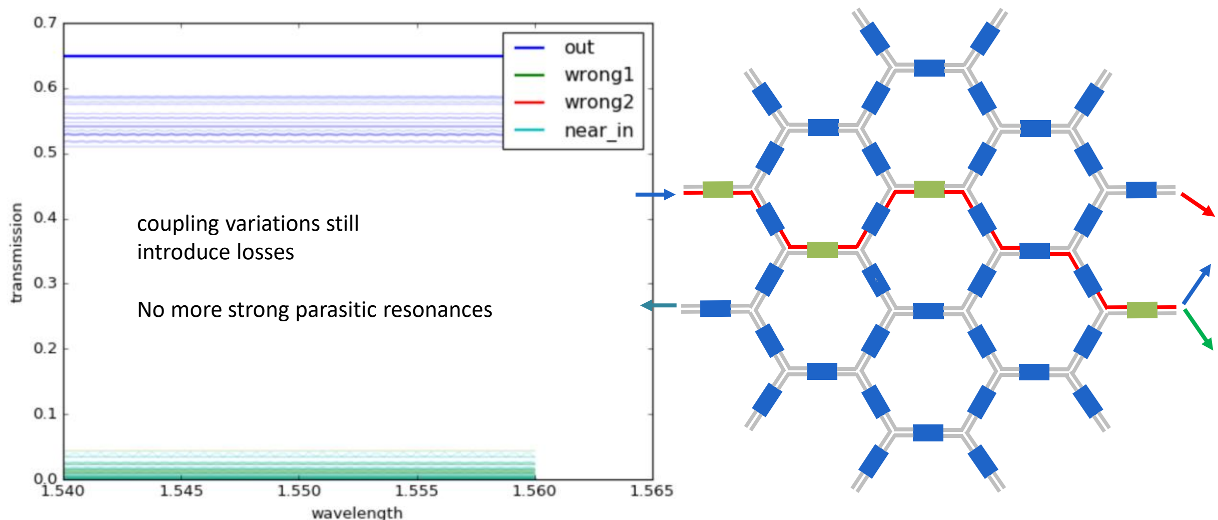


I. Zand, Photon.Res. 2020 143

143

Optimizing the 'unused' couplers (Cross state)

3% random Variations on the nominal coupling



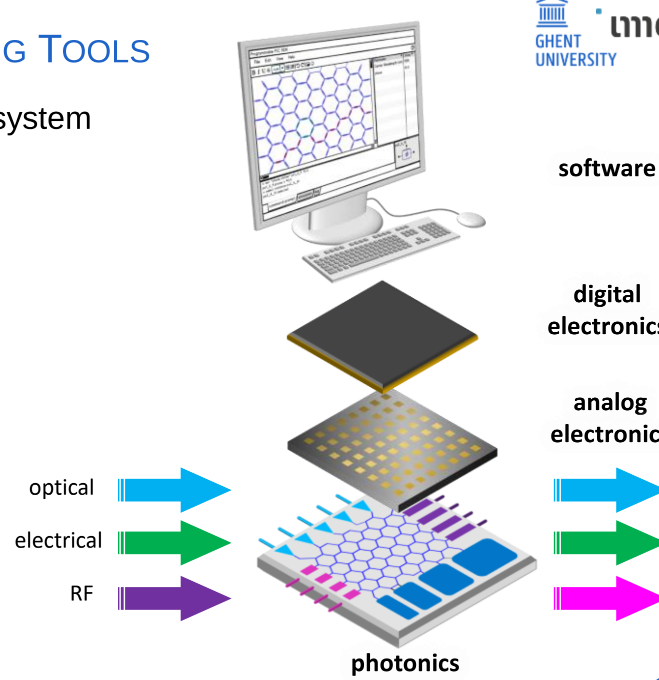
I. Zand, Photon.Res. 2020 145

145

Interfaces and Programming Tools

Programmable circuits are part of a system

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



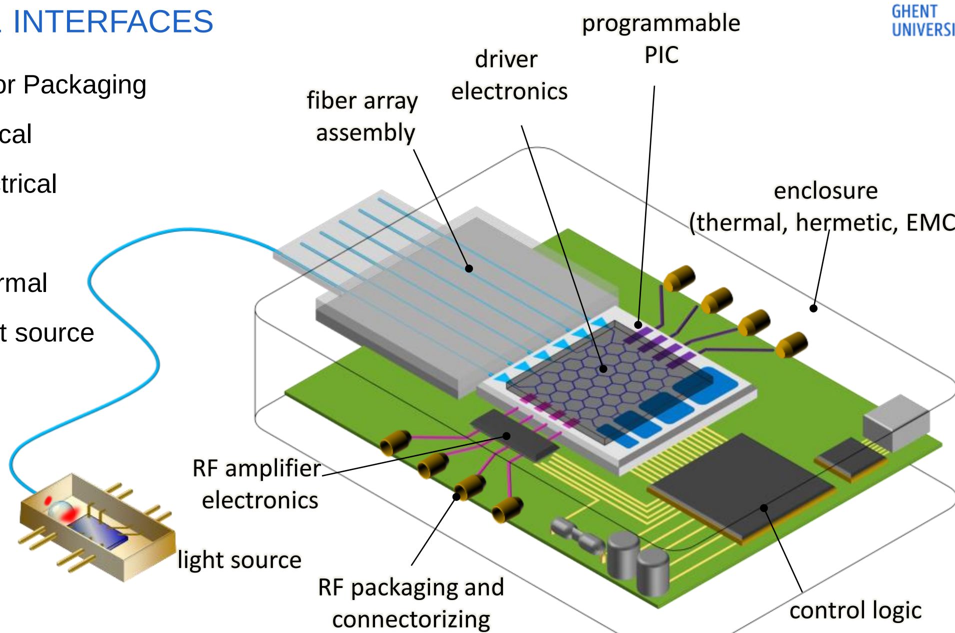
146

146

Physical Interfaces

Need for Packaging

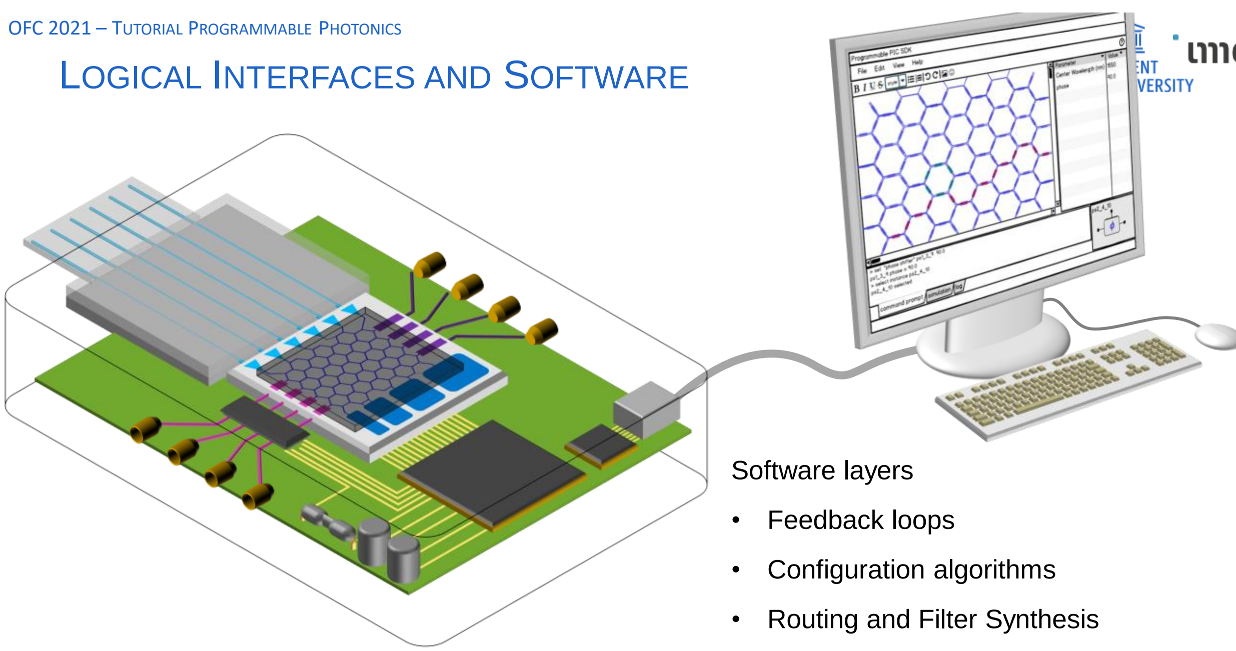
- Optical
- Electrical
- RF
- Thermal
- Light source



