Self-adaptive photonic integrated processors for communication and computing

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Summary

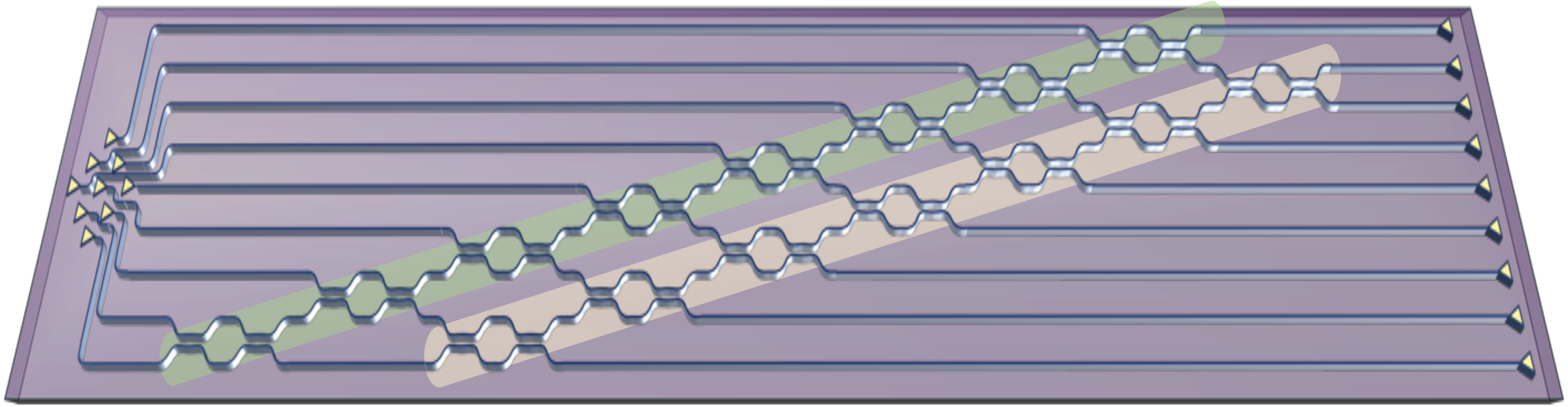
The Programmable Photonic Processor

Free Space Optic communication link (with turbulence mitigation)

Towards optical MIMO

Finding optimal communication channels (& computing)

Mach-Zehnders Mesh



The basic building block

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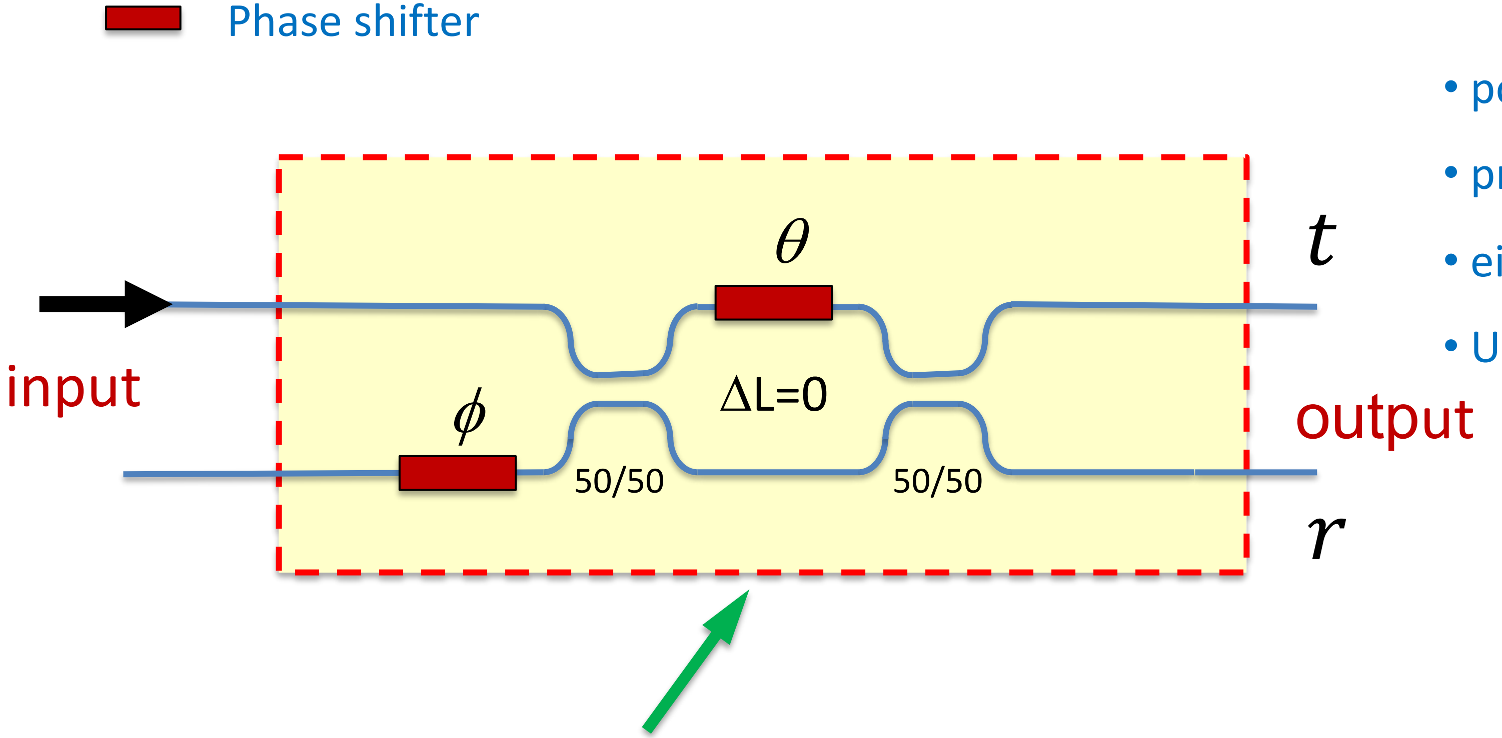
Mach-Zehnder Interferometer (MZI)



2x2 Unitary Transformation

- power conservation
- preserves “length” & “angle” (only a “rotation”)
- eigenvalues on unit circle, orthogonal eigenvectors
- $U^{\dagger}U=I$, $U^{-1}=U^{\dagger}$, det (U) =1

$$\theta = 2\cos^{-1} r$$

$$t = \sqrt{1-r^2}$$

$$\boldsymbol{H} = -je^{-j\theta/2}\begin{bmatrix}\sin(\theta/2) & \cos(\theta/2)\,e^{-j\phi} \\ \cos(\theta/2) & -\sin(\theta/2)\,e^{-j\phi}\end{bmatrix} = -je^{-j\theta/2}\begin{bmatrix} t & re^{-j\phi} \\ r & -te^{-j\phi}\end{bmatrix}$$

The basic photonic combiner

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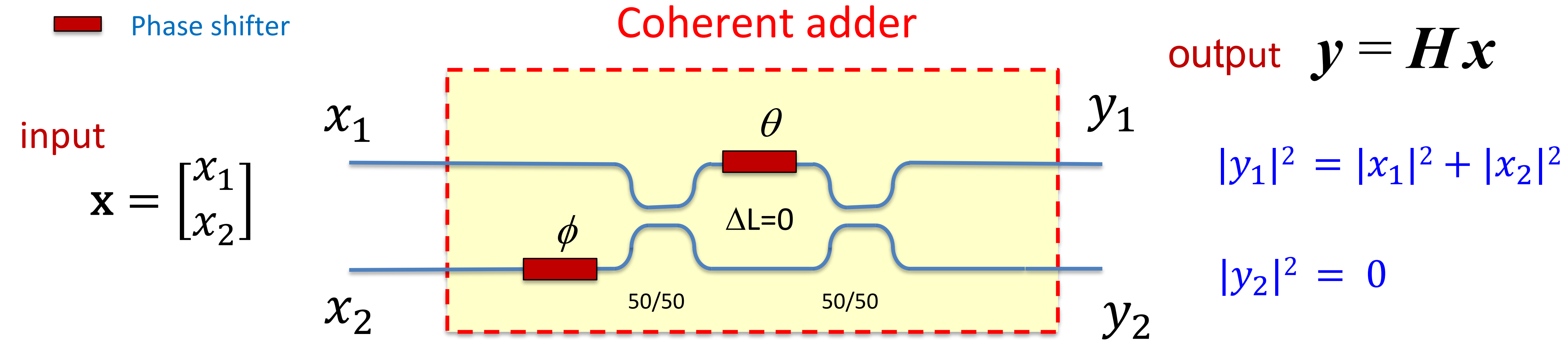
Mach-Zehnder Interferometer (MZI)

