Institut des Nanotechnologies de Lyon UMR 5270

Signed Convolution in Photonics with Phase-Change Materials using Mixed-Polarity Bitstreams

Raphael Cardoso, C Zrounba, M Abdalla, P Jimenez, MG de Queiroz, B Charbonnier, F Pavanello, I O'Connor, S Le Beux

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Application and platform

Signed Convolution in Photonics

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Specific material

with Phase-Change Materials

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Mathematical technique

using Mixed-Polarity Bitstreams

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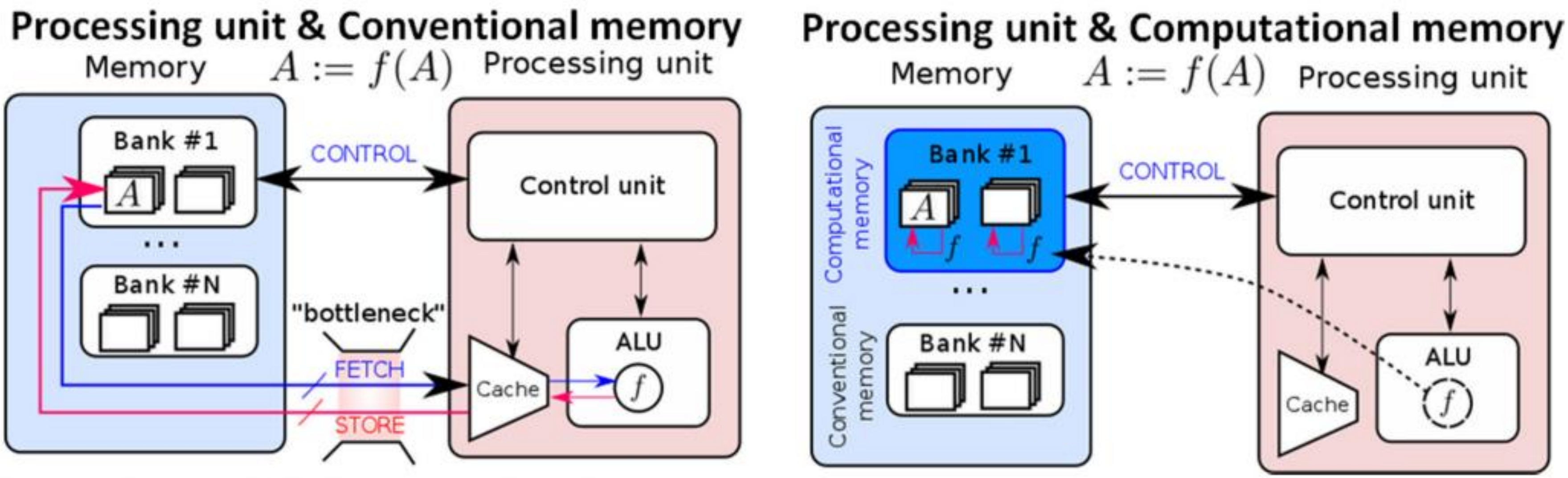
Summary

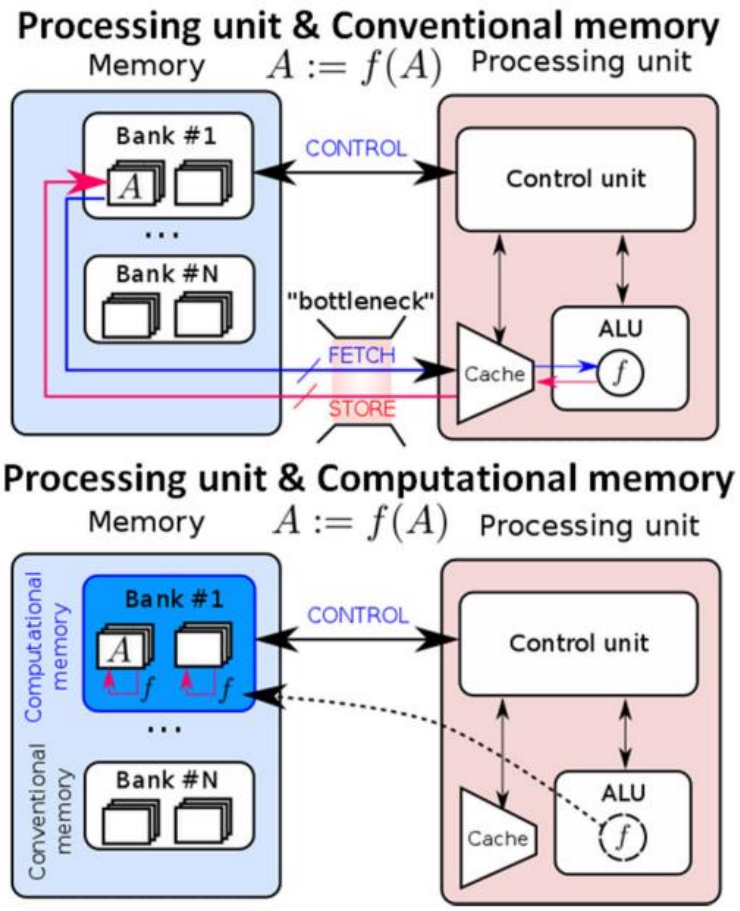
- *Motivation*
- *Photonic computing cells*
- *Proposed circuits*
- *Simulation results*
- *Conclusions and challenges*

An architectural paradigm shift

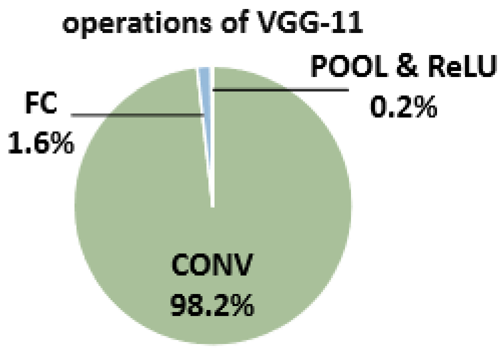


Sebastian et al., Tutorial: Brain-inspired computing using phase-change memory devices, 2018

Operations in neural networks



Sebastian A. et al., Tutorial: Brain-inspired computing using phase-change memory devices, 2018



