Microwave Photonics (MWP) and Artificial Intelligence (AI)

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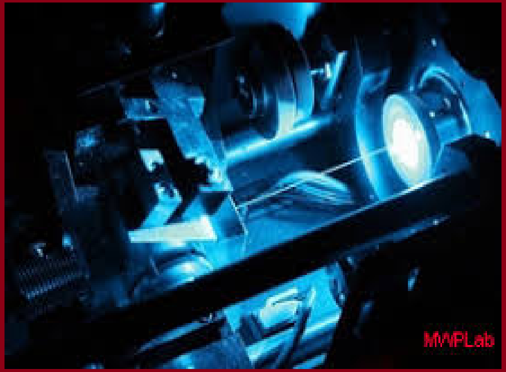

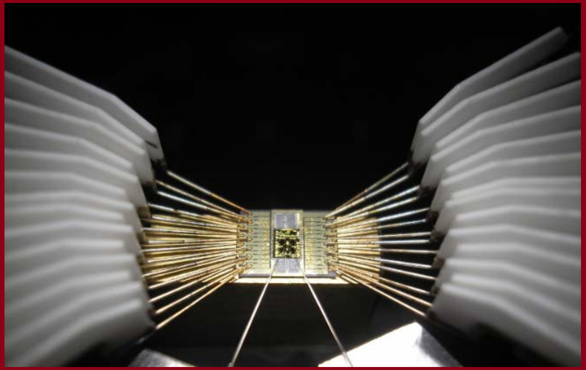

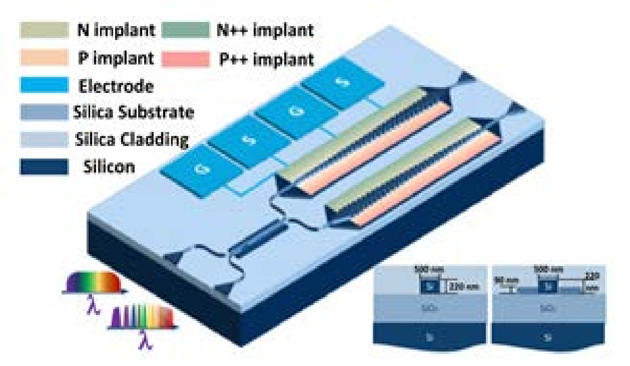

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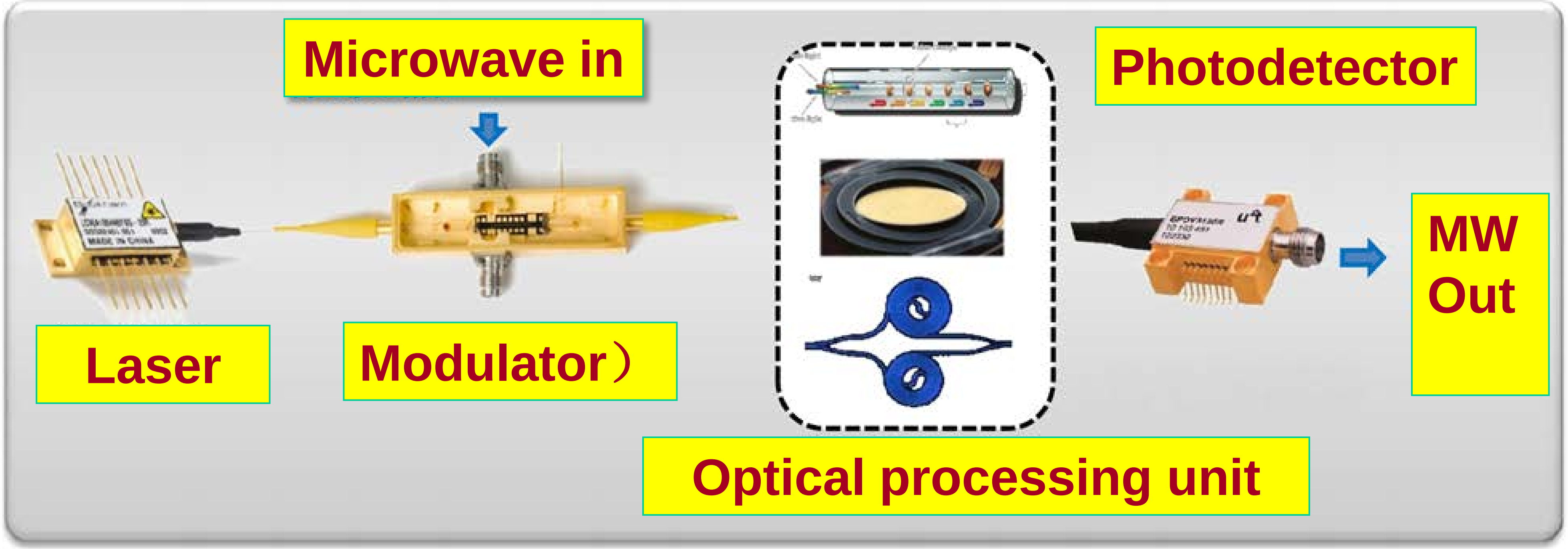
Outline

- What is MWP
- MWP and Optical Computing
- MWP and AI
  - Convolutional Neural Network
    - Fiber-optic implementation
    - Photonic integrated implementation
  - Optical Reservoir Computing
    - Fiber optic implementation
    - Photonic integrated implementation
- Conclusion

What is MWP

Use light as a carrier and use photonic and optoelectronic devices for the generation, transmission, control, and processing of microwave signals, to implement microwave devices and systems with improved perfromance.



