iPRONICS
Programmable Photonics

RF/mm and Programmable Photonics

José Capmany

Cadence Photonics Summit and Workshop
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www.ipronics.com

Agenda

01 Introduction

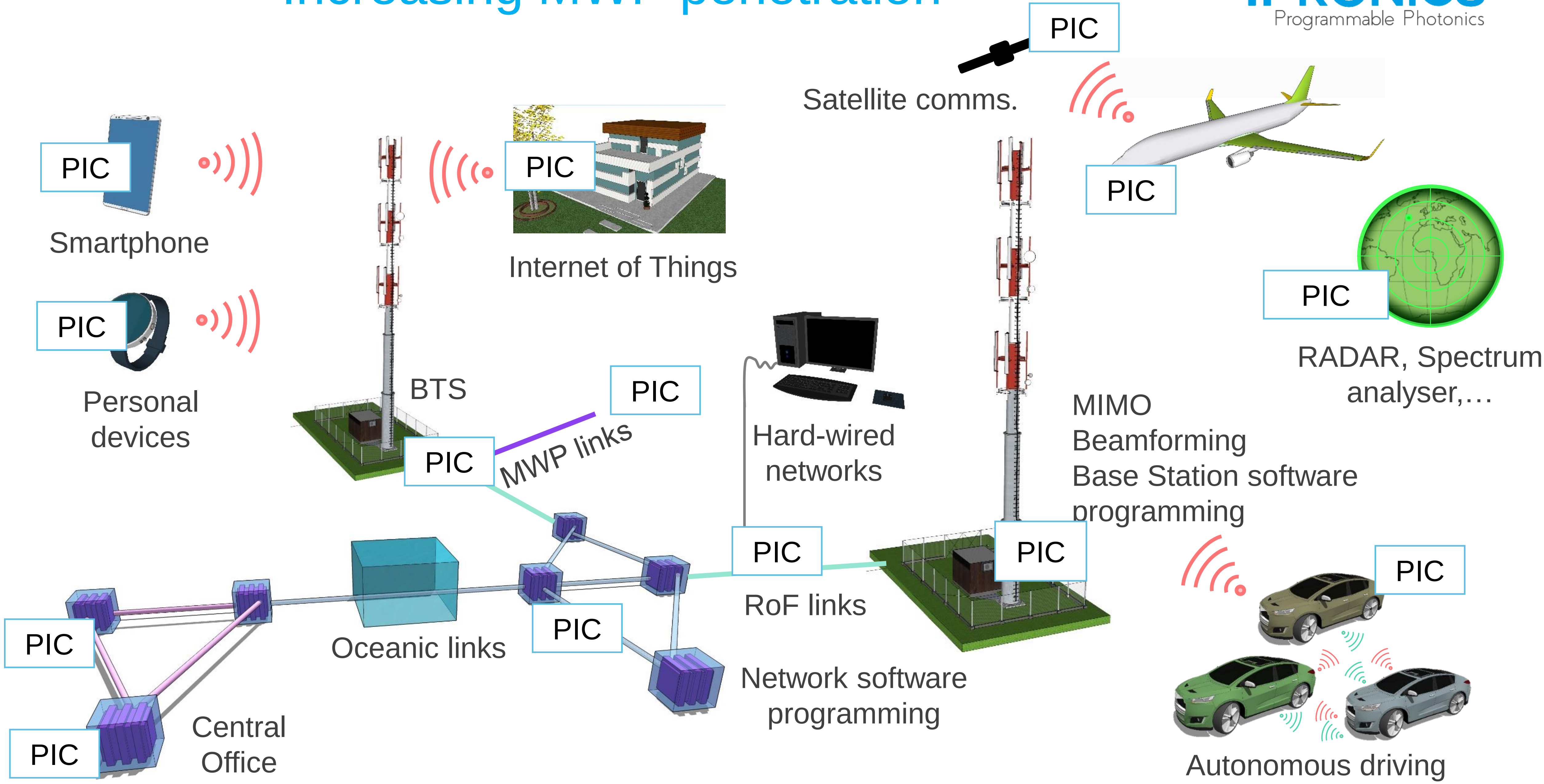
02 RF/mm Photonics

03 Programmable Integrated Photonics

04 Summary & Conclusions

Introduction

Increasing MWP penetration



RF/mm Photonics

Integrated MWP

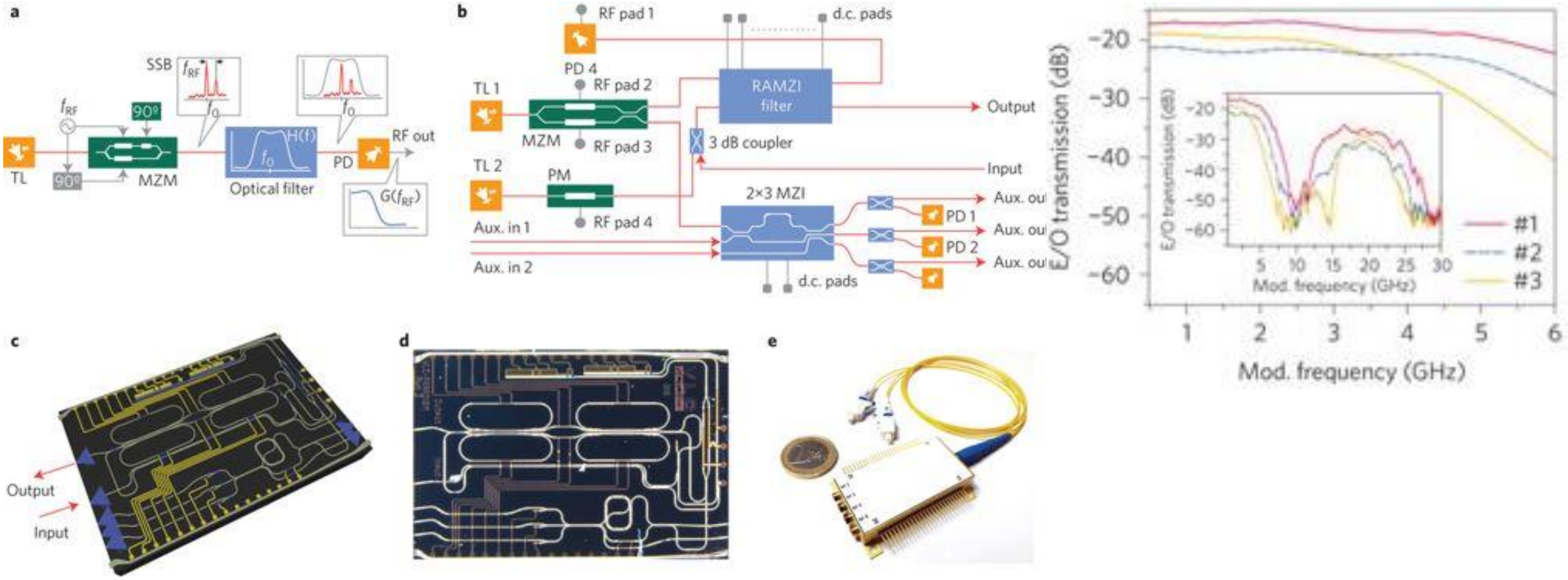
IMWP ASPICS

- Designed to carry only a given functionality
- Feature some degree of flexibility enabled tuning some of its internal parameters by means of appropriate control signals.
- Fixed physical topology.
- A considerable amount of circuits reported in the literature (SOI, InP, SiN)

  - Filters
  - Delay lines
  - RF phase shifters
  - Switches, Add/Drop MuXes
  - Beamformers
  - Arbitrary waveform generators
  - Optoelectronic oscillators

IMWP ASPICS

Reconfigurable Filters



J. Fandiño et al, Nature Photonics, 124–129 (2017)

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IMWP ASPICS

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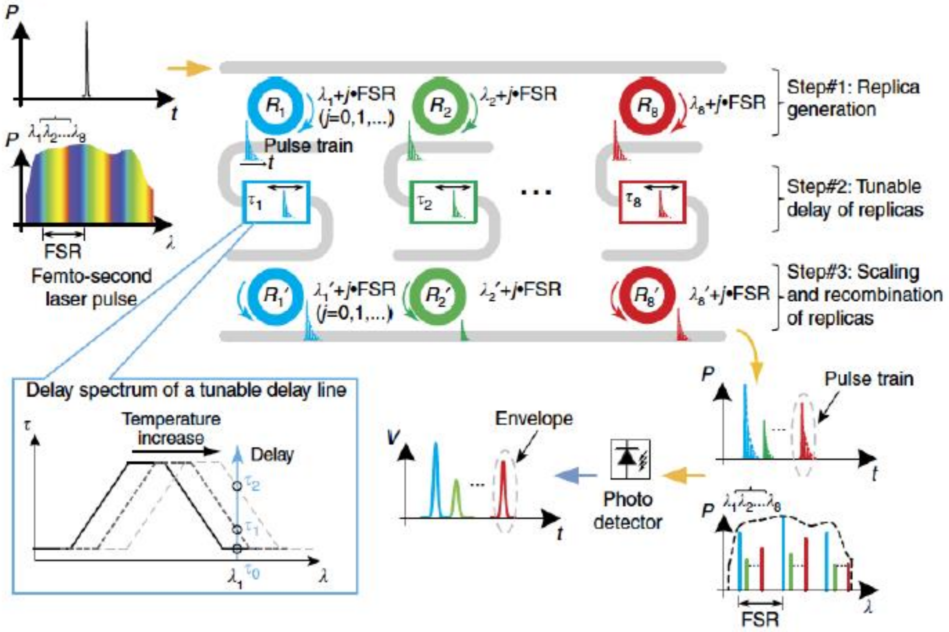
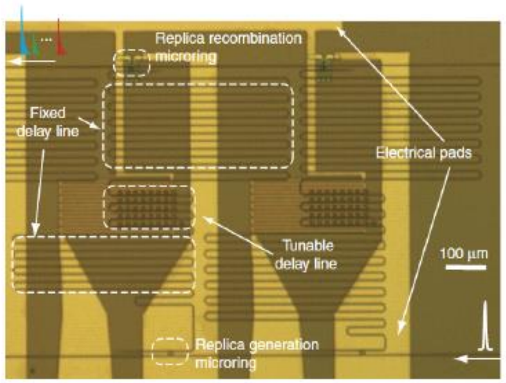
Tunable Arbitrary waveform generator

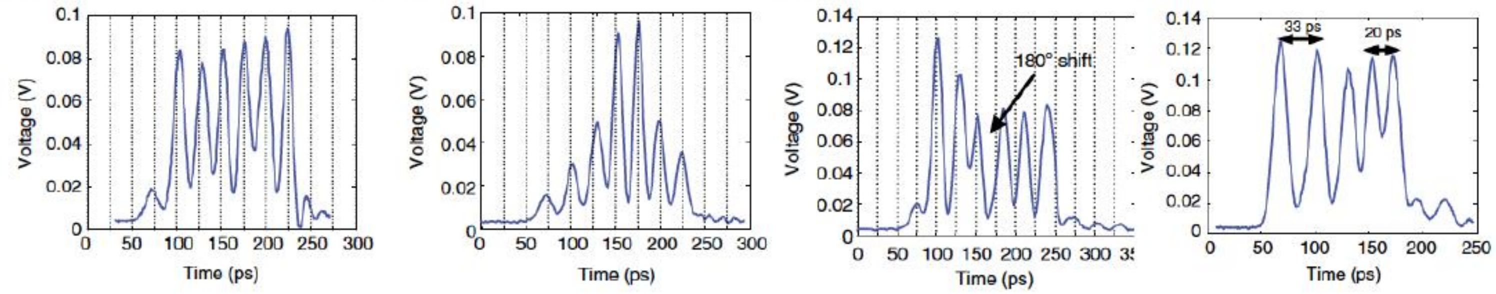
(a)



(b)



(c) (d) (e) (f)



PURDUE
UNIVERSITY

J. Wang et al., "Reconfigurable radio-frequency arbitrary waveforms synthesized in a silicon photonic chip, " Nature Comms. 6, 5957 (2015).

IMWP ASPICS

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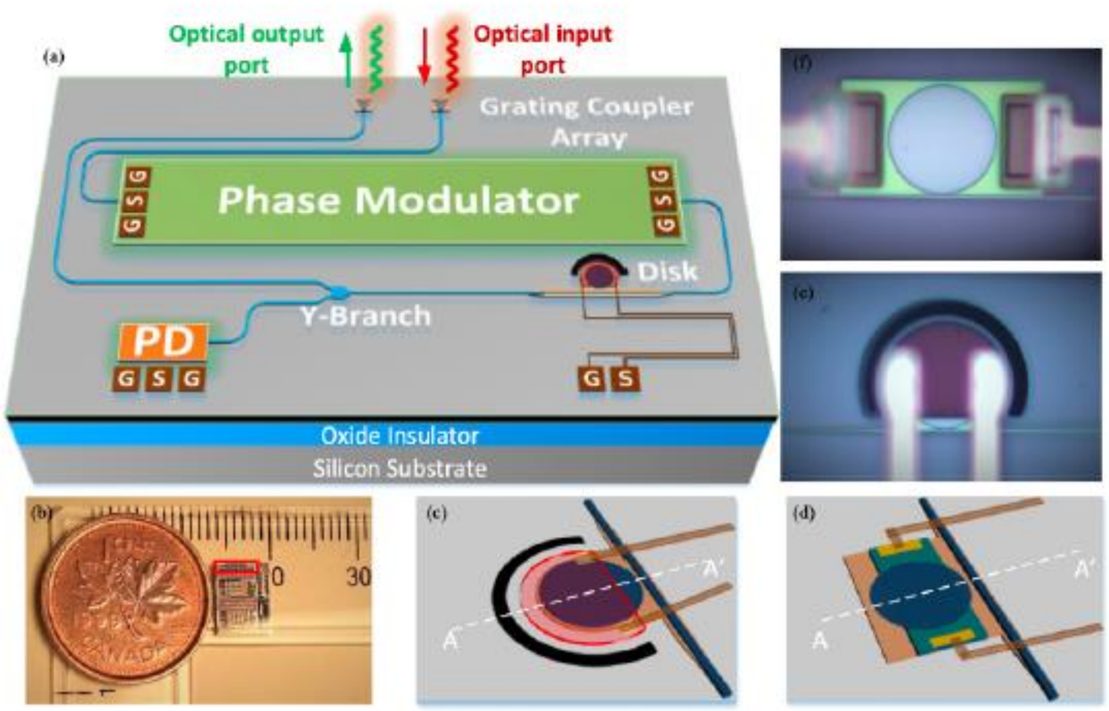
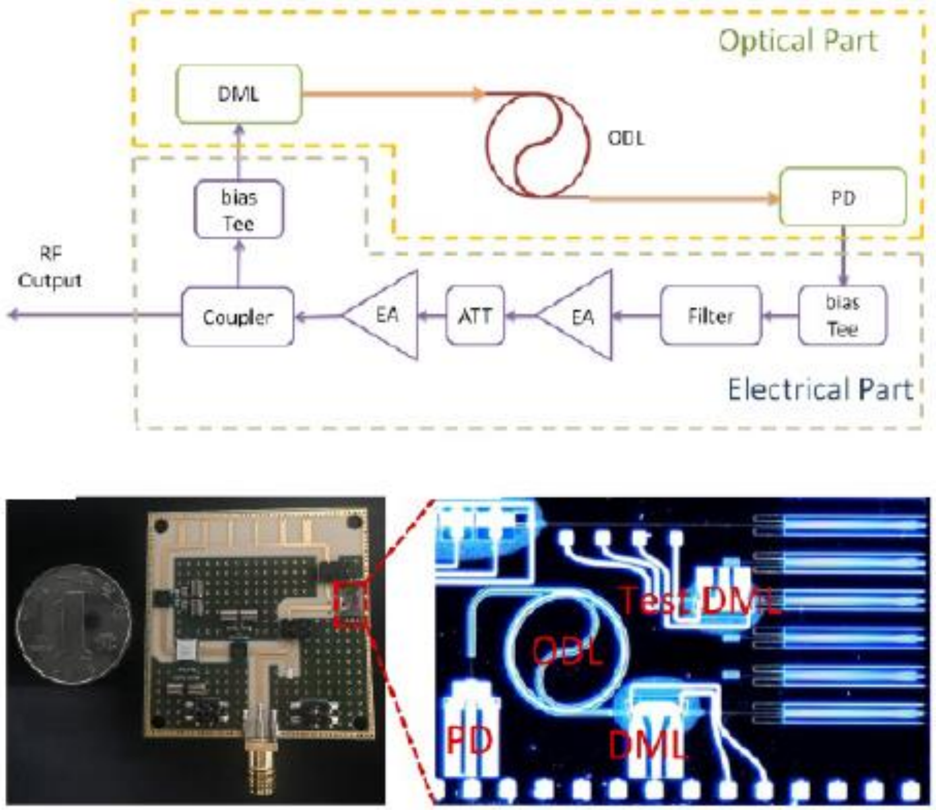
Optelectronic Oscillators