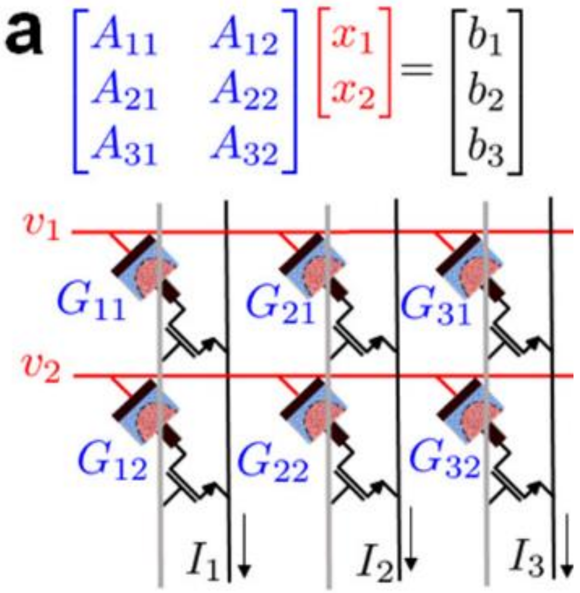
Guo et al., A Survey of FPGA-Based Neural Network Inference Accelerator, 2018

$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau)g(t-\tau)\,d\tau.$$

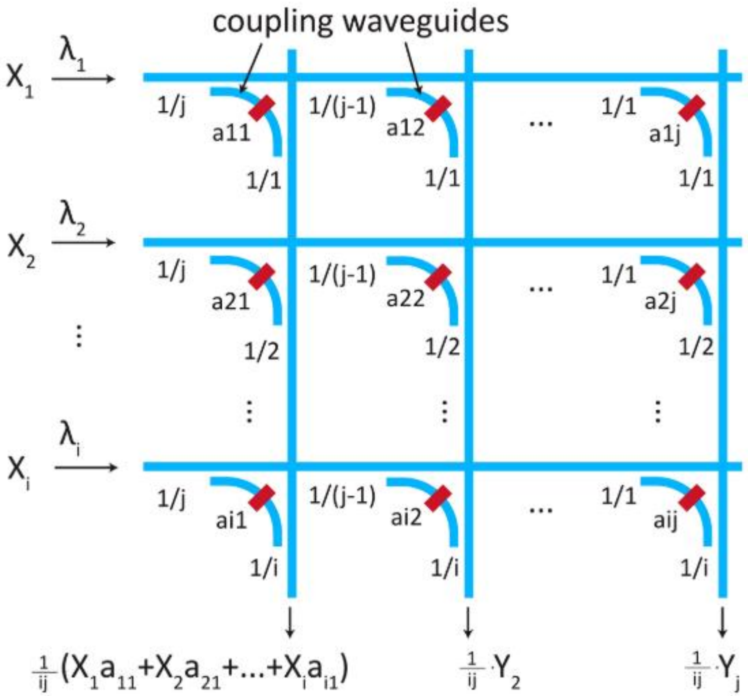
accumulate multiply

(MAC)

MAC crossbars in memory

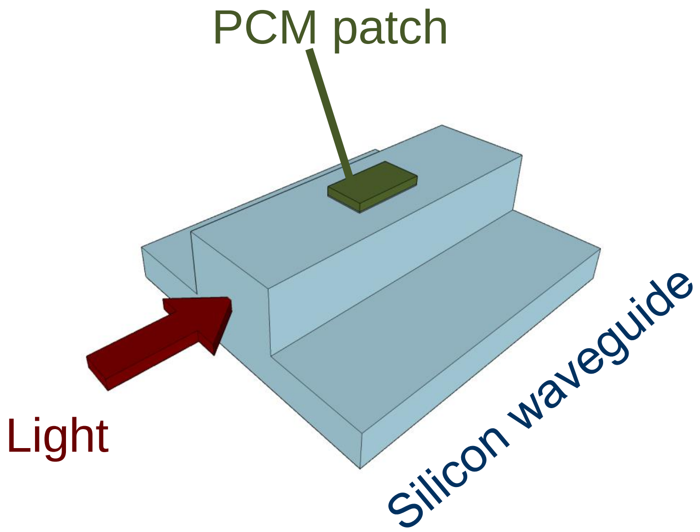


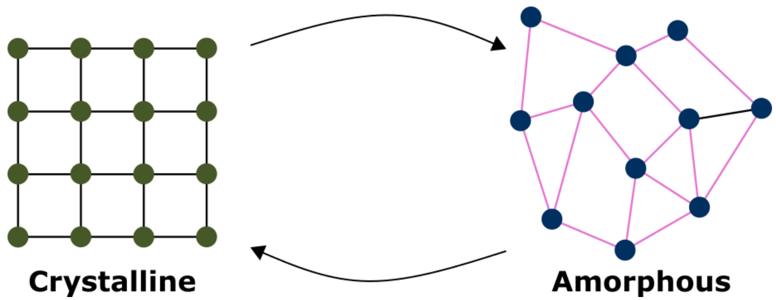
Sebastian et al., Computational phase-change memory: beyond von Neumann computing, 2019