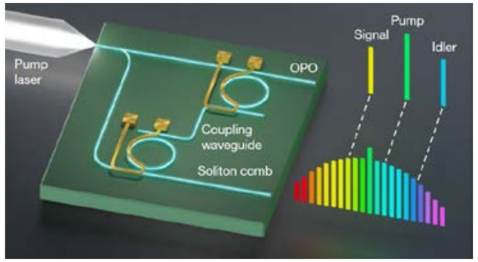
Advantages of MWP

- ➢ To solve the **bottleneck problems (limited bandwidth)**
- ➢ To make microwave devices and systems to be **higher frequency, wider bandwidth and lower loss**

Photonics vs Microwave:

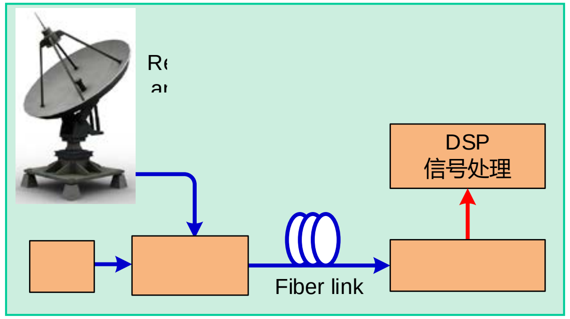
- ✓ **Wide bandwidth： 2,000 ~ 10,000 wider than RF**
- ✓ **Light weight： fiber: 1.7 kg/km << copper cable 567 kg/km**
- ✓ **Low loss: fiber 0.2 dB/km << copper cable 360 dB/km**
- ✓ **Immune to electromagnetic interference (EMI)**
- ✓ **Integratable and small (Photonic Integrated Circuits or PICs)**
- ✓ **Fast and parallel processing - Important for Optical Computing**

MWP Applications



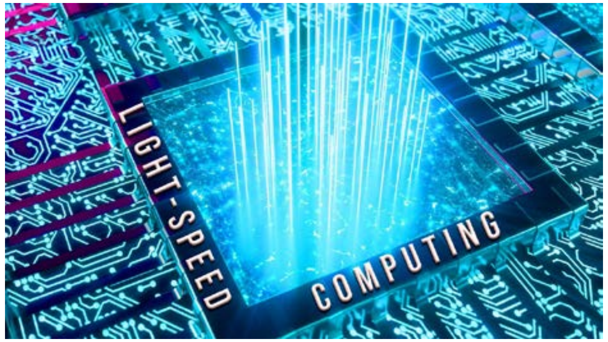
- ❑ **Low phase noise microwave generation**

  (ultra-low phase noise, -170 dBc/Hz at 10 kHz)



- ❑ **Microwave photonic links (low loss and wideband)**
- ❑ **True time delay for broadband beamforming**

- ❑ **Photonic ADC (high speed and low time jitter)**
- ❑ **MWP sensors and radar (high resolution, wide bandwidth)**
- ❑ **Optical computing：ultra-high speed and parallel computing**



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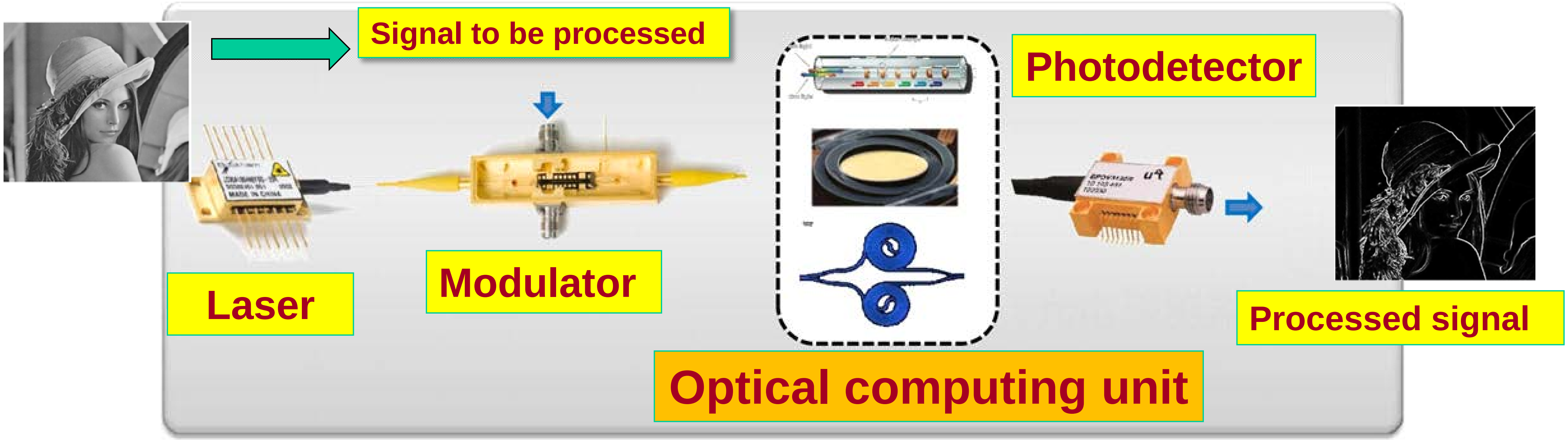
MWP and Optical Computing