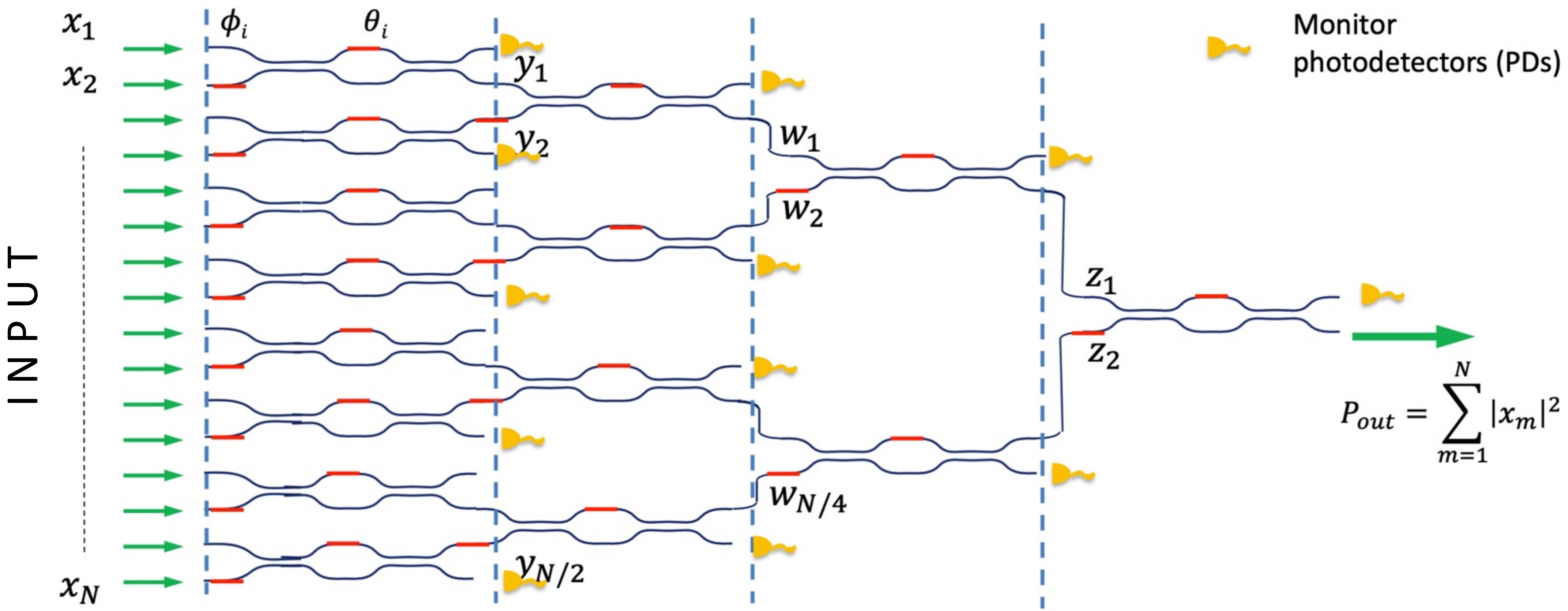


Condition to null the output power at port 2

$$y_2 = -je^{-j\theta/2}\left[\cos\left(\frac{\theta}{2}\right)x_1 - e^{-j\phi}\sin\left(\frac{\theta}{2}\right)x_2\right] = 0$$

$$\Rightarrow \cos\left(\frac{\theta}{2}\right)x_1 = e^{-j\phi}\sin\left(\frac{\theta}{2}\right)x_2 \quad \Rightarrow \begin{cases} \theta = 2\tan^{-1}\left|\frac{x_1}{x_2}\right|, \quad \theta \in [0, \pi] \\ \phi = (\angle x_2 - \angle x_1) + 2N\pi \end{cases}$$

Nx1 coherent adder



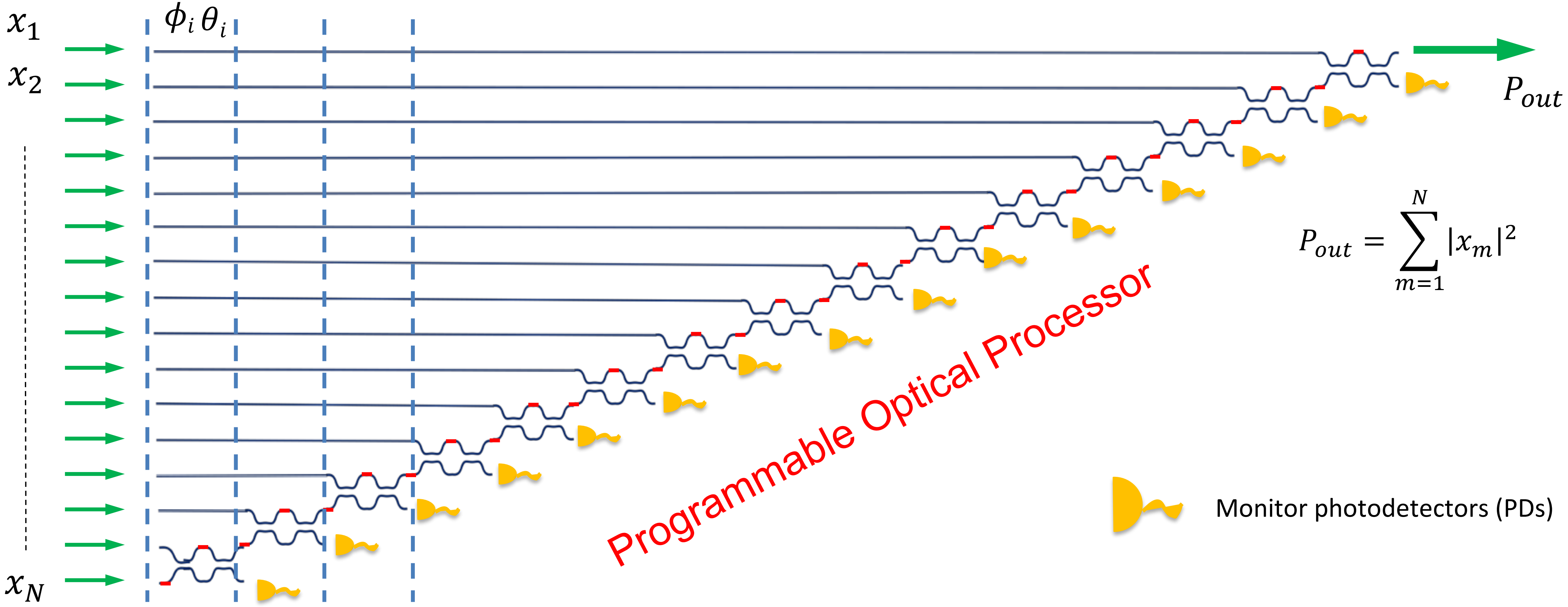
$$\phi_i = \angle x_{i+1} - \angle x_i$$

$$\theta_i = 2\tan^{-1}\left|\frac{x_i}{x_{i+1}}\right|$$

- Combining 2x1 coherent adders, an arbitrary number of inputs signals can be coherently summed
- Calibration strategy: zeroring the power at monitor ports

W. Bogaerts, … F. Morichetti, A. Melloni
Programmable photonic circuits, Nature 586, 207–216 (2020)

Nx1 coherent adder



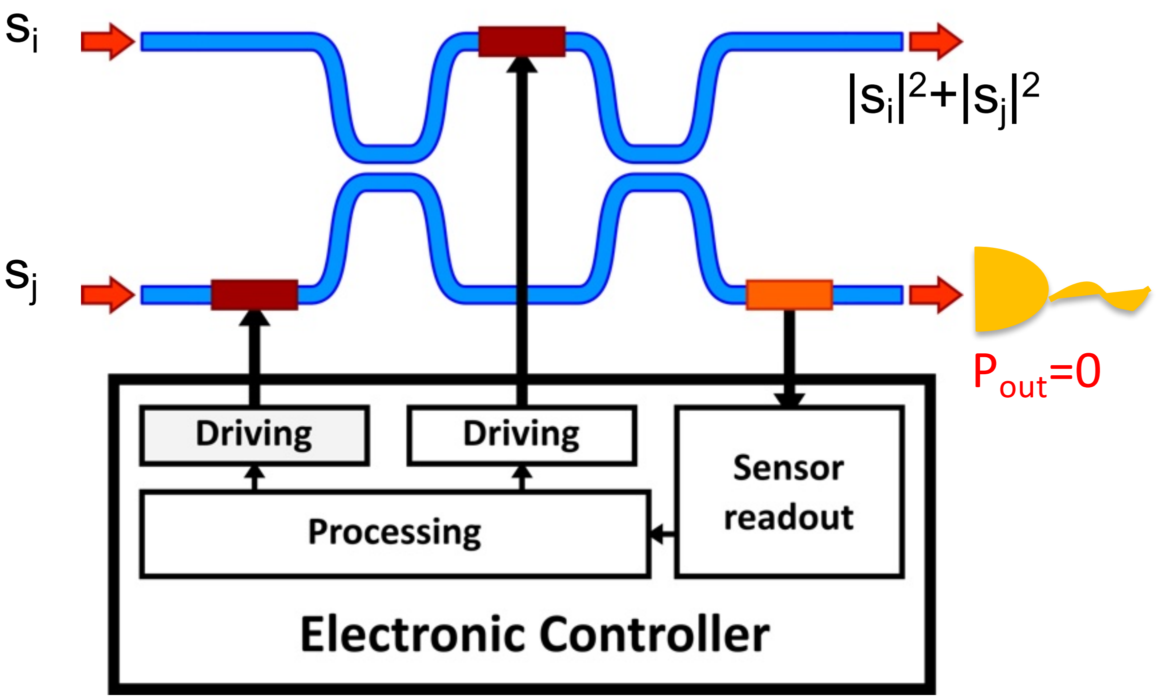
$\phi_i = \angle x_{i+1} - \angle x_i$

$\theta_i = 2\tan^{-1}\left|\frac{x_i}{x_{i+1}}\right|$

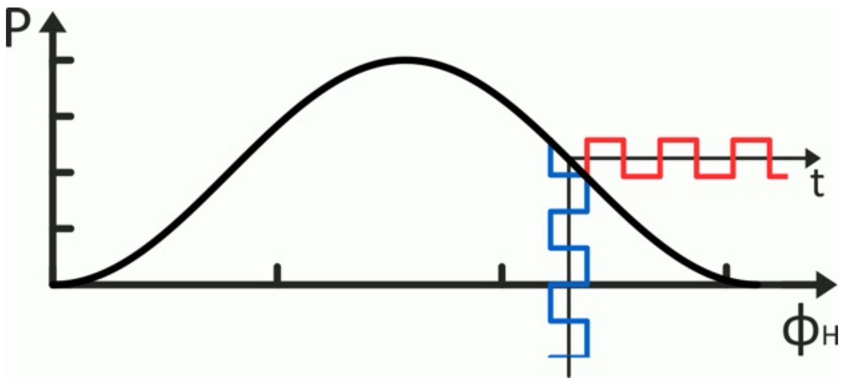
- The output of each 2x1 MZI is added to the next input signal
- Calibration strategy (same as before): zeroring the power at monitor ports

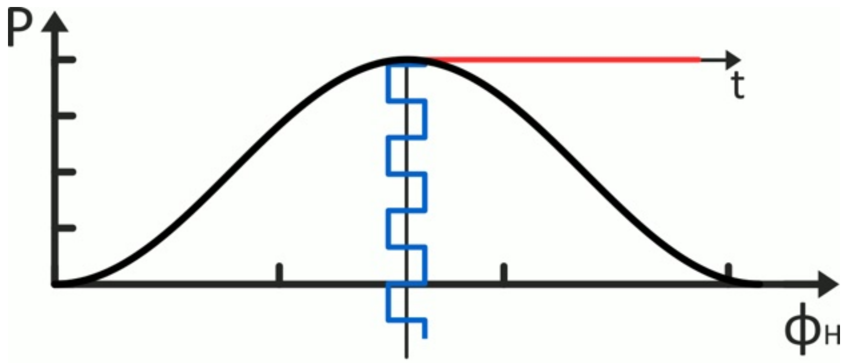
David A. B. Miller, "Self-aligning universal beam coupler," Opt. Express 21, 6360-6370 (2013)