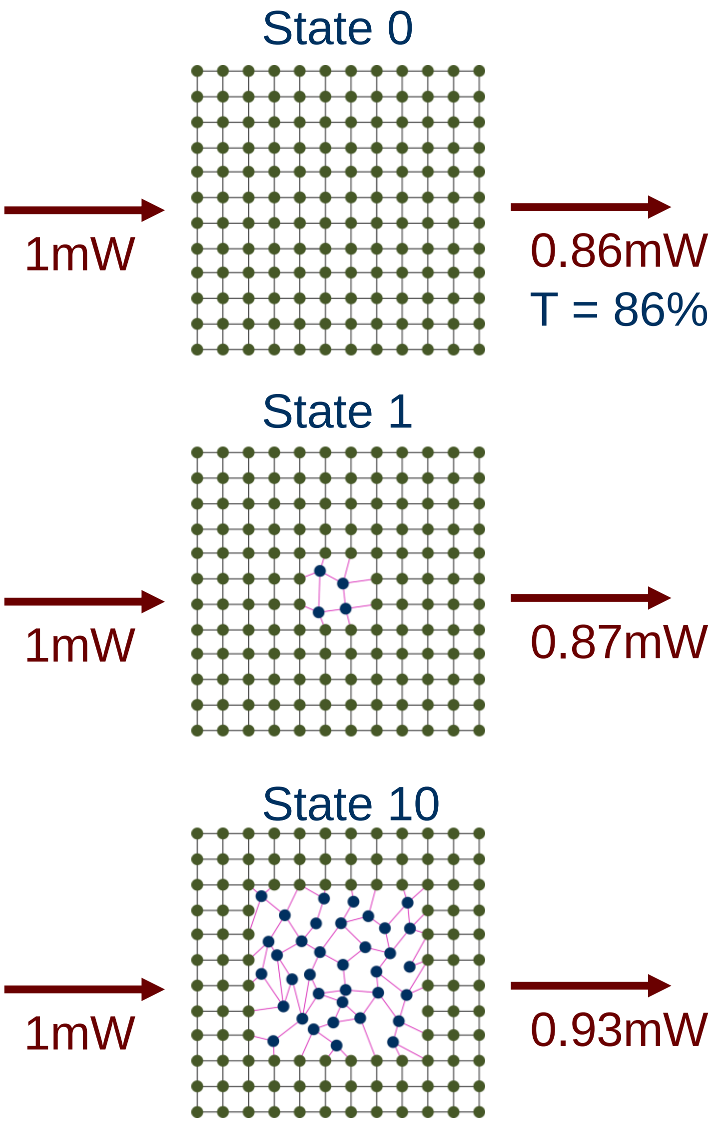


Brückerhoff-Plückelmann, et al., Chalcogenide phase-change devices for neuromorphic photonic computing, 2022

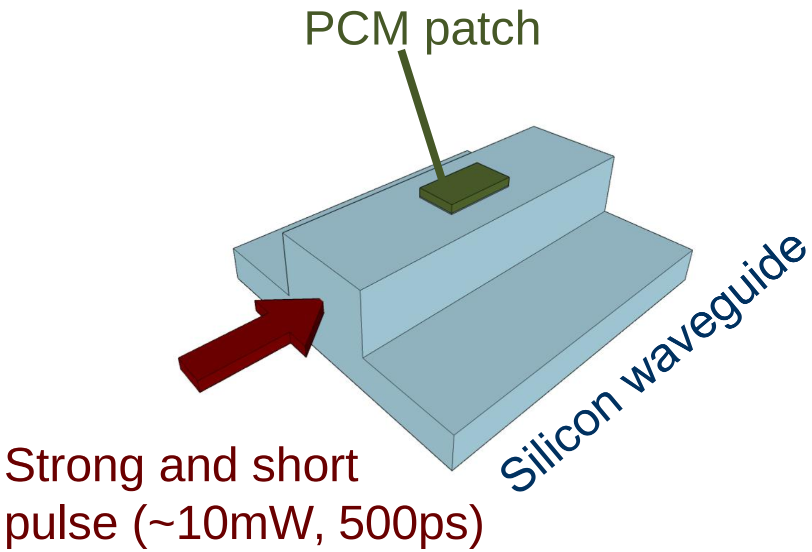
Phase-change materials in optics (oPCM)

