Sustainable Hardware: Photonics-based Machine Learning

Ingo Fischer

Claudio Mirasso

Miguel C. Soriano

Apostolos Argyris

Silvia Ortín

Jyoti Deka

I. Estebánez

G. Donati

M. Pflüger

L. Talandier

M. Goldmann

Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC, UIB-CSIC), Palma

Why a hardware implementation of AI systems is important?

- Era of BIG data → Era of HUGE Data → Processing speed is crucial
- Energy Consumption → More Efficient
- New kind of computation → Traditional computers
- It can be integrated with already existing devices
- It would allow for parallel (and architecture-adapted) implementations

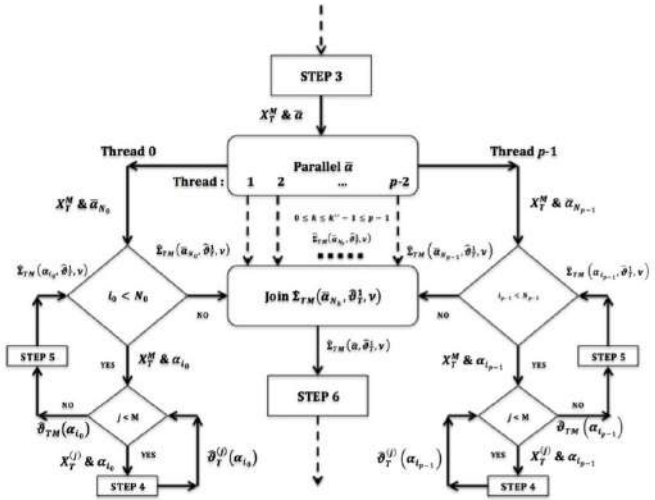
"Neuromorphic engineering is partly an attempt to move elements of machine learning and artificial intelligence algorithms to hardware that reflects their massively distributed nature."

Why machine learning in photonics?

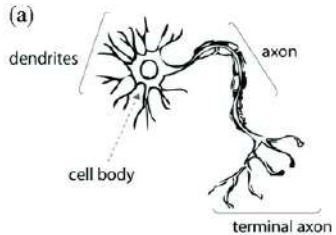
- ML tools are mostly developed using a large variety of algorithms-> very good but are slow and inefficient in terms of energy consumption
- Hardware-based ML is becoming very popular.
- Can be implemented using photonics components: Neuromorphic Photonics.
  - Fast & energy efficient; parallel processing, time and wavelength multiplexing.
  - Optical signals: high bandwidth; low attenuation/distance
  - Dissipate less heat and are less susceptible to electromagnetic interference.
- Despite its potential, research and development is still at an early stage.

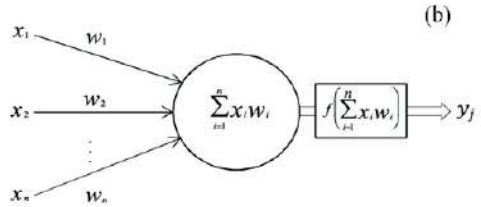
Scalability challenging: 4x4 neurons ~ 1.2 mm^2 Brain: 120.000 neurons