Control electronics for self-configuring MZI

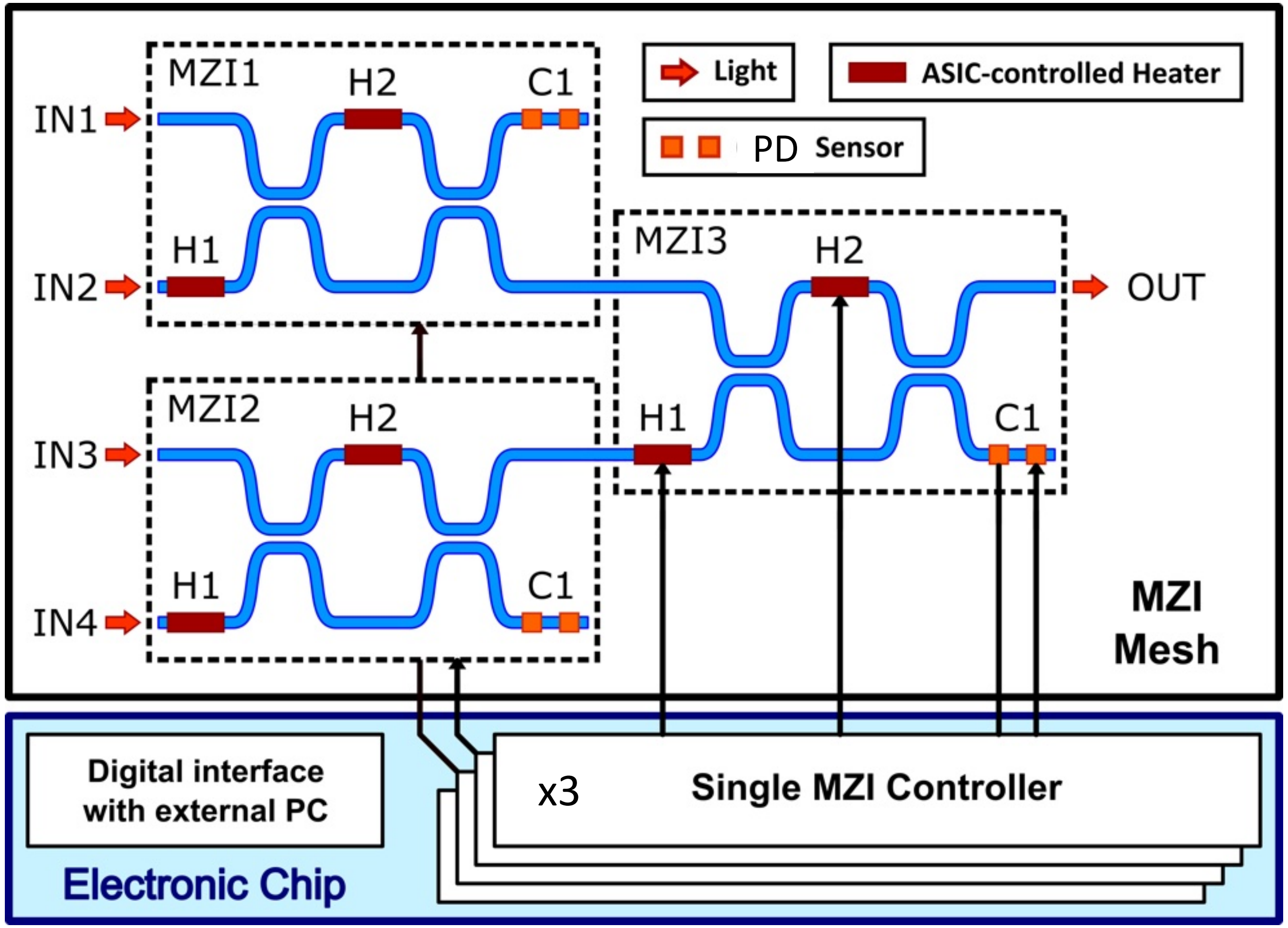


- Automatic (dithering-based) self-configuration of a MZI from any initial condition
- Track input signal changes (amplitude/phase)
- Compensate thermal fluctuation & fabrication variability
- Full processor stabilization in ms scale
- Double-dithering control strategy



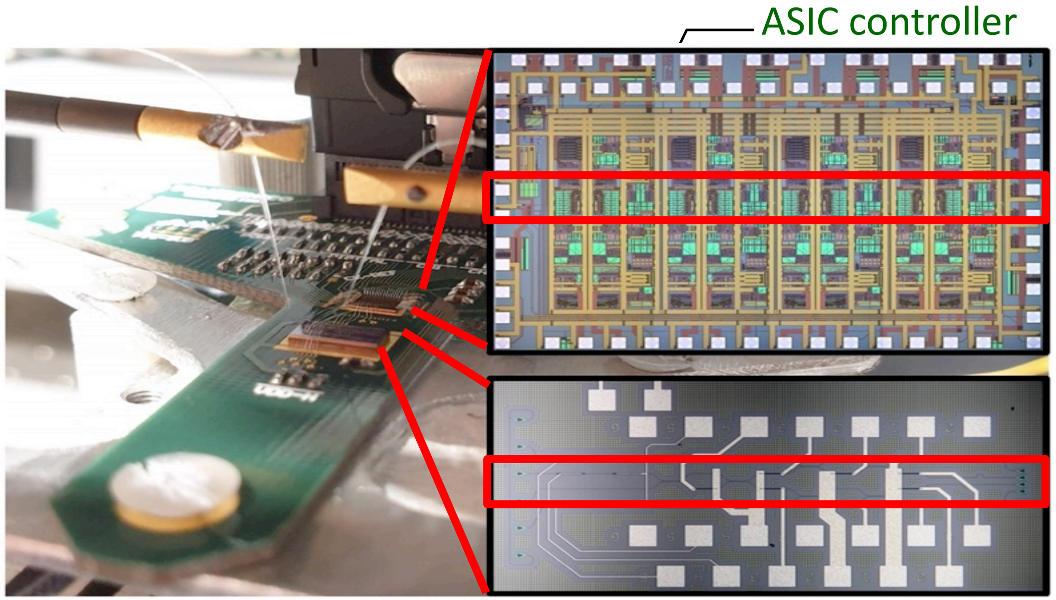


The control electronics – Scaling



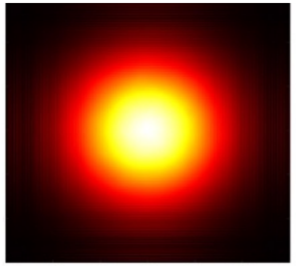
M. Sampietro, OPTICS 2023, Session 1, 8th Nov.

- Automatic self-configuration of MZIs from any initial condition
- Control in parallel, not sequential
- Complexity Scaling: linear with *M*
- Time convergence scaling $M^{1/2}$
- Stabilization of 8 cascaded MZIs in <10 ms