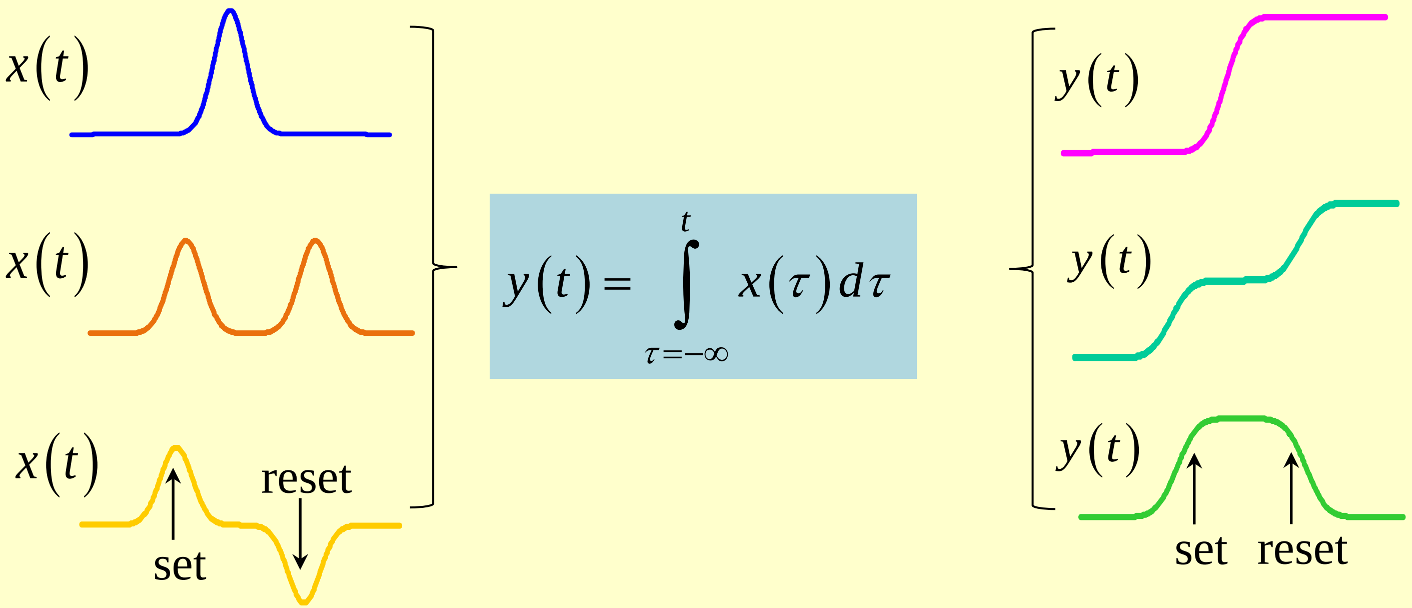
- Temporal Integrator
- Temporal Differentiator
- Temporal Hilbert Transformer
- Fourier transformer

Temporal Integrator and Applications

Data storage

Bit counting

Optical memory

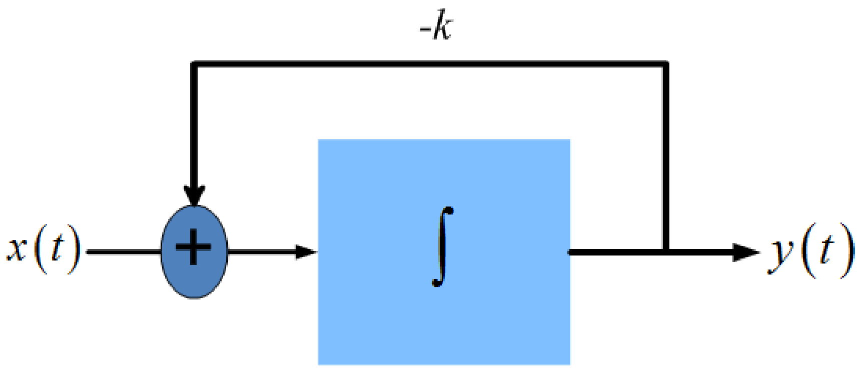


$$y(t)=\int_{\tau=-\infty}^{t} x(\tau)\,d\tau$$

Optical computing

(Linear Differential Equation)