W. Zhang, J. Yao, IEEE J. Lightwave Tech. 36, 4655-4663, (2018).

uOttawa



J. Tang, et al., Opt. Express 26, 12257-12265 (2018).

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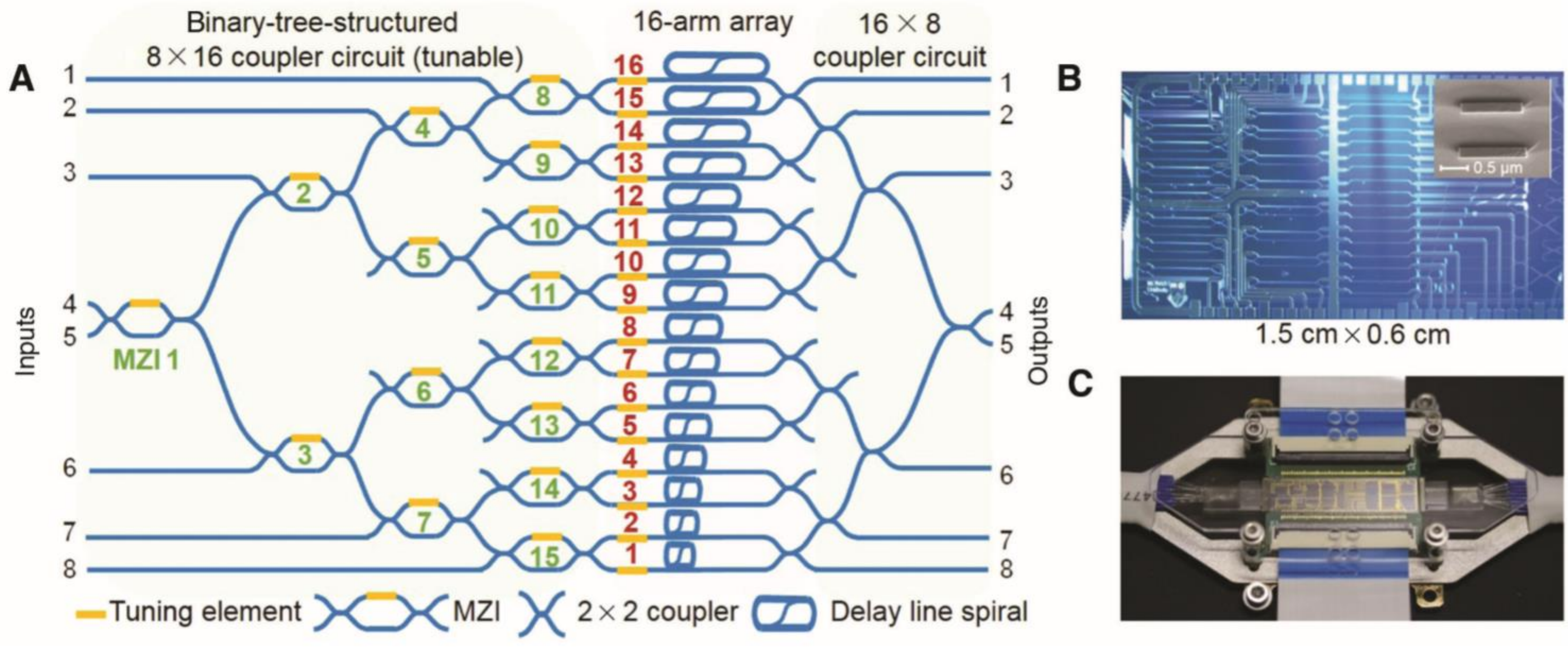
IMWP Multiport circuits

Signal Processors & Beamformers



Yiwei Xie, et al., nanophotonics 2017,0113 2018

IMWP ASICS

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Comprehensive Reviews

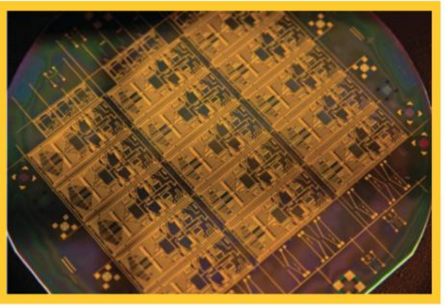
2013

LASER & PHOTONICS REVIEWS

Laser Photonics Rev. 7, No. 4, 506–538 (2013) / DOI 10.1002/lpor.201200032

REVIEW ARTICLE

Abstract Microwave photonics (MWP) is an emerging field in which radio frequency (RF) signals are generated, distributed, processed and analyzed using the strength of photonic techniques. It is a technology that enables various functionalities which are not feasible to achieve only in the microwave domain. A particular aspect that recently gains significant interests is the use of photonic integrated circuit (PIC) technology in the MWP field for enhanced functionalities and robustness as well as the reduction of size, weight, cost and power consumption. This article reviews the recent advances in this emerging field which is dubbed as integrated microwave photonics. Key integrated MWP technologies are reviewed and the prospective of the field is discussed.



Integrated microwave photonics

David Marpaung[1,4,*], Chris Roeloffzen[1], René Heideman[2], Arne Leinse[2], Salvador Sales[3], and José Capmany[3,5]

REVIEW ARTICLE
https://doi.org/10.1038/s41566-018-0310-5

nature photonics

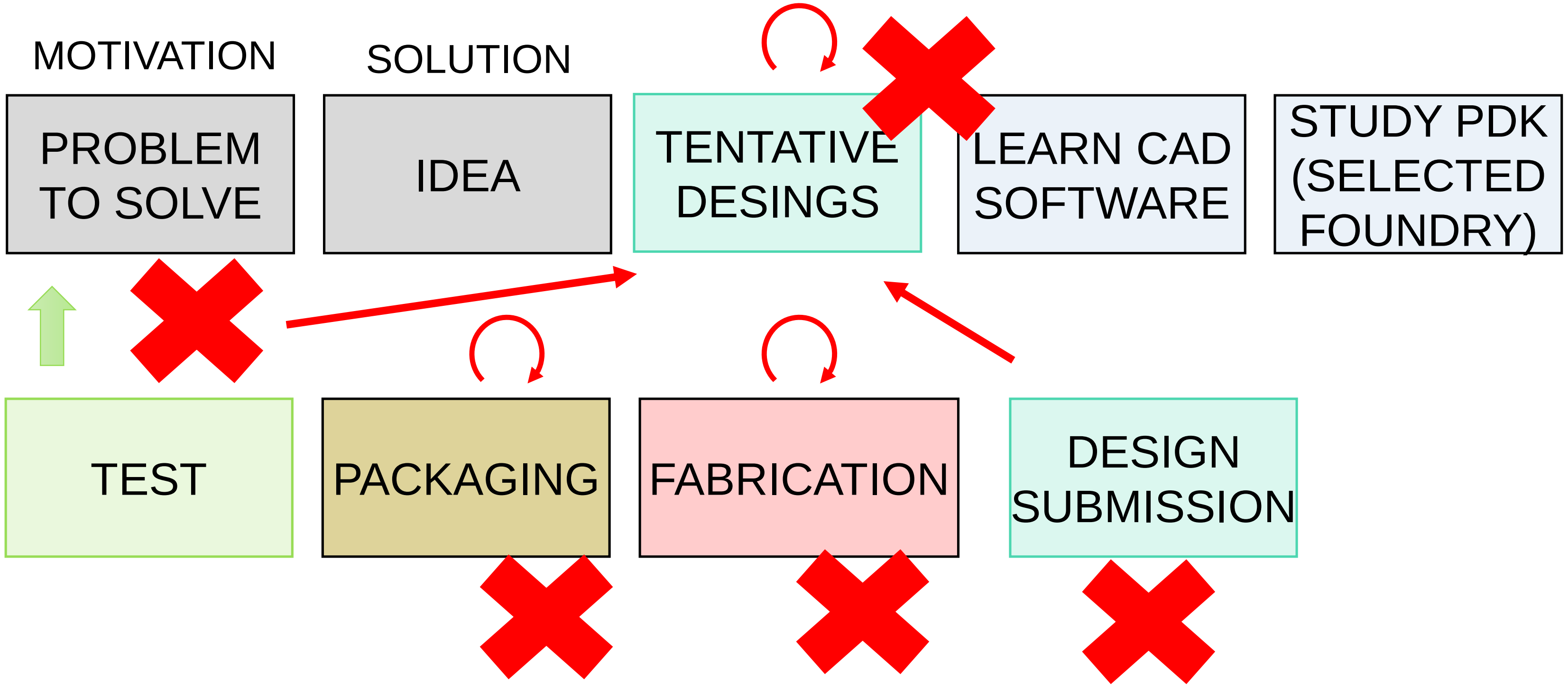
Integrated microwave photonics

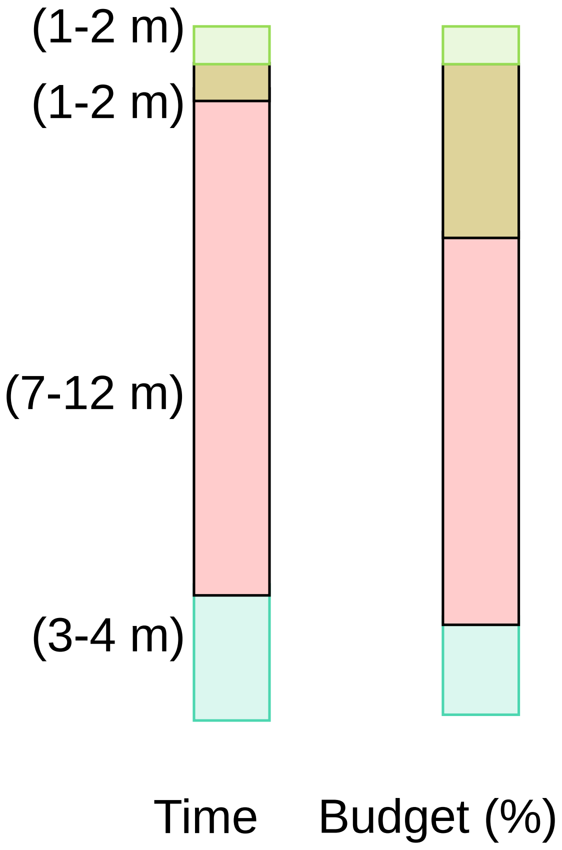
David Marpaung[1*], Jianping Yao[2] and José Capmany[3]

NATURE PHOTONICS | VOL 13 | FEBRUARY 2019 | 80–90 | www.nature.com/naturephotonics

2019

ASPIC Limitations





A failure at any stage origins iteration loops in the design procedure

12-24 months > 200 k€

Iteration runs no included

ERC-ADG-2016 UMWP-Chip Project

European Research Council

Established by the European Commission

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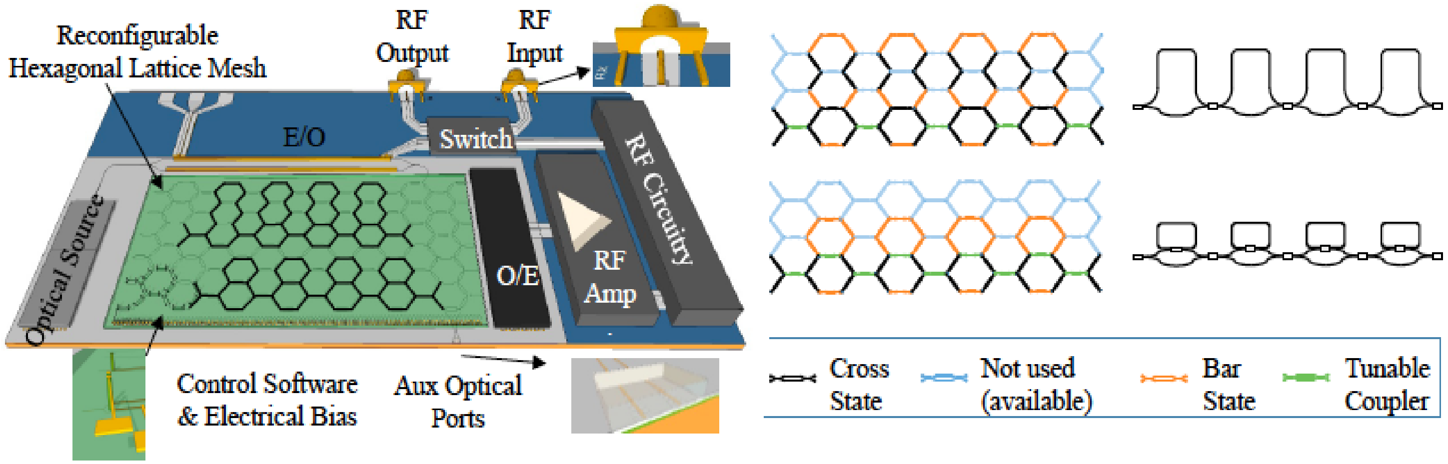
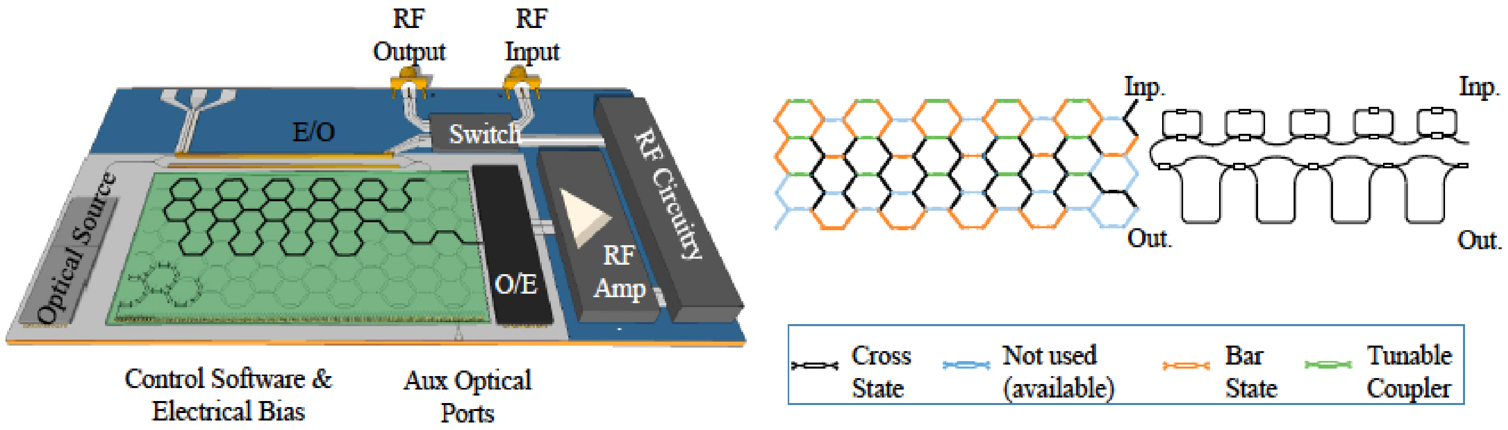
The main objective of UMWP-CHIP is the design, implementation and validation of a universal integrated microwave photonics programmable signal processor, capable of performing the most important MWP functionalities featuring unique broadband and performance metrics,





ERC-ADG-2016 UMWP-Chip Project

European Research Council
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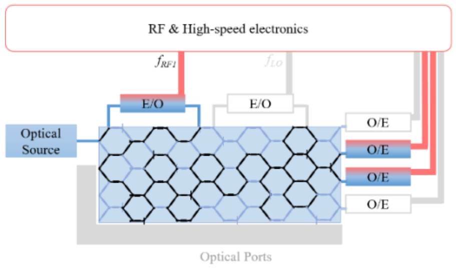
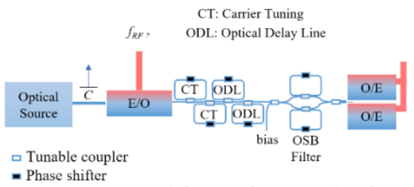
Target functionalities

(a)

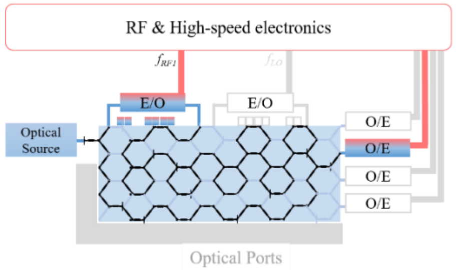
SCT True Time Delay Line

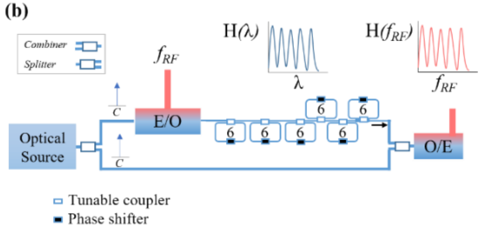




(b)

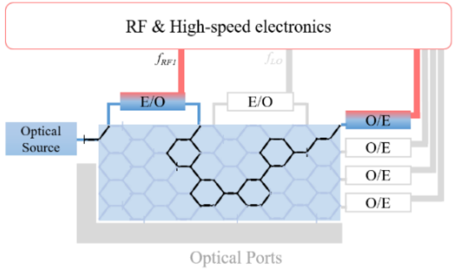
Self beating Rf Filter

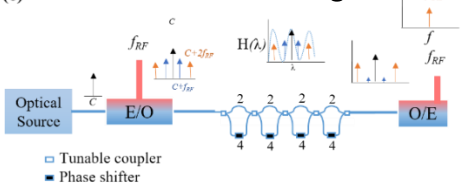




(c)

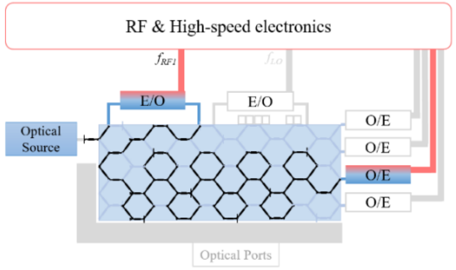
mm-wave tone generator

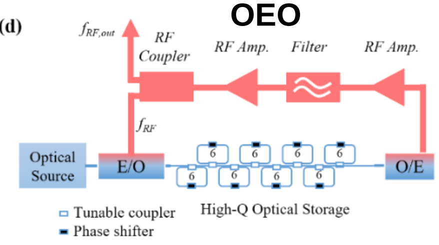




(d)