Bogaerts, JSTQE 2020, Nature 2020 147

147

Logical Interfaces and Software



Software layers

- Feedback loops
- Configuration algorithms
- Routing and Filter Synthesis
- Development and Debug tools

Bogaerts, JSTQE 2020, Nature 2020 148

148

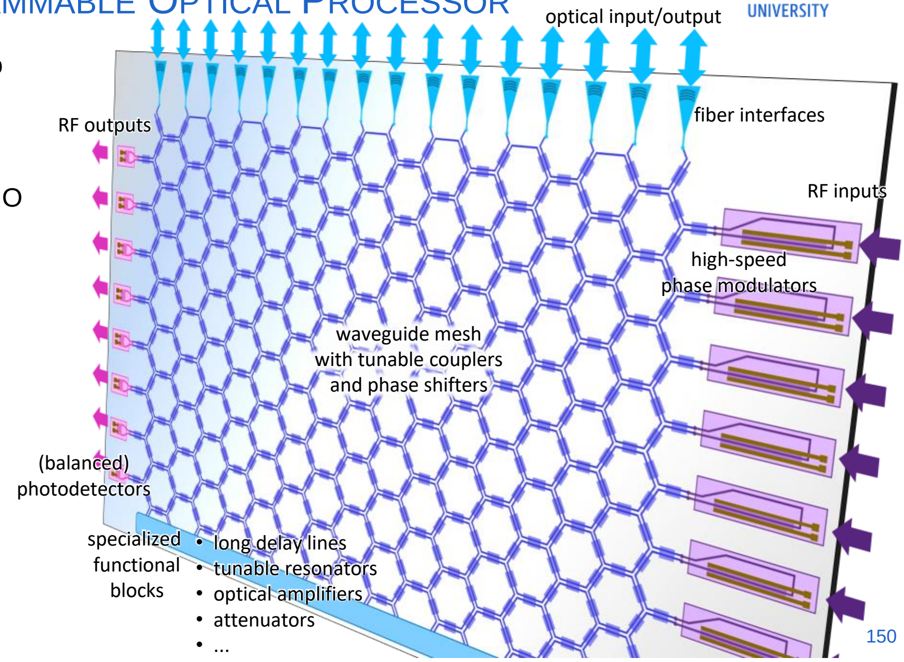
A complete technology stack

developer kit	**programming environment**			**development board**	
programming	**reusable programming blocks (IP)**	**routing and filter synthesis algorithms**		**software interface to the individual elements**	
control strategies	**global control algorithms**	**model generation and parameter extraction**		**local control strategies**	
packaging	**1000s of DC connections (flip-chip / 3D stacking / interposer)**			**RF waveguides and connectors**	**fiber array interface**
digital electronics (microcontroller, FPGA)	**high-level control loops**	**PWM or DAC**	**ADC**	**RF self-test functions**	
analog electronics	**fast control loops**	**current or voltage drivers**	**readout amplifiers**	**RF drivers trans-impedance amplifier (TIA)**	
programmable PIC chip	**mesh topologies**	**actuators: phase shifters tunable couplers**	**monitors power and phase**	**RF: modulators detectors**	**optical IO: fiber couplers**

Generic Programmable Optical Processor

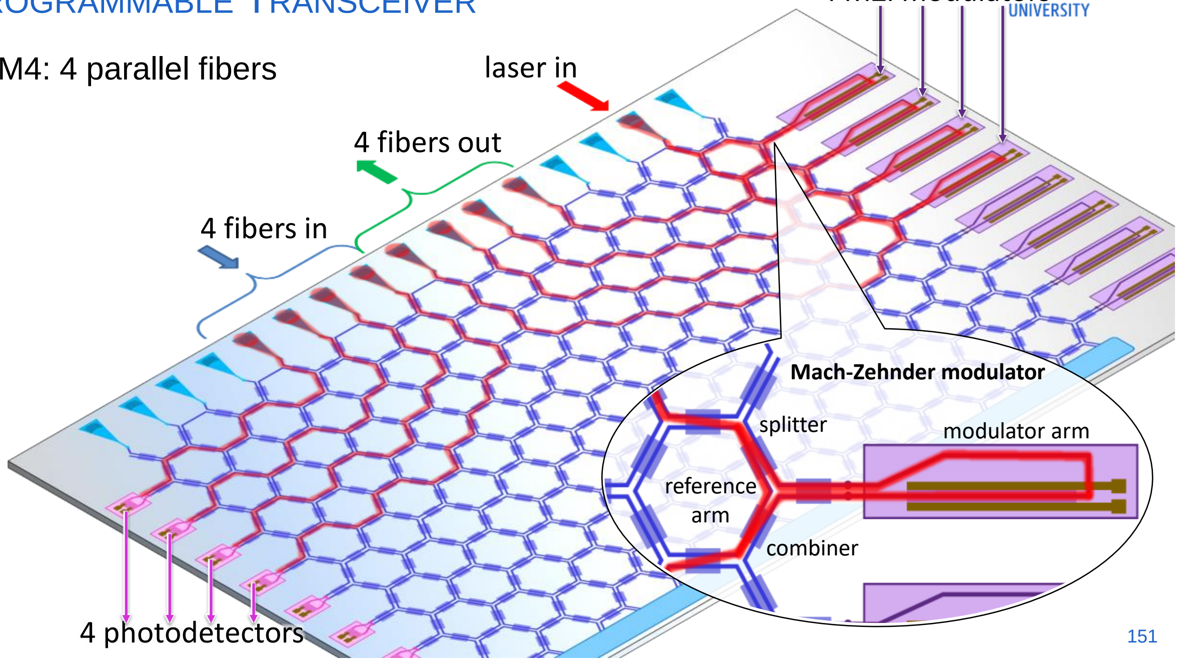
Add optical functionality to the linear circuit