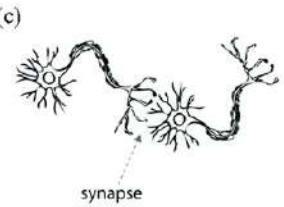
Software-based AI

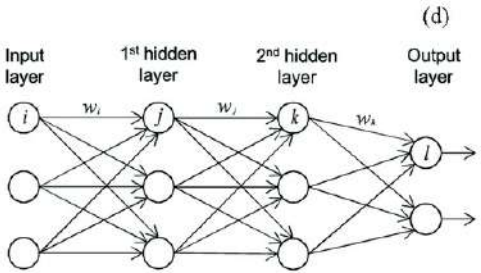


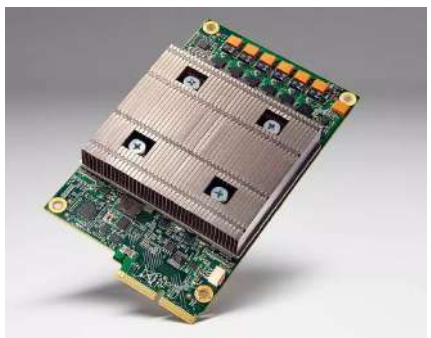
Artificial Neural Networks



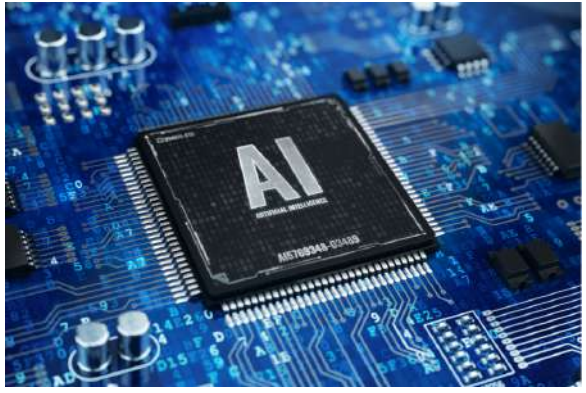


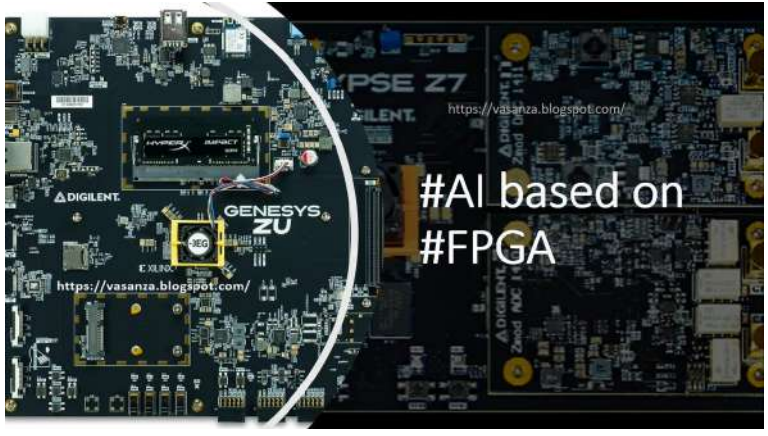


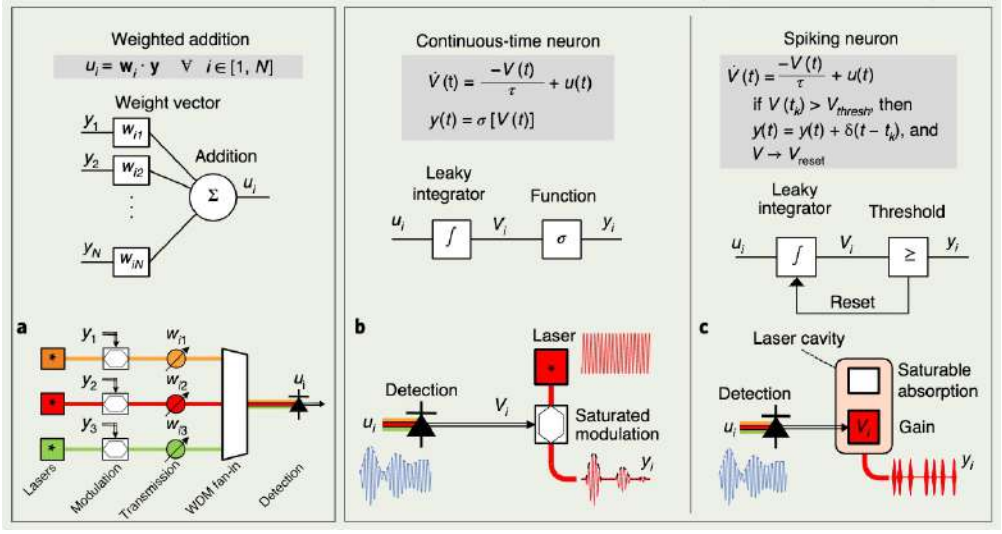




Hardware-based AI







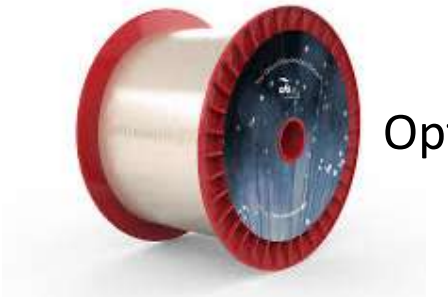
REVIEW ARTICLE | FOCUS
https://doi.org/10.1038/s41566-020-00754-y
nature photonics
Check for updates

Photonics for artificial intelligence and neuromorphic computing

Bhavin J. Shastri[1,2,7]✉, Alexander N. Tait[2,3,7]✉, T. Ferreira de Lima[2], Wolfram H. P. Pernice[4], Harish Bhaskaran[5], C. D. Wright[6] and Paul R. Prucnal[2]

Components for Hardware-based Photonics AI

SCLs



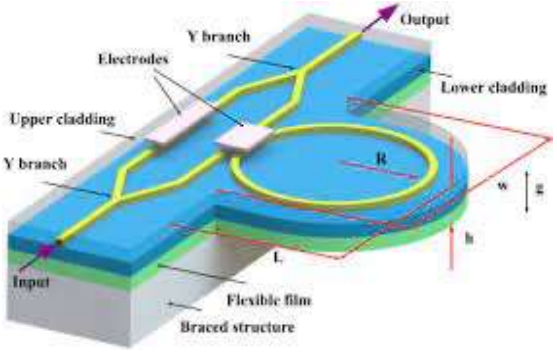
Optical Fibers

Optical attenuators

SOAs

Photodetectors

Delay lines



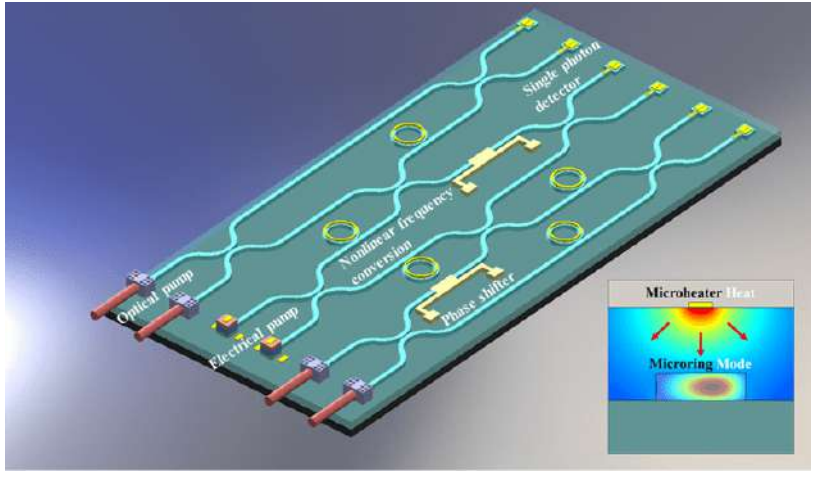
Optical waveguides

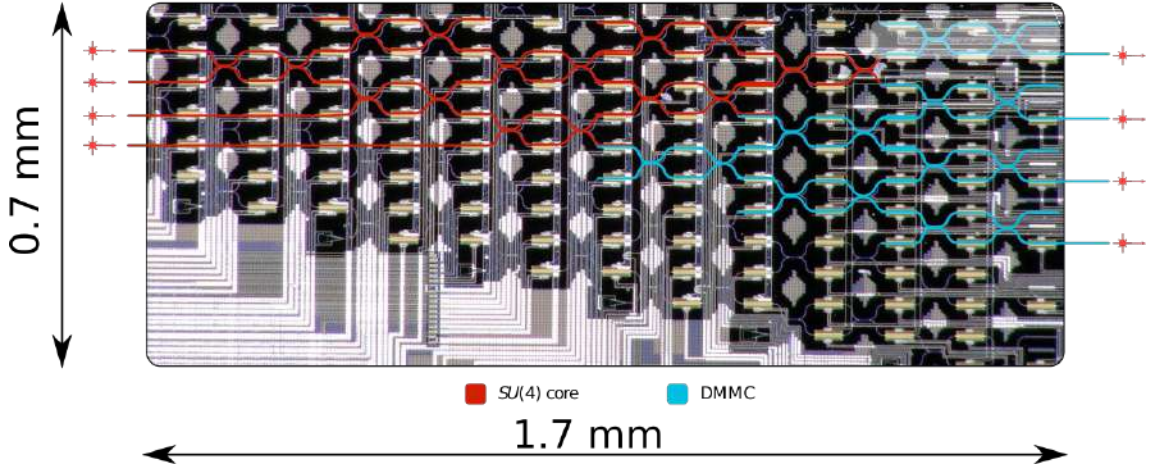
Optical Modulators

Polarization Controllers

Photonics Integrated Circuits

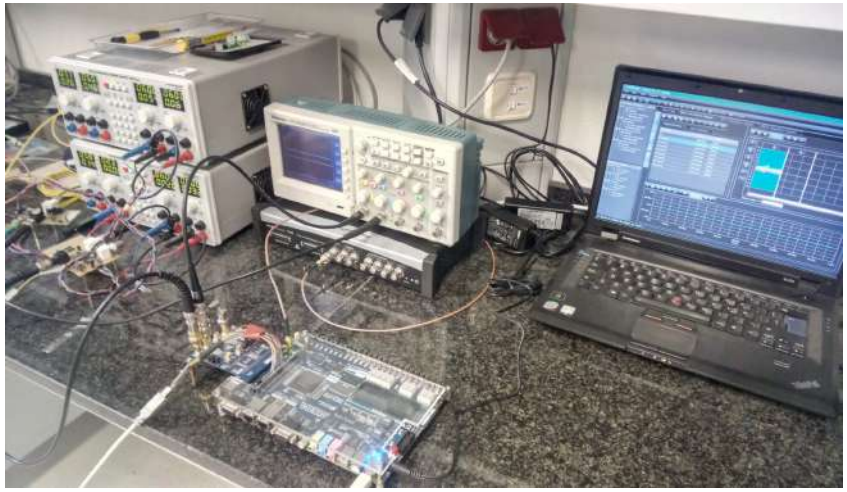
But the future lies in the integrated photonic circuits