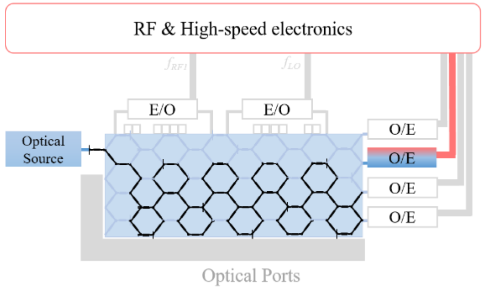
OEO

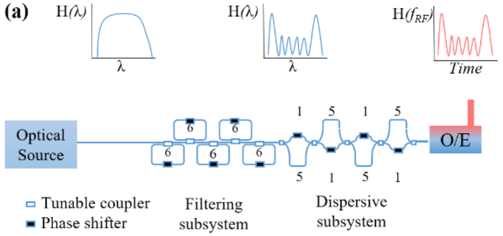




Wavelength to time mapping AWG

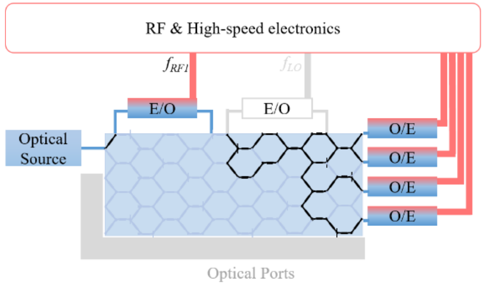
(a)

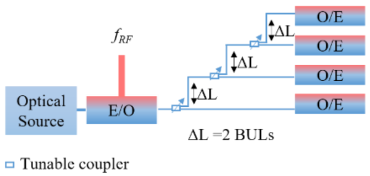




(b)

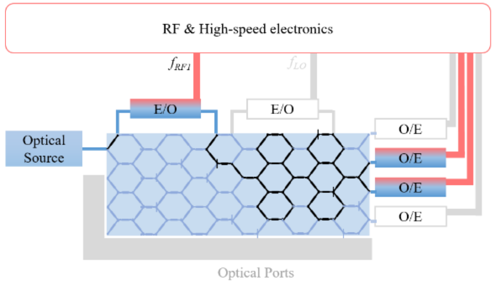
Beamforming network

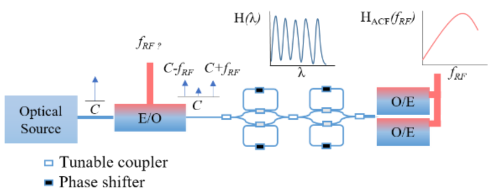




(c)

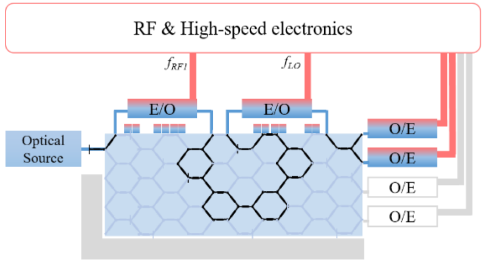
Instantaneous freq measurement

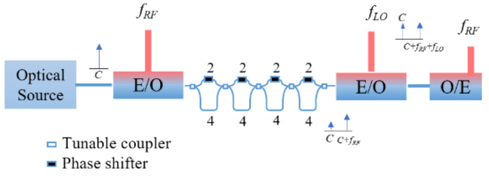




(d)

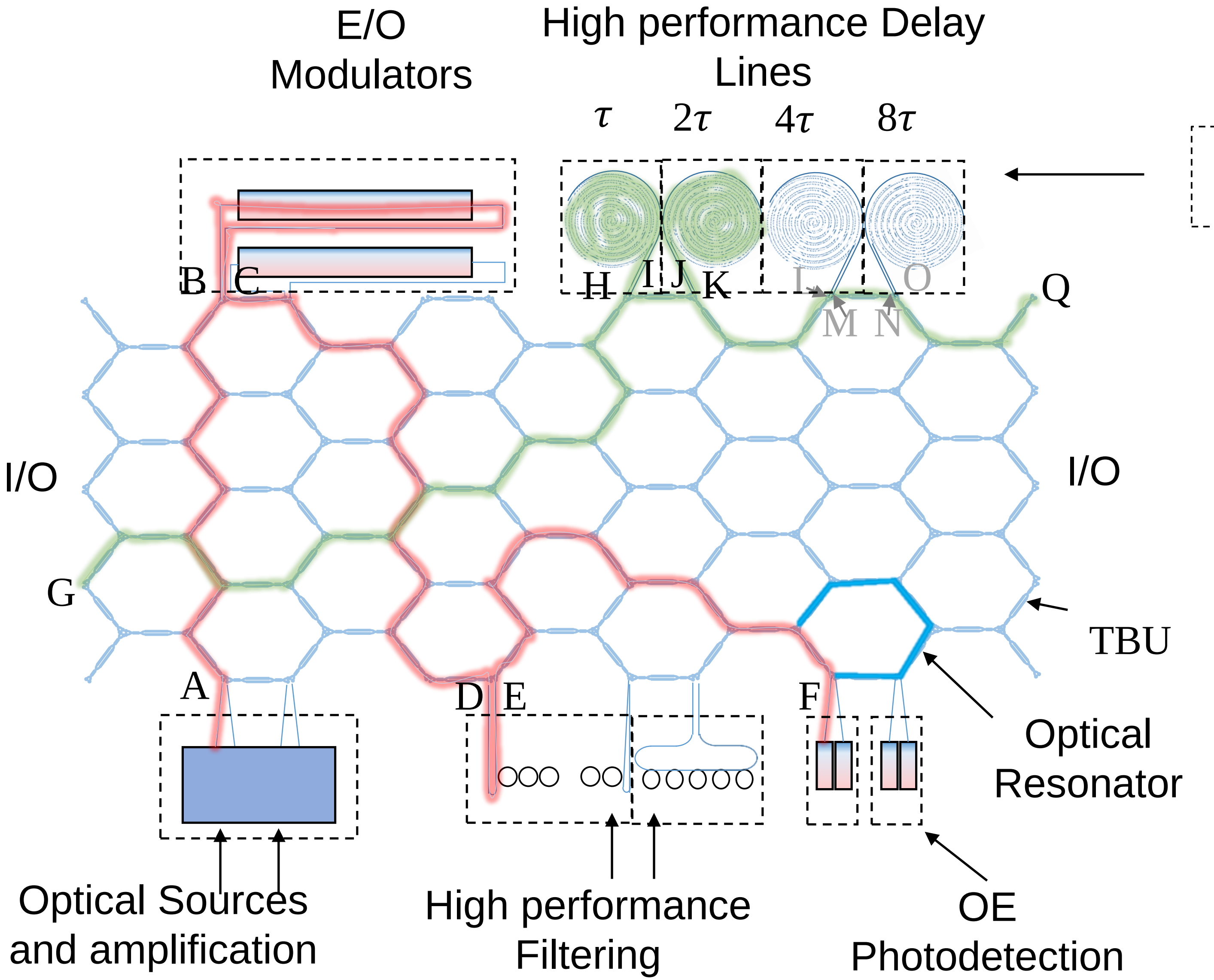
Up/down converter



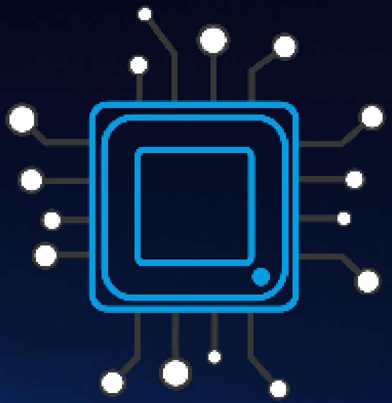


Beyond ERC-ADG-2016→ERC-POC-2019 FPPAS

Outsourcing special blocks outside the core



This configuration is novel in photonics, but certainly not (with some important differences) in electronics



Programmable Electronics vs Photonics

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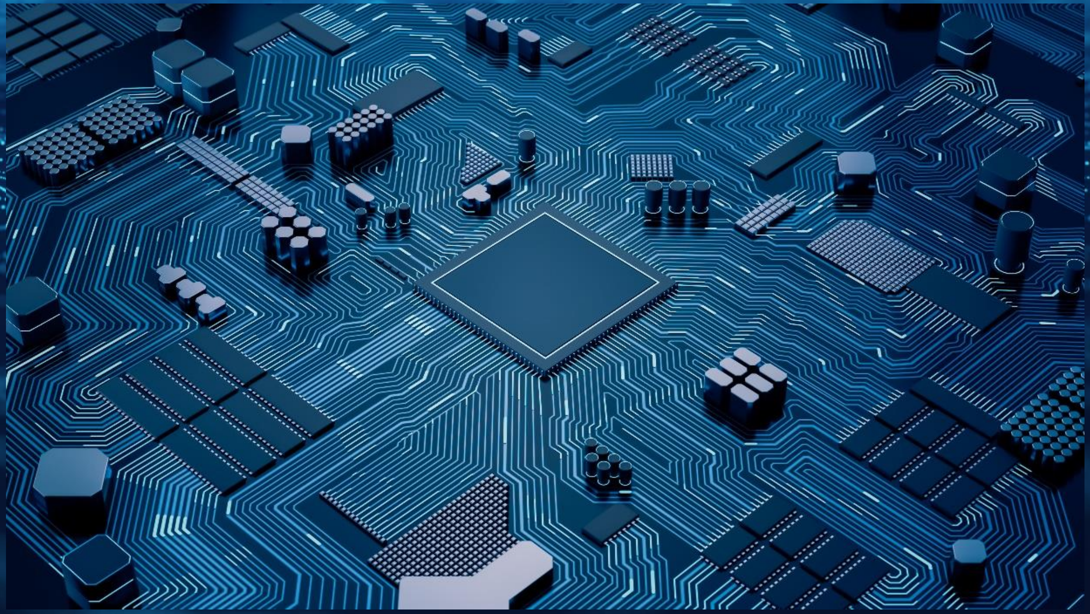
Some comparisons and lessons



Reusability in ITC systems

***Re-usability | versatility | flexibility | Programmability* are key features in past and future revolutions**

SpaceX believes a fully and rapidly ***reusable*** rocket is the pivotal breakthrough needed to substantially reduce the cost and reduced development times of space access:

*“60 000 000 $ total project cost, used 1000 times, becomes **three-order magnitude reduction** in space missions' costs. ”*

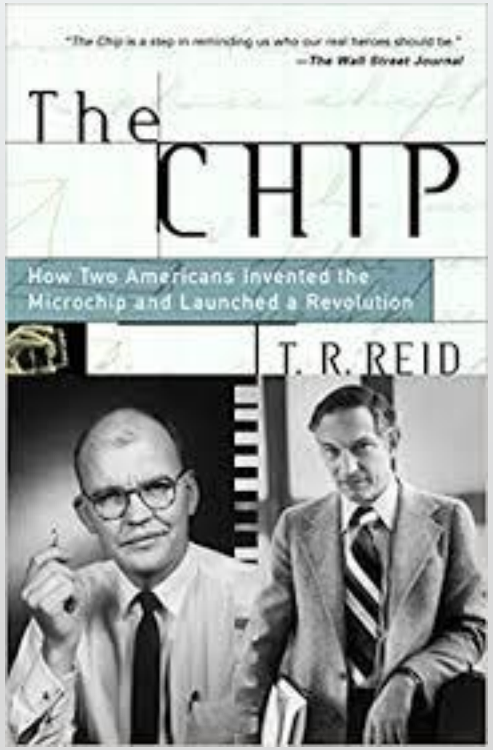
- In **Electronics**: FPGAs instead of ASICs
- In **networks**: SDN instead of ad-hoc topologies and configurations
- In **radio**: Software radio instead of specific RF receivers

Birth of Programmable Electronics

….By the end of the sixties, Noyce was worried about the rapid proliferation of different integrated circuits, each designed for its own special purpose……

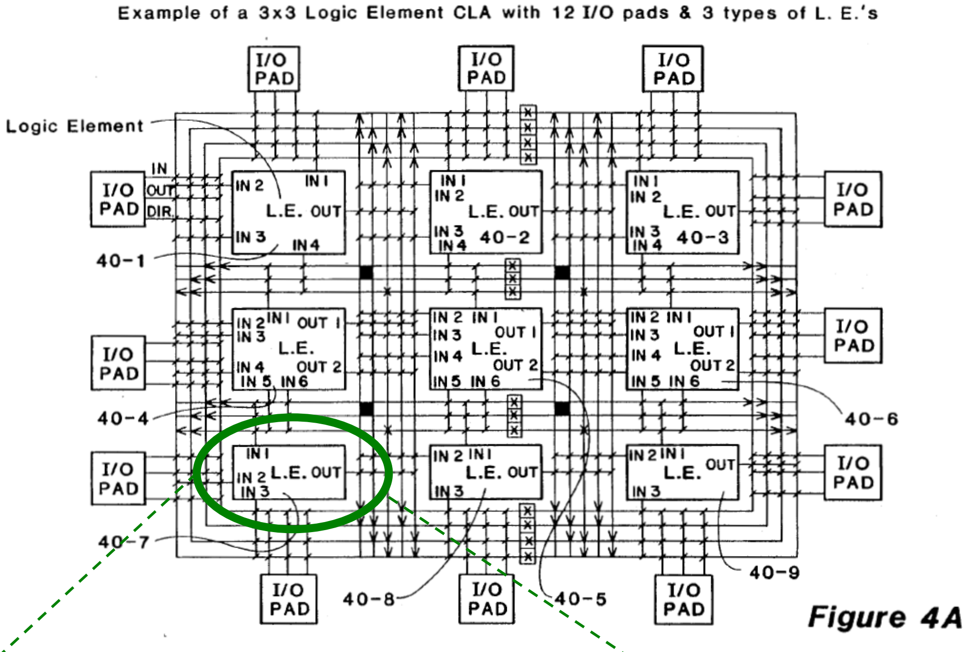
…Looking ahead, Noyce saw that the solution to proliferation of special-purpose integrated circuits would be the development of general-purpose chips that could be manufactured in huge quantities and adapted ("programmed") for specific applications.

T.R. Reid "The Chip: How Two Americans Invented the Microchip and Launched a Revolution"



FPGA Fast Refresher

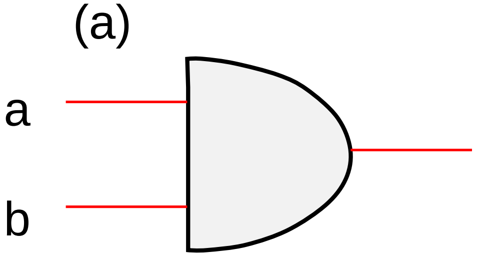
FPGAs are mainly built using **irreversible 2x1 gates** defined by truth tables
FPGAs work with **digital signals** and **Boolean Algebra**



James Barnet

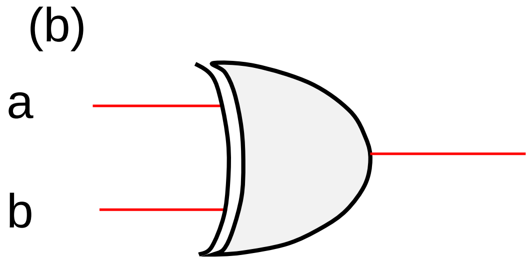
Ross Freeman

Bernie Voderschmitt



a AND b

a	b	a AND b
0	0	0
0	1	0
1	0	0
1	1	1



a XOR b

a	b	A XOR b
0	0	0
0	1	1
1	0	1
1	1	0

Why FPGAS in Electronics?

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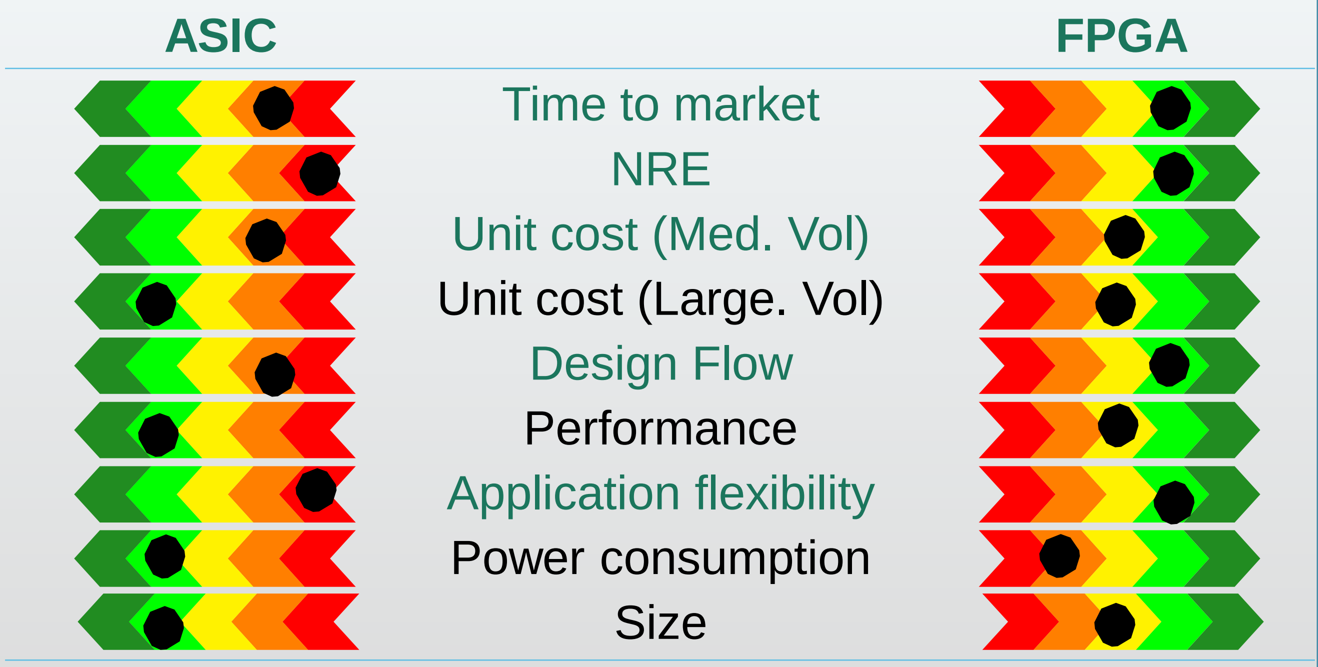
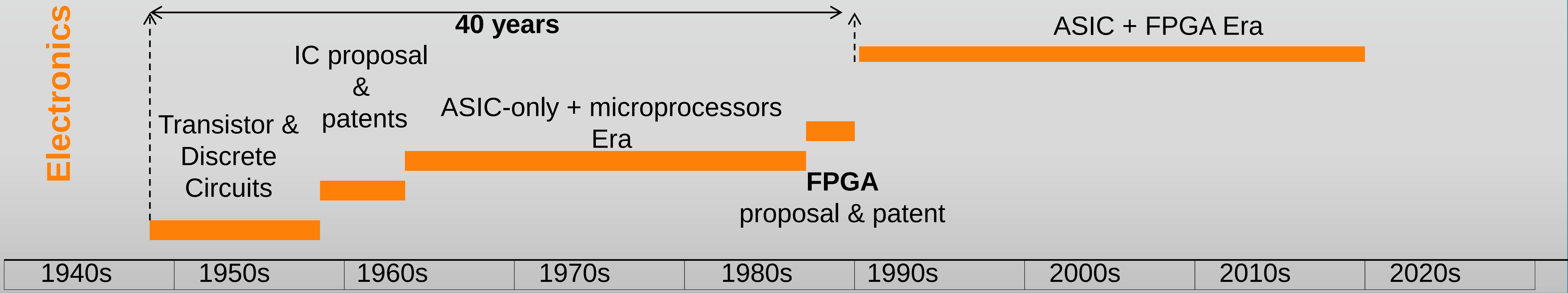
Electronic Integrated Circuit second revolution: reconfigurable ICs.
Currently, programmable and multipurpose EICs represent more than 50% of the market.