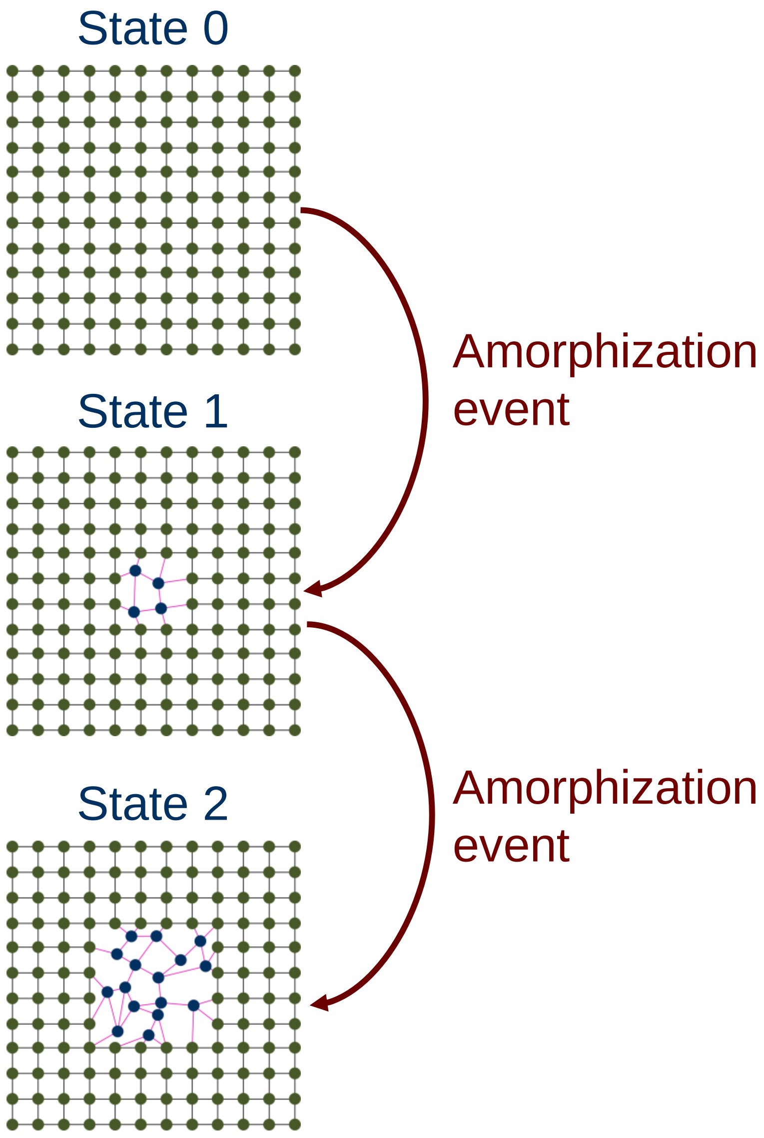






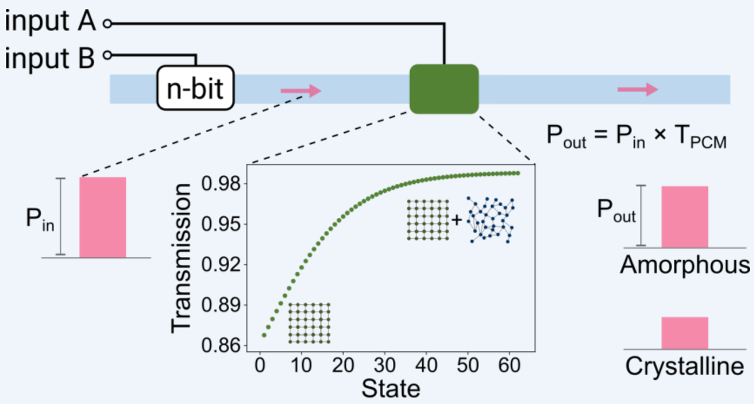
Changing between states





Photonic computing cells

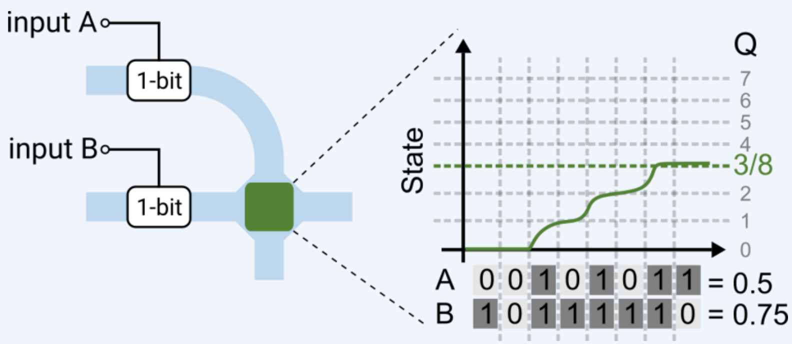
Baseline



- Performs a multiplication
- Constant PCM state (read)
- No native error

J. Feldmann, et al., Parallel convolutional processing using an integrated photonic tensor core, *2021*

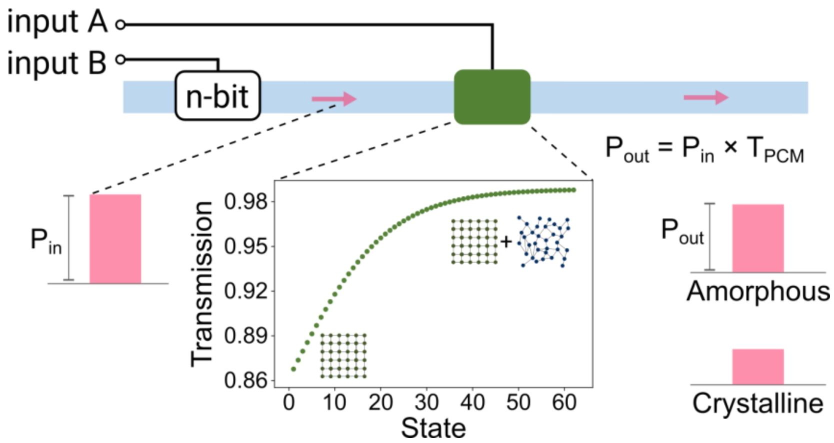
Stochastic-oPCM

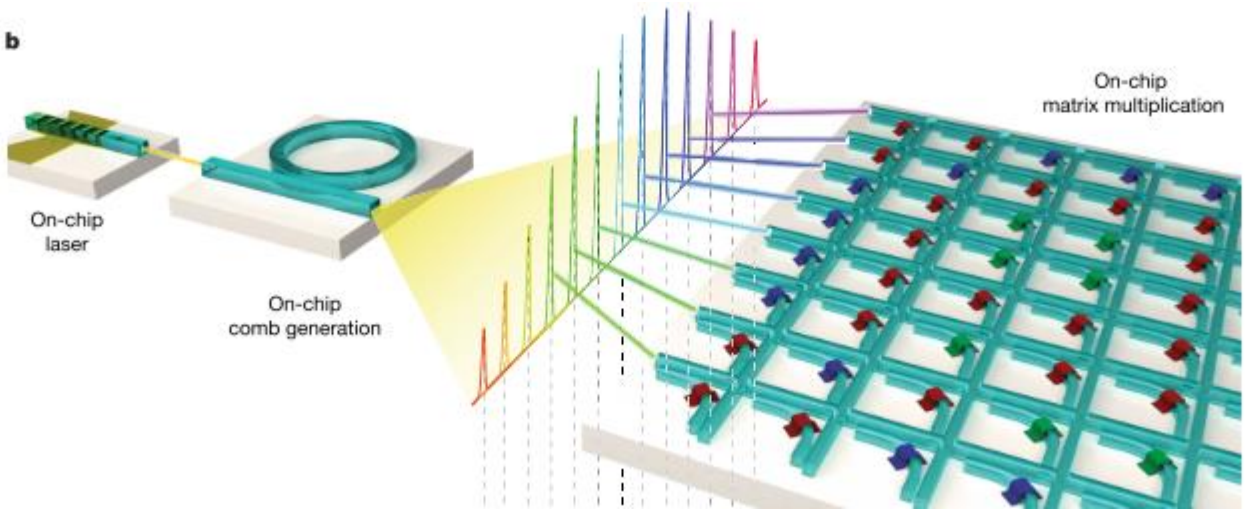


- Performs sums of multiplications
- Changes PCM state (write)
- Has native error