$$\frac{dy(t)}{dt}+ky(t)=x(t)$$

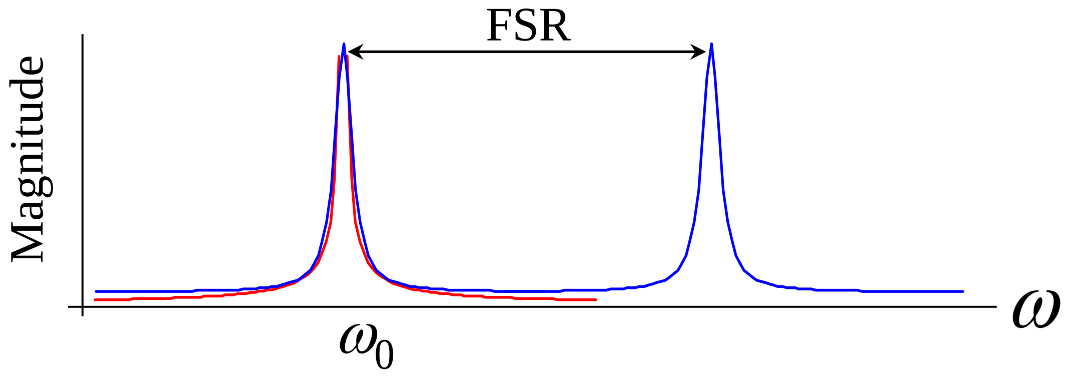


M. Ferrera et al., "On-chip CMOS-compatible all-optical integrator," Nature Commun., vol. 1, 2010, Article 29.

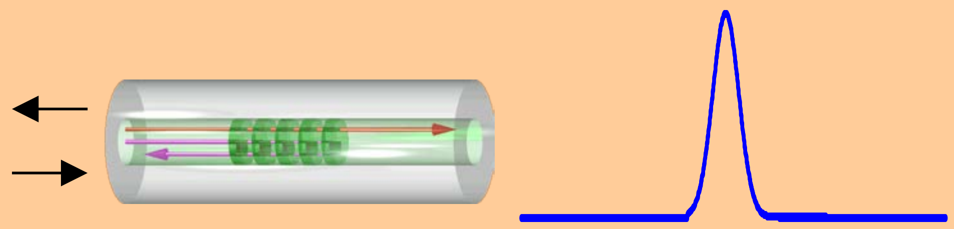
Photonic Temporal Integrator Implementation

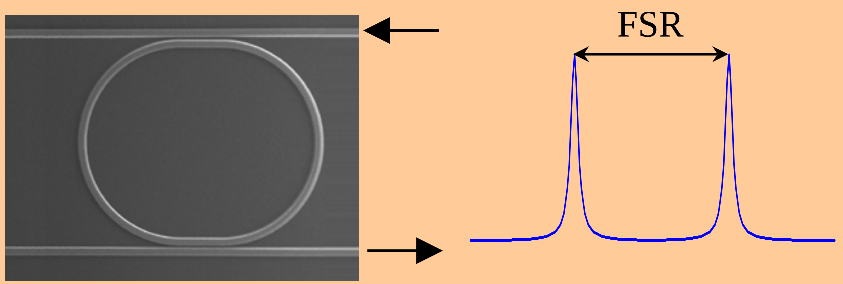
Mathematically, a temporal integrator can be implemented using a linear device with a transfer function given by

$$y(t) = \int_{\tau=-\infty}^{t} x(\tau)\,d\tau \;\Rightarrow\; H(\omega) = \frac{1}{j(\omega-\omega_0)}$$



A photonic temporal integrator can be implemented using a **fiber Bragg grating** (FBG) or a **microring resonator**.