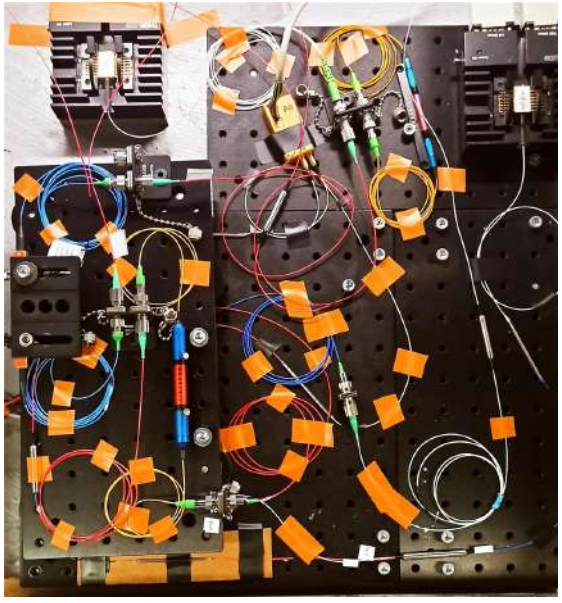




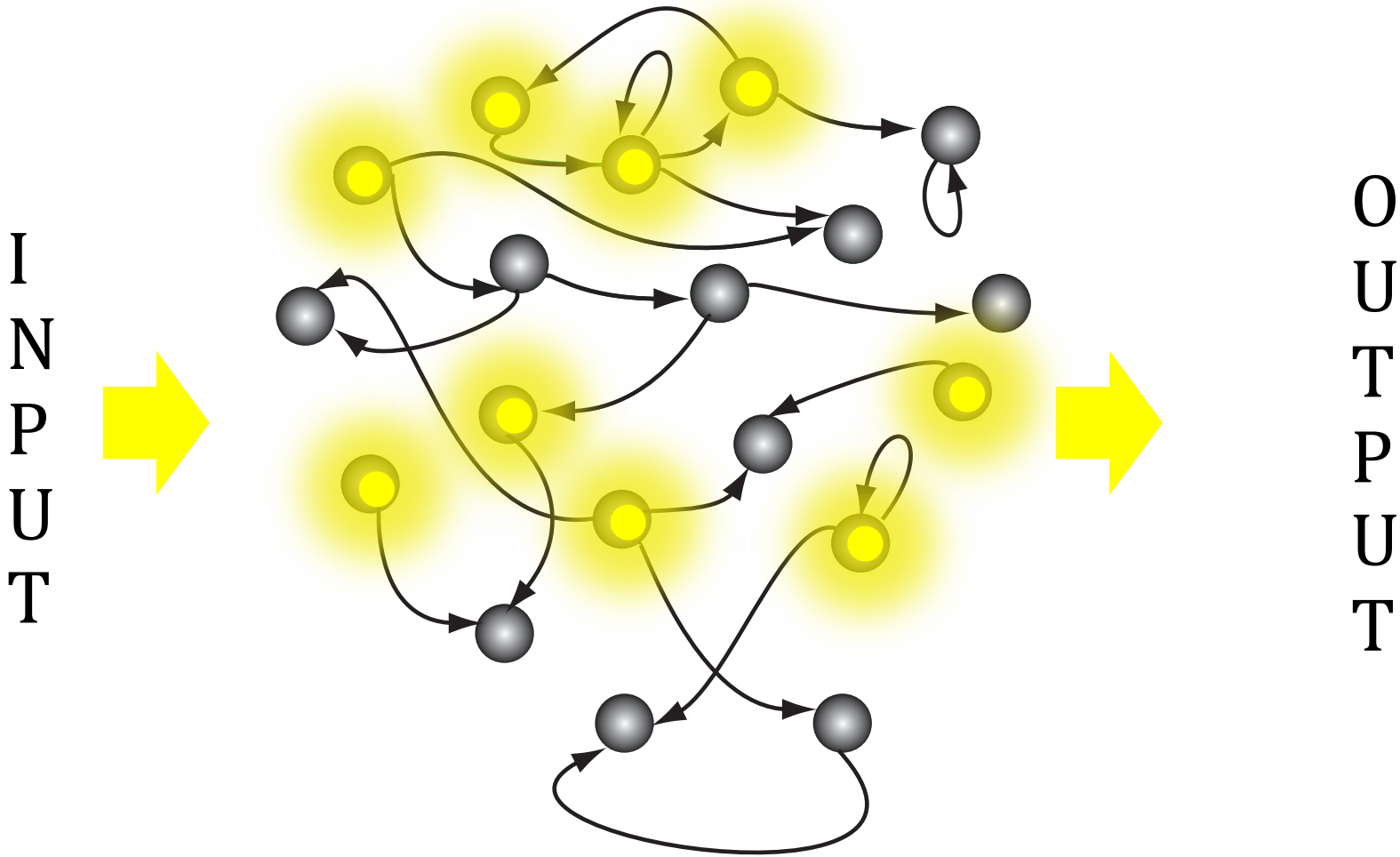
Shen, *et al.*, Nature Photonics **11**, 441-446 (2017).

Fundamental and Applications of Hardware-based AI @ IFISC





Artificial Neural Networks



Reservoir Computing:

Neuro-inspired concept

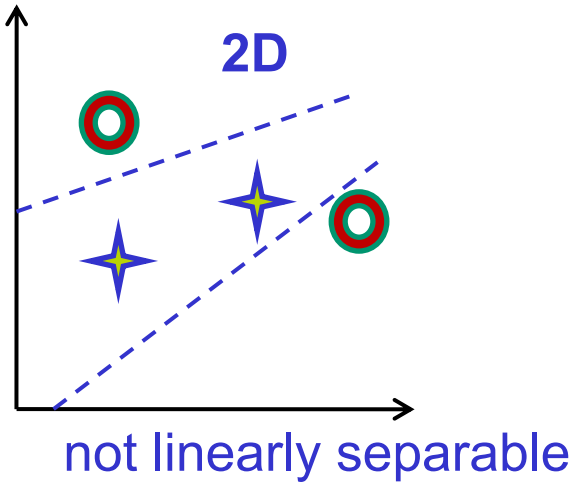
Consider brain a “black-box“ complex recurrent network

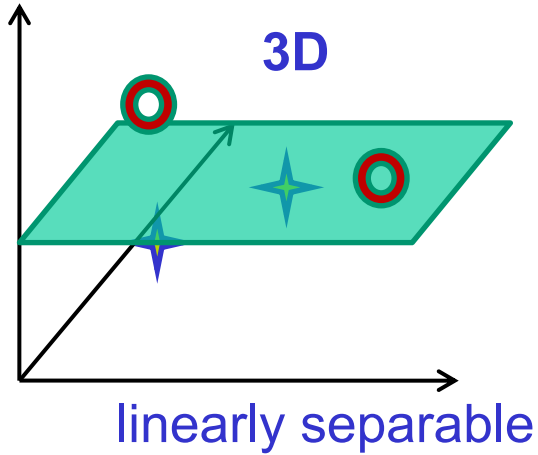
Analyzes transient responses to (sensory) input

Echo State Networks
(H. Jaeger, 2002)
Liquid State Machines
(W. Maass et al 2003)

How does Reservoir Computing work?