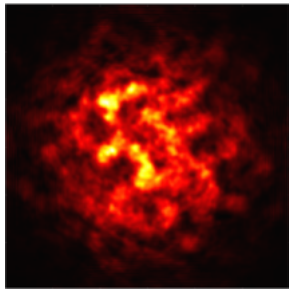


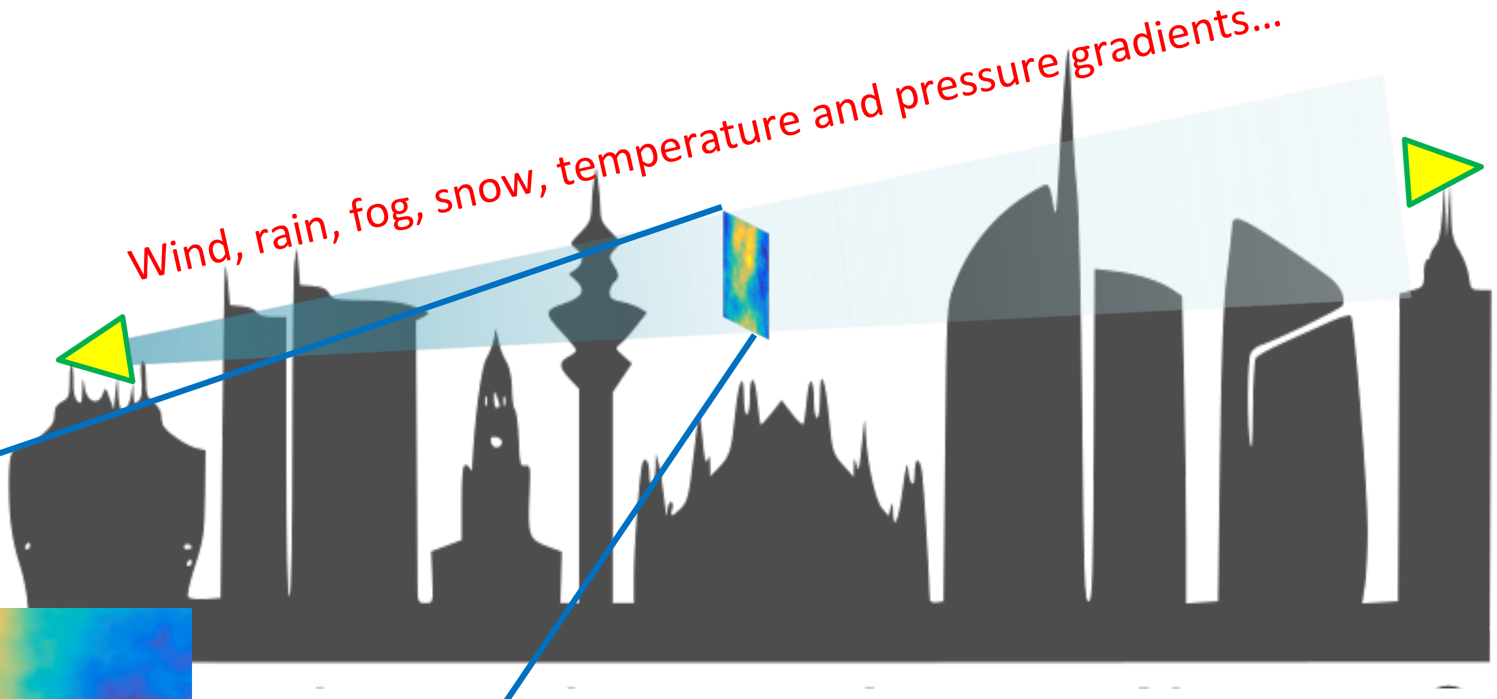
Free Space Optical (FSO) Link

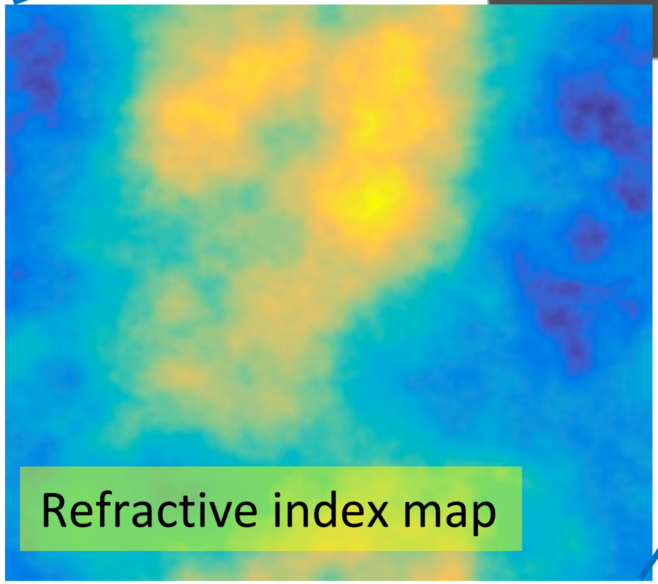
Transmitter - TX



Receiver - RX



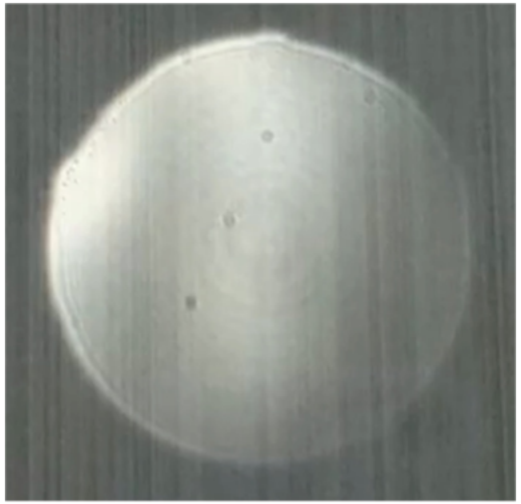




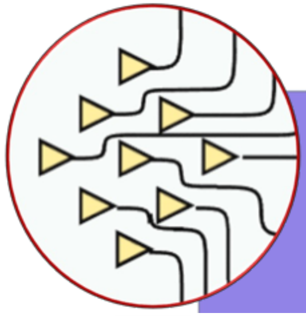
Free Space Channel

- Attenuation
- Multipath
- Time varying channel
- **Turbulence** (scintillation & wander)
- Obstacles
- Polarization

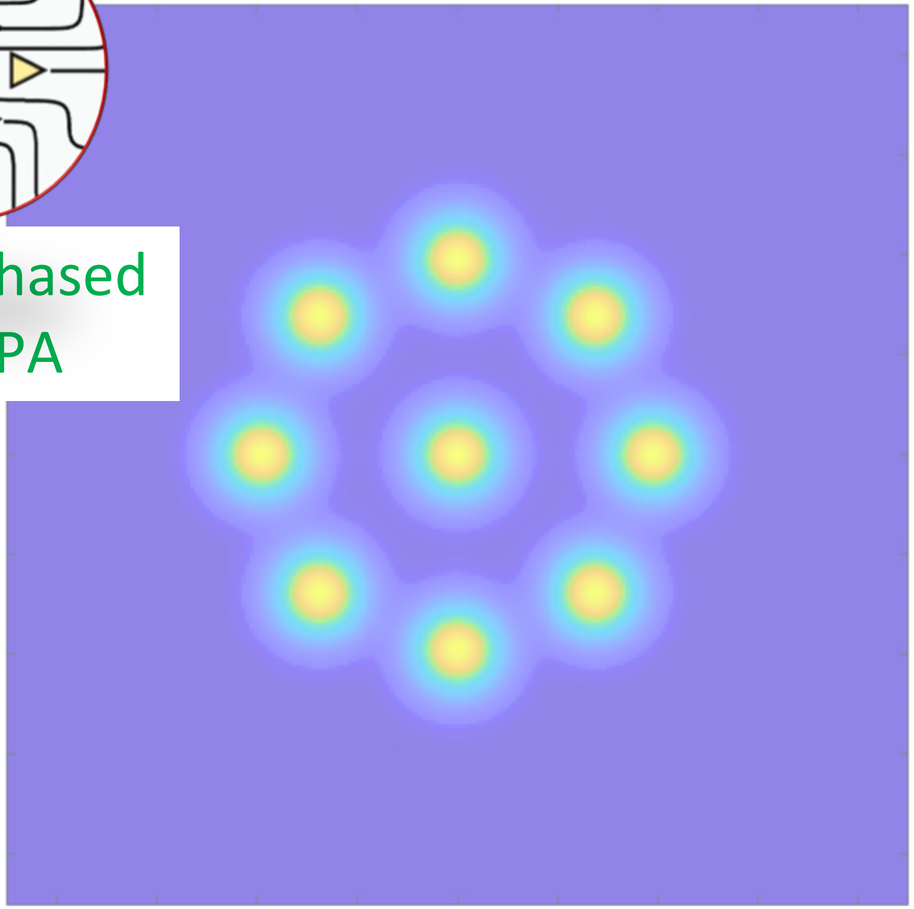
summer, clear sky
320 m FSO link
100 fps

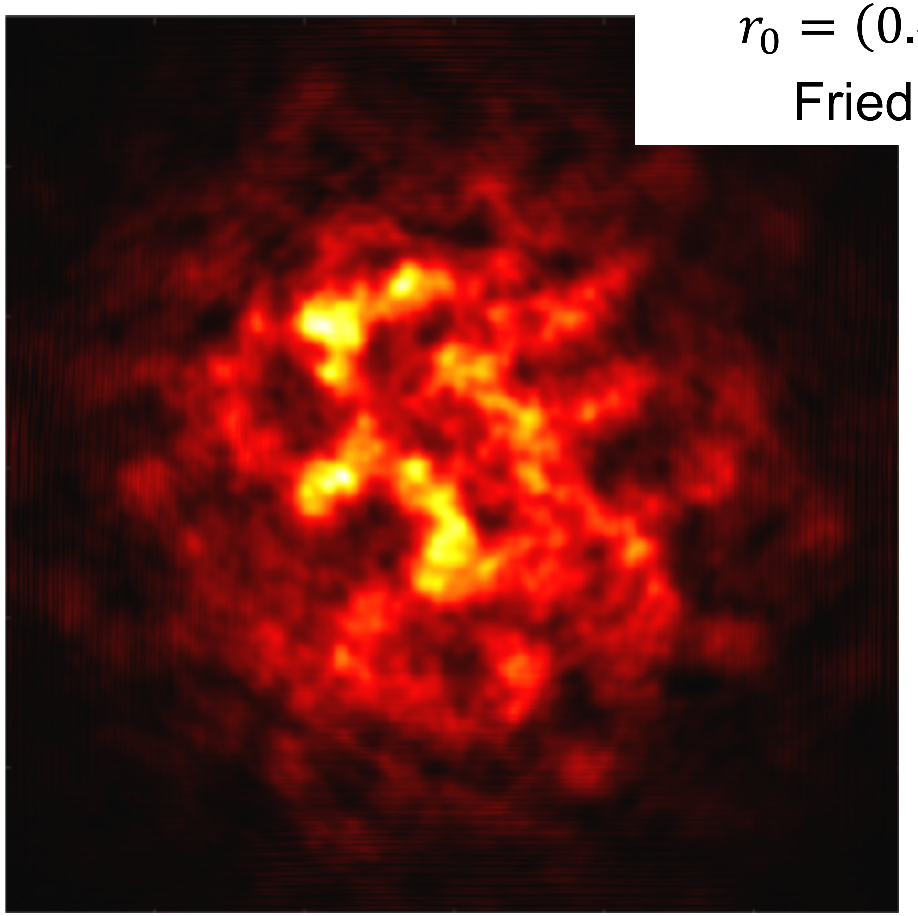


MULTIAPERTURE receiver for a turbulence affected beam



Optical Phased Array - OPA





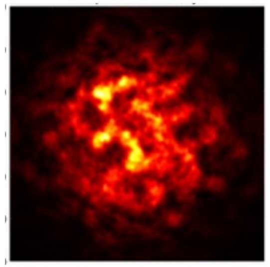
$$r_0 = (0.423 k^2 C_n^2 L)^{-\frac{3}{5}}$$