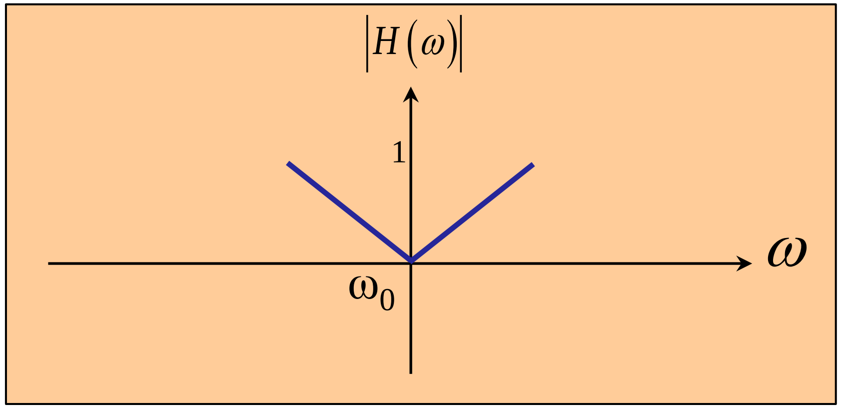


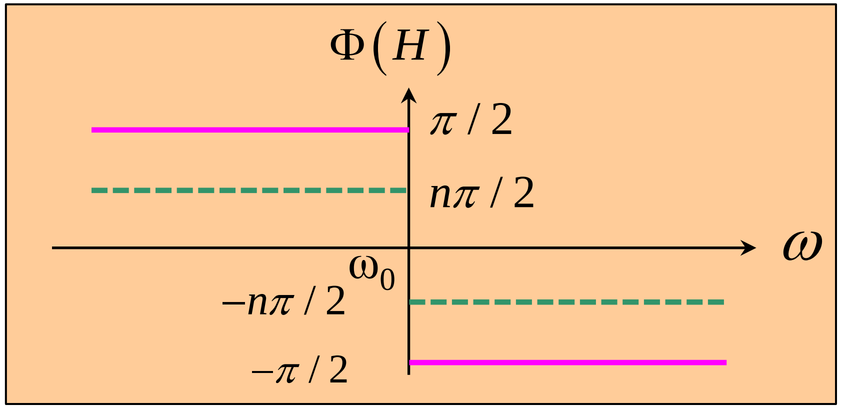


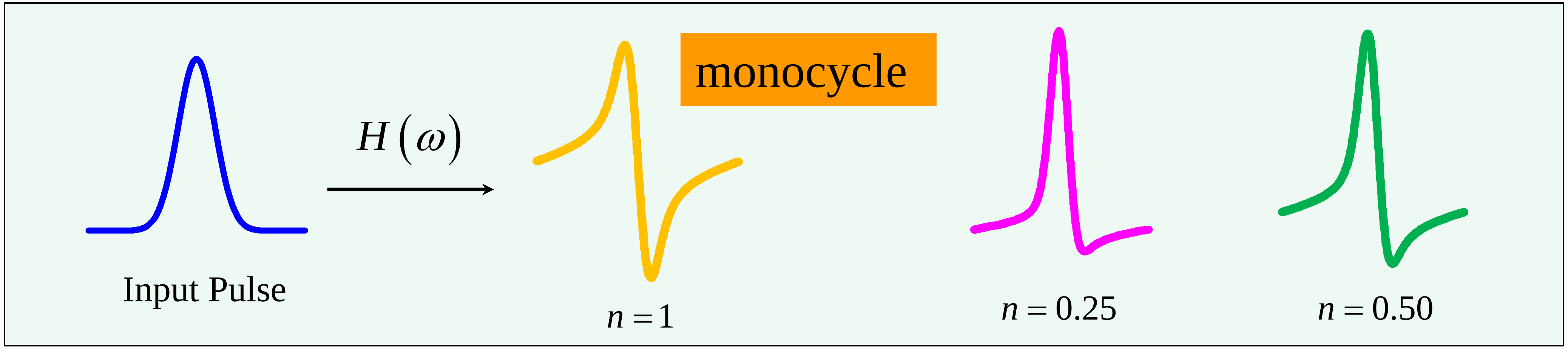
Temporal Differentiator

$$y(t) = \frac{d^n x(t)}{dt^n} \Rightarrow H(\omega) = \left[j(\omega - \omega_0) \right]^n$$

where n is the order of differentiation, and n can be a fractional order. When n = 1, it is a first order differentiator.