R. Cardoso, et al., Towards a Robust Multiply-Accumulate Cell in Photonics using Phase-Change Materials, *2023*

Baseline circuit





J. Feldmann, et al., Parallel convolutional processing using an integrated photonic tensor core, *2021*

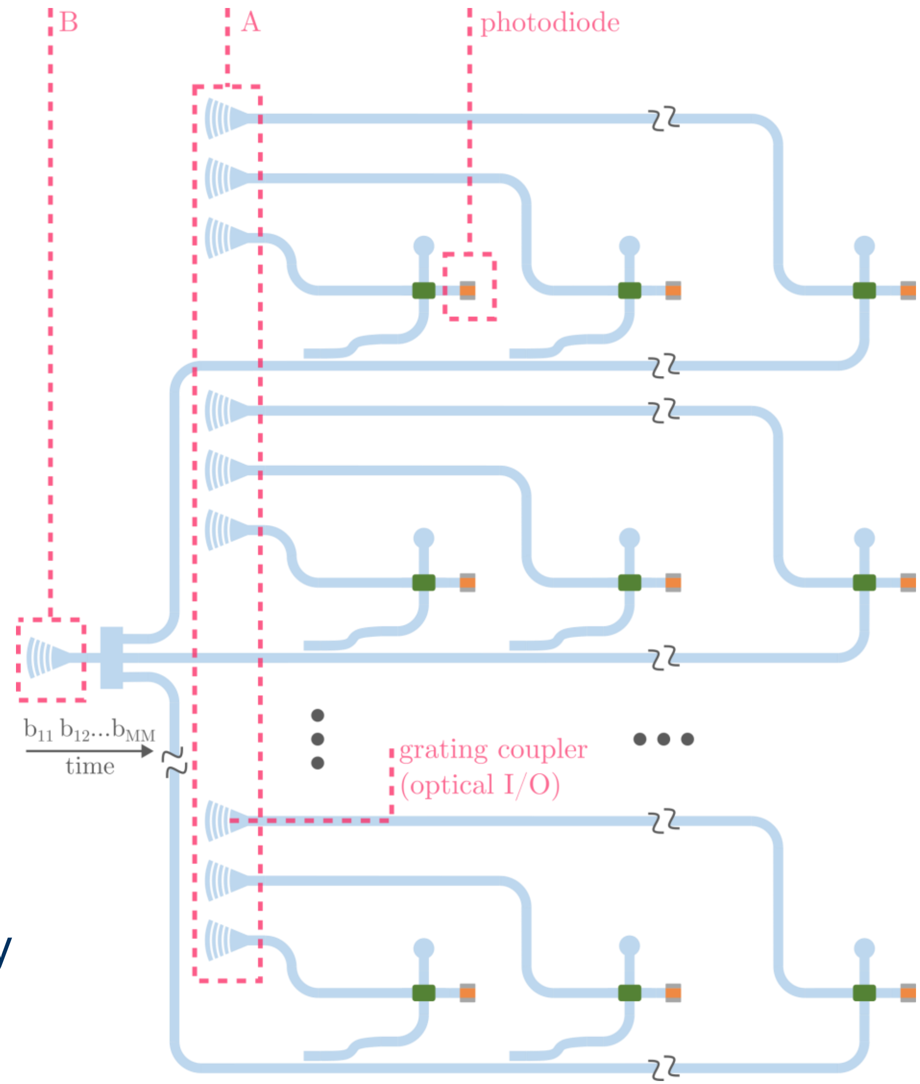
Stochastic-oPCM convolution circuit

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}$$

$$\begin{aligned} c_{11} &= a_{11}\, b_{11} + a_{12}\, b_{12} + a_{21}\, b_{21} + a_{22}\, b_{22} \\ c_{12} &= a_{12}\, b_{11} + a_{13}\, b_{12} + a_{22}\, b_{21} + a_{23}\, b_{22} \\ c_{21} &= a_{21}\, b_{11} + a_{22}\, b_{12} + a_{31}\, b_{21} + a_{32}\, b_{22} \\ c_{22} &= a_{22}\, b_{11} + a_{23}\, b_{12} + a_{32}\, b_{21} + a_{33}\, b_{22} \end{aligned}$$

time →

- Convolution result written as PCM states → no need to spend energy and time sending to memory



R. Cardoso, et al., Photonic Convolution Engine Based on Phase-Change Materials and Stochastic Computing, *2023*

Only positive operands are supported

Applications of Mixed-Polarity operation

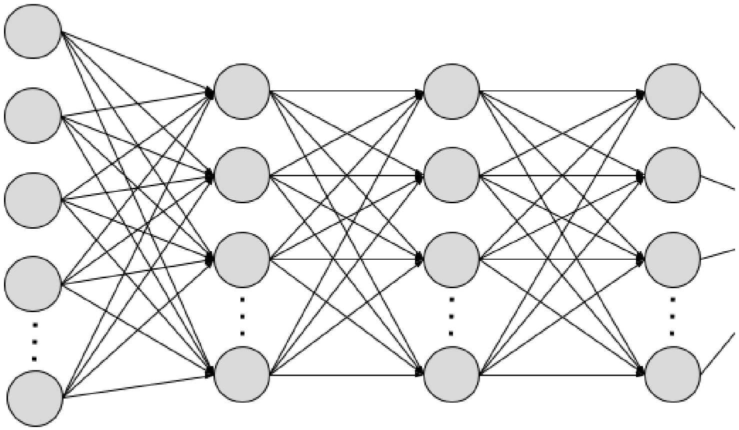
- Mixed polarity:

$$a \times b$$

b → signed

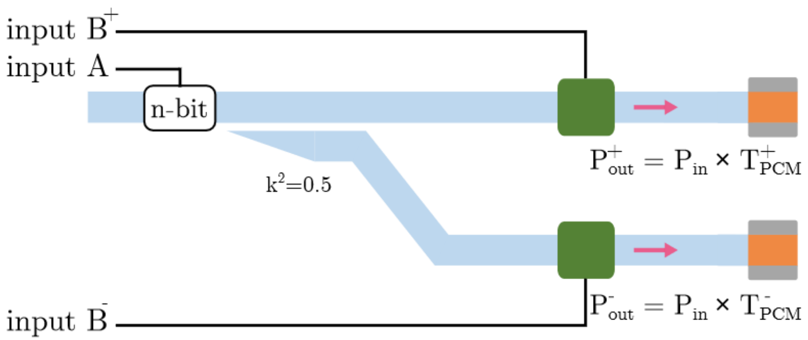
a → unsigned

Filter-based image processing

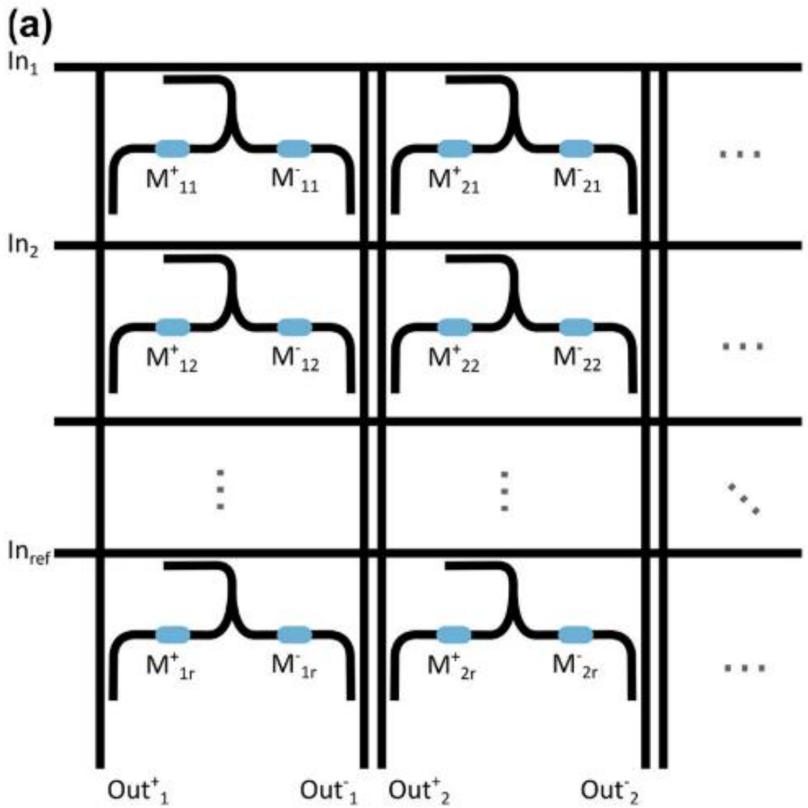


Deep learning *

Extension of baseline circuit



Needs two PCMs to deal with sign



F. Brückerhoff-Plückelmann, *et al.*, Broadband photonic tensor core with integrated ultra-low crosstalk wavelength multiplexers, *2022*