Fried parameter

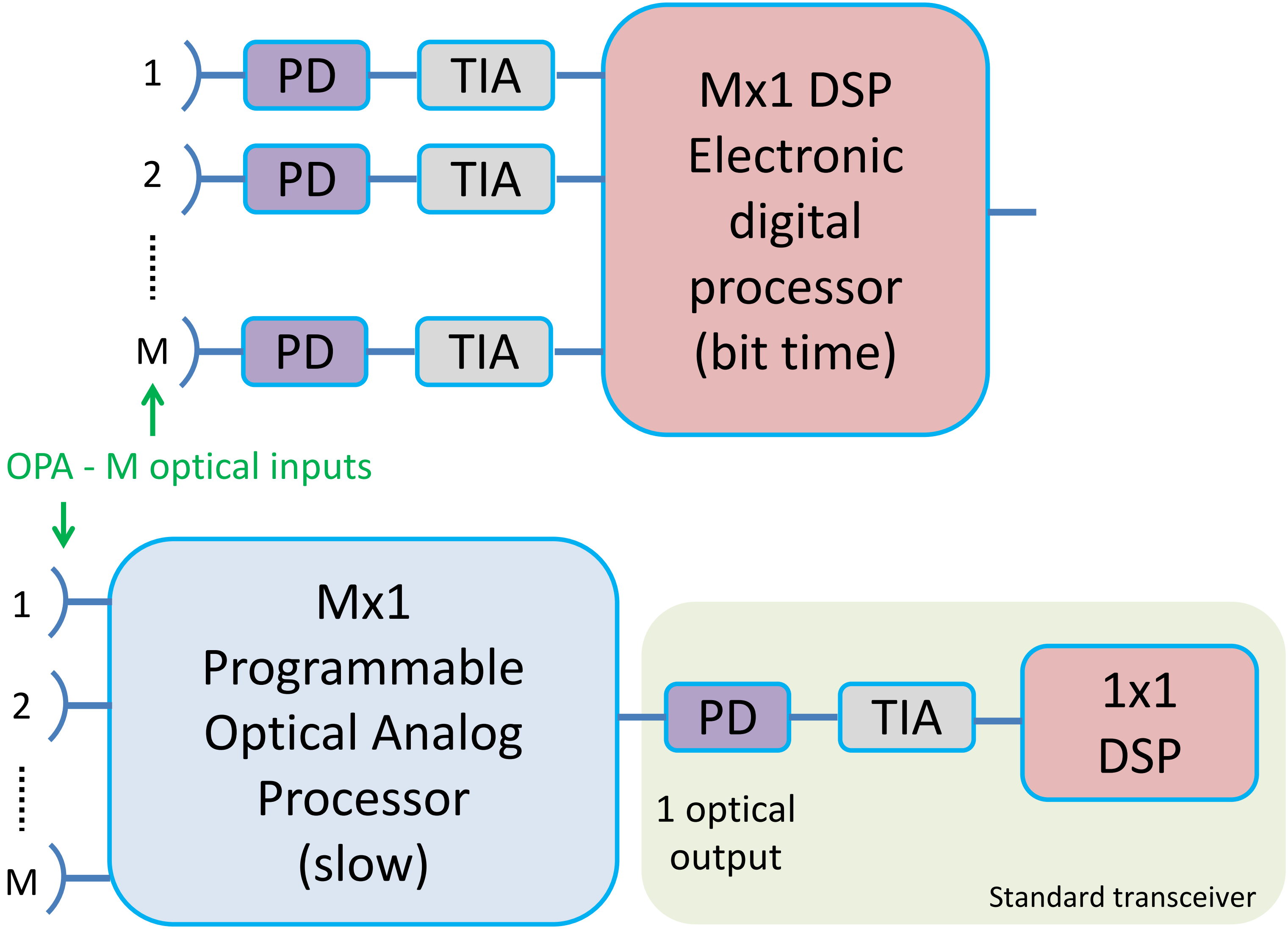
M field contributions to be combined coherently…
in the electrical or optical domain?

Optical analog processor vs electronic digital processor

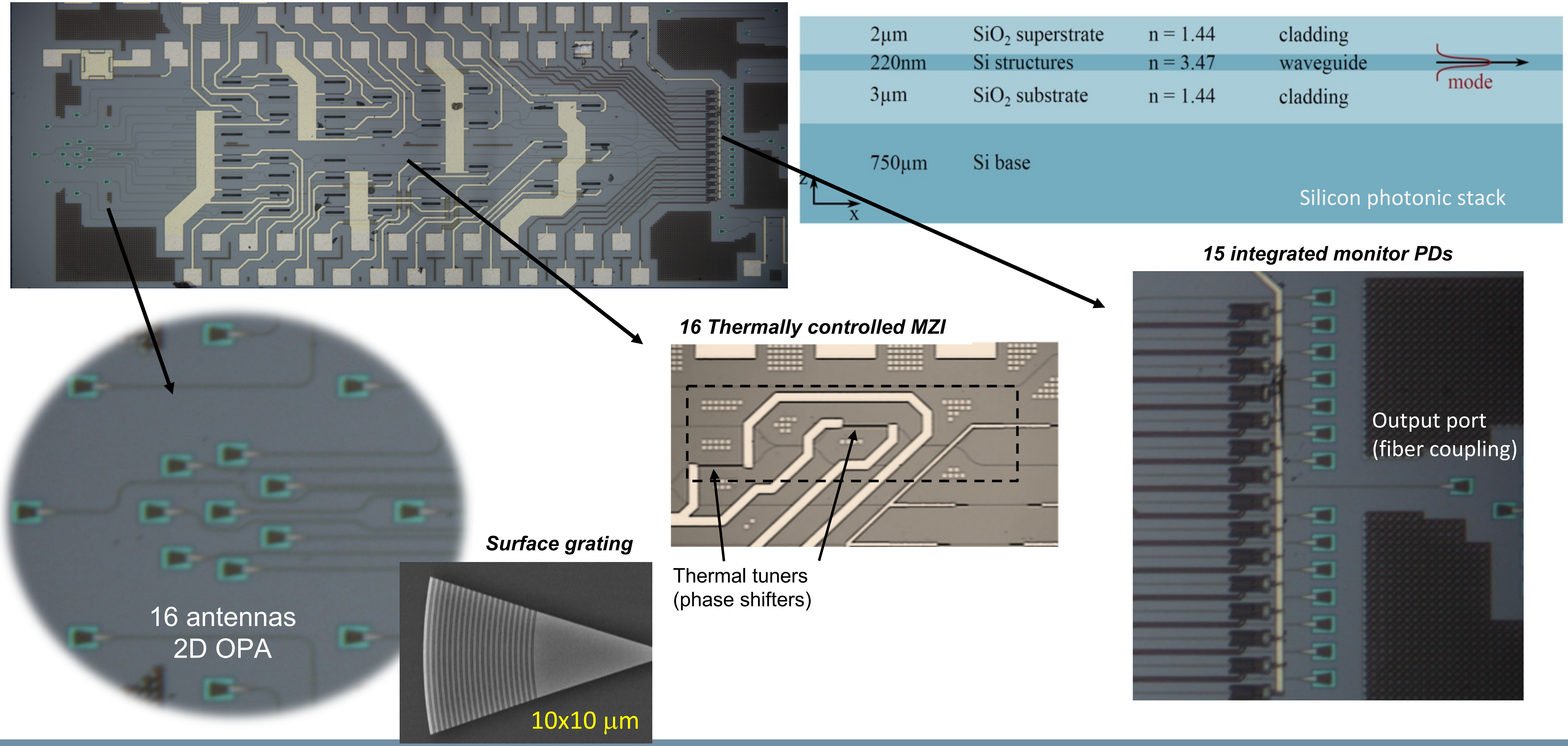
Spatially
non-coherent beam



- Optical output
- Turbulence is a slow process (**100s Hz speed**)
- "slow optical analog processor" vs "bit-time scale Mx1 electronic DSP"
- Energy and cost effective
- Scalability to high M optical inputs
- Coherent (QAM) modulation formats