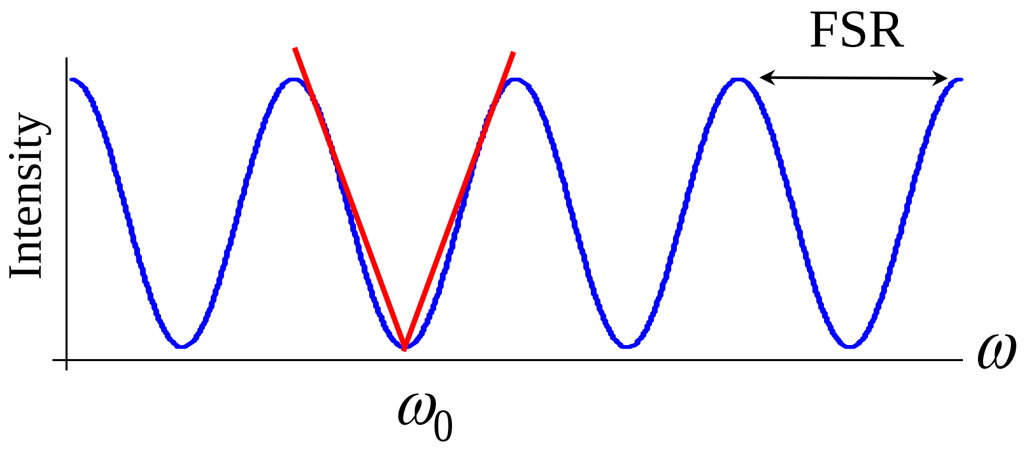


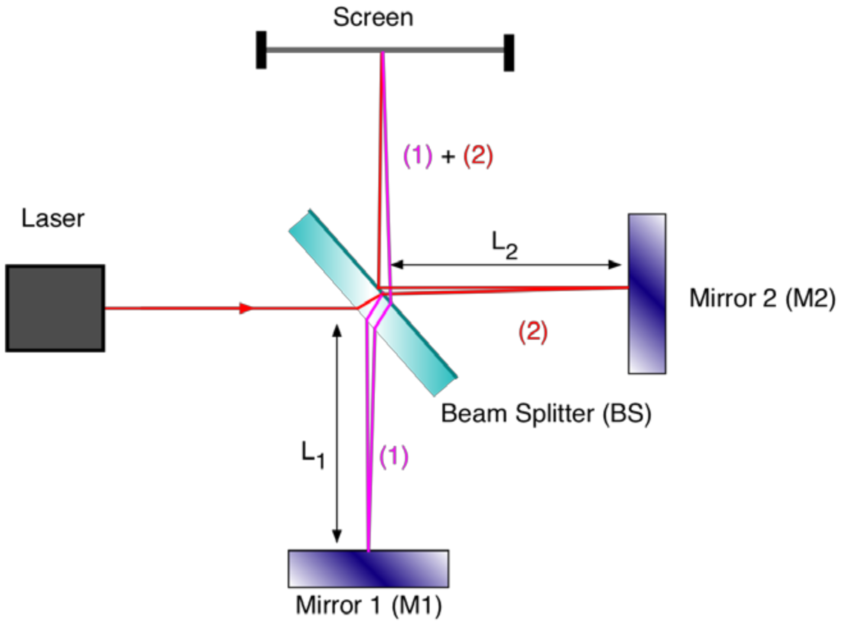




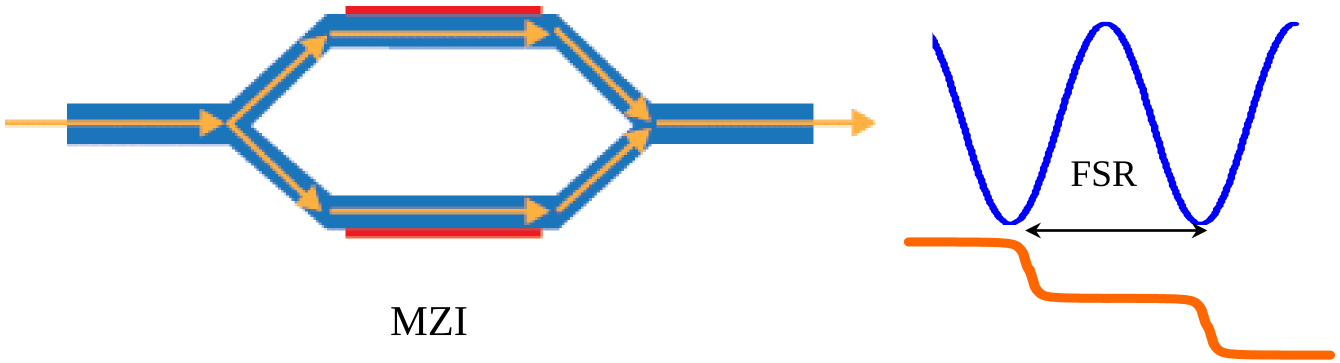
Photonic Temporal Differentiator Implementation

Practically, a temporal differentiator can be implemented using an optical interferometer, such as a Michelson interferometer, or a Mach-Zehnder interferometer (MZI).