Electronics/Photonics: a parallel evolution?

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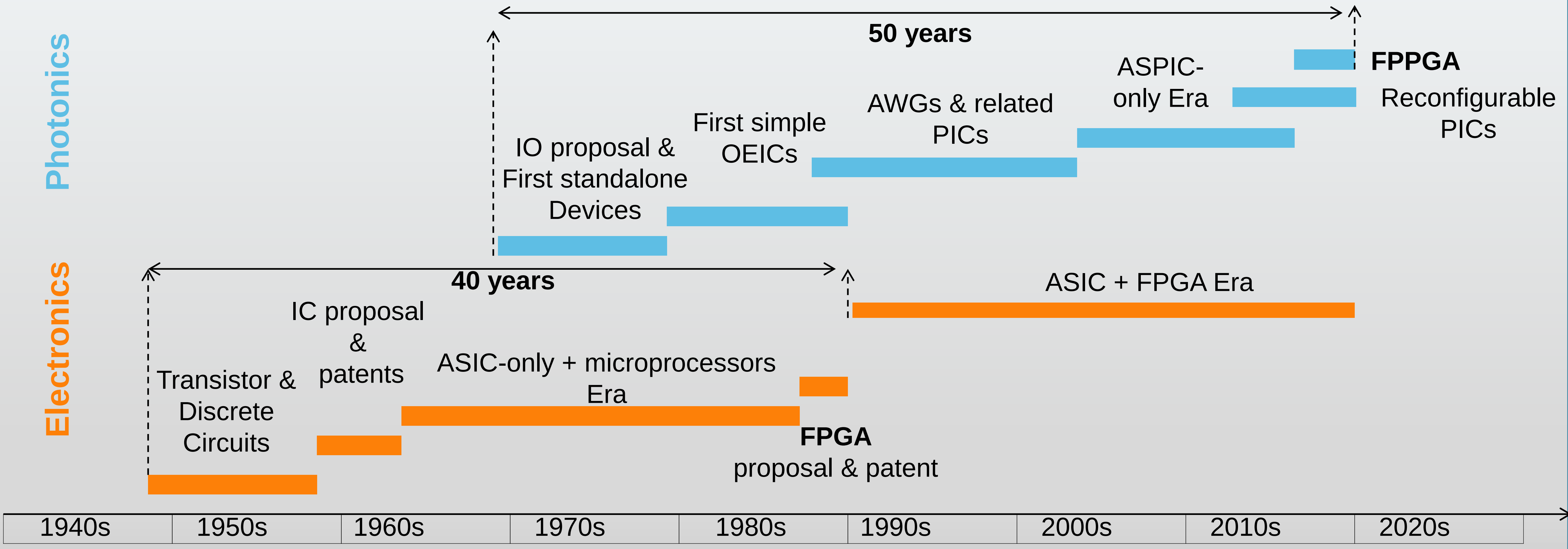
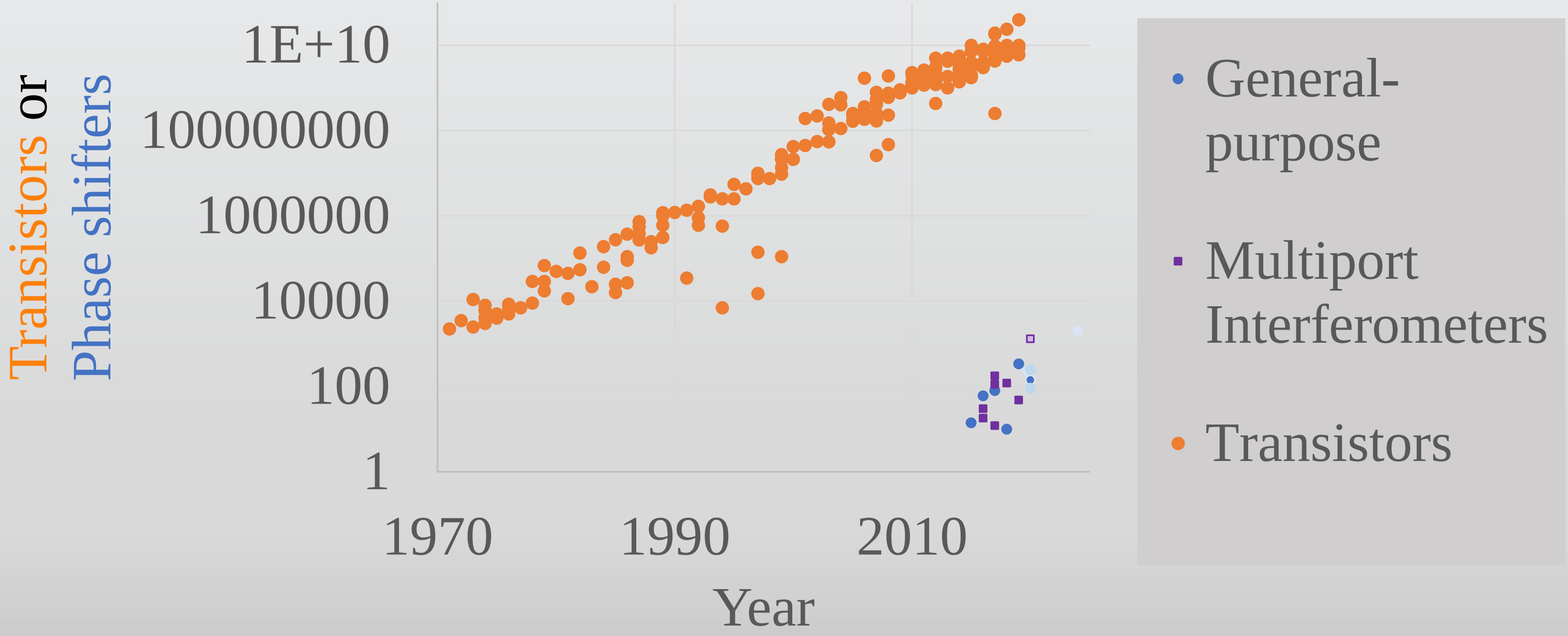


Electronics/Photonics: a parallel evolution?

Are we in front of another observational law in semiconductor technologies?



Evolution steps in Programmable Photonics

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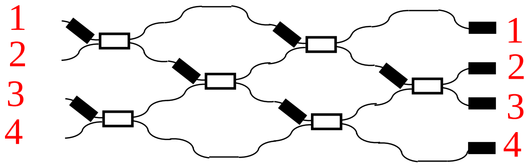
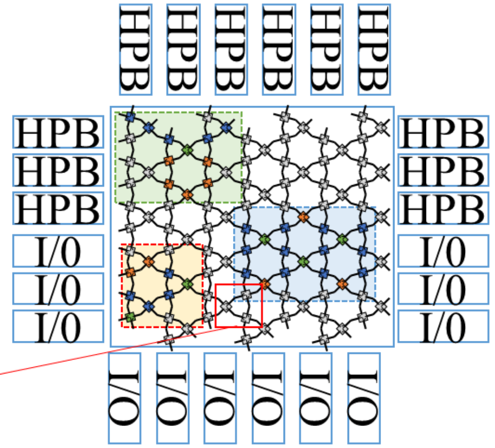
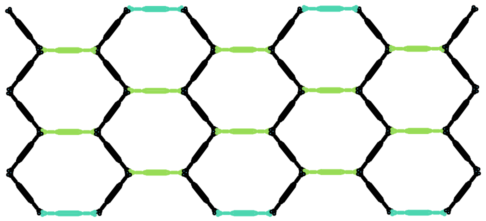
FPPGA



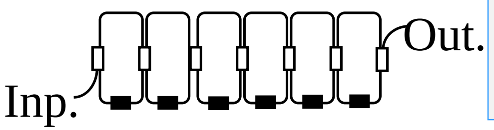
Programmable Multifunctional PICs



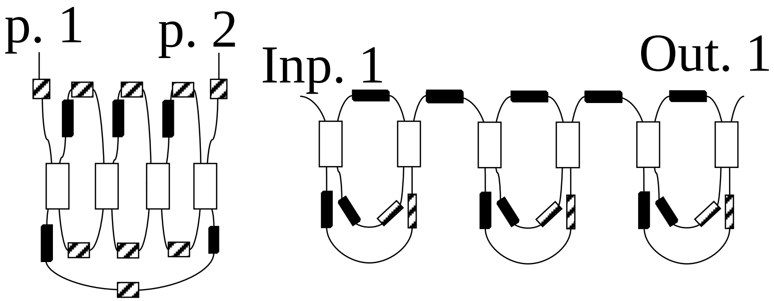
Multiport **Interferometers**



FEW-FUNCTIONAL **ASPICS**



Reconfigurable ASPICS



Semiconductor Optical Amplifier (SOA) | Phase shifter | Tunable Coupler

Some Relevant Literature in Programmable Photonics

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[1] M. Reck, A. Zeilinger, H.J. Bernstein, P. Bertani. Experimental realization of any discrete unitary operator. Phys Rev Lett 1994, 73, 58–61.
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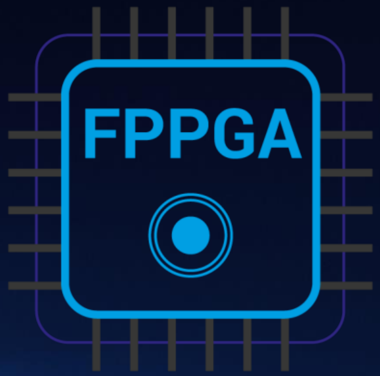
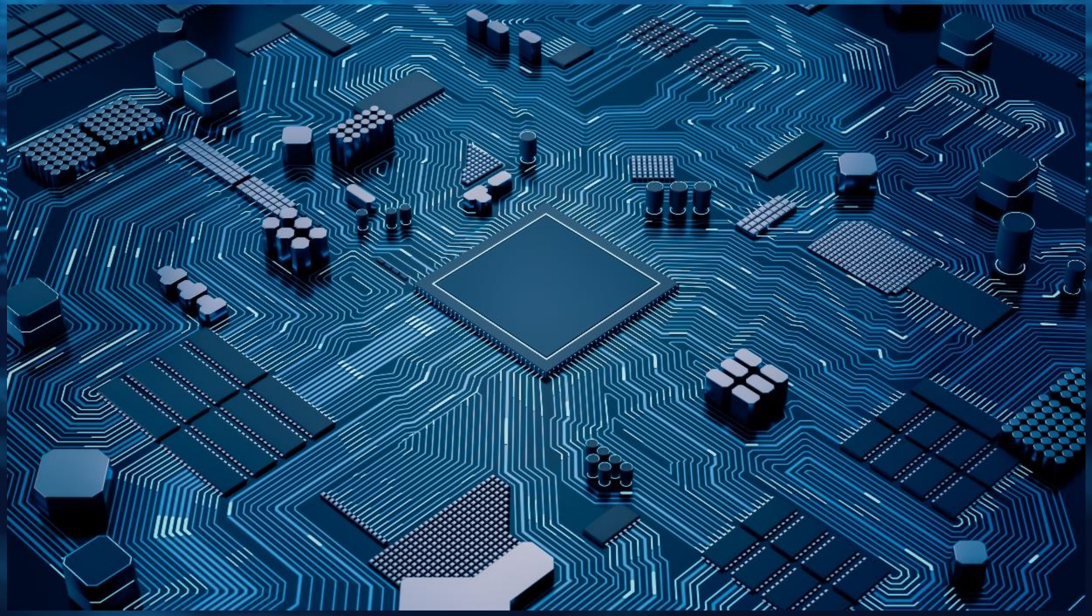
[17] A. Politi et al. Silica-on-silicon waveguide quantum circuits. Science 2008, 320, 646–9.



Programmable Photonics

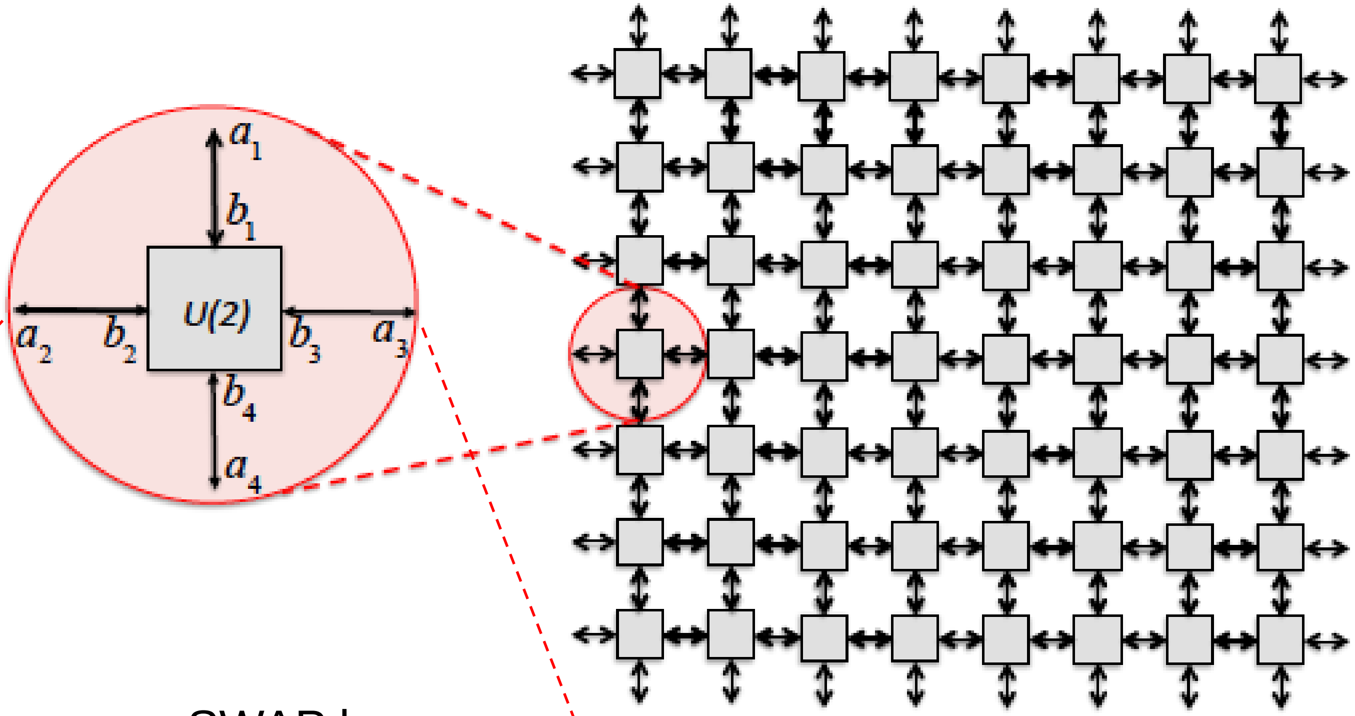
The Field Programmable Photonics Gate Array



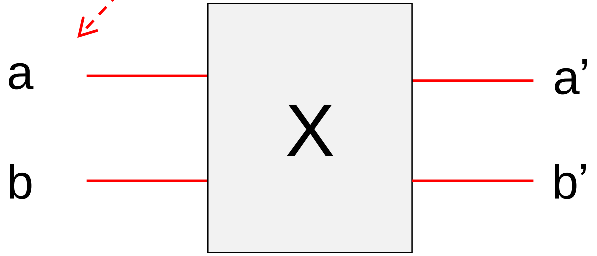
The basics

FPPGAs are built using a 2D mesh of interconnected **reversible 2x2 unitary gates** implementing unitary analog transformations