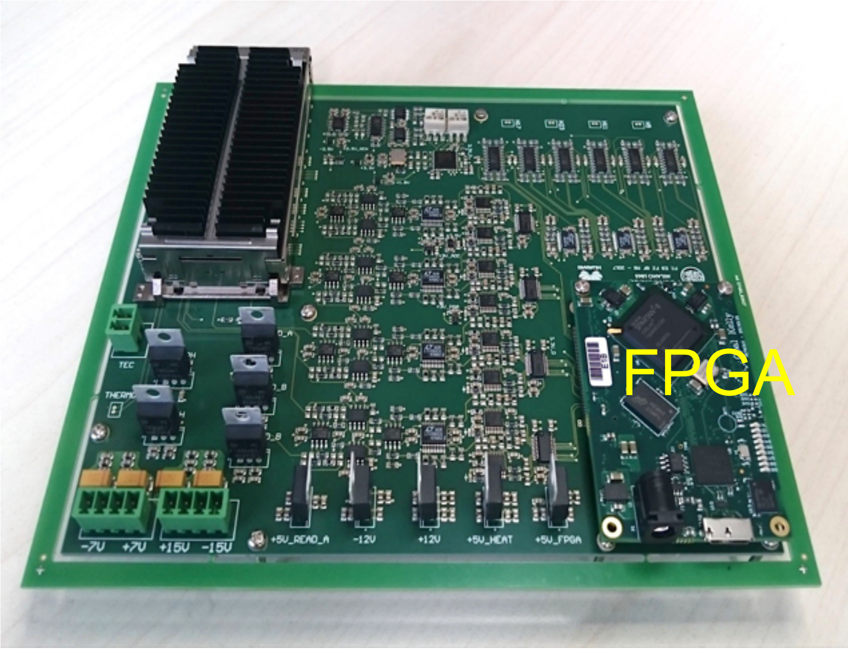


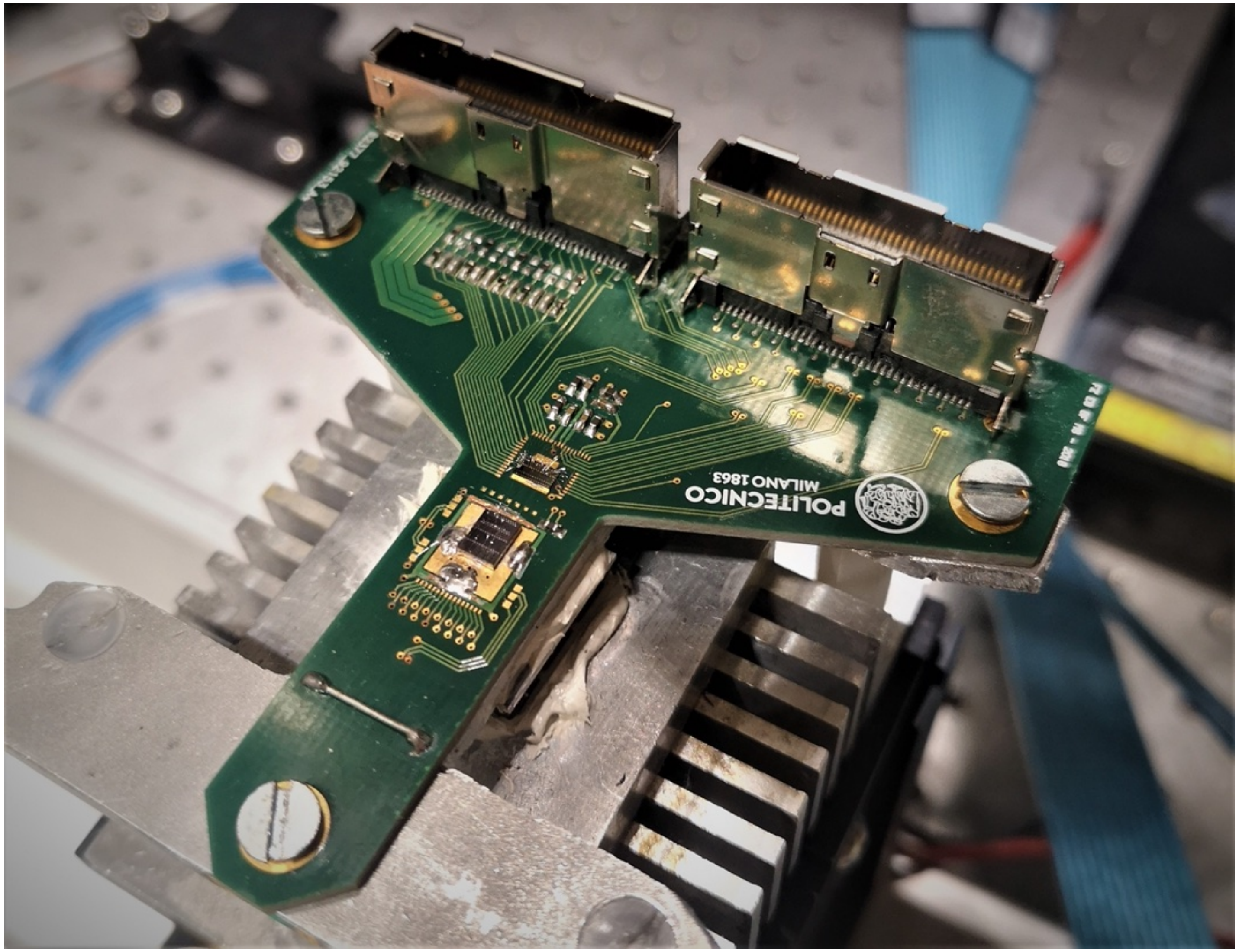
Silicon Programmable Optical Processor



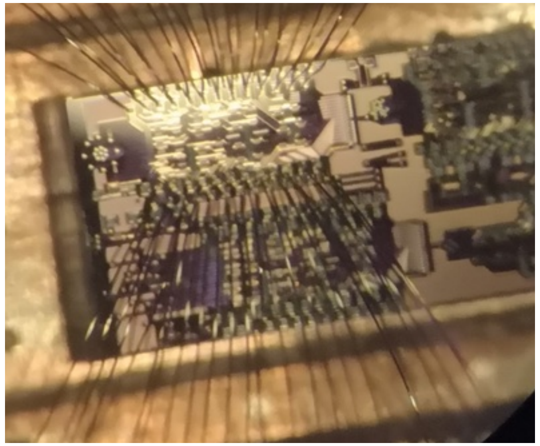
Chip assembly and control electronics

Thanks to **Prof. Sampietro**'s group (PoliMi)





Wire-bonded photonic chip



Setting up the Photonic Processor-receiver automatically

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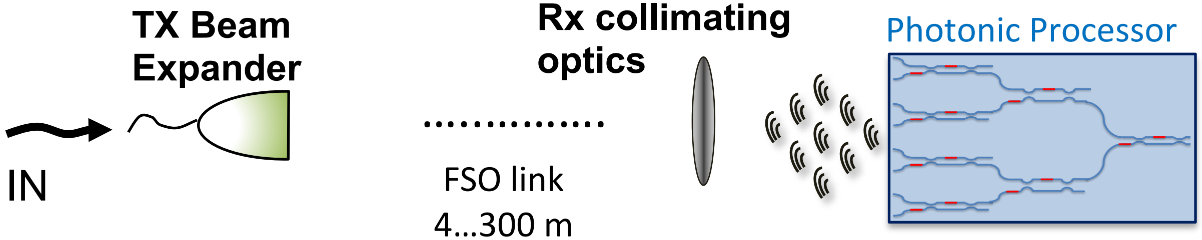
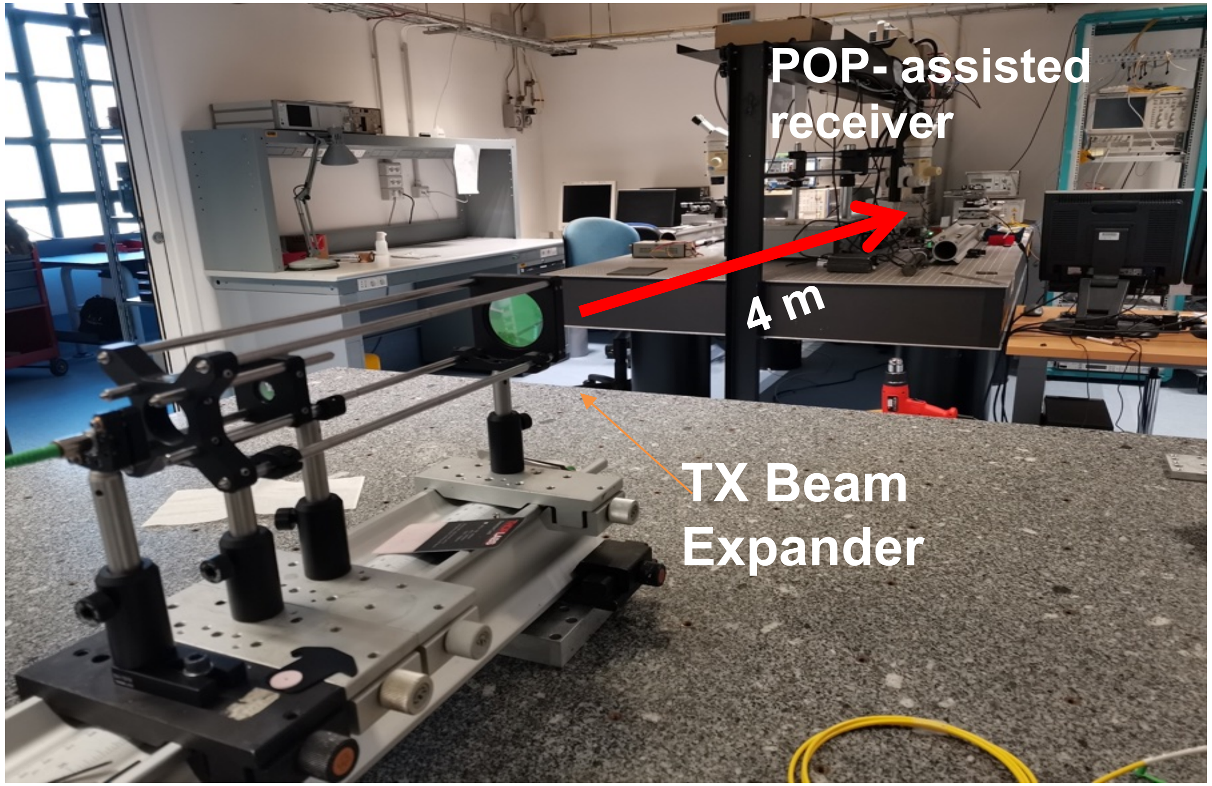
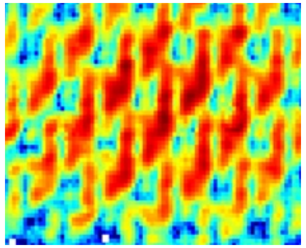


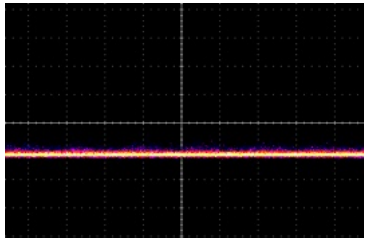
$$P_{out} = \sum_{i=1}^{M} |s_i|^2$$



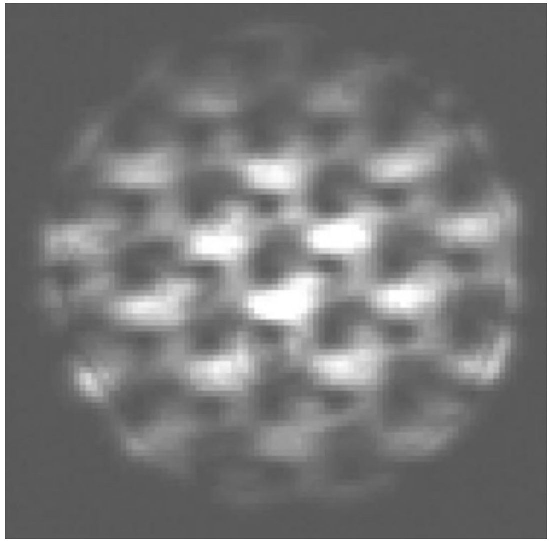
10 Gbit/s OOK modulated channel

OPA pattern (processor OFF)



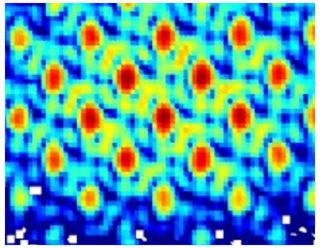


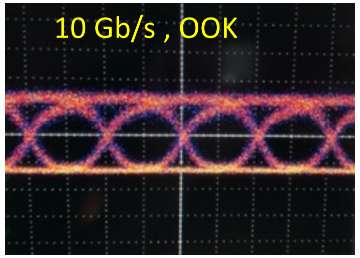
No POP tuning (control OFF)



Evolution of beam front along the tuning (intentionally slowed)

OPA pattern (processor ON)