Our contributions

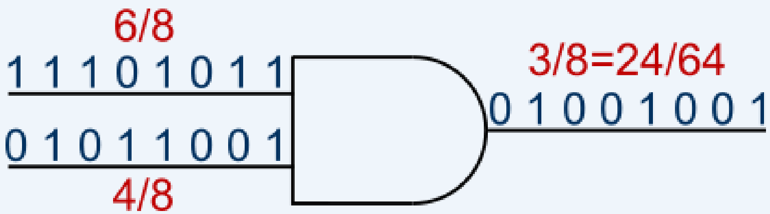
1. Development of a Stochastic Computing formalism to Mixed-Polarity inputs

2. Development of a mixed-polarity photonic cell and circuit with PCM

3. Conservative comparison between methods with respect to noise

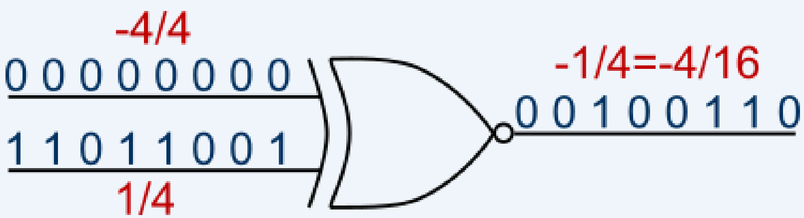
Stochastic computing

Unipolar



- Digital 0 encoded to +0, digital 1 encoded to +1
- Multiplication done by AND

Bipolar



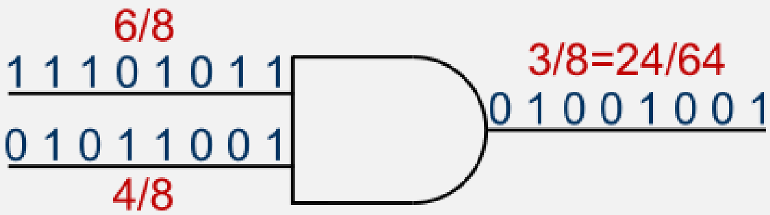
- Digital 0 encoded to -1, digital 1 encoded to +1
- Multiplication done by XNOR

A. Alaghi, et al., Survey of stochastic computing, *2013*

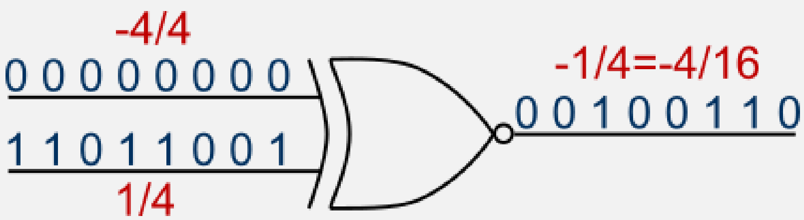
In both cases, the result is recovered by a counter at the output

Mixed-polarity in stochastic computing

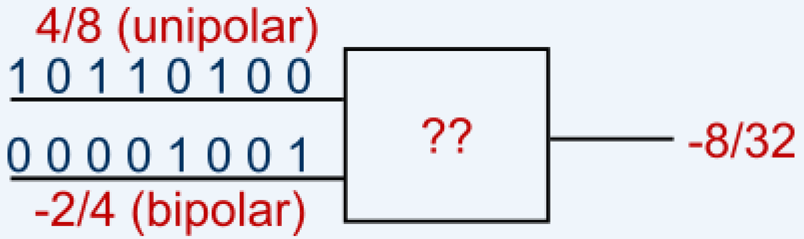
Unipolar



Bipolar

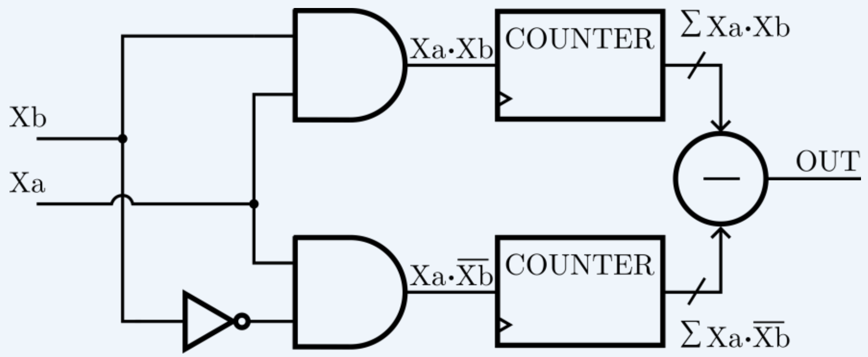


Mixed-polarity



Mixed-polarity in stochastic computing

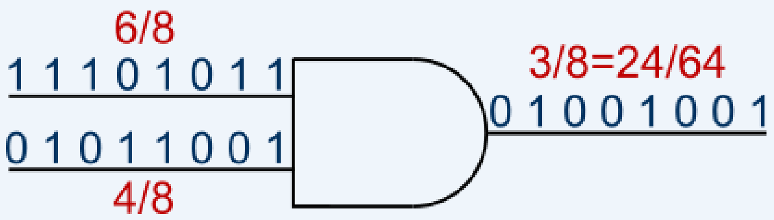
Mixed-polarity

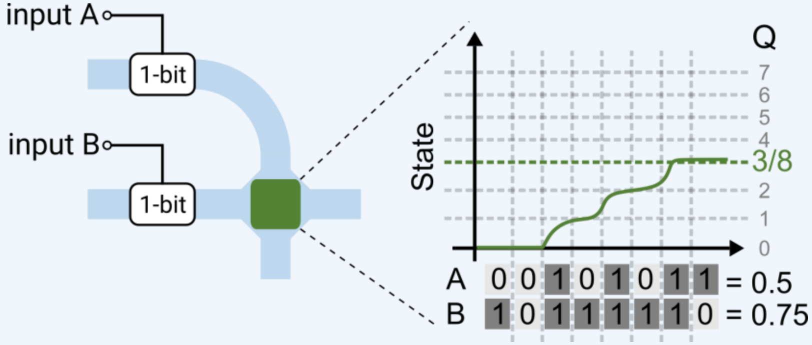


- Output is not stochastic
- Uses only AND and counters
- Proof of validity provided