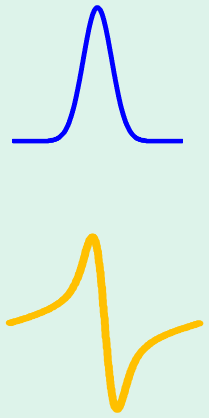


Michelson Interferometer

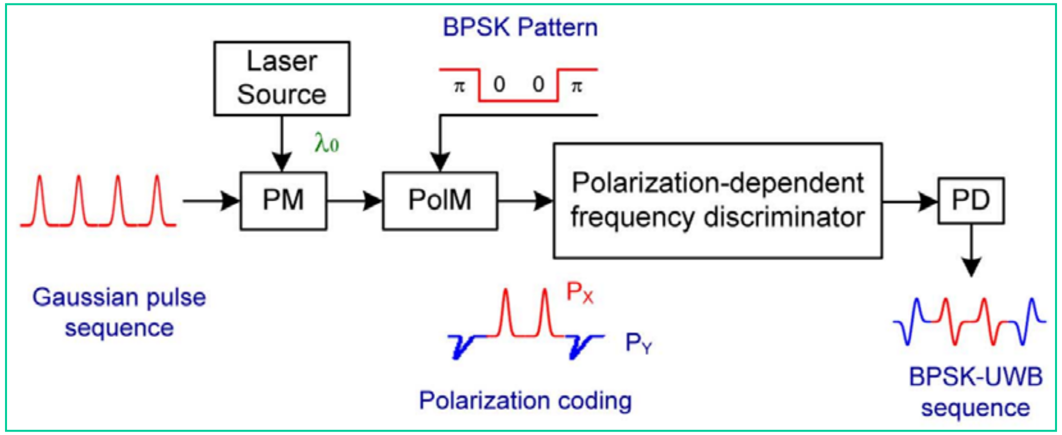


MZI

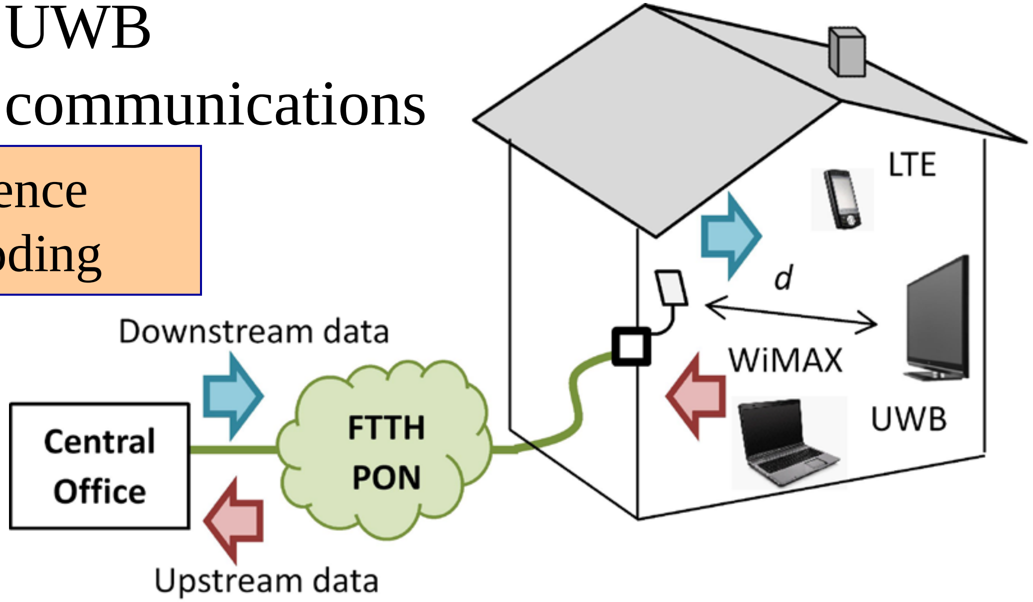
Temporal Differentiators and Applications



monocycle



UWB communications



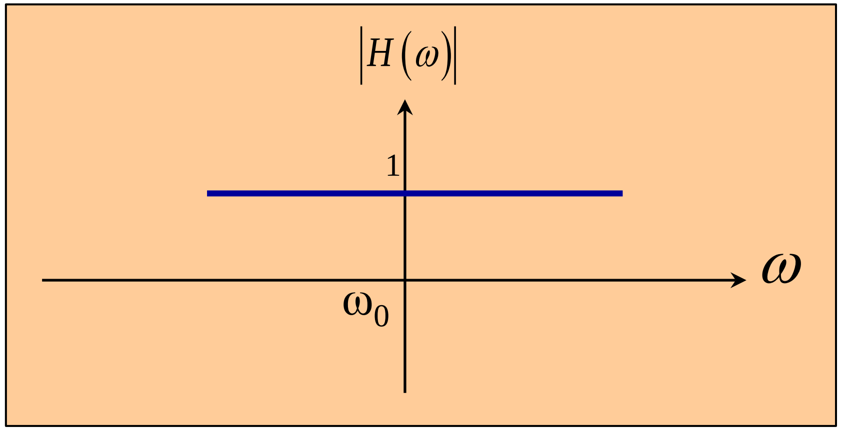
UWB pulse sequence generation and coding

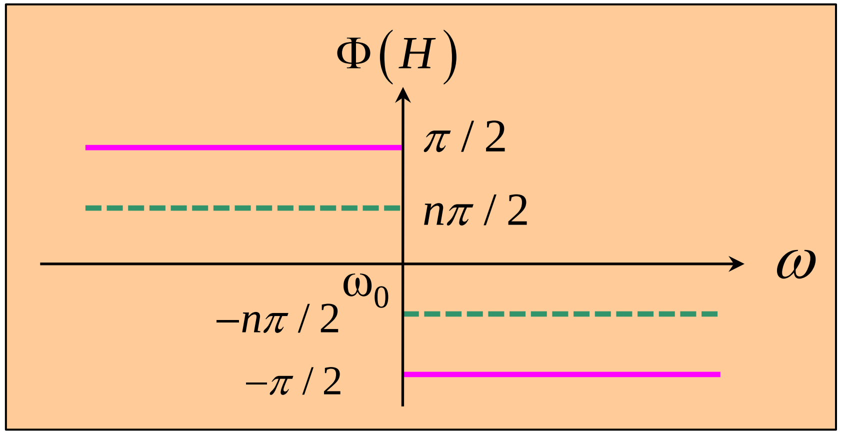
Tunable image enhancement or edge detection

Y. Dai and J. Yao, “High-chip-count UWB bi-phase coding for multi-user UWB-over-fiber system,” IEEE/OSA J. Lightw. Technol., vol. 27, no. 11, pp. 1448-1453, Jun. 2009.