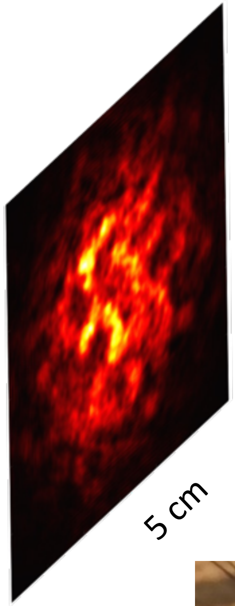




FSO link automatically established

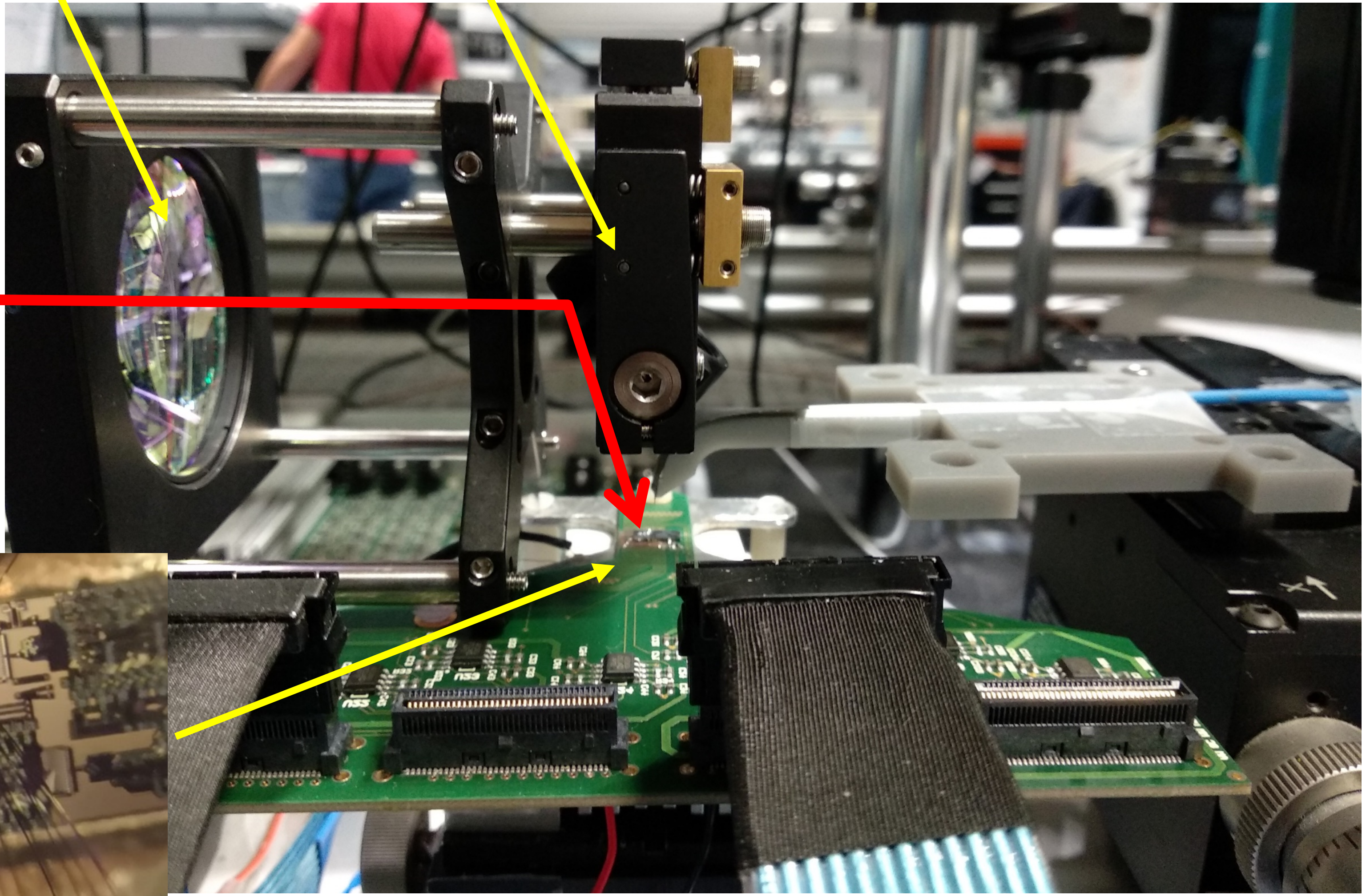
The POP- assisted receiver

Turbulent free space optical beam



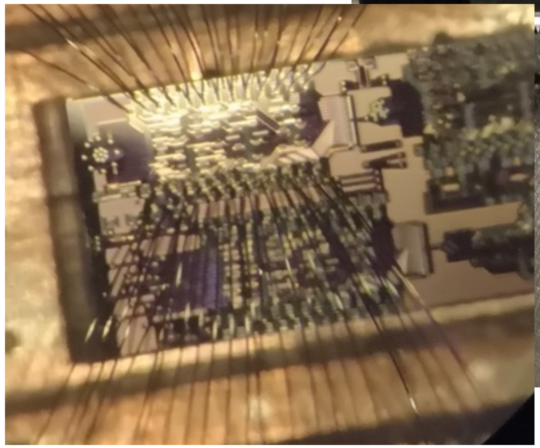
Collimating optics

45° turning mirror

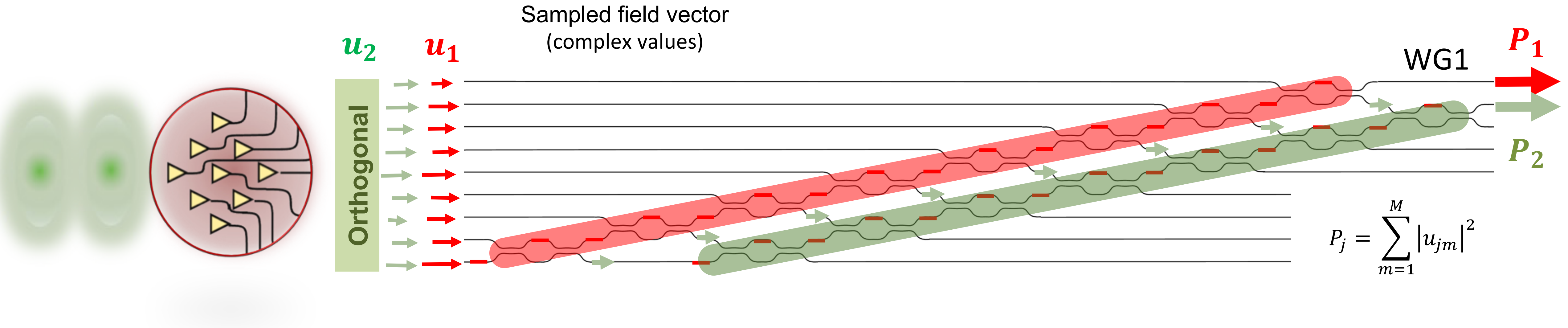


OUT
Optical fiber

Wire-bonded photonic chip



Separating orthogonal free space modes



The photonic processor can separate pairs of arbitrary orthogonal beams at the output ports WG_j

Preprint: Milanizadeh et al. arXiv:2112.13644

Beam orthogonality: $\boldsymbol{u}_2^{\dagger}\boldsymbol{u}_1 = \mathbf{0}$

The photonic processor can SEPARATE arbitrary orthogonal beams AT the OUTPUT ports WG_j

The photonic processor can GENERATE arbitrary orthogonal beams FROM the INPUT ports WG_j

Why not using a photonic processor also at the Tx side?

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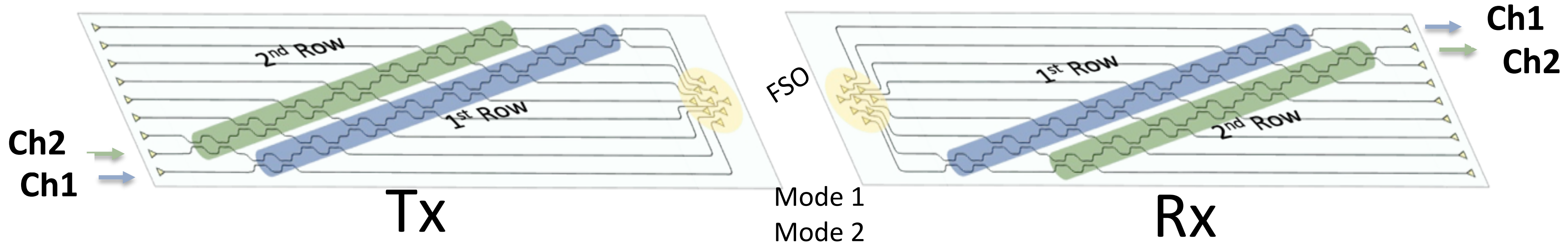
M. Milanizadeh et al., *Light: Science & Applications*, 2022

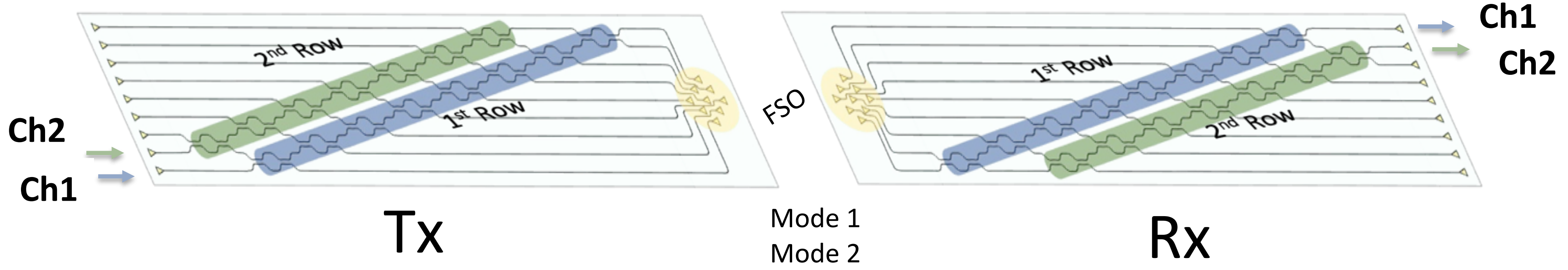


Precompensation of the channel (turbulence)

Establishing the best communication channels in a FSO link

Why not using a photonic processor also at the Tx side?