FPPGAs work with **analog signals** and unitary **2x2 matrix Algebra U(2)**



a SWAP b



a	b	a’	b’
0	0	0	0
0	1	1	0
1	0	0	1
1	1	1	1

$$U = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

FPPGA

The basics

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Reversible gates are built by transforming the **Pauli Matrices**, which are well known in quantum information

$$s_o = I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; \quad s_1 = X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix};$$

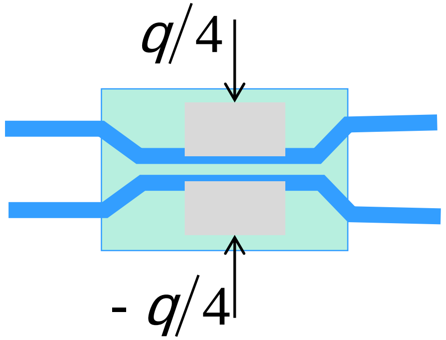
$$s_2 = Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \quad s_3 = Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

The required transformations are known as **Rotations**

The basics

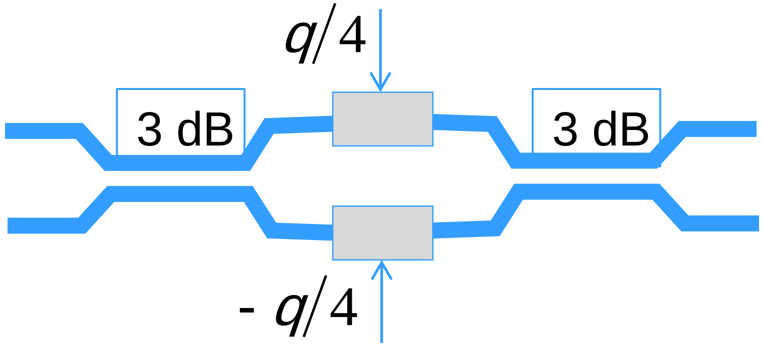
Rotations have simple physical implementations in integrated photonics

$$R_x(q) = e^{-i\frac{q}{2}X} = \begin{pmatrix} \cos(q/2) & i\sin(q/2) \\ i\sin(q/2) & \cos(q/2) \end{pmatrix}$$



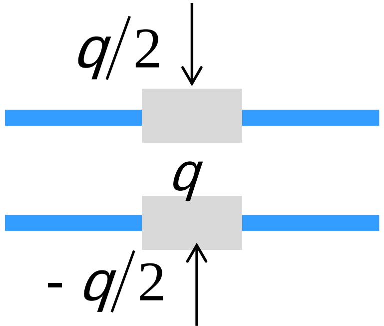
Dual drive directional coupler

$$R_y(q) = e^{-i\frac{q}{2}Y} = \begin{pmatrix} \cos(q/2) & -\sin(q/2) \\ \sin(q/2) & \cos(q/2) \end{pmatrix}$$



Dual drive 3 dB Balanced MZM

$$R_z(q) = e^{-i\frac{qZ}{2}} = \begin{pmatrix} e^{-i(q/2)} & 0 \\ 0 & e^{i(q/2)} \end{pmatrix}$$



Two parallel waveguides with opposite phase shifts

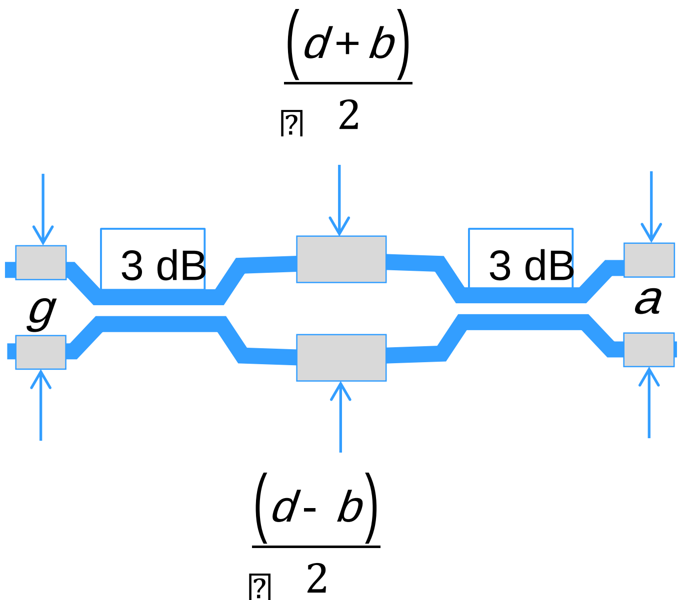
The basics

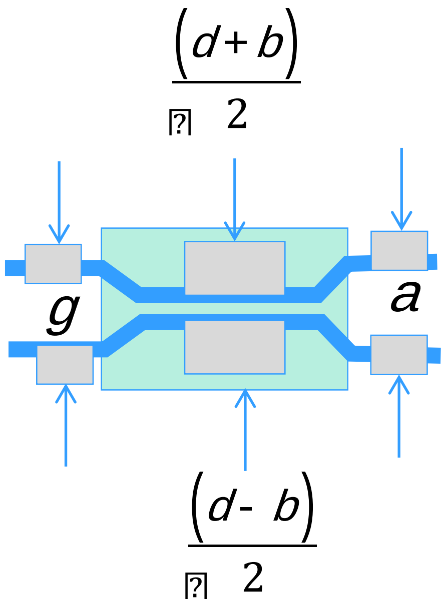
Rotations are key because **any unitary 2x2 matrix transformation** can be obtained using the following cascade of rotation matrices:

$$U = e^{jd} R_z(a) R_y(b) R_z(g)$$

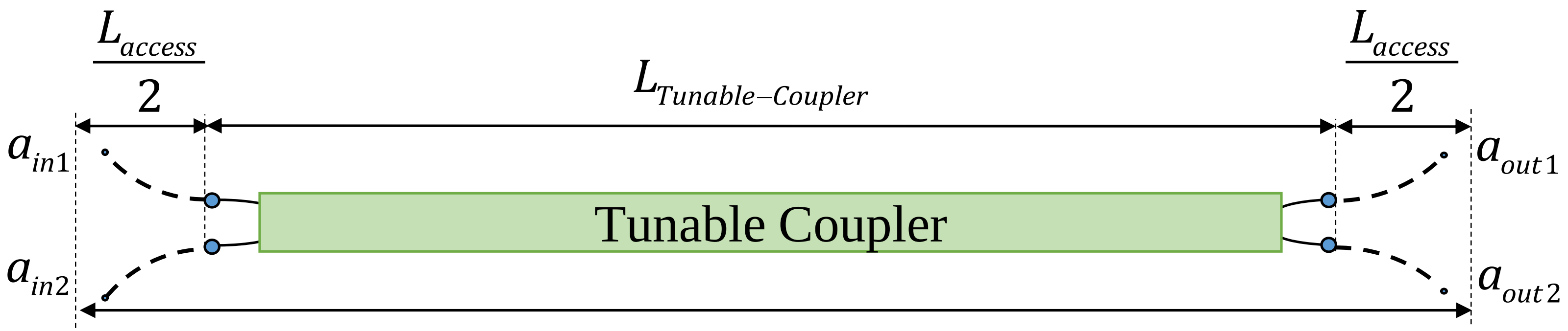
$$U = e^{jd} R_z(a) R_x(b) R_z(g)$$

The former prescriptions (others are possible) allow two options for the compact photonic implementation of any unitary 2x2 matrix

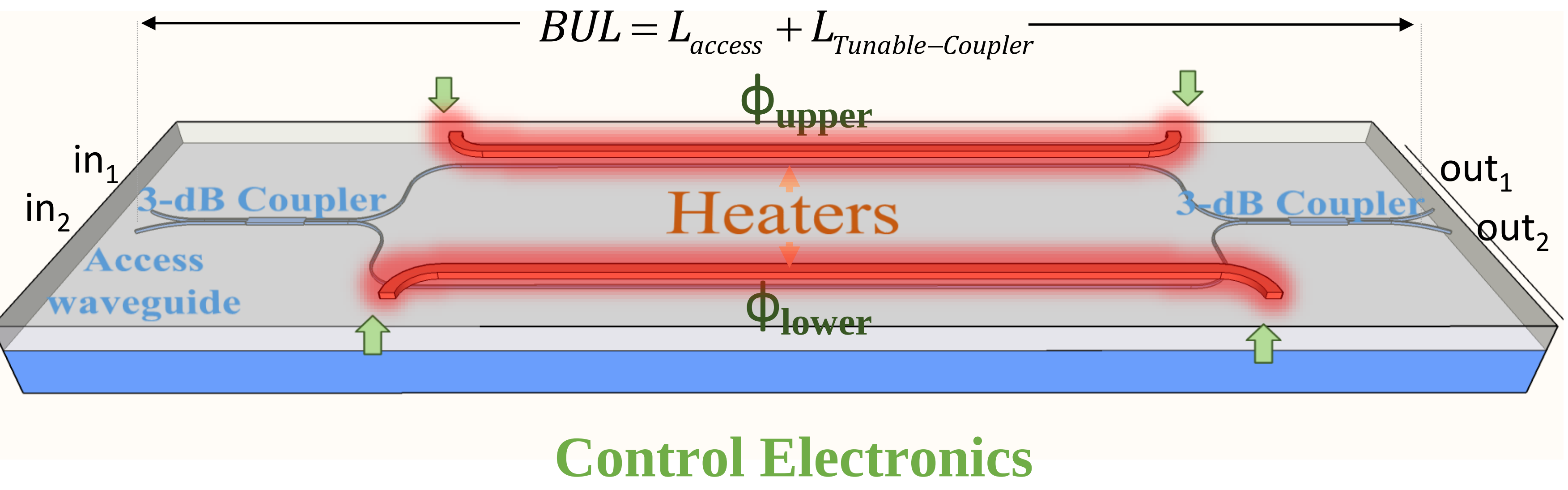


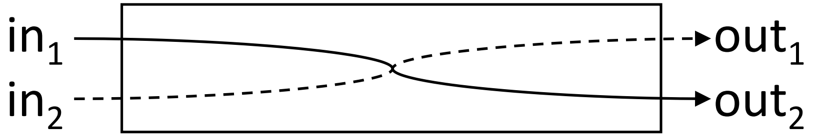


Example: ZYZ implementation



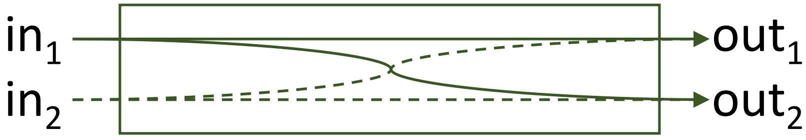
$$BUL = L_{access} + L_{Tunable-Coupler}$$





θ = 0
Cross-state (CS)

θ = π/2
Bar-state (BS)



θ = [0,π/2]
Tunable coupler (TC)

TBUs can also be activated by carrier injection modulation

The basics

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Feedforward signal processing architectures

Any unitary nxn transformation can be implemented by means of n(n-1)/2 two dimensional unitaries (Hurwitz, 1897).

Ueber die Erzeugung der Invarianten durch Integration.

Von

A. Hurwitz in Zürich,

correspondirendem Mitgliede der Gesellschaft.

Vorgelegt von dem vorsitzenden Secretär in der Sitzung am 6. März 1897.

die orthogonale Substitution

$$(15)\quad \begin{cases} x_\alpha = \cos\varphi \,.\, x'_\alpha + \sin\varphi \,.\, x'_{\alpha+1}, \\ x_{\alpha+1} = -\sin\varphi \,.\, x'_\alpha + \cos\varphi \,.\, x'_{\alpha+1}, \\ x_\beta = x'_\beta. \end{cases}$$

Nun nehme man $\frac{n(n-1)}{2}$ Winkel

- Triangular (Reck et al, 1994)
- Rectangular (Clements et al, 2016)

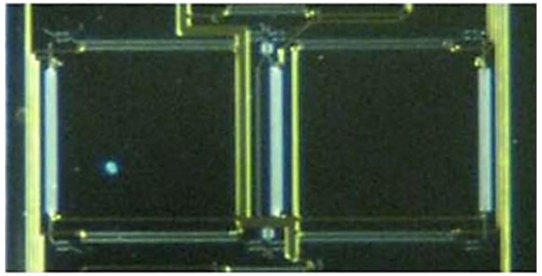
Feedbackward signal Processing archtectures

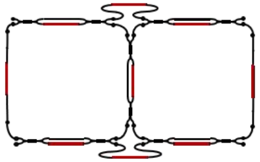
IIR & FIR+IIR structures can be implemented by cascading full 2x2 unitary transformations and partial 1x1 and 1x2 transformations (Pérez et al 2017).

Core Implementations

(a)

2 Square Cells size: 3.5 x 8.5 mm   BUL= 3450 µm n_g= 1.72



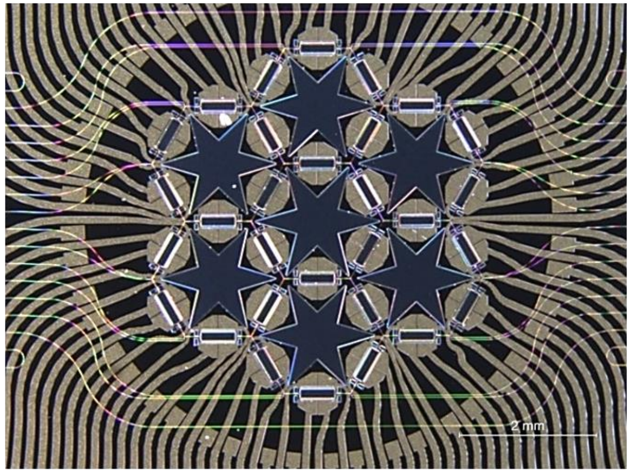


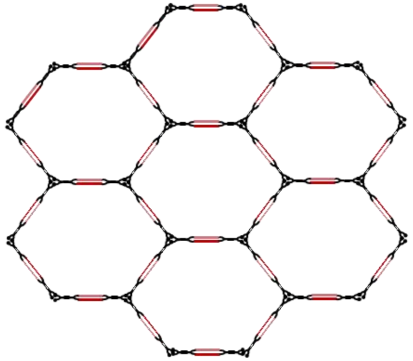
Phase Shifter
Waveguide

Zhuang, et. al.,(2015)

(b)

7 Hexagonal Cells size: 15 x 20 mm   BUL= 975 µm n_g= 4.18



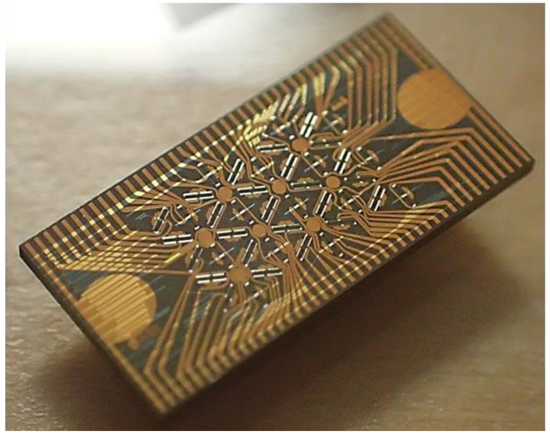


Phase Shifter
Waveguide

Pérez, et. al.,(2016)

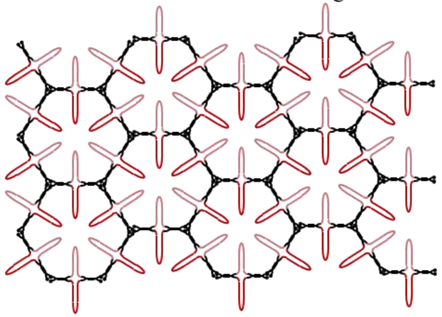
(c)

10 Hexagonal Cells size: 5.5 x 11 mm

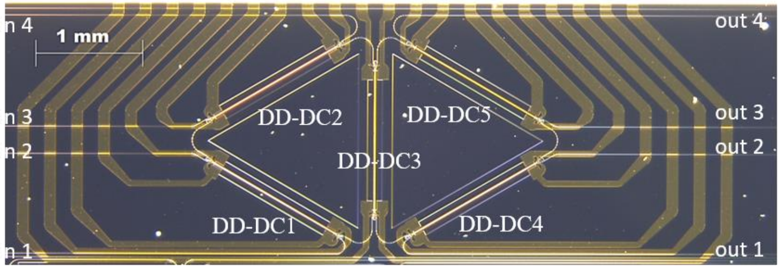


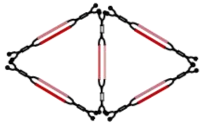
Pérez, et. al.,(2017)

BUL= 1315 µm n_g= 1.92



(d)