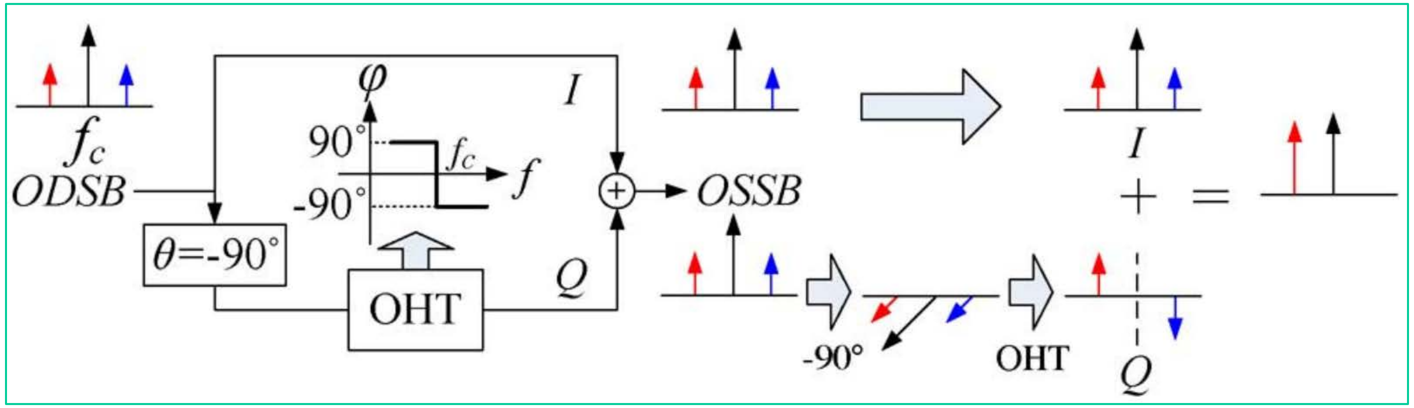
Temporal Hilbert Transformer and Applications

$$H(j\omega) = \begin{cases} e^{-jn\frac{\pi}{2}} & \omega > 0 \\ e^{+jn\frac{\pi}{2}} & \omega < 0 \end{cases}$$





where n is the order of differentiation, and n can be a fractional order. When n = 1, it is a first order differentiator.

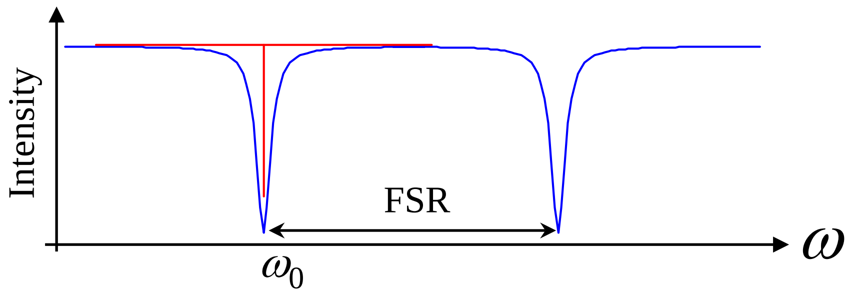


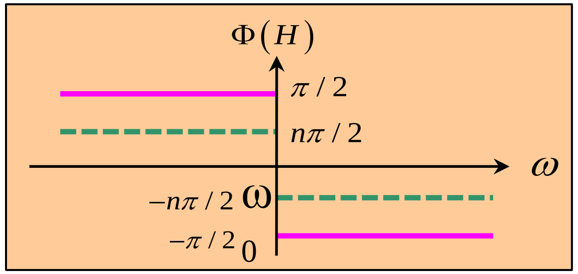
Single Sideband (SSB) Modulation

Image processing - edge detection/enhancement

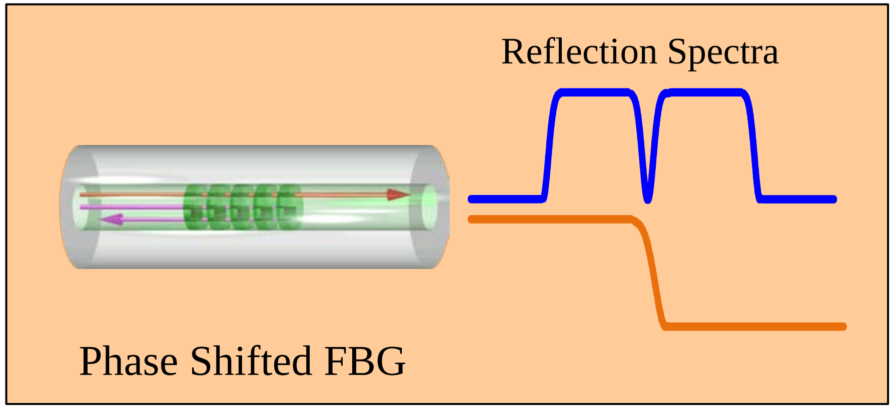
Photonic Temporal Hilbert transformer