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



Programmable Transceiver

PSM4: 4 parallel fibers



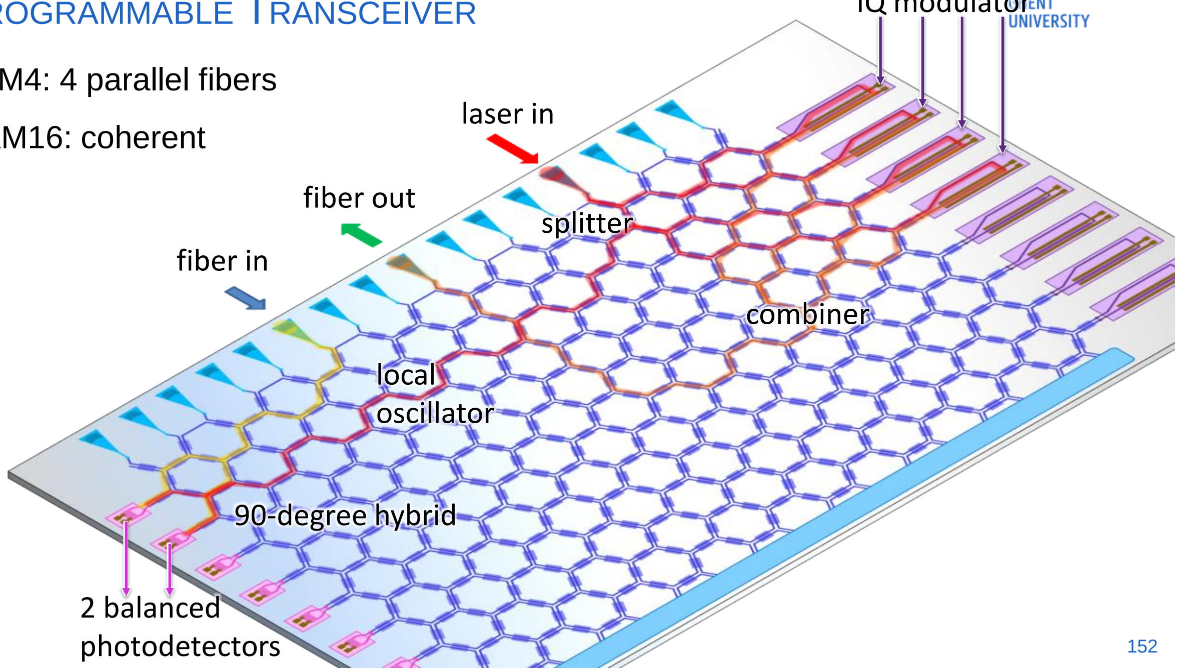
151

151

Programmable Transceiver

PSM4: 4 parallel fibers

QAM16: coherent



152

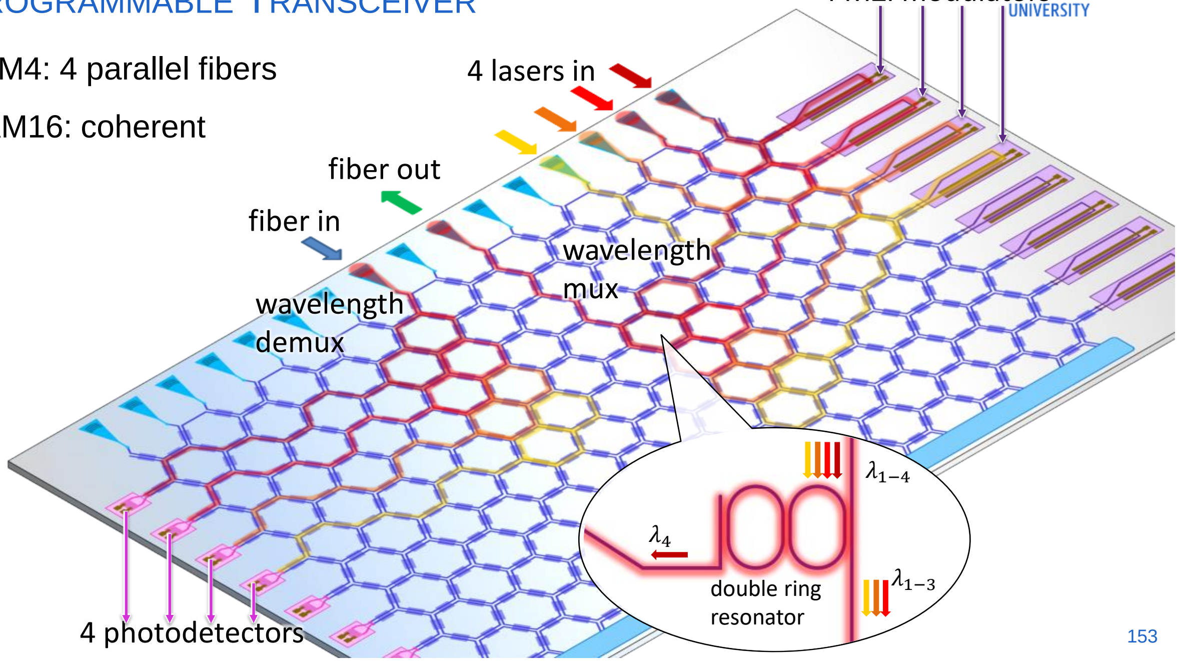
152

OFC 2021 – TUTORIAL PROGRAMMABLE PHOTONICS

PROGRAMMABLE TRANSCEIVER

PSM4: 4 parallel fibers

QAM16: coherent



153