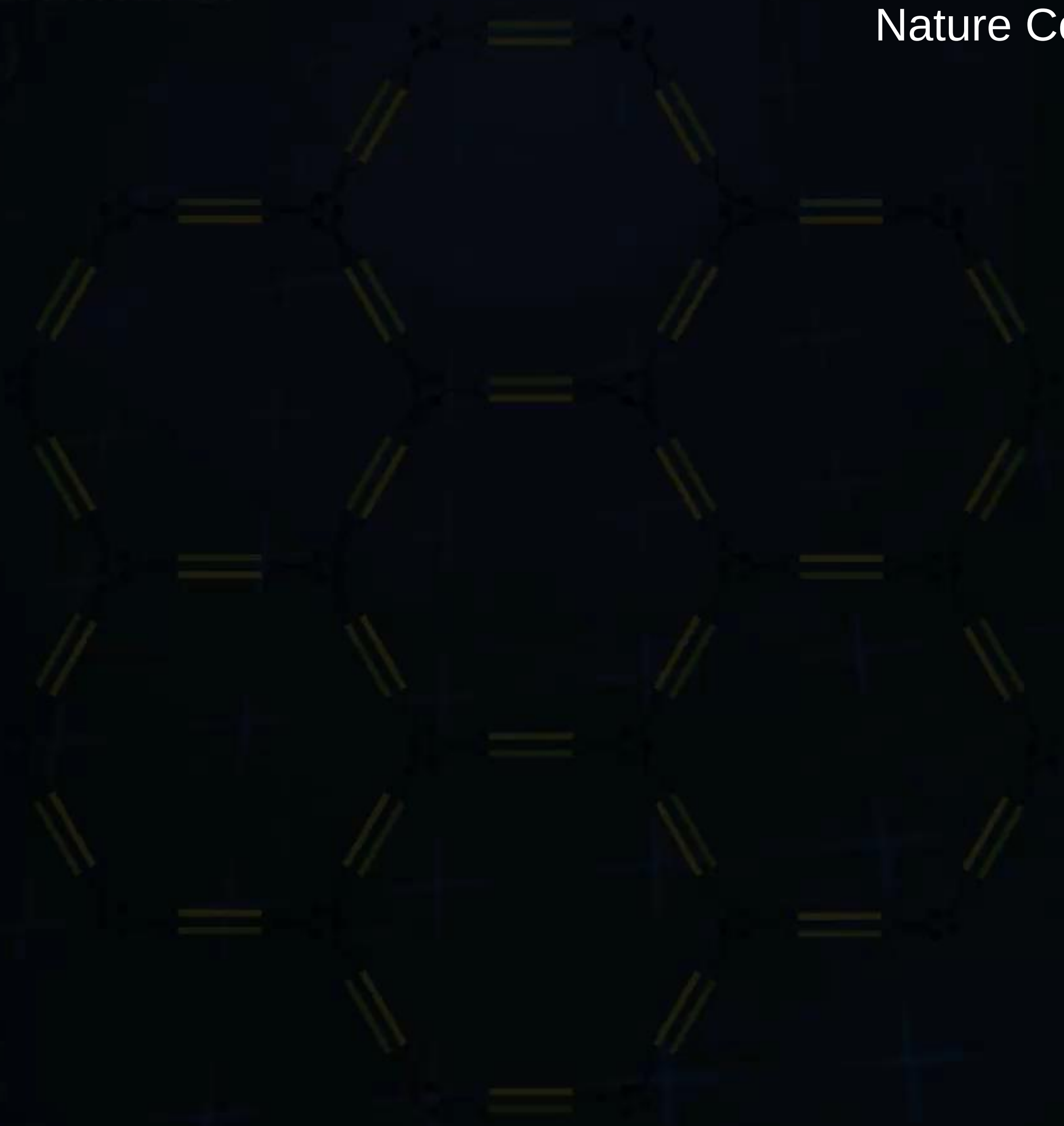




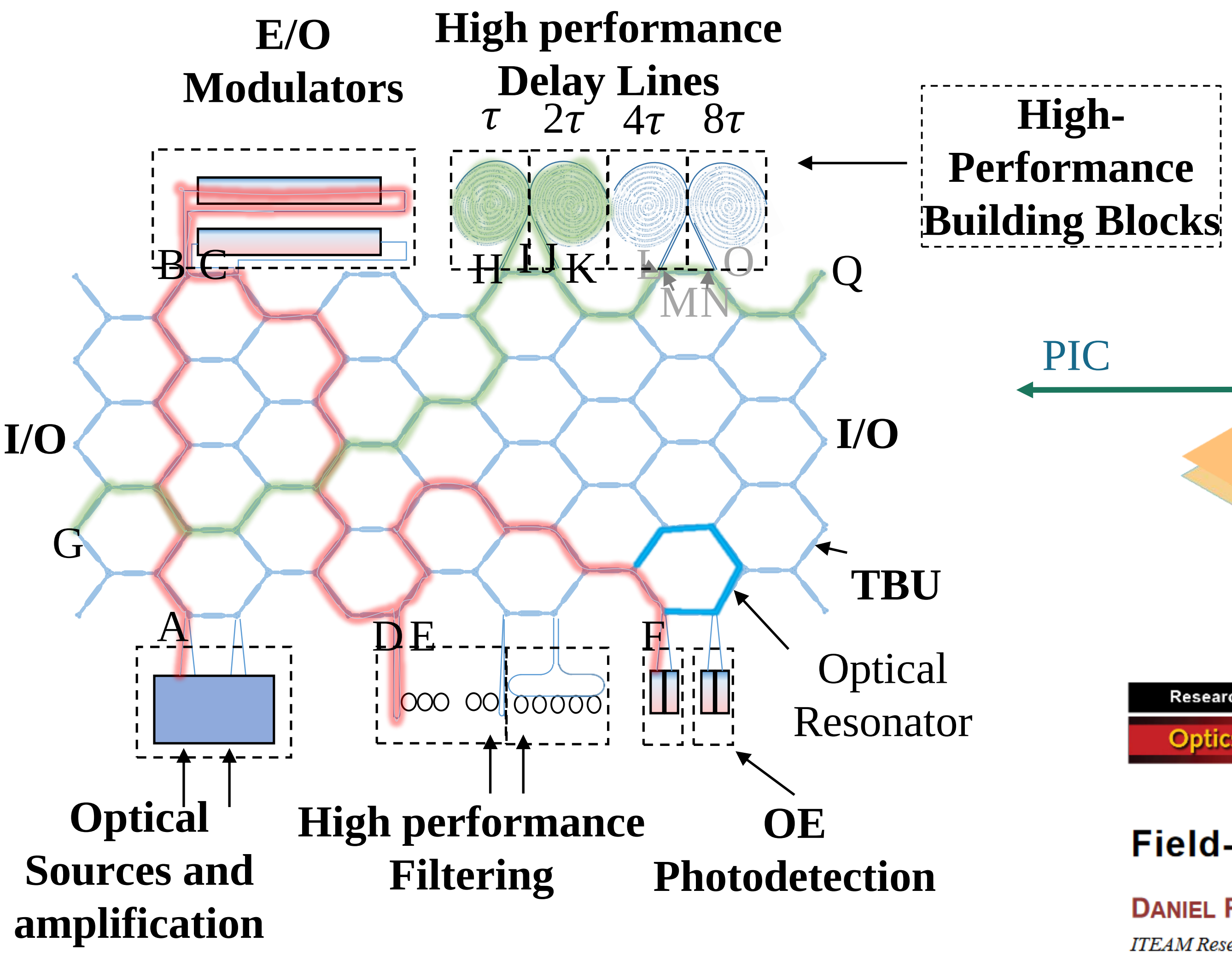
Phase Shifter
Waveguide

Pérez, et. al.,(2019)

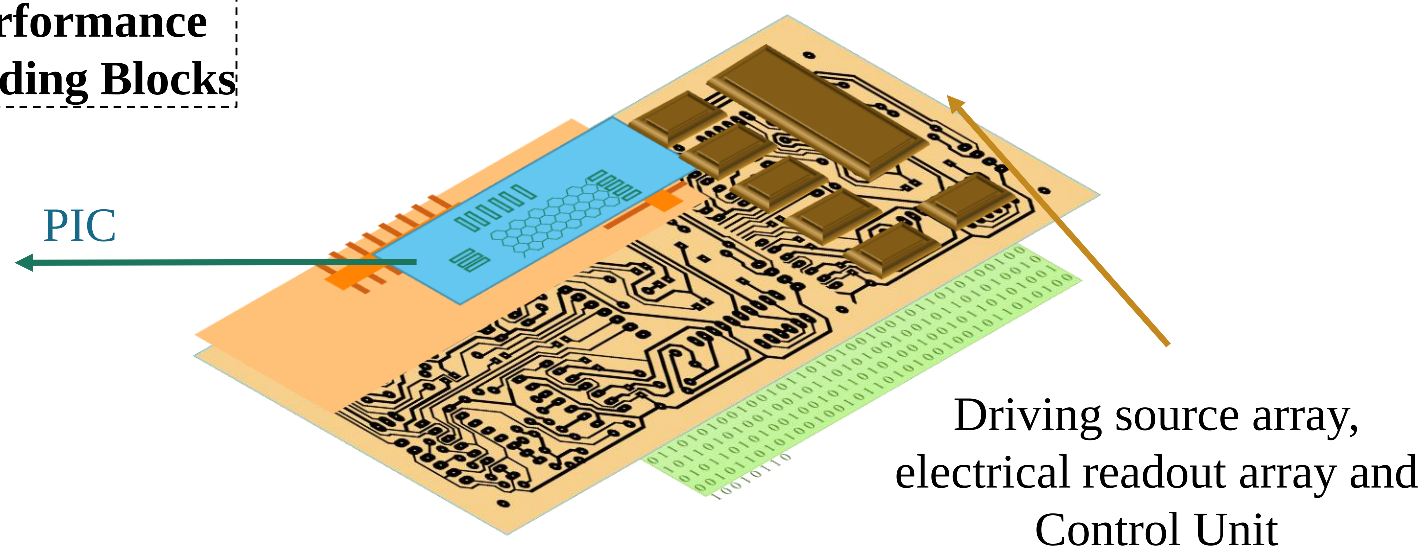
Nature Communications **8**, 636, 2017



Additional Hardware Elements



Tier 1: Photonics
Tier 2: Electronics and RF-mmW
Tier 3: Software & Control



Research Article Vol. 26, No. 21 | 15 Oct 2018 | OPTICS EXPRESS 27265
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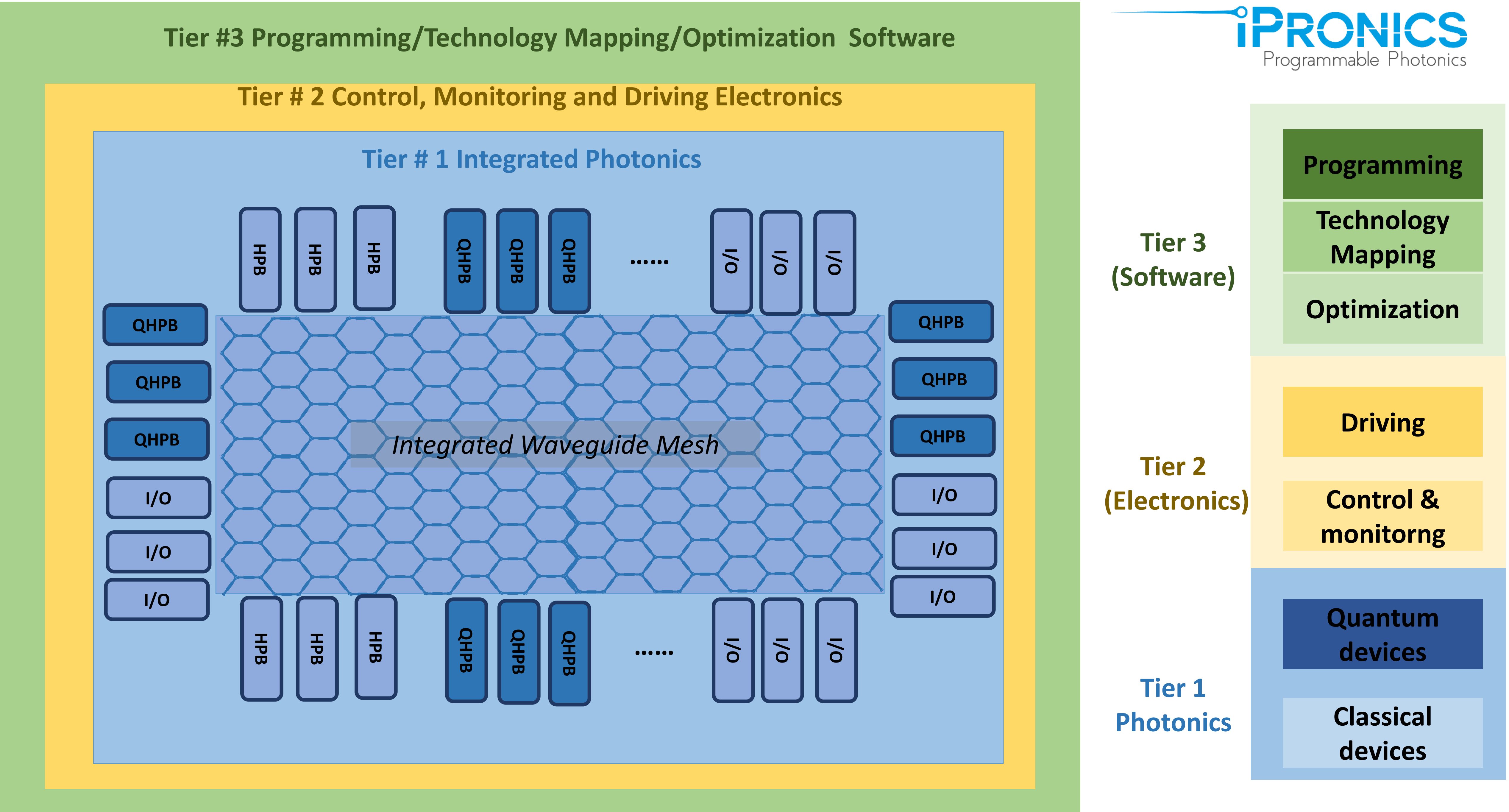
Field-programmable photonic arrays

DANIEL PÉREZ, IVANA GASULLA, AND JOSE CAPMANY*
ITEAM Research Institute, Universitat Politècnica de València, Camino de Vera 46022 Valencia, Spain
**jcapmany@iteam.upv.es*



Tier #3 Programming/Technology Mapping/Optimization Software
Tier # 2 Control, Monitoring and Driving Electronics
Tier # 1 Integrated Photonics
HPB
HPB
HPB
QHPB
QHPB
QHPB
......
I/O
I/O
I/O
QHPB
QHPB
QHPB
I/O
I/O
I/O
Integrated Waveguide Mesh
QHPB
QHPB
QHPB
I/O
I/O
I/O
HPB
HPB
HPB
QHPB
QHPB
QHPB
......
I/O
I/O
I/O
iPRONICS
Programmable Photonics
Tier 3
(Software)
Programming
Technology Mapping
Optimization
Tier 2
(Electronics)
Driving
Control & monitorng
Tier 1
Photonics
Quantum devices
Classical devices

iPRONICS
Programmable Photonics

	Waveguide Mesh	HPBs	I/O	QHPBs
Quantum devices				- *Spiralled nanowire SFWM single Photon sources* - *CROW single photon SFWM sources* - *Integrated Bragg+ Ring cavity SFWM single Photon sources* - *Integrated Single photon detectors* *-Ancilla qbit readers*
Classical devices	- *NxN programmable Linear mode transformers* - *Tunable filers* - *Switches* *Delay lines*	- *Photodetectors* - *Optical sources* - *Tunable filters* - *Switches* - *Modulators* - *Delay lines*	- *Chip-chip couplers* - *Chip-fiber couplers*	

Hardware Scalability challenges

Power consumption

Accumulated optical loss

Electrical Interfacing

System integration

Optical monitoring points.

Optical crosstalk

Tuning crosstalk

Some of them can be mitigated by a smart software layer and thanks to the massively interconnected nature of the FPPGA core.

Software Challenges

Control and operation based on **global algorithms and presets**

- Requires the pre-characterization of the FPPGA core.
- Includes preset configurations, auto-routing algorithms, user-defined configurations.

Control and operation based on **computational optimization algorithms**

- Enables *self-configuring*, *self-healing*, *black-box optimizations* and *mitigates non-ideal operation* of photonic components.

High Level Description and specification language

- To enable the high-level programming of the FPPGA resources.