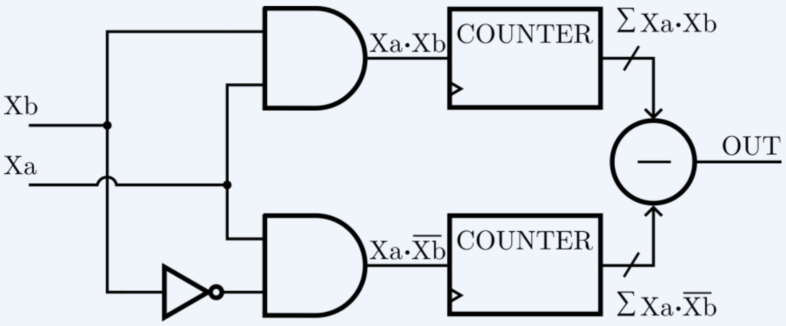
Photonic mixed-polarity cell

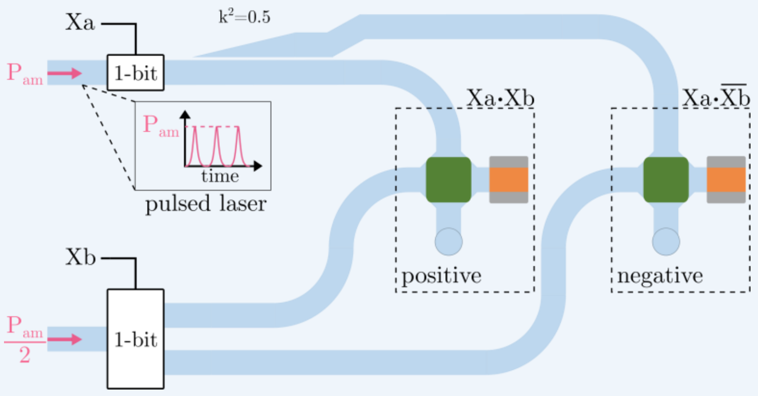
Unipolar





Mixed-polarity





Photonic mixed-polarity circuit

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} * \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}$$

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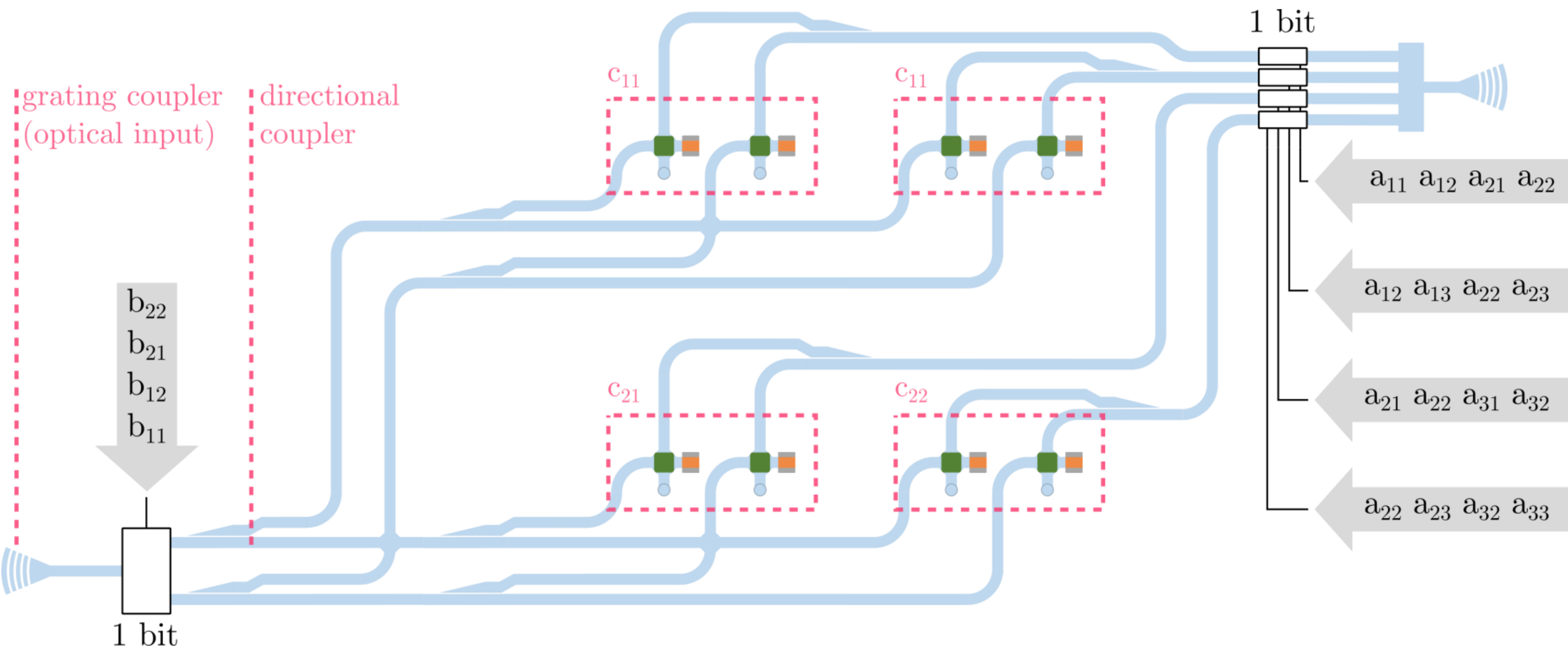
$$c_{21} = a_{21} b_{11} + a_{22} b_{12} + a_{31} b_{21} + a_{32} b_{22}$$
$$c_{22} = a_{22} b_{11} + a_{23} b_{12} + a_{32} b_{21} + a_{33} b_{22}$$