Utilizes projection of input state (usually low dimensional) onto a high-dimensional feature space





- Nonlinear mapping onto a higher dimensional state space can make a classification problem linearly separable
- Linear separability becomes exponentially more likely with increasing state space dimension

Photonic implementation of RC using a network of coupled Semiconductor Optical Amplifiers as the basic building blocks for the reservoir

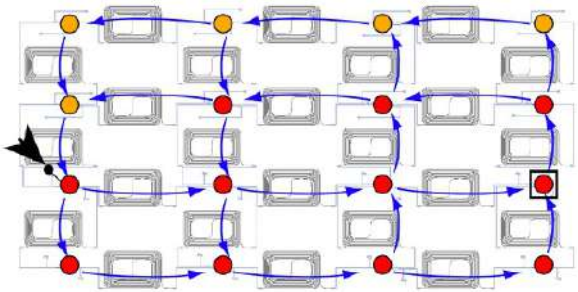
Optics Express Vol. 16, Issue 15, pp. 11182-11192 (2008) · https://doi.org/10.1364/OE.16.011182

OPTICA PUBLISHING GROUP

Toward optical signal processing using Photonic Reservoir Computing

Kristof Vandoorne, Wouter Dierckx, Benjamin Schrauwen, David Verstraeten, Roel Baets, Peter Bienstman, and Jan Van Campenhout

Passive photonic silicon reservoir was used as a generic computational platform for diverse tasks



nature COMMUNICATIONS

ARTICLE

Received 13 Aug 2013 | Accepted 4 Mar 2014 | Published 24 Mar 2014 DOI: 10.1038/ncomms4541 OPEN

Experimental demonstration of reservoir computing on a silicon photonics chip

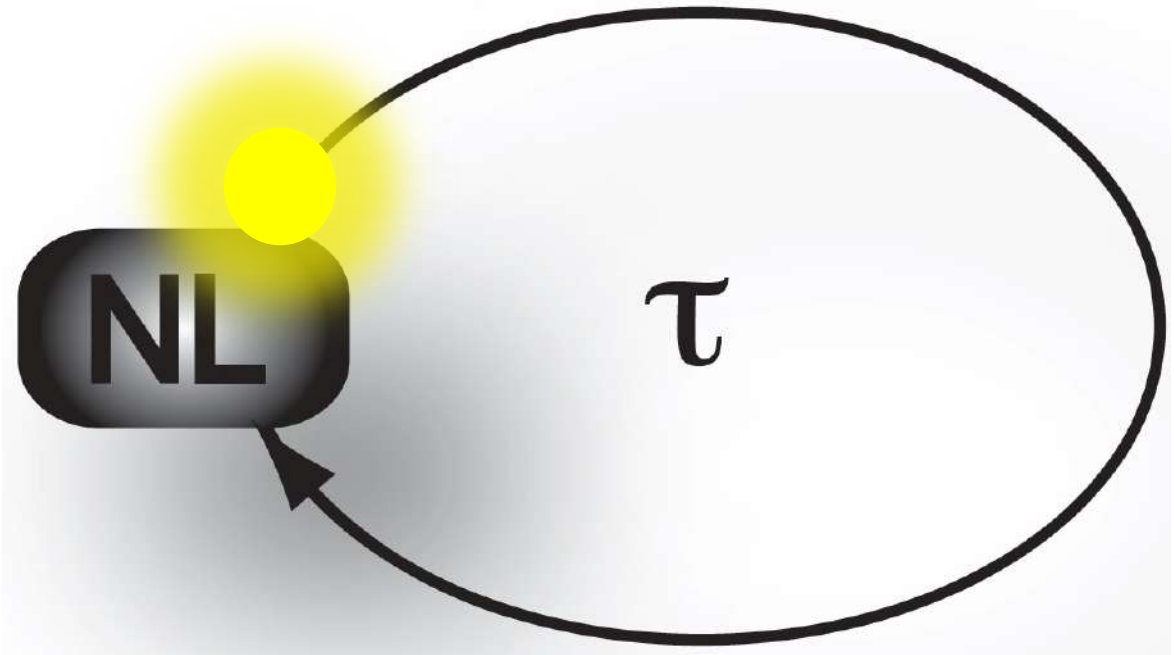
Kristof Vandoorne[1,2], Pauline Mechet[1,2], Thomas Van Vaerenbergh[1,2], Martin Fiers[1,2], Geert Morthier[1,2], David Verstraeten[3], Benjamin Schrauwen[3], Joni Dambre[3] & Peter Bienstman[1,2]

erc European Research Council Established by the European Commission

St. Grant P. Bienstman

"Novel paradigms for massively parallel nanophotonic information processing

How can an ANN be boiled down into the minimum number of ingredients that makes it easily implementable in hardware?



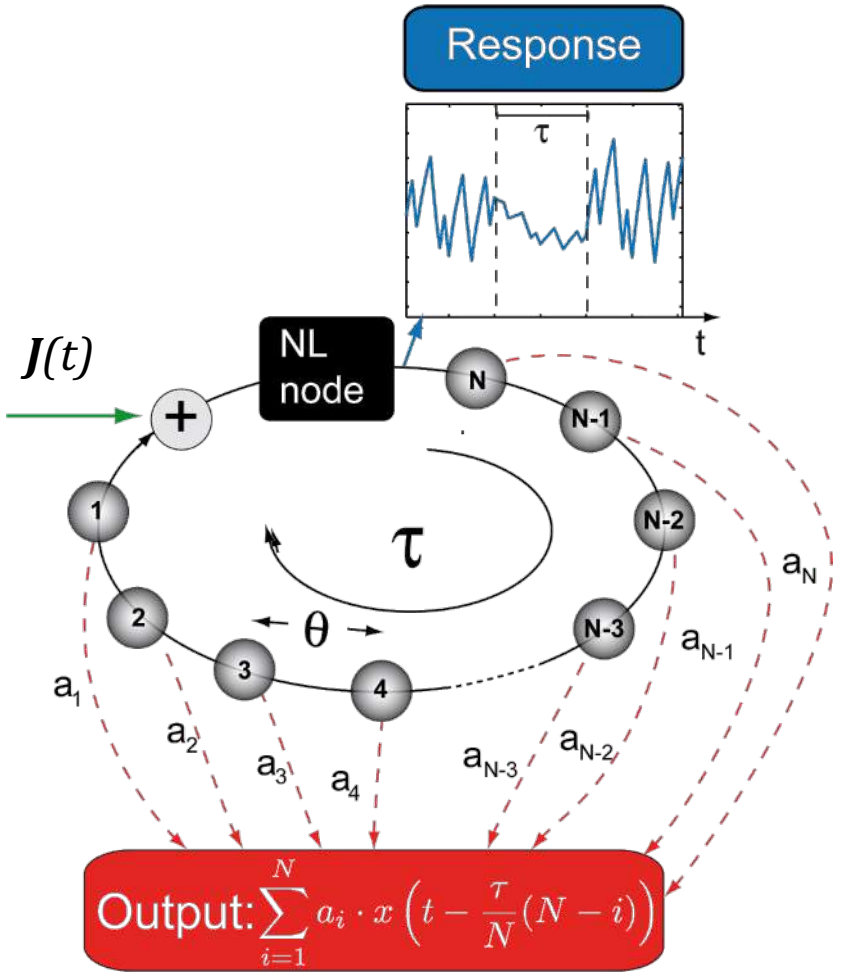
In how far can we replace the complex network by the delay system?