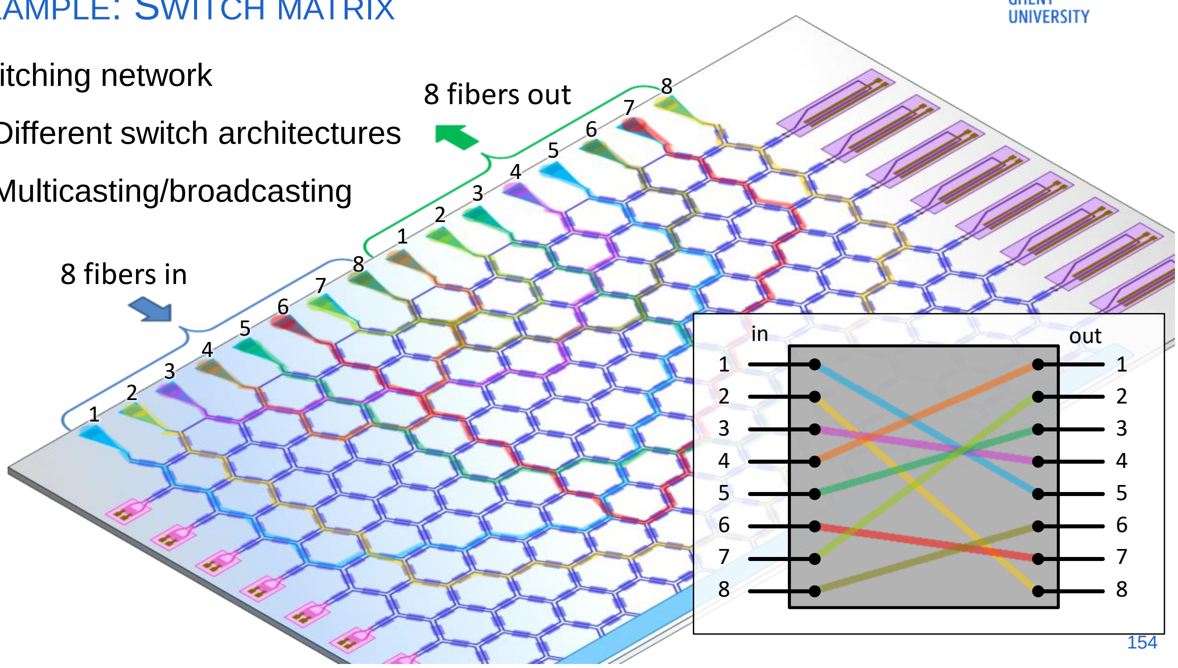
153

OFC 2021 – TUTORIAL PROGRAMMABLE PHOTONICS

EXAMPLE: SWITCH MATRIX

Switching network

- Different switch architectures
- Multicasting/broadcasting



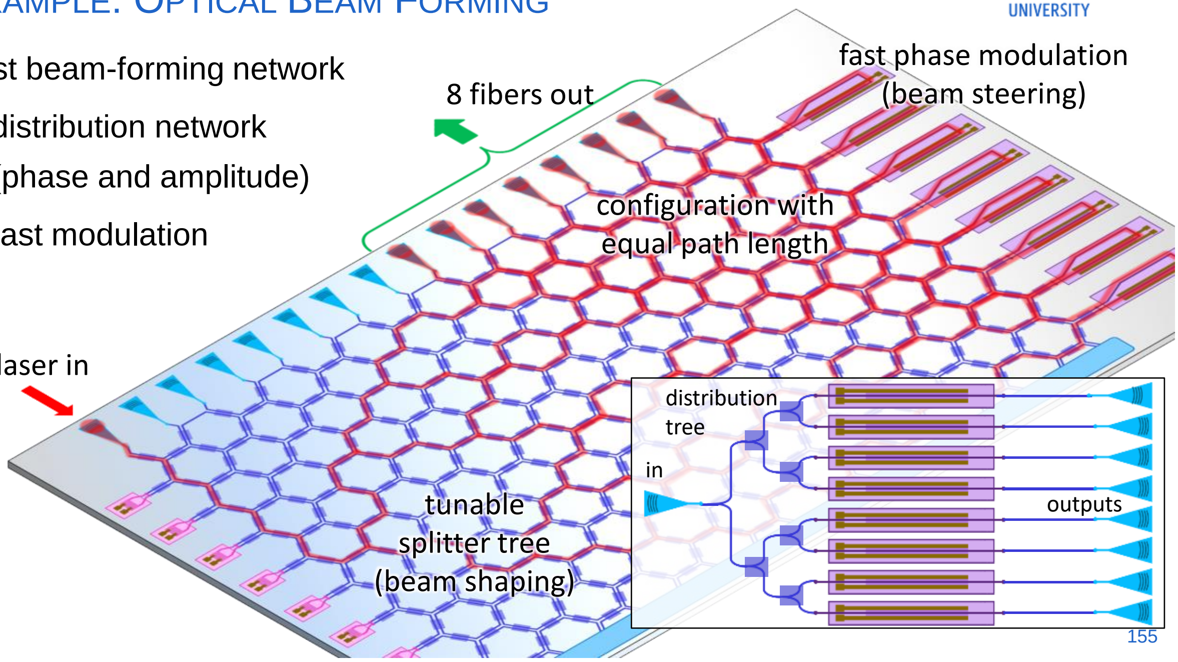
154

154

Example: Optical Beam Forming

Fast beam-forming network

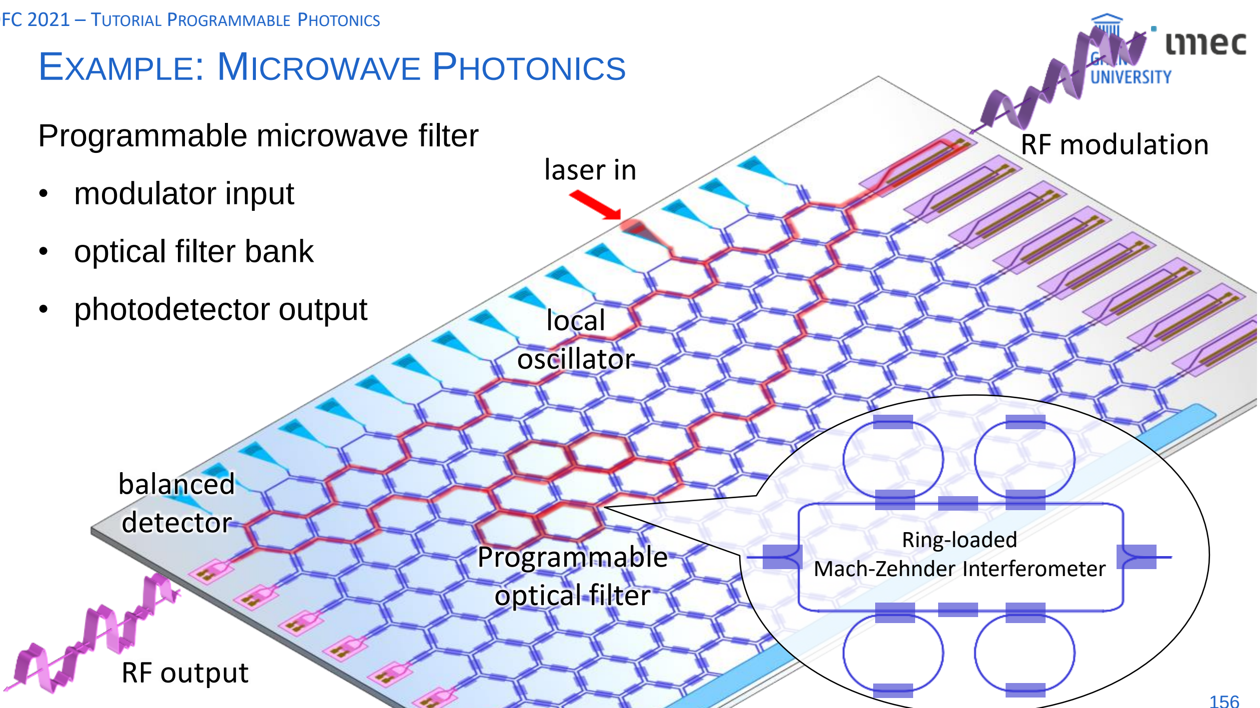
- distribution network (phase and amplitude)
- fast modulation