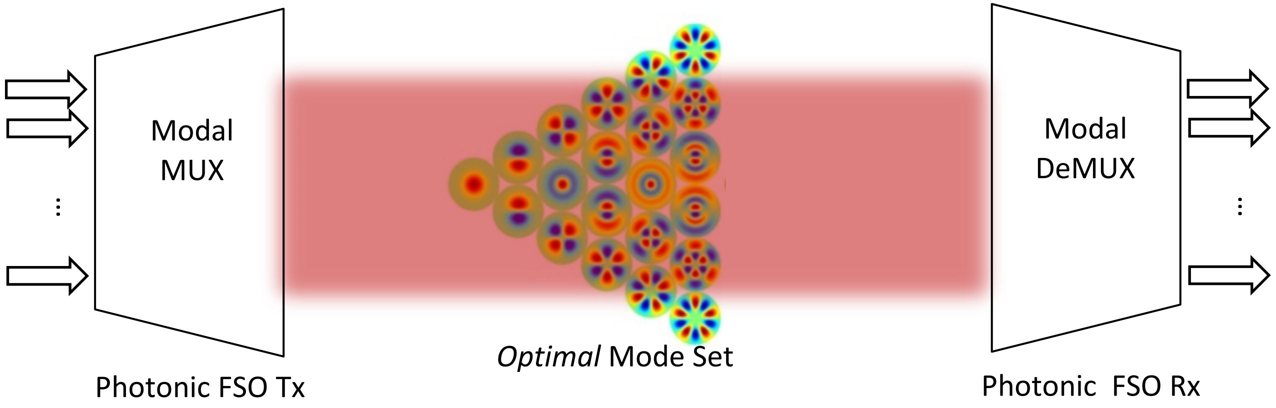
M. Milanizadeh et al., *Light: Science & Applications*, 2022



Precompensation of the channel (turbulence)

Establishing the best communication channels in a FSO link

N antennas… up to N spatial **orthogonal** modes → Towards free-space optical MIMO

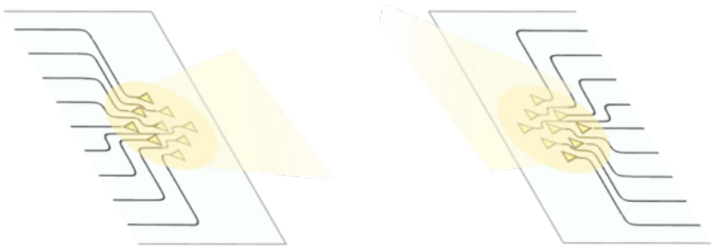


The BEST communication channels (MODES) of a link

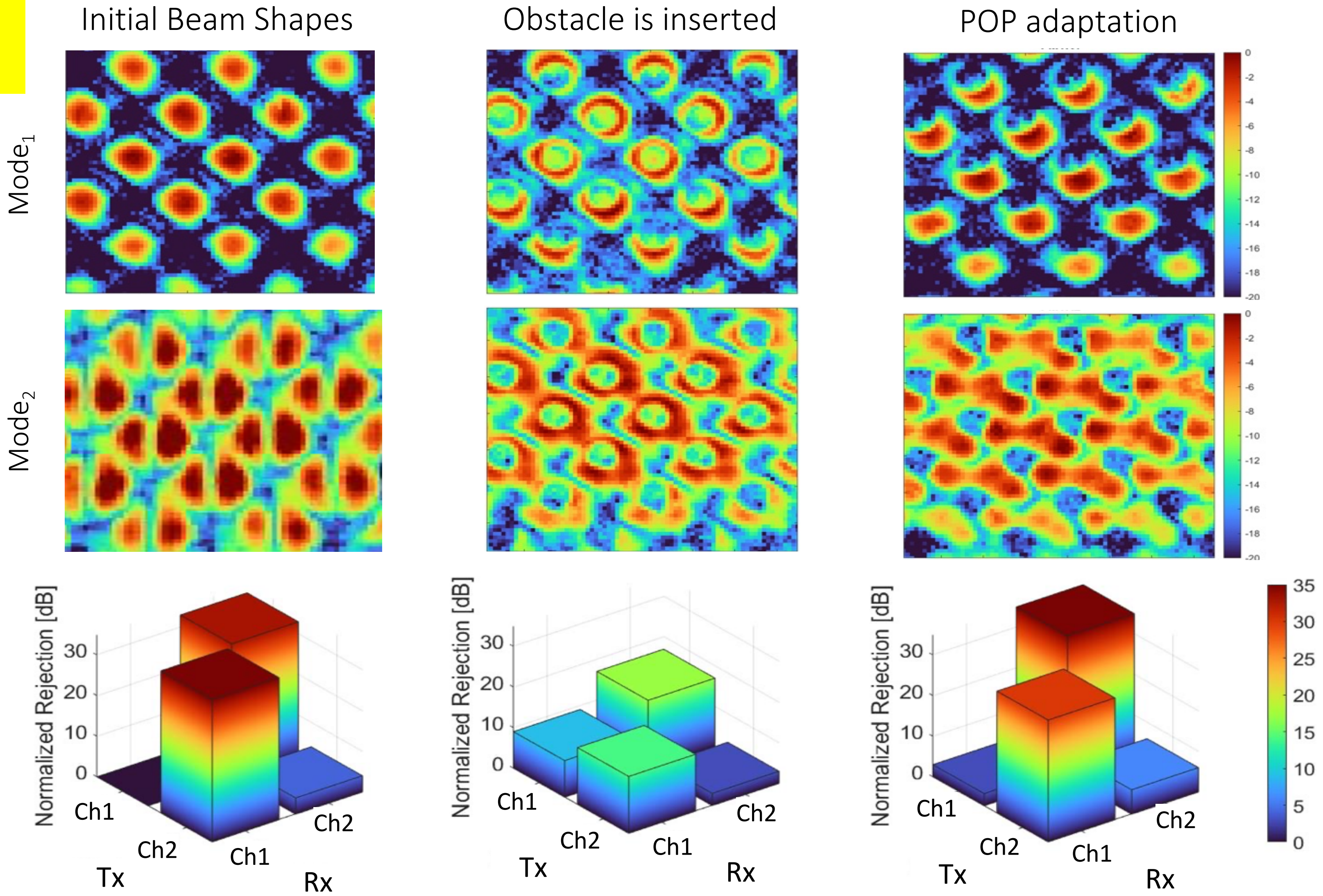
Research Square | A. Melloni et al, 2023

... through any scatter or turbulent medium

Inserting an obstacle in the far field: e.g. a pattern of obstructing spots

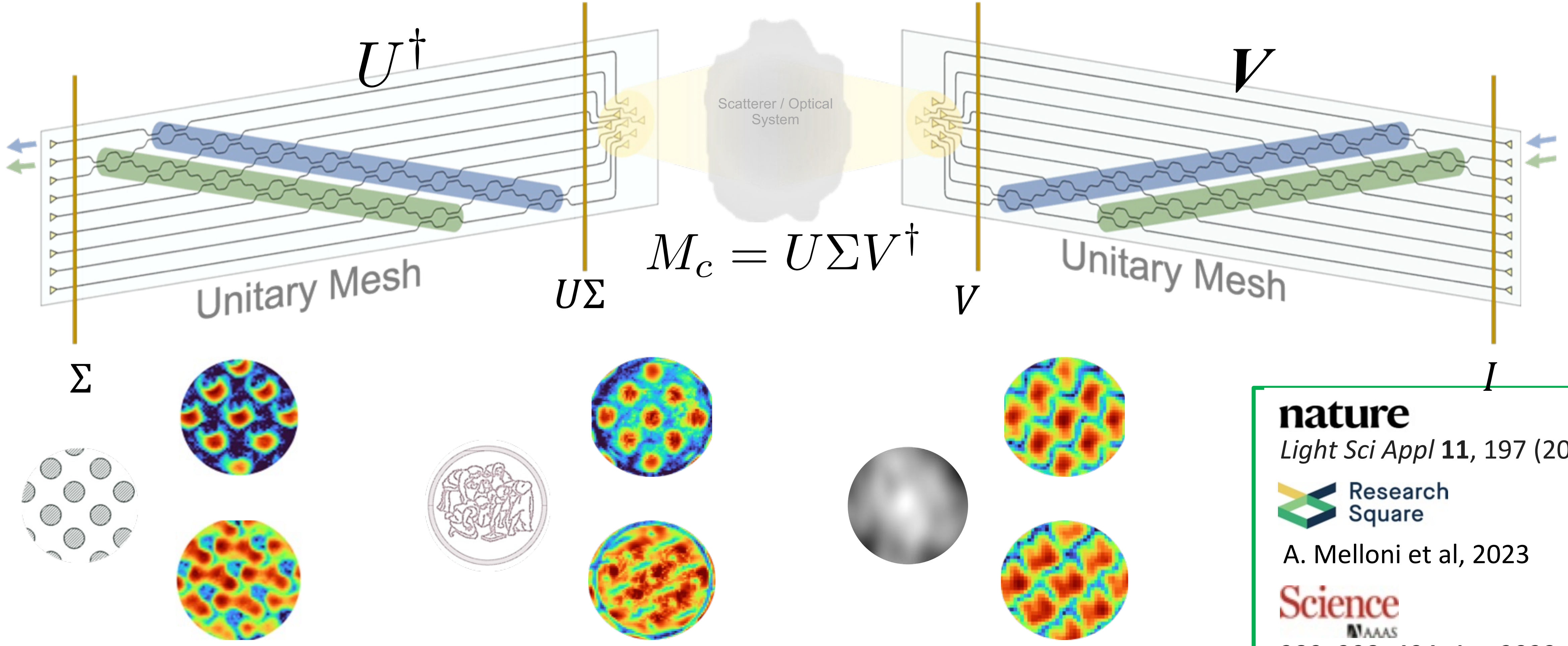


Beam shapes not belonging to any standard family of modes, yet mutually orthogonal



The processors are performing calculations… !

This is a physical implementation of **singular value decomposition (SVD)** of the channel transmission matrix



nature
Light Sci Appl **11**, 197 (2022)

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Science
380, 398–404, Apr 2023

Applications: general purpose, Matrix Algebra, mathematical accelerators, convolutional NN, tensor cores,…

Conclusions

- A Mesh of Mach-Zehnder interferometer implements a reconfigurable **UNITARY MATRIX**
- The processor performs vector-matrix and matrix-matrix **ANALOG** calculations
- Applications: Photonic processor assisted receiver for **turbulence mitigation in FSO links**. A two-processor (Tx-Rx) link opens to optical MIMO with “best” modes.
- Two-processors can perform the **singular-value decomposition** of the transmission matrix
- The system can self-configure adaptively, automatically and **without any calculations**

Acknoledgements

Photonic Devices Group

Prof. Marco Sampietro Group
for the development of the control electronics