Many degrees of freedom distributed within the delay loop

→ virtual nodes within the delay line

Time multiplexing is used to feed the information

Fading memory introduced by delay



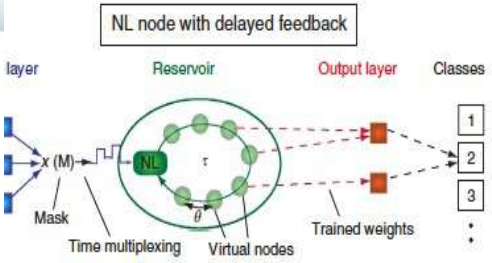
nature COMMUNICATIONS OPEN

ARTICLE

Received 23 Dec 2010 | Accepted 12 Aug 2011 | Published 13 Sep 2011 DOI: 10.1038/ncomms1476

Information processing using a single dynamical node as complex system

L. Appeltant[1], M.C. Soriano[2], G. Van der Sande[1], J. Danckaert[1], S. Massar[3], J. Dambre[4], B. Schrauwen[4], C.R. Mirasso[2] & I. Fischer[2]



phocus
towards a PHOtonic liquid state machine based on delay-CoUpled Systems

- Spoken Digit Recognition
- Chaotic time series prediction

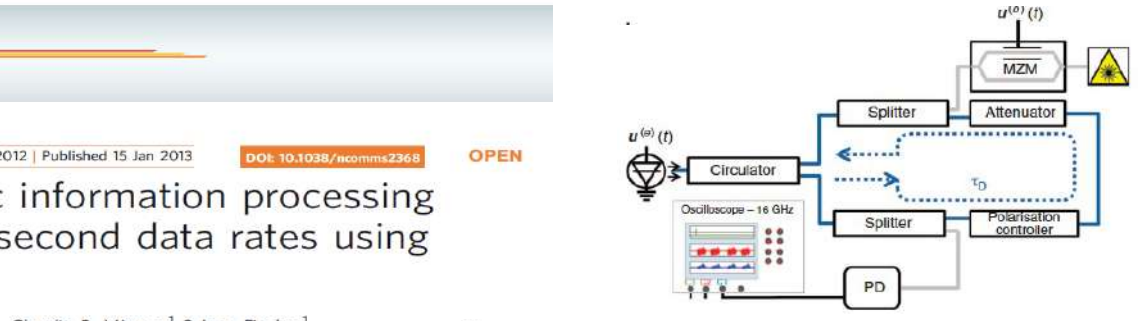
nature COMMUNICATIONS

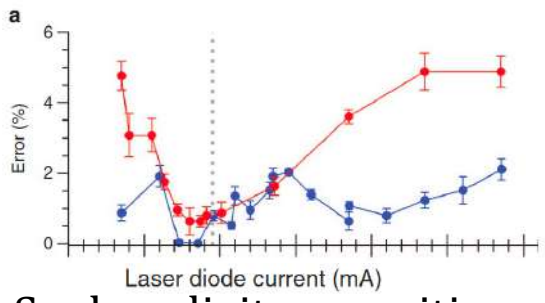
ARTICLE

Received 16 Aug 2012 | Accepted 10 Dec 2012 | Published 15 Jan 2013 DOI: 10.1038/ncomms2368 OPEN

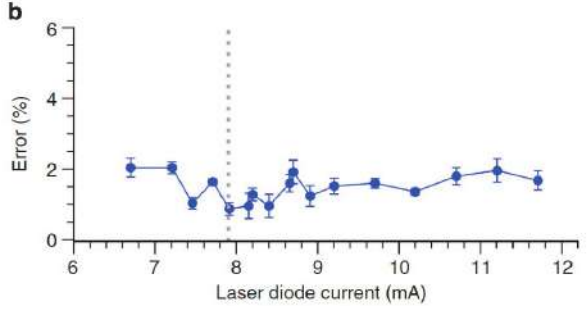
Parallel photonic information processing at gigabyte per second data rates using transient states

Daniel Brunner[1], Miguel C. Soriano[1], Claudio R. Mirasso[1] & Ingo Fischer[1]





Spoken digit recognition

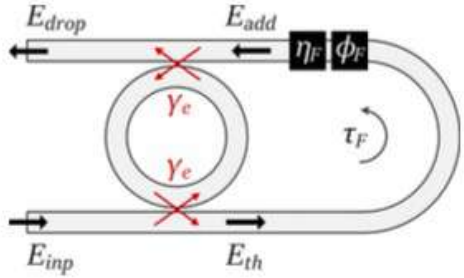


Speaker recognition

Lowest reported error rate (0.014%) at highest data rate (5×10^5 words/s)

Time-series prediction with an error of 10.6% with a prediction rate of 1.3×10^7 data points/s.

Microrring Resonators



Research Article Vol. 30, No. 1 / 3 Jan 2022 / Optics Express 522
Optics EXPRESS

Microring resonators with external optical feedback for time delay reservoir computing

GIOVANNI DONATI,[1,2,*] CLAUDIO R. MIRASSO,[1] MATTIA MANCINELLI,[2] LORENZO PAVESI,[2] AND APOSTOLOS ARGYRIS[1]

Passive element can operate in the linear or nonlinear regime depending on the input power