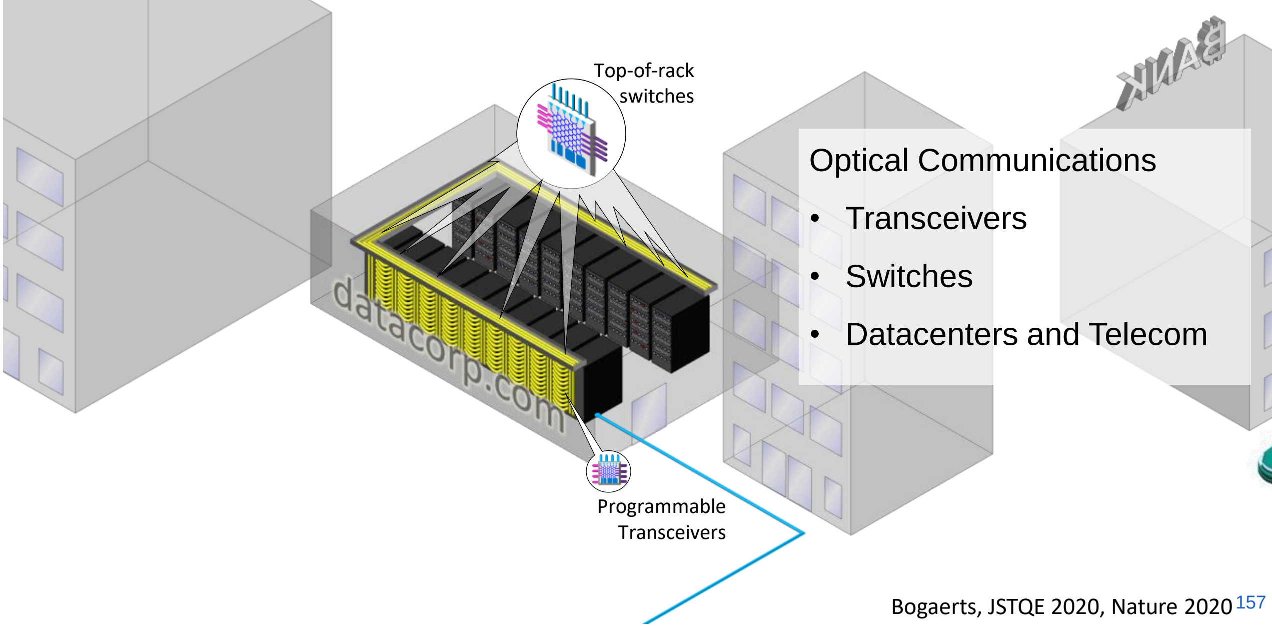
Example: Microwave Photonics

Programmable microwave filter

- modulator input
- optical filter bank
- photodetector output



Programmable Photonics can be used in many places



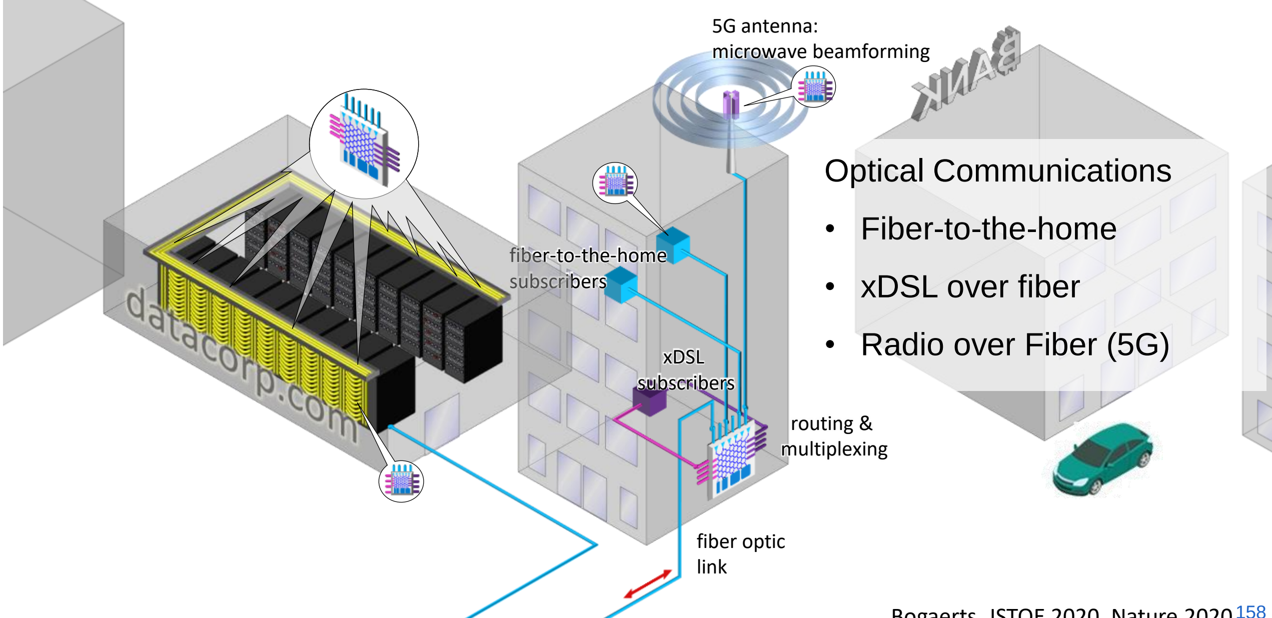
Optical Communications
- Transceivers
- Switches
- Datacenters and Telecom

Bogaerts, JSTQE 2020, Nature 2020 157

157

OFC 2021 – Tutorial Programmable Photonics

Programmable Photonics can be used in many places

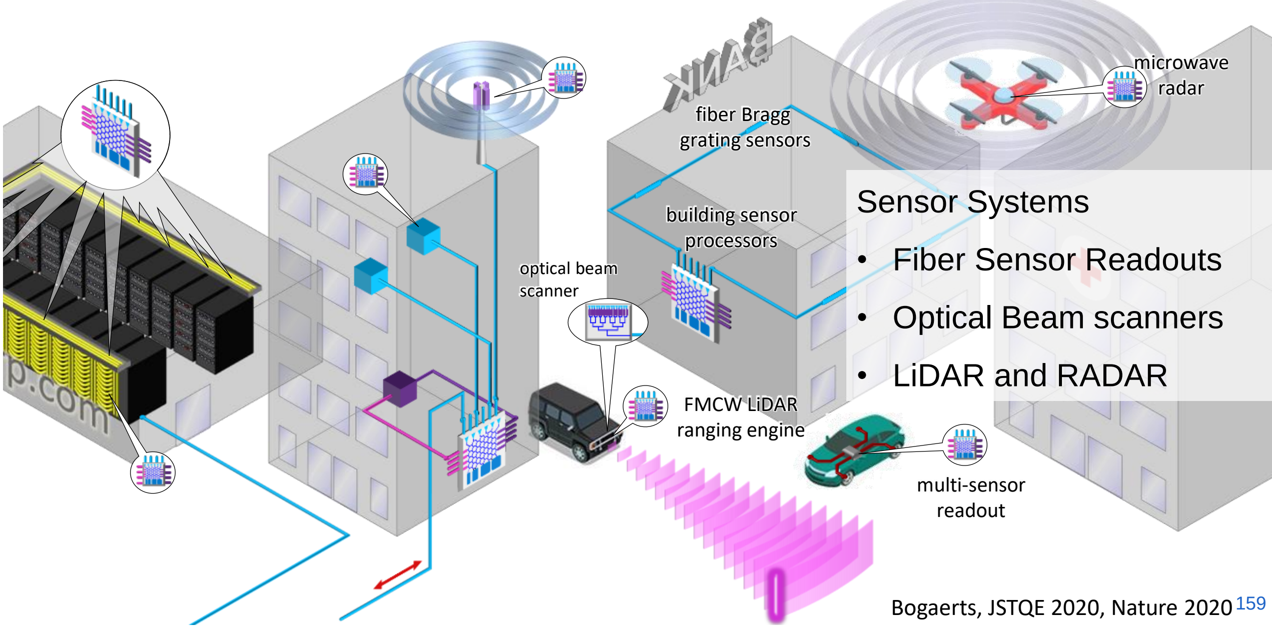


Optical Communications
- Fiber-to-the-home
- xDSL over fiber
- Radio over Fiber (5G)