Control and operation based on **global algorithms and presets**

Develop / compute control vectors for each configuration:

$C_1 = [\, H01_U,\ H01_D,\ H02_U,\ H02_D,\ \ldots,\ H30_D]$

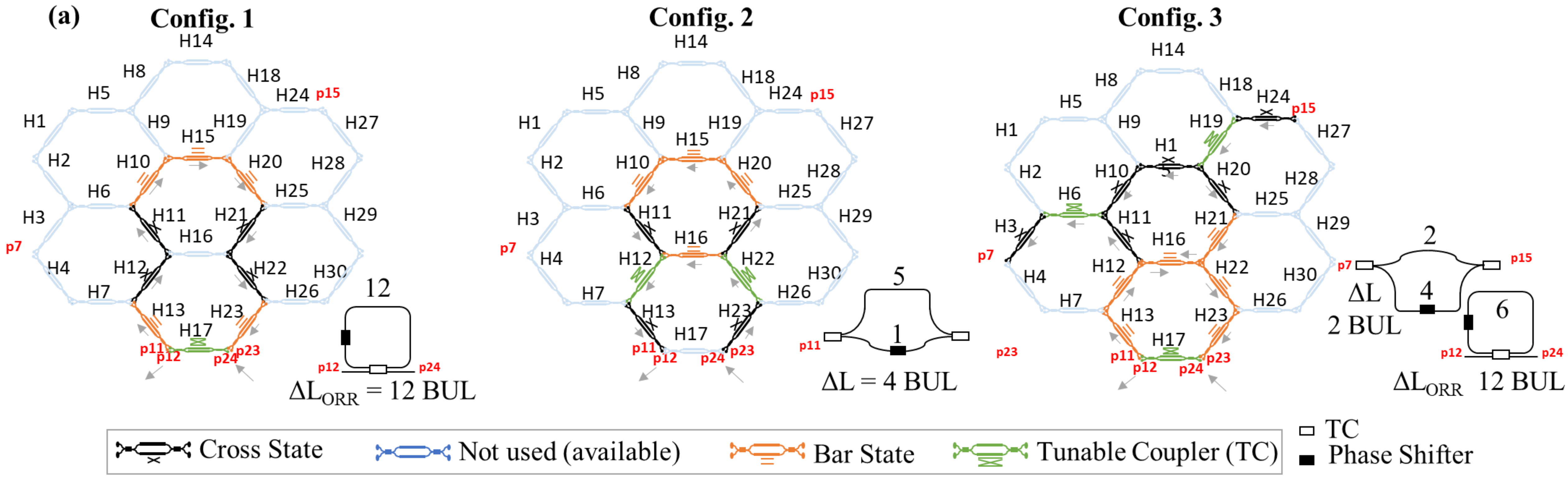
$C_2 = [\, H01_U,\ H01_D,\ H02_U,\ H02_D,\ \ldots,\ H30_D]$

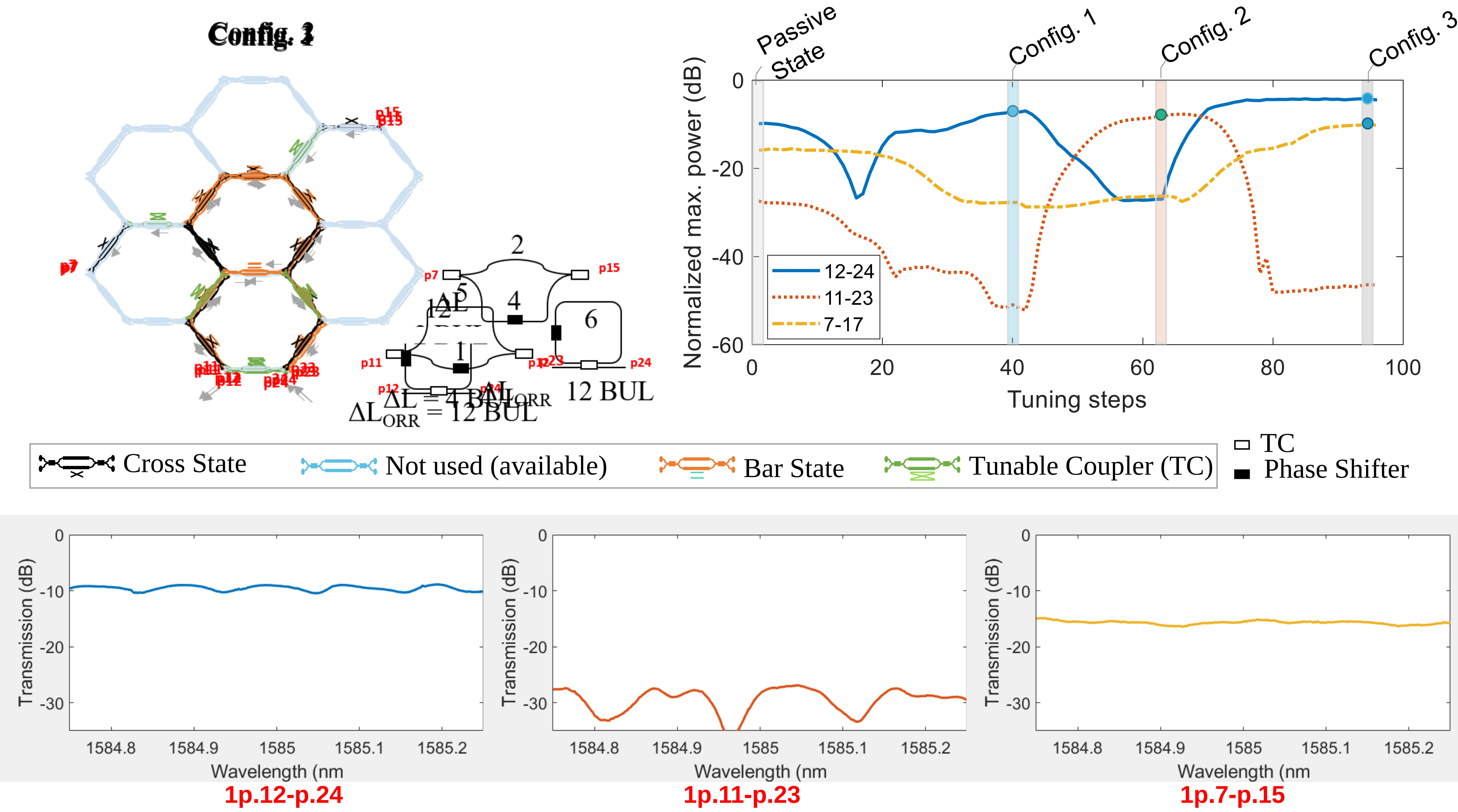
$C_3 = [\, H01_U,\ H01_D,\ H02_U,\ H02_D,\ \ldots,\ H30_D]$

Predefined pre-sets.

A. López *et al., presented at ECOC 2019.*

J. Capmany, D. Pérez, "Programmable Integrated Photonics", in press Oxford University Press (2019)





p7
p15
p11
p12
p23
p24
2
4
6
1
12 BUL
Passive State
Config. 1
Config. 2
Config. 3
Normalized max. power (dB)
Tuning steps
12-24
11-23
7-17
Cross State
Not used (available)
Bar State
Tunable Coupler (TC)
TC
Phase Shifter
Transmission (dB)
Wavelength (nm
1p.12-p.24
1p.11-p.23
1p.7-p.15

FPPGA

Applications

iPRONICS
Programmable Photonics

5G and Beyond

Bio instruments

Internet of Things

Neurocomputing and AI

HW acceleration

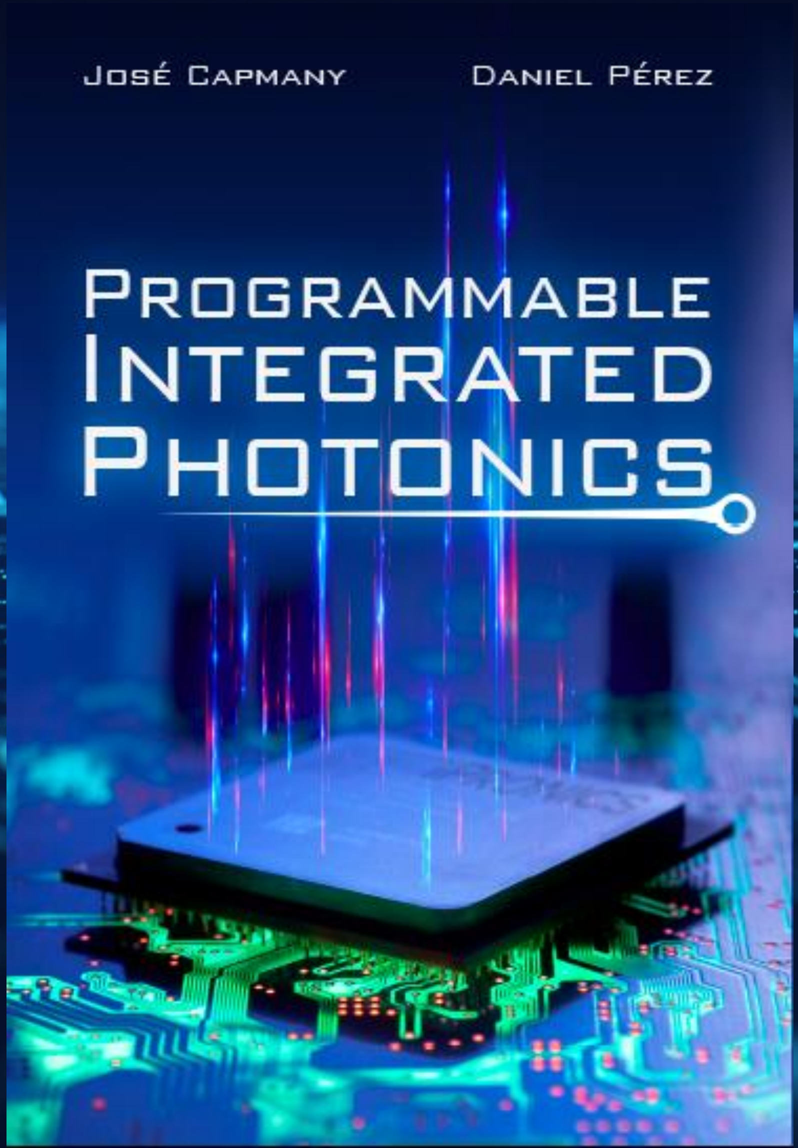
Transport

Quantum Information

Sensors

More Information?, stay tuned

iPRONICS
Programmable Photonics



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Jan-Feb 2020

Summary, Conclusions & Take Away Messages

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Programmable Photonics

Summary and Conclusions

iPRONICS Programmable Photonics

- MWP is becoming a key enabling technology in a variety of application scenarios
- For efficient penetration into these photonic **integration is key**
- A considerable number of Application Specific Photonic Integrated Circuits (**ASPICs**) **have** been reported with **a limited degree of functionality**
- Functionality and cost efficiency can be improved **by** means of **reconfigurability**. A general purpose programmable chip for MWP applications is under current R&D
- **Programmable chips with** the incorporation of **extra elements** (IP blocks, control electronics and specialized software) **enable the equivalent of the electronic FPGA**
- The FPPGA relies on different basic operations (analog vs digital) compared to electronics, but these are required to handle lightwave signals
- FPPGA applications span a myriad of fields other than MWP

Take Away Messages

Programmable Photonics is going to happen, YES or YES.

It shares commonalities with integrated Electronics

Yet it is completely different

iPRONICS
Programmable Photonics

INVENT THE FUTURE OF PHOTONIC INTEGRATION

www.ipronics.com

Programmable Photonic Protocols

FPPGA

AI-Machine Learning- algorithms

Advanced Optimization Routines

spin·off upv

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Oct 2019

Support Viegraphs

ww

Examples & extra technical material

Landmarks in programmable electronics

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1948
Transistor
Shockley Brattain, Bardeen

1956
Shockley Semiconductors
Shockley, Bob Noyce and Gordon Moore

1957
Fairchild
Fairchild, Noyce, Moore. *Integrated circuit, Moore's Law*

1968
INTEL
Noyce & Moore
4004 Memory chips

1972
INTEL
Hoff, Faggin, Shima, Mazor,
8080 microprocessor

1974
Zilog
Faggin
Freeman & Vonderschmitt,
Z80 microprocessor

1984
XilinX
Freeman & Vonderschmitt, *FPGA*

Is the right time for FPPAS?

Electronics

(1984-1991)

Age of Invention
- Cost containment
- Maximize efficiency in cost & functionality
- Eliminate waste in logic blocks
- Design efficient 2D interconnection
- Manual design, placement & routing
- Multi-Chip partitioning

(1992-1999)

Age of Expansion
- Moore law enabled doubling the size of largest FPGAs and halving cost per function (area less precious)
- Smaller & simpler logic units/more complex logic blocks
- Longer connections not only nearest neighbors
- Design automation (placing, routing synthesis) essential
- Increase in addressable ASIC market

(2000-2007)

Age of Accumulation
- Larger size FPGAs are no longer essential
- FPGAs include logic function + High performance predefined building dedicated blocks interconnected
- Customized products for communications

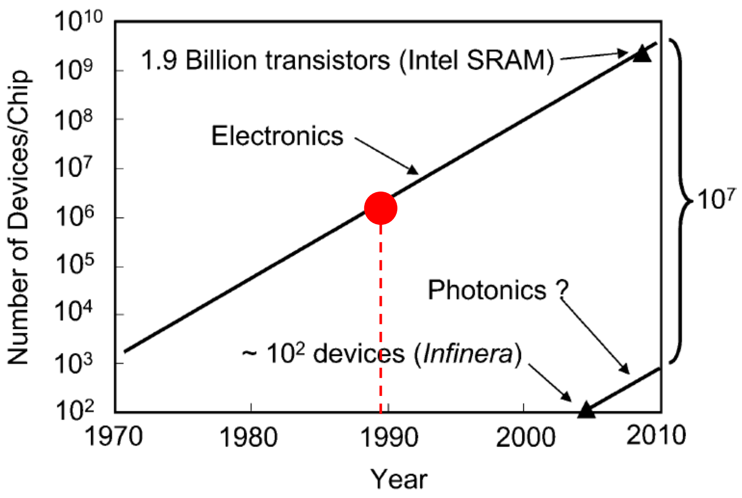
Photonics

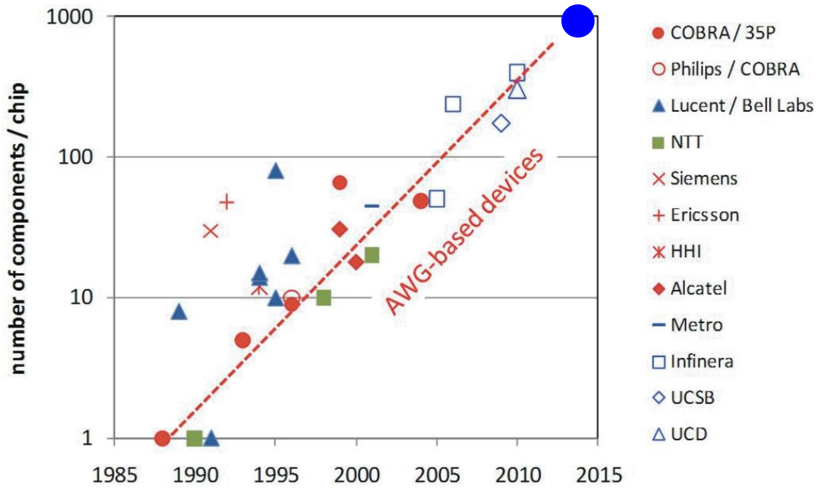
(2015-2022)

Age of Invention
- Material technology platform
- Maximize efficiency in cost & functionality
- Define photonic analog gates/locks
- Design efficient 2D interconnection meshes
- Manual design, placement & routing
- Automatic control, bias, monitoring
- Interfacing with RF and electronic bias

Is the right time for FPPAS?

$\frac{\textit{Photon Wavelength}}{\textit{Electron Wavelength}}$ » 10^3 Þ $\frac{\textit{Photonic}\text{ Integration density/surface unit}}{\textit{Electronic}\text{ Integration density/surface unit}}$ » 10^{-3}



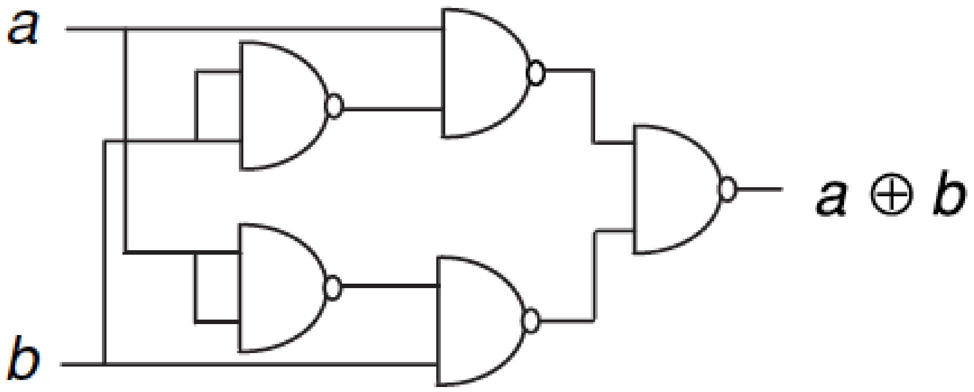


Integration density when FPGA was proposed 10^6

Equivalent Integration density when FPPGA have been proposed $10^6 x 10^{-3} = 10^3$

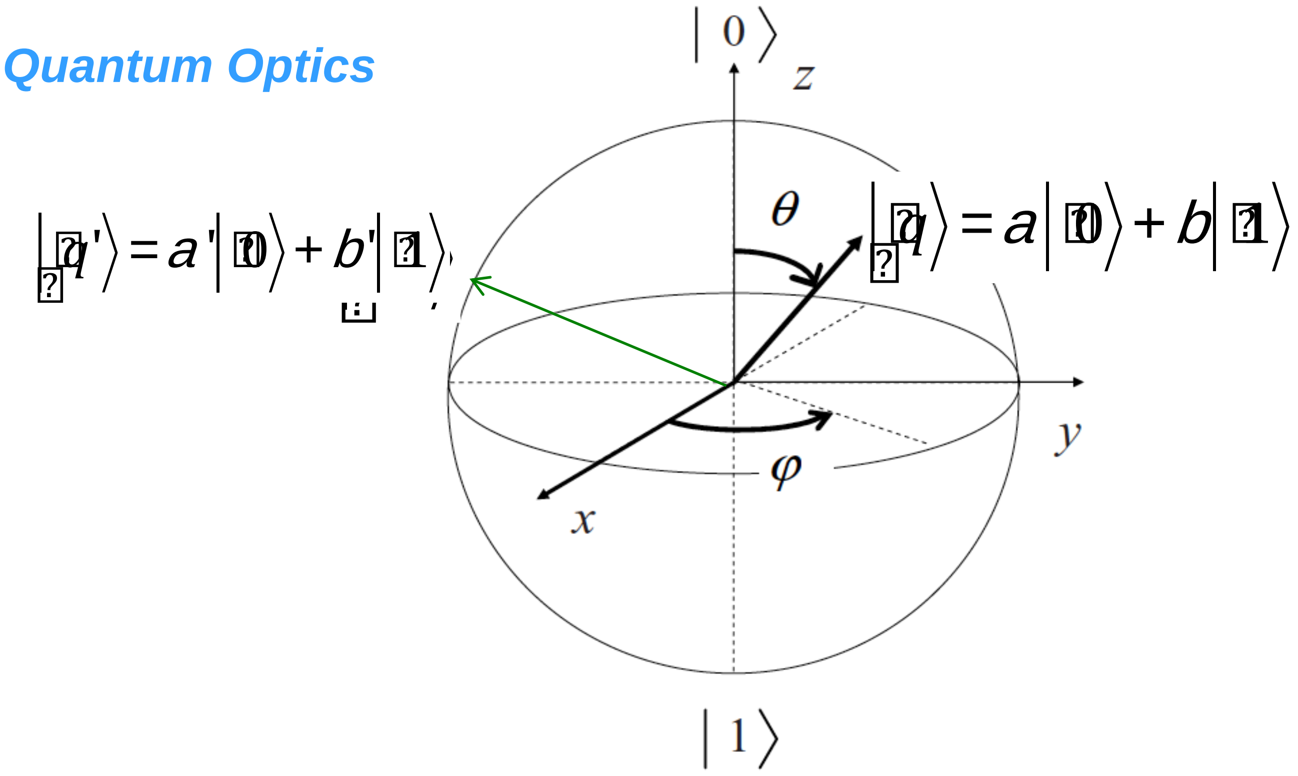
Analog vs Digital Bit Processing

Digital Electronics



XOR

Quantum Optics



In digital electronics, bits 0 and 1 are **digitally** processed using the rules of **Boolean Algebra**