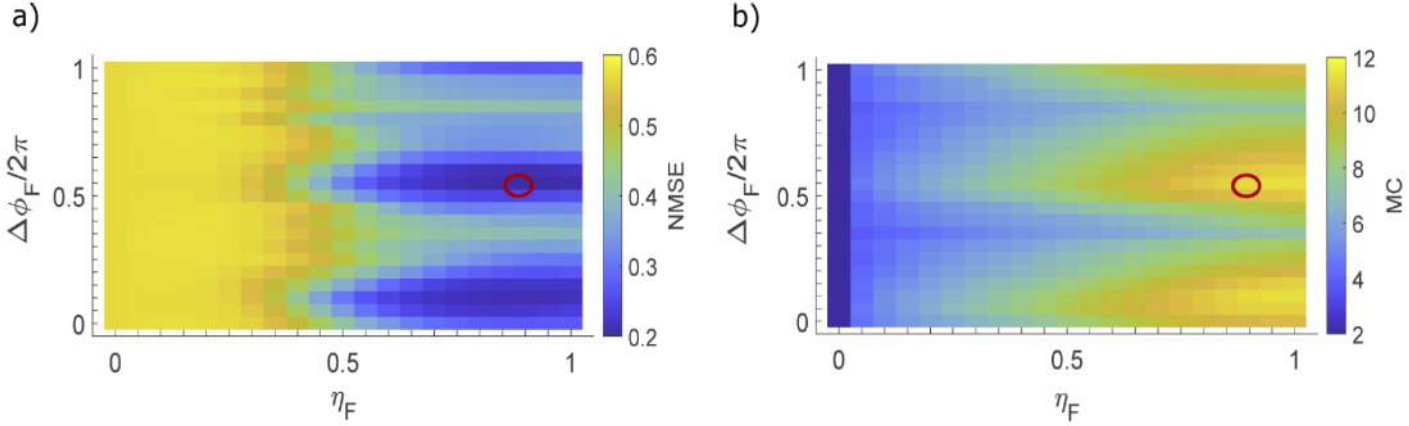
Two characteristic times scales: one of ~ 1ns; the other ~ 100 ns.

Prof. Lorenzo Pavesi
Advanced ERC GRANT 2017

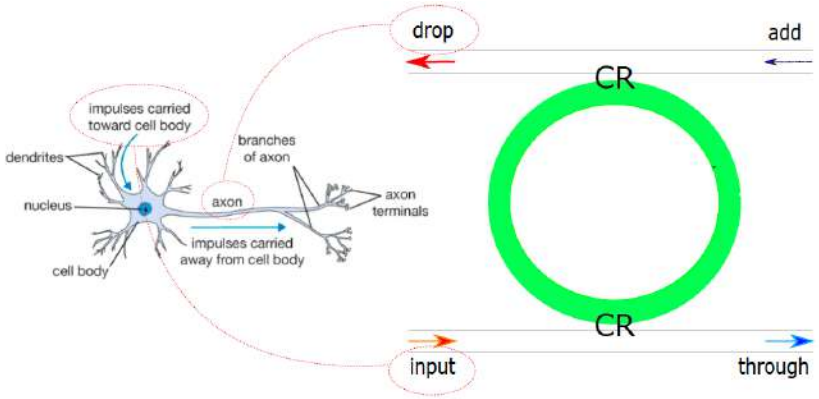
NanoLab Department of Physics — UNIVERSITY OF TRENTO - Italy

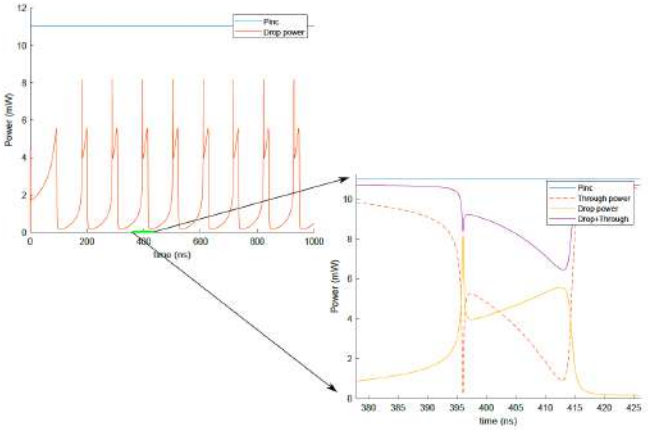
"Unveiling the relationship between brain connectivity and function by integrated photonics"