Bogaerts, JSTQE 2020, Nature 2020 158

158

Programmable Photonics can be used in many places



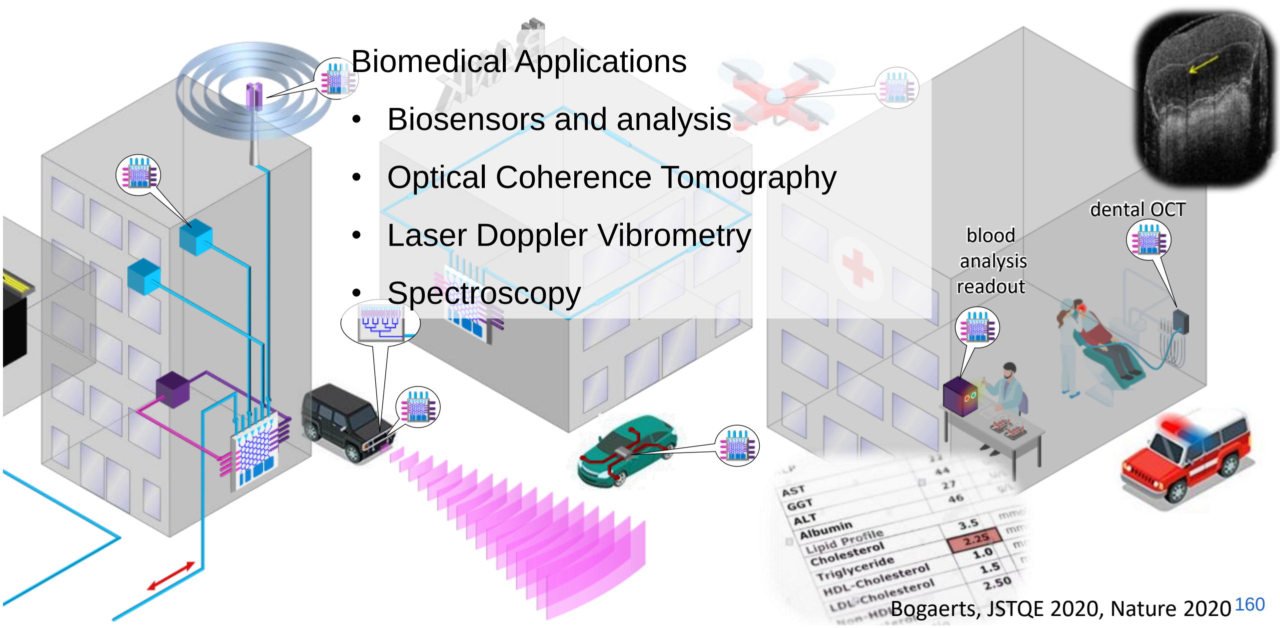
Sensor Systems

- Fiber Sensor Readouts
- Optical Beam scanners
- LiDAR and RADAR

Bogaerts, JSTQE 2020, Nature 2020 159

159

Programmable Photonics can be used in many places



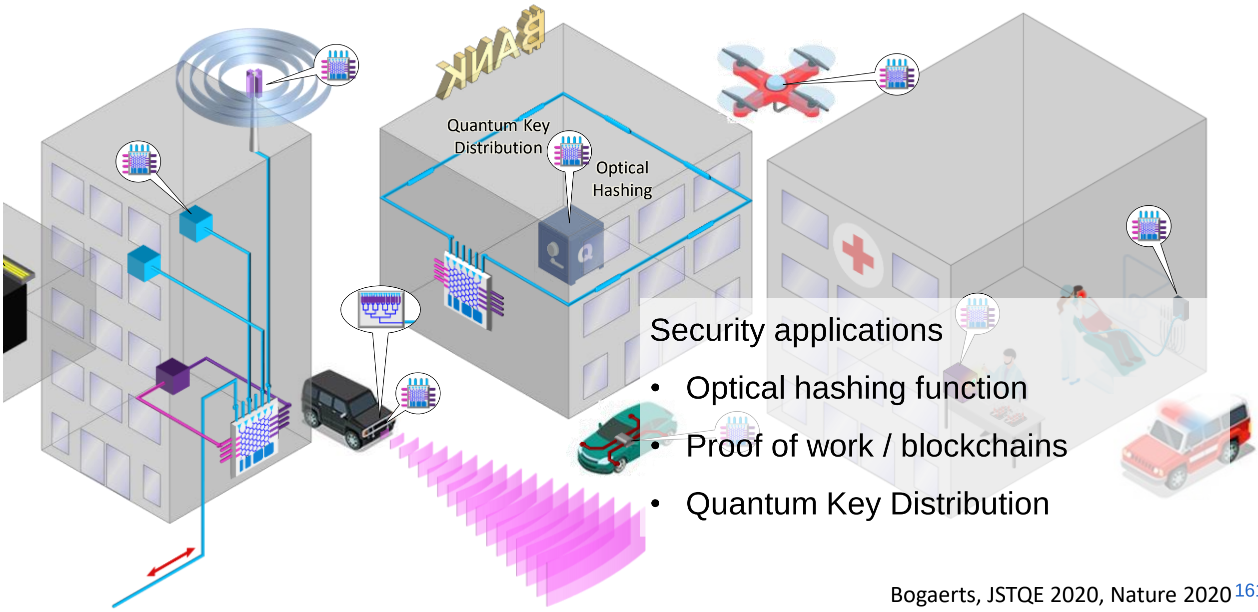
Biomedical Applications

- Biosensors and analysis
- Optical Coherence Tomography
- Laser Doppler Vibrometry
- Spectroscopy

Bogaerts, JSTQE 2020, Nature 2020 160

160

Programmable Photonics can be used in many places



Security applications

- Optical hashing function
- Proof of work / blockchains
- Quantum Key Distribution

Bogaerts, JSTQE 2020, Nature 2020 161

161

One Chip to Rule them All?