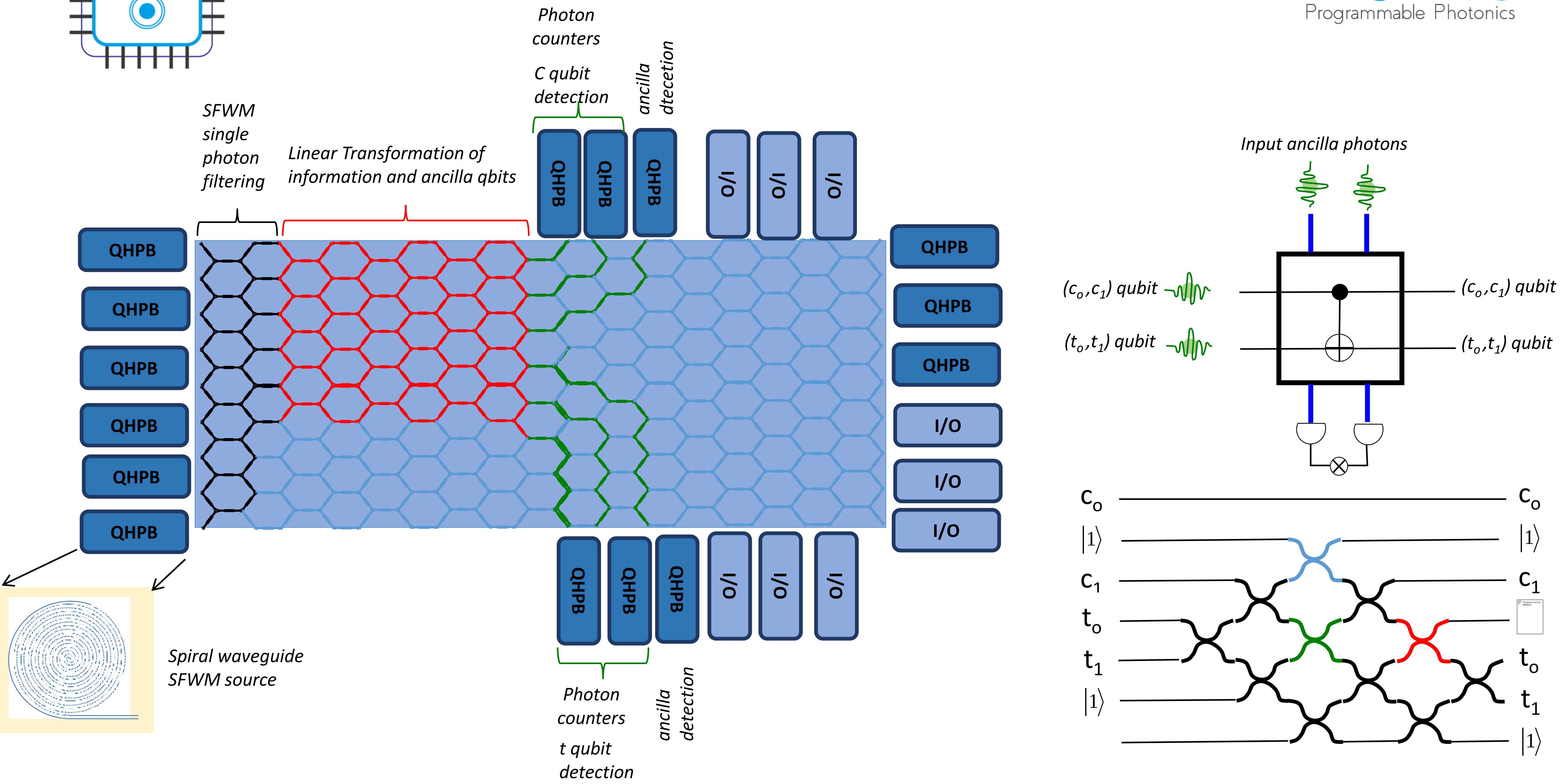
Qubits are **analog** processed (amplitudes), using the rules of 2x2 unitary Matrix Algebra

$$y = f(a,b)$$

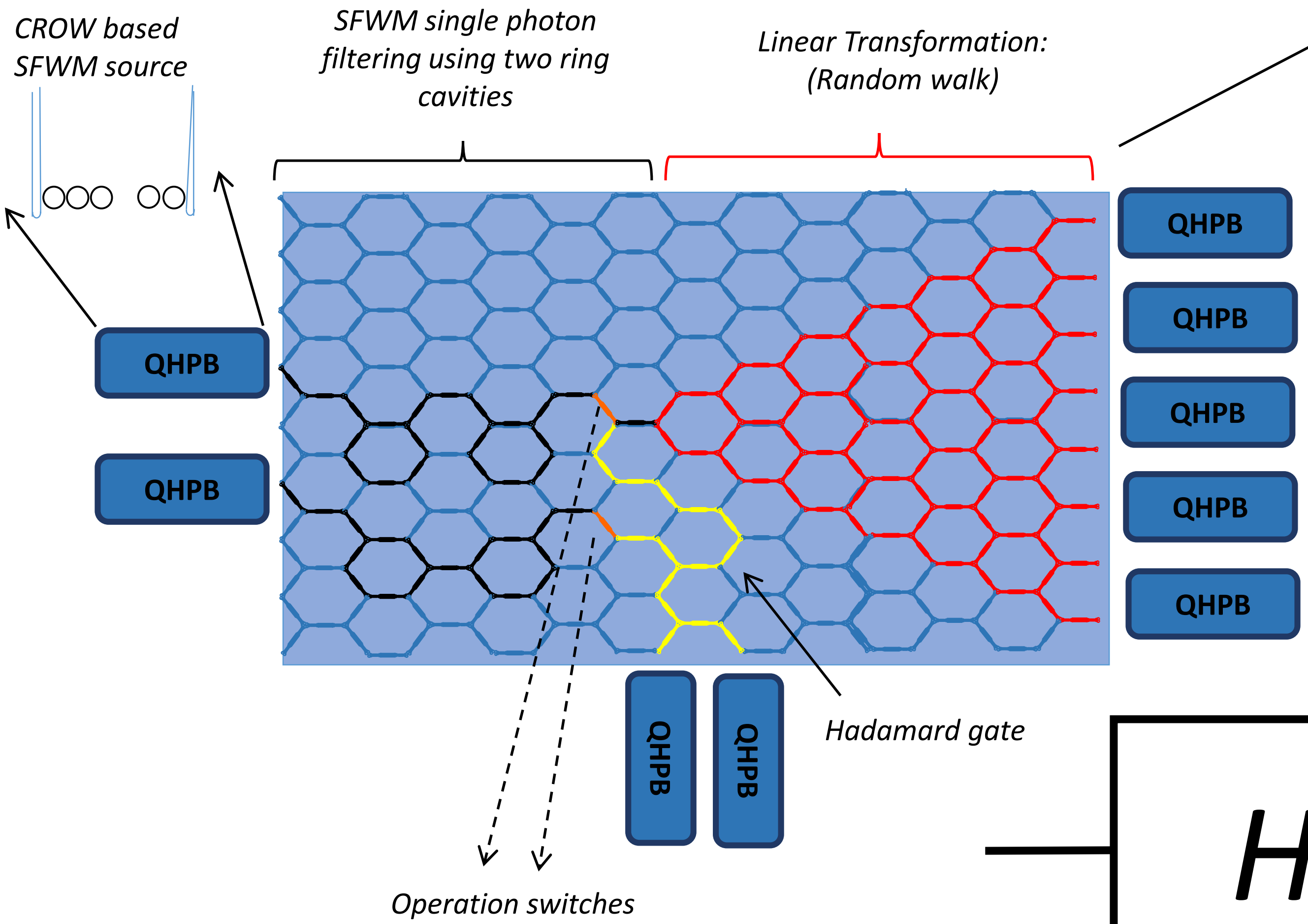
$$a,b = \{0,1\}$$

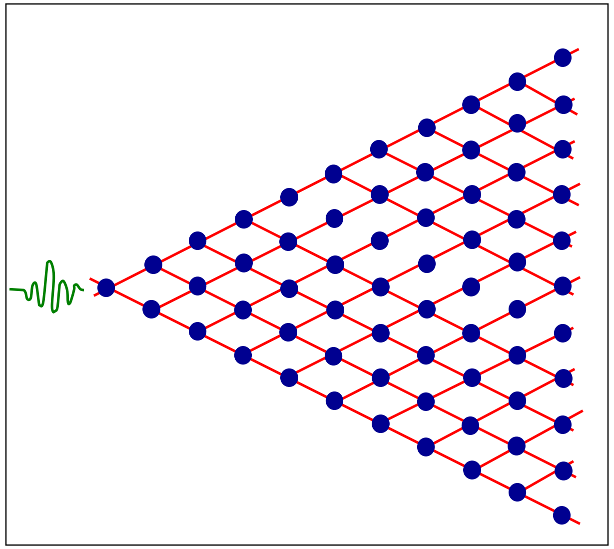
$$\begin{pmatrix} a' \\ b' \end{pmatrix} = \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

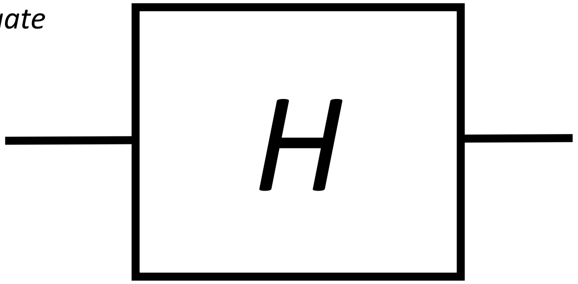
Example 1: Heralded CNOT Quantum Gate implementation



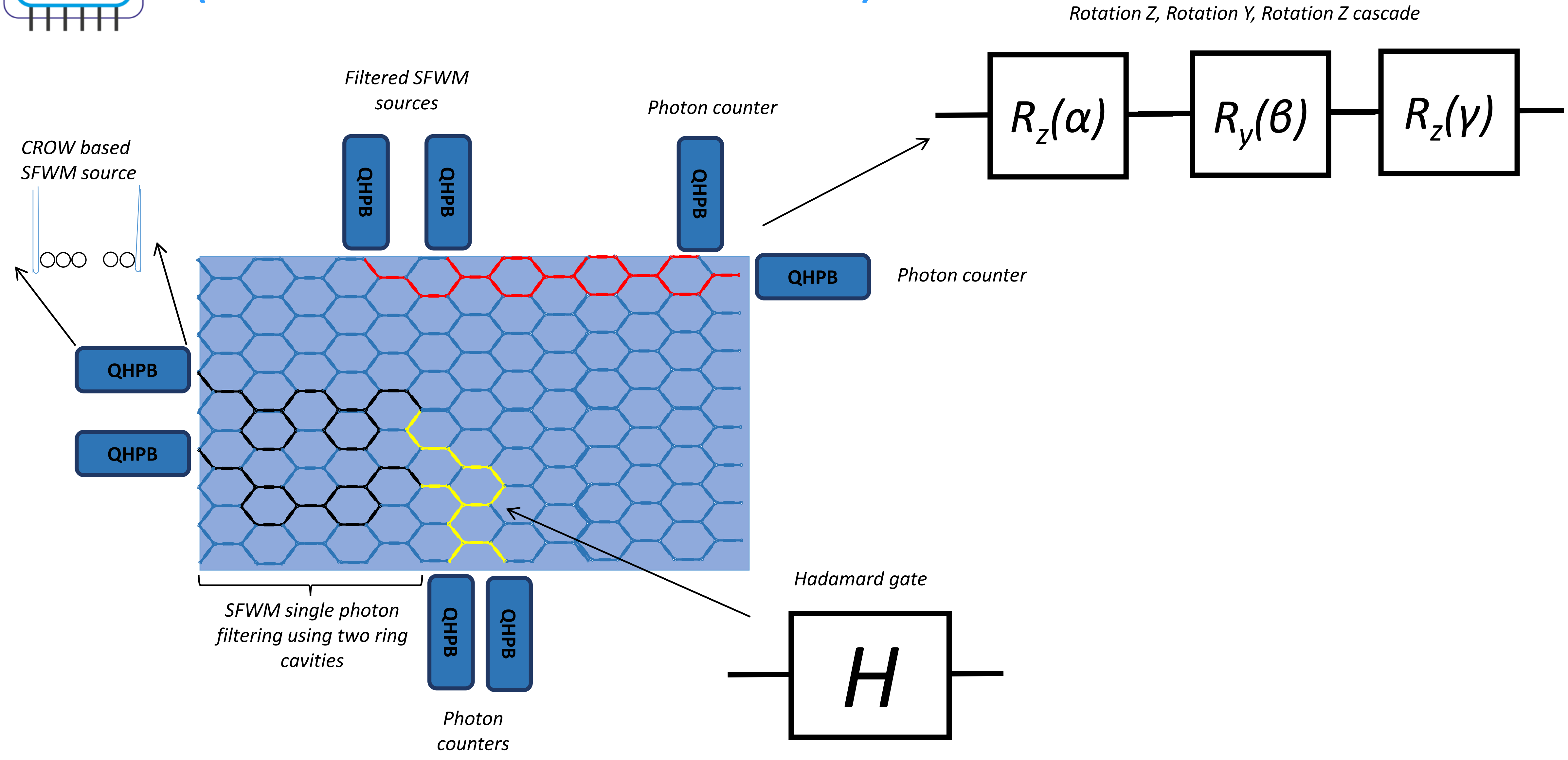
Example 2: Switched quantum circuits (Boson Sampler & Hadamard gate)







Example 3: Simultaneous quantum circuits (Rotation cascade and Hadamard Gate)



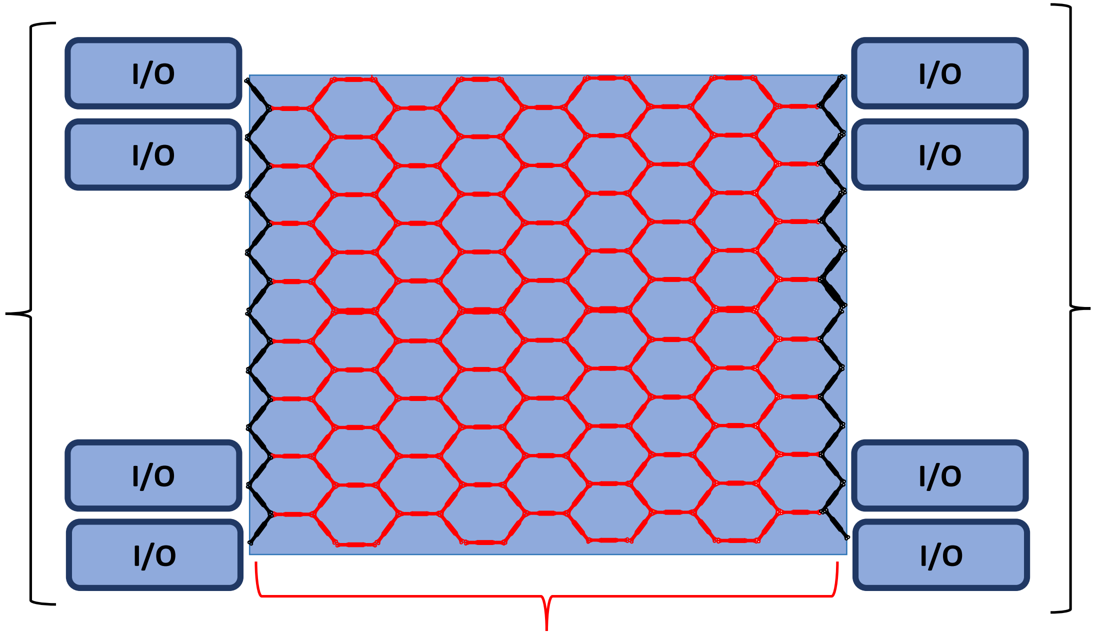
Example 4: Quantum Fourier Tranformer

Input state

$$|y\rangle = \sum_{k=0}^{N-1} x_k |k\rangle$$

$$|k\rangle = \begin{pmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{pmatrix}$$

K+1 row



Output state

$$|\tilde{\psi}\rangle = \mathbf{QFT}|\psi\rangle = \sum_{k=0}^{N-1}\sum_{n=0}^{N-1} M_{nk} x_k |k\rangle$$

Unitary matrix for QFT

$$M = \frac{1}{\sqrt{N}} \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \cdots & \omega^{N-1} \\ 1 & \omega^2 & \omega^4 & \cdots & \omega^{2(N-1)} \\ 1 & \vdots & \vdots & \ddots & \vdots \\ 1 & \omega^{N-1} & \omega^{2(N-1)} & \cdots & \omega^{(N-1)(N-1)} \end{pmatrix}; \quad \omega = e^{i\frac{2\pi}{N}}$$

Example 5: Simultaneous quantum & classical circuits (Rotation cascade and SCISSOR)