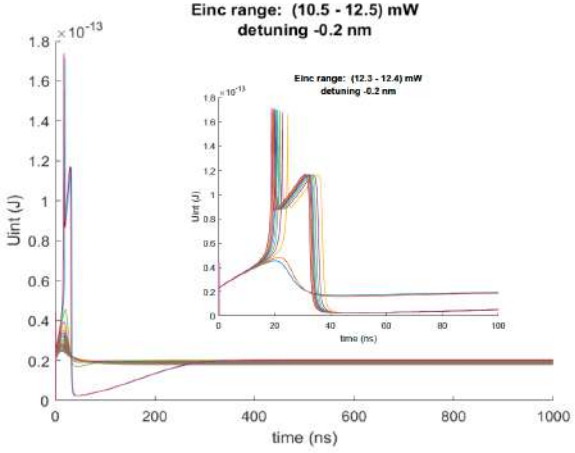
NARMA 10 Test

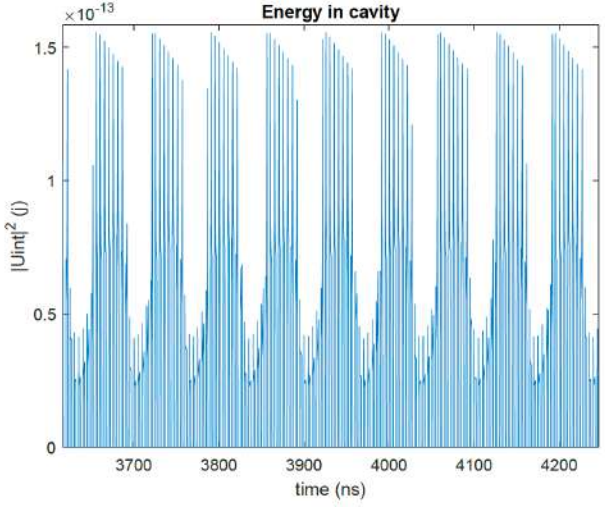


Microrring Resonators





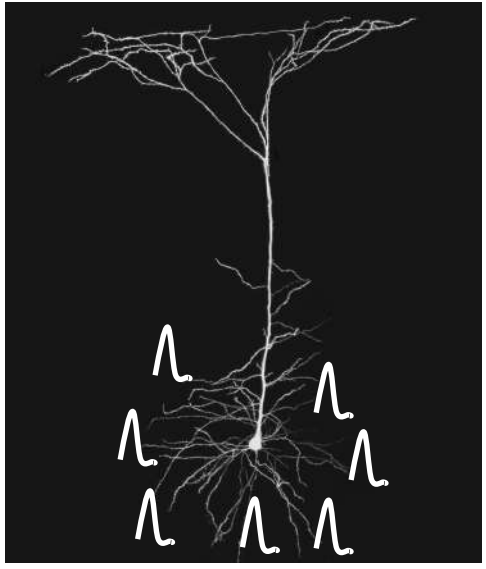




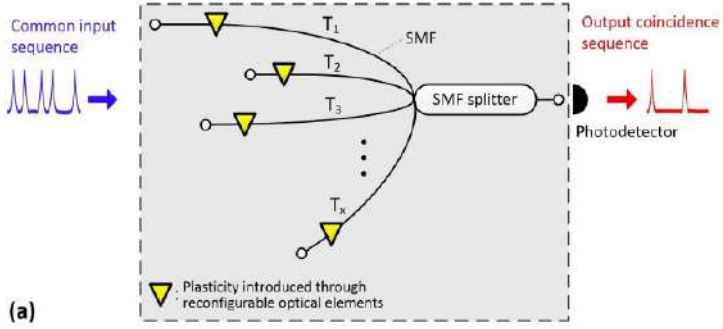
Photonics Dendritic Computation

AD PD

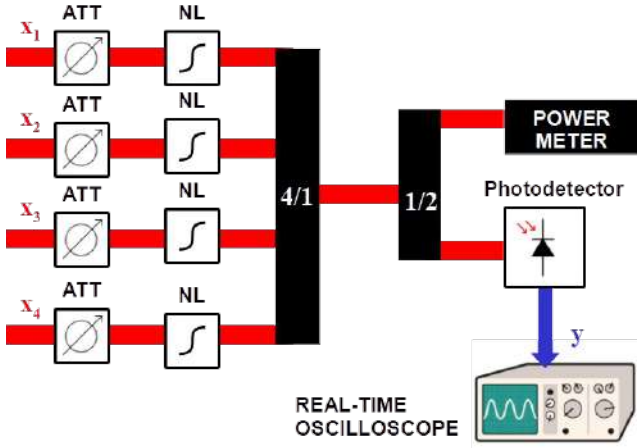
EC Project; 2020-2023)



Neurons can perform spatial and temporal integration to process information

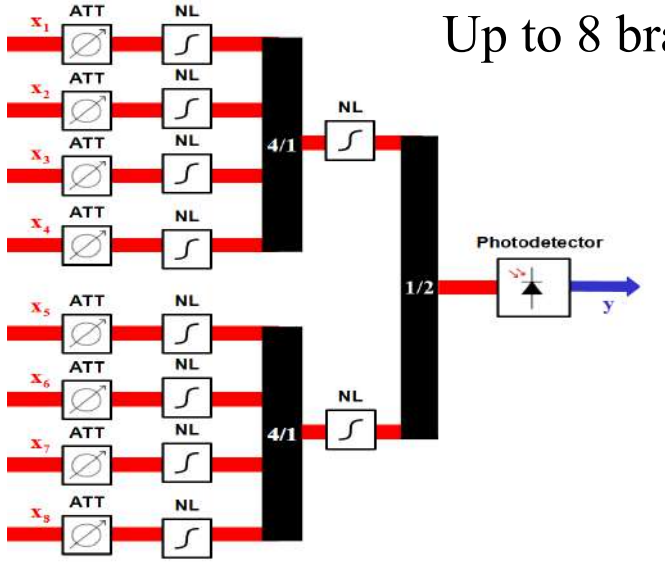


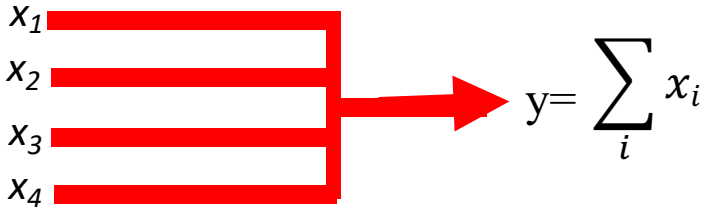
SMF-based dendritic tree with variable input delay paths and adjusted plasticity for temporal pattern classification tasks



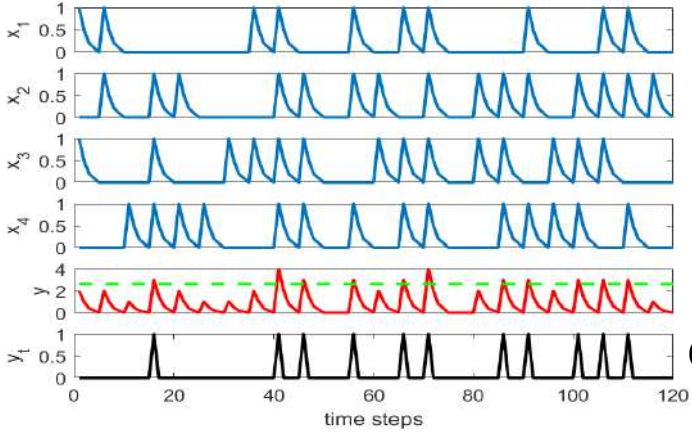
Several branches combine in a single output

Up to 8 branches





$$y = \sum_i x_i$$

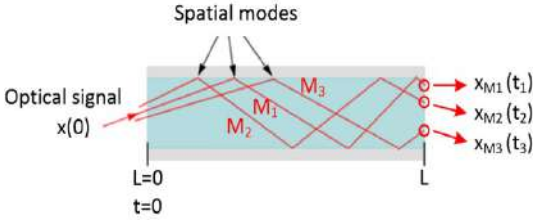


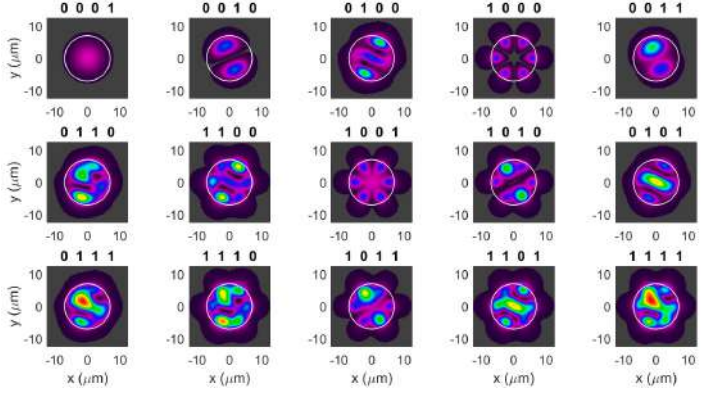
Threshold

Coincident pulses

Dendritic Computation with MMF

How do we mimic a dendritic arbor with a MMF?

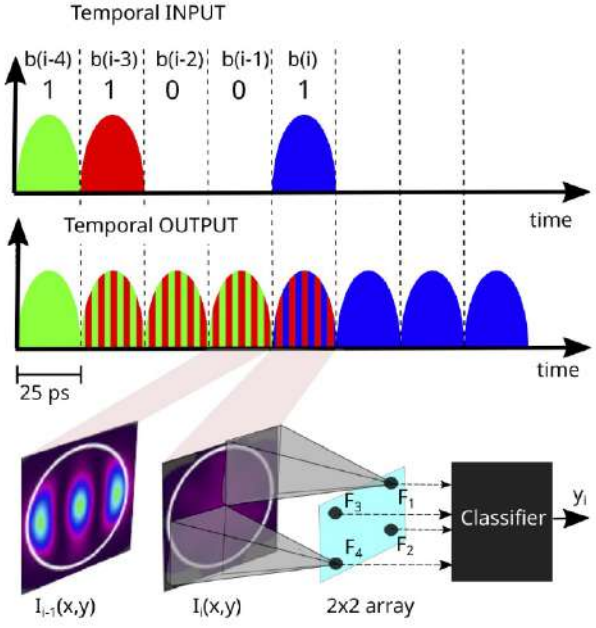





Research Article
Vol. 12, No. 5 / 1 May 2022 / Optical Materials Express 1907
Optical Materials EXPRESS