Can handle many functions

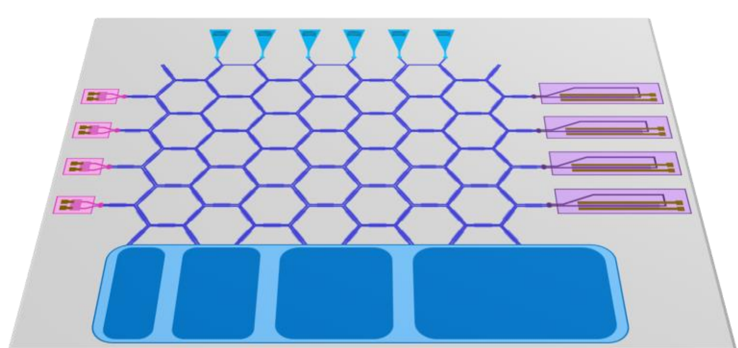
Can combine RF and Optical

Flexible to program

Large chip = expensive

Many elements = high loss

Power consumption

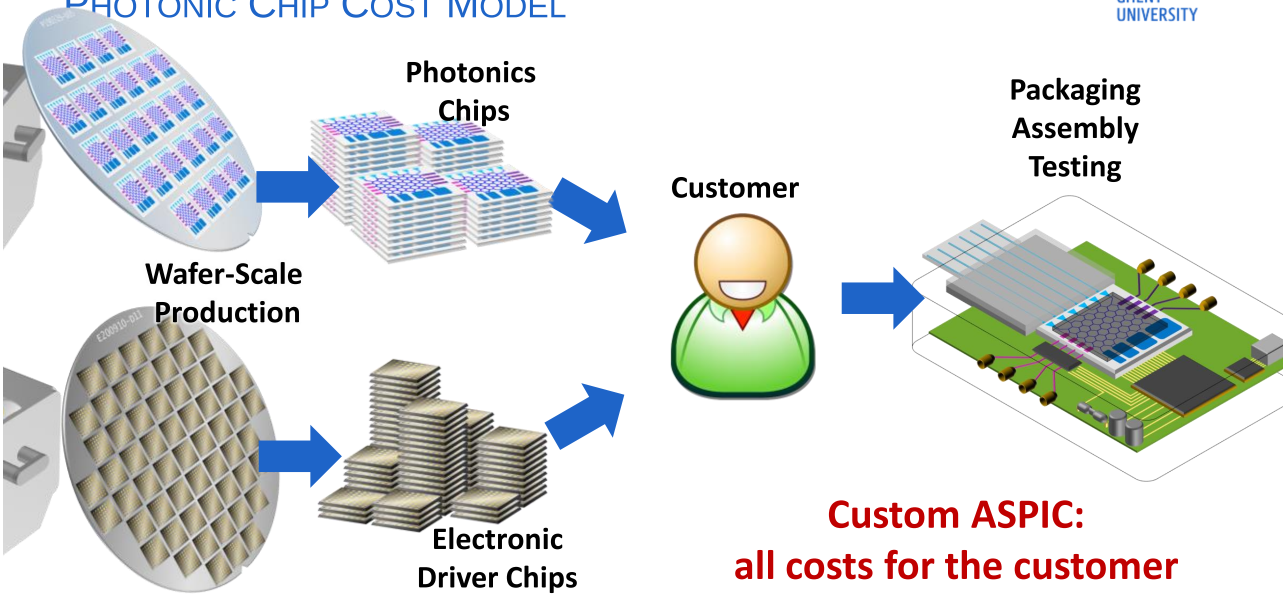


162

162

GHENT UNIVERSITY imec

Photonic Chip Cost Model

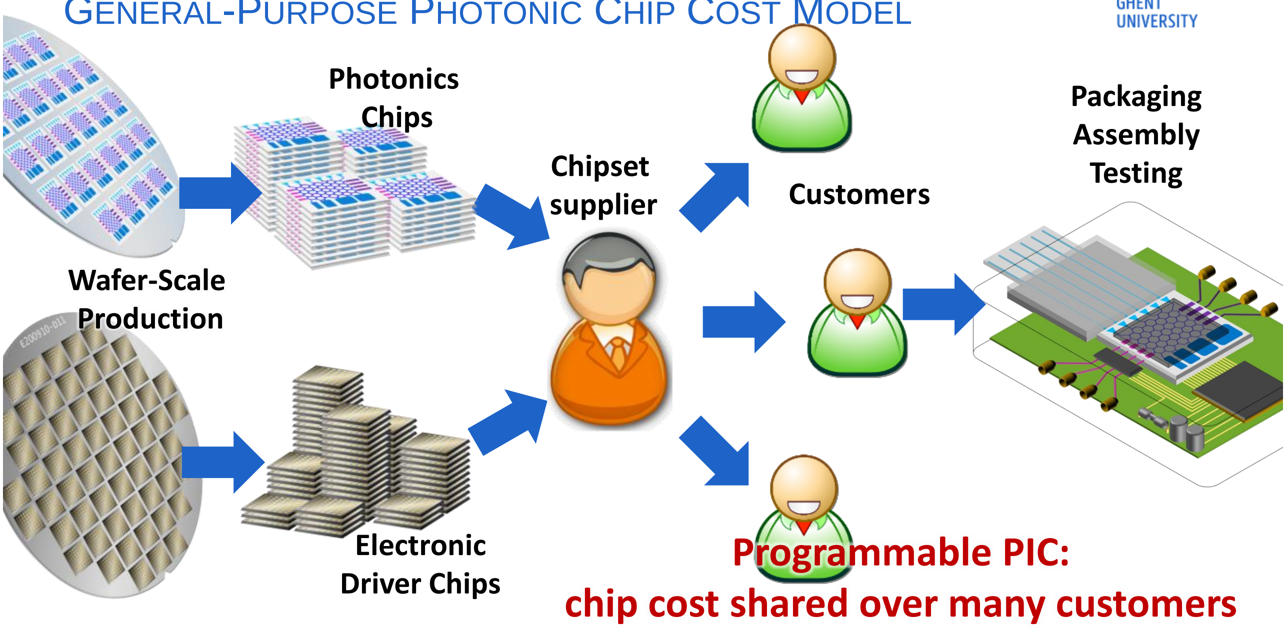


Bogaerts, JSTQE 2020 164

164

GHENT UNIVERSITY imec

General-Purpose Photonic Chip Cost Model



Bogaerts, JSTQE 2020 166

166

OFC 2021 – Tutorial Programmable Photonics

Where are the costs?

Silicon Photonics Chip
- Chip Design
- Wafer-scale fabrication
- Testing

Driver Electronics ASIC
- Custom chip design
- Chip fabrication
- Testing

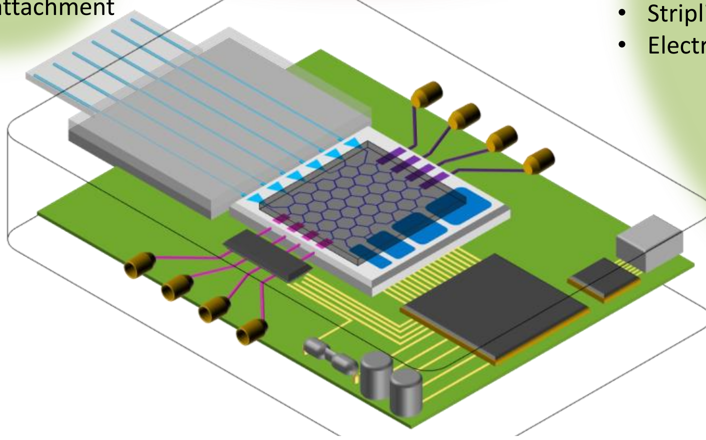
Large NRE cost

Optical IO:
- Fiber array
- Fiber attachment

High-speed RF IO
- Connectors
- High-speed substrates
- Stripline design
- Electronic amplifiers

Interfaces
- Support electronics
- Circuit boards
- Flip-chip and Wirebonding
- Packaging

Large Proportional Fabrication Cost

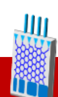


Bogaerts, JSTQE 2020 167

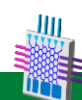
167

OFC 2021 – Tutorial Programmable Photonics

Three scenarios

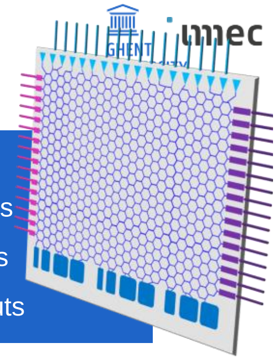


No-RF (passive)
- 8 fiber ports



Few-RF
- 8 fiber ports
- 4 RF inputs
- 4 RF outputs

Many-RF
- 32 fiber ports
- 16 RF inputs
- 16 RF outputs

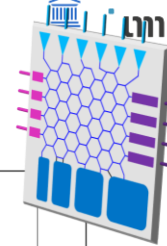


Cost Model:
- PIC design + fabrication
- Driver EIC design + fabrication
- Package development
- Testing

Bogaerts, JSTQE 2020 168

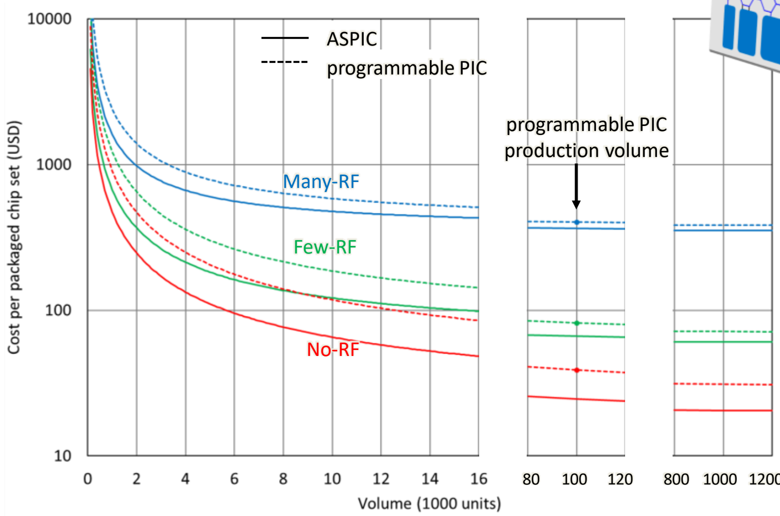
168

Programmable PICs can be Cheaper!



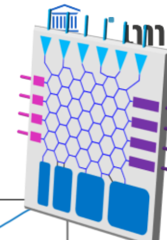
Programmable PICs are fabricated in larger volumes

- Shared design cost
- Shared mask costs
- Shared processing of full wafer lots



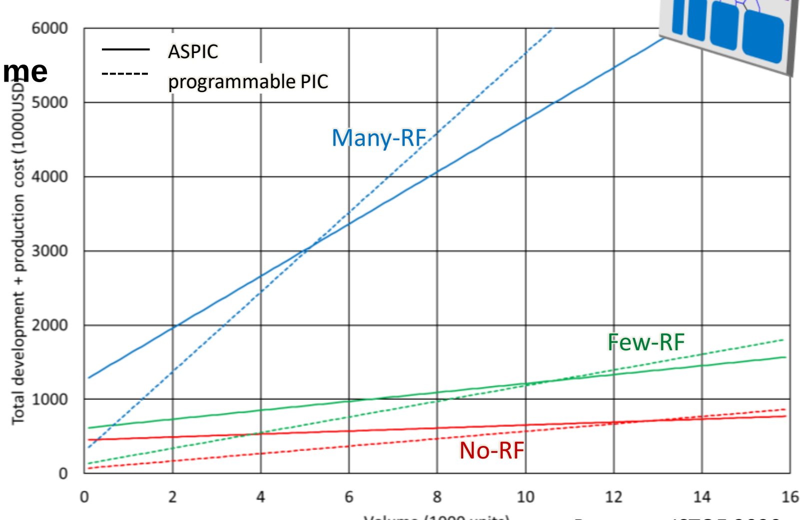
Bogaerts, JSTQE 2020

Programmable PICs can be Cheaper!