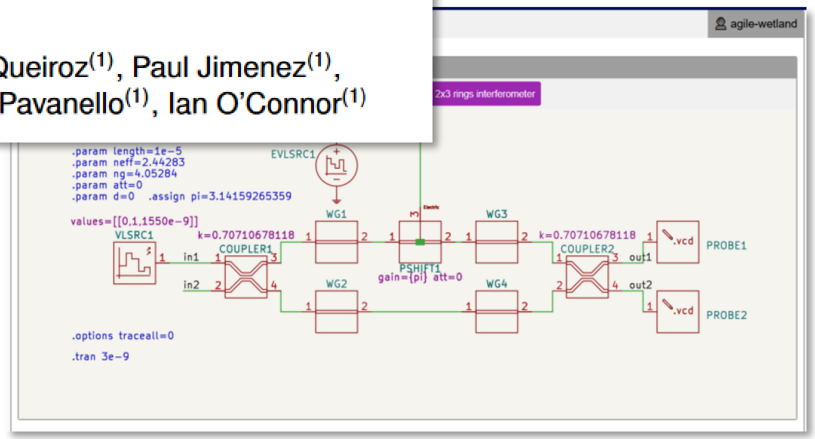
time →



A visualizable convolution application

Introducing SPECS: Scalable Photonic Event-driven Circuit Simulator

Clément Zrounba[1], Raphael Cardoso[1], Maurício Gomes de Queiroz[1], Paul Jimenez[1], Mohab Abdalla[1,2], Alberto Bosio[1], Sébastien Le Beux[3], Fabio Pavanello[1], Ian O'Connor[1]



demo.zrounba.fr/specs/

A visualizable convolution application

Edge detection filter

- Input: 28x28 grayscale images
- Application: edge detection with Sobel filters
- Quantization: 6 bits
- Output bandwidth: 1 GHz

$$* \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix}$$

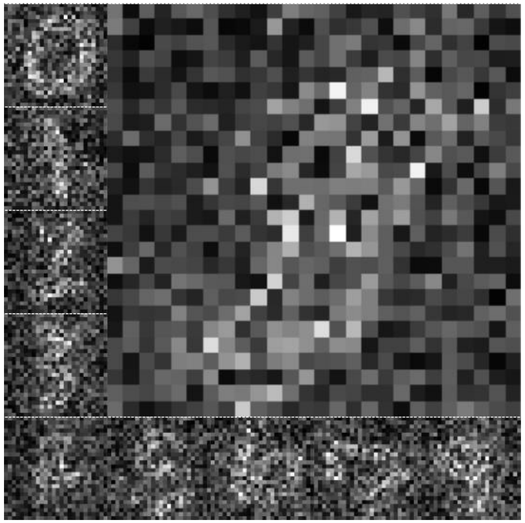
$$* \begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix}$$

Ideal operation

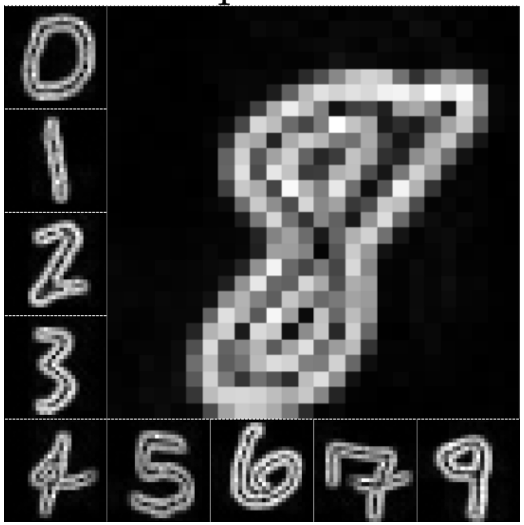
Filter in photonics

Ideal

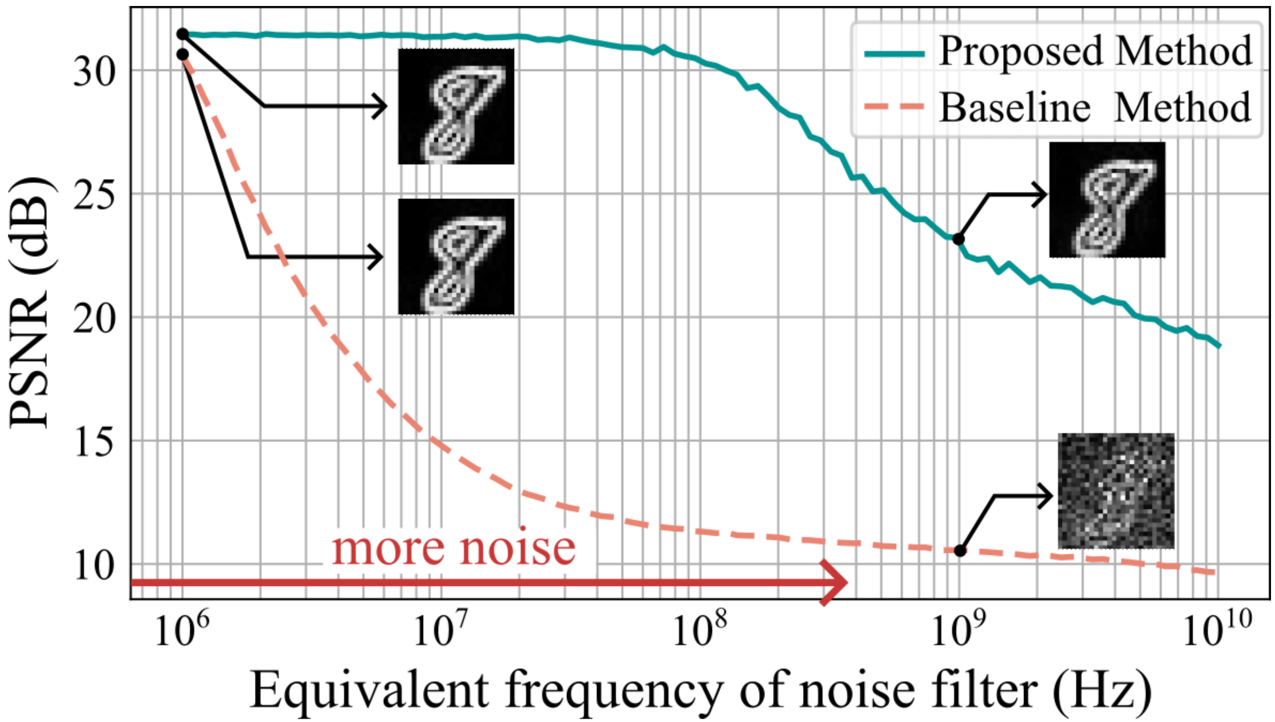
Baseline Method



Proposed Method



Noise dependency



- Noise is a function of the filter in the output (bandwidth)
- Speed is limited by noise in the baseline

Conclusions and perspectives

- Confirmed noise robustness of the stochastic computing cell in photonics
- Speed in our case limited by the time between amorphization events in a PCM (~1ns/event)
- Challenges:
  - Limited endurance of the PCMs
  - Natural randomness in PCM phase dynamics
  - Testing a fabricated stochastic-oPCM cell (taped out!)

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