Optical dendrites for spatio-temporal computing with few-mode fibers [Invited]

SILVIA ORTÍN,* MIGUEL C. SORIANO, INGO FISCHER, CLAUDIO R. MIRASSO, AND APOSTOLOS ARGYRIS



VCSEL Array

femto-st SCIENCES & TECHNOLOGIES

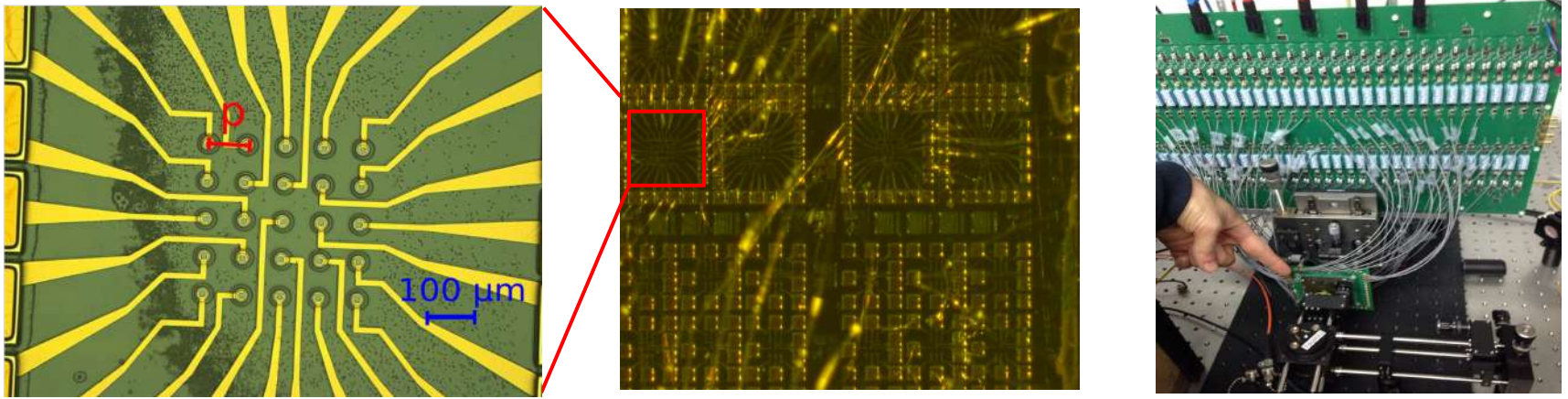


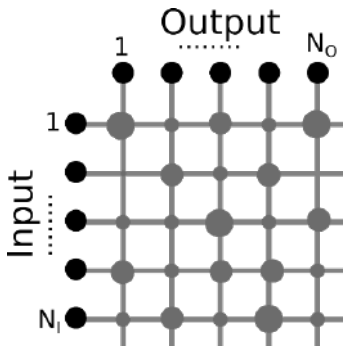
Image from Tobias Heuser, Stephan Reitzenstein group, TU Berlin

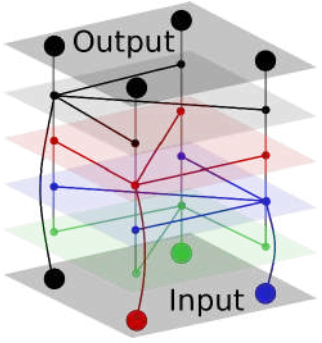
Input: The input layer of our reservoir computer is realized by the intensity-modulated injection laser. VCSELs' currents can be manipulated independently.

Connections: between nodes and from the input layer to the reservoir are established via an external cavity

Output: The response of the nodes (VCSELs' signals) are recorded with a photodiode and an oscilloscope.

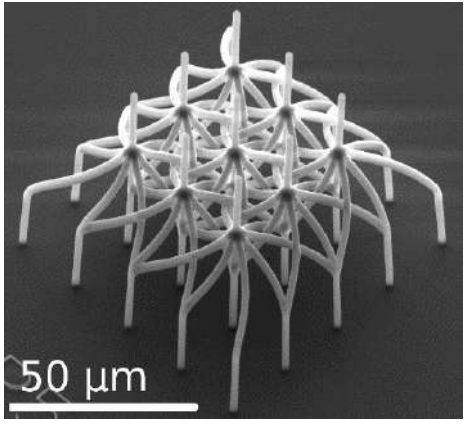
2D/3D Network

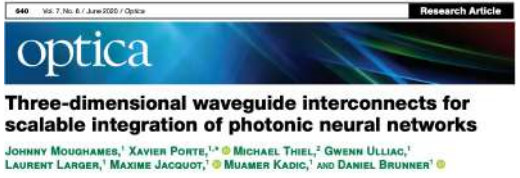




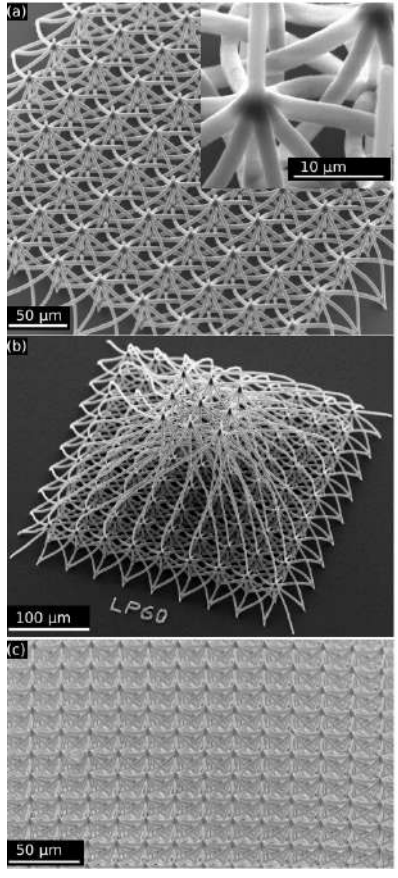
3D long-range connected network

3D printing: Waveguides 1.2 µm diameter, 20 µm pitch





femto-st SCIENCES & TECHNOLOGIES



DANIEL BRUNNER WINNER OF AN ERC CONSOLIDATOR GRANT 2021

To develop three-dimensional photonic circuits, coupled to active media, in order to realize integrated three-dimensional neural networks

Conclusions

- There are a variety of photonic components that can be used for non-traditional computing: active devices such as lasers, electro-modulators, SOAs, EDFAs, etc. and passive ones such as microrring resonators, optical fibers, waveguides, etc.

- Computation can be performed in the range of 1 to hundreds of GHz and with low energy consumption.

- Also: Parallel processing, time and wavelength multiplexing, high bandwidth, low attenuation/distance, low heat dissipation, less susceptible to electromagnetic interference, etc.

- Integrated photonics over different substrates, silica, III-V components or even graphene are being investigated.

Thanks for your attention