Especially for prototyping and smaller volumes

+ shorter development time

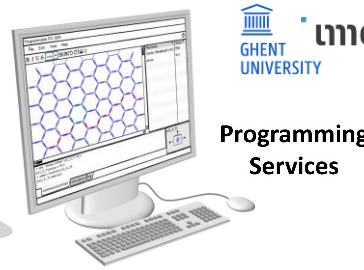


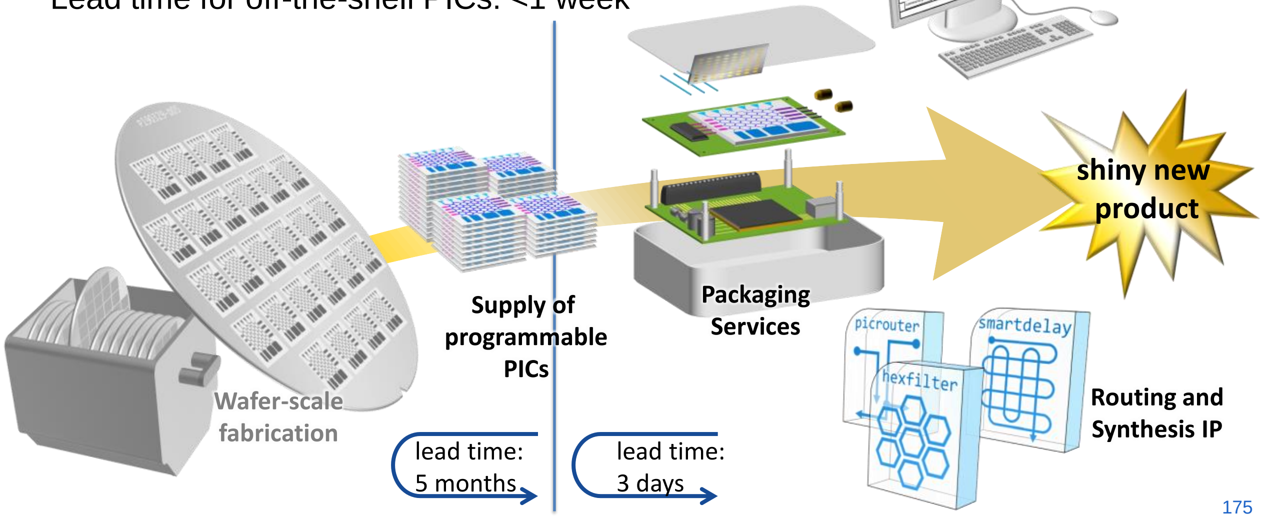
Bogaerts, JSTQE 2020

Shortening the Lead Time

Lead time for custom designed PIC: >1 year

Lead time for off-the-shelf PICs: <1 week

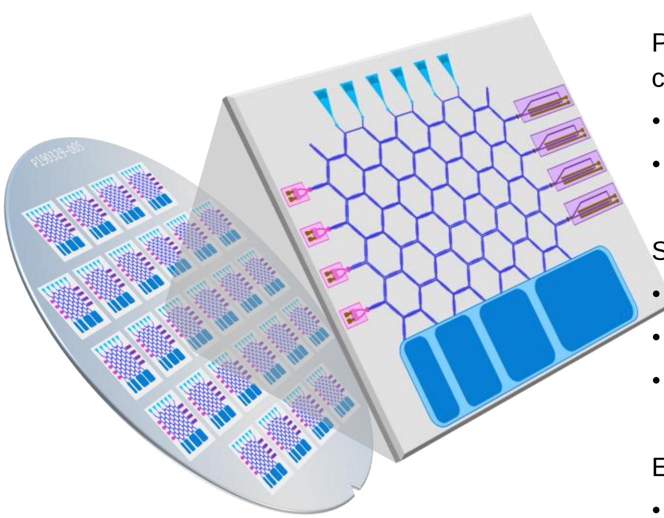




175

175

Programmable PICs can make photonics SMART



Programmable PICs can become a game-changer:

- Rapid prototyping and development
- Different applications

Scaling challenges

- loss and power: couplers and phase shifters
- control electronics and packaging
- programming algorithms

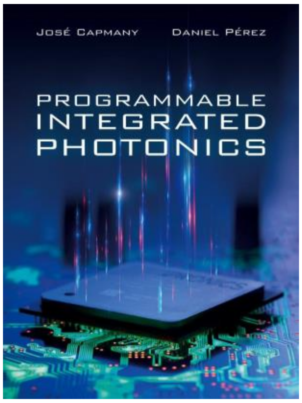
Economic benefits

- Faster prototyping
- Lower adoption threshold
- Lower cost for low-volume specialty products

176

176

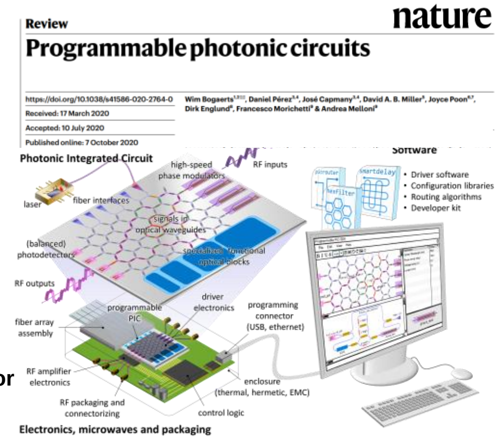
Further Reading



Wim Bogaerts, Daniel Pérez, José Capmany
David A.B. Miller, Joyce Poon, Dirk Englund
Francesco Morichetti, Andrea Melloni
Programmable Photonic Circuits
Nature 586, DOI: 10.1038/s41586-020-2764-0

José Capmany & Daniel Pérez
Programmable Integrated Photonics
ISBN: 978-0-19-884440-2 - 2020

Wim Bogaerts & Abdul Rahim
Programmable Photonics: An Opportunity for an Accessible Large-Volume PIC Ecosystem
J. Sel. Top. Quantum Electron. 26(5) - 2020



David AB Miller
Silicon photonics: Meshing optics with applications
Nature Photonics 11(7) - 2017

Thanks for the contributions

Funding Support:

PhotonICSWARM grant 725555

PHOTONICS PUBLIC PRIVATE PARTNERSHIP

morphic grant 780283

Mi Wang
Abdul Rahim
Hong Deng
Iman Zand
Xiangfeng Chen
Antonio Ribeiro
Umar Khan
Nagarjun KP
Lukas Van Iseghem
Banafsheh Abasahl
Alejandro Diaz-Tormo

Niels Quack (EPFL)
Hamed Sattari (EPFL)
Yuji Takabayashi (EPFL)
Pierre Edinger (KTH)
Kristinn Gylfason (KTH)
David A.B. Miller (Stanford)
Jose Capmany (UP. Valencia)
Daniel Perez (UP. Valencia)
Andrea Melloni (Politecnico di Milano)

PHOTONICS RESEARCH GROUP

Wim Bogaerts

Professor in Silicon Photonics

wim.bogaerts@ugent.be

+32 9 264 3324

@PhotonicsUGent

@WimBogaerts

www.photonics.intec.ugent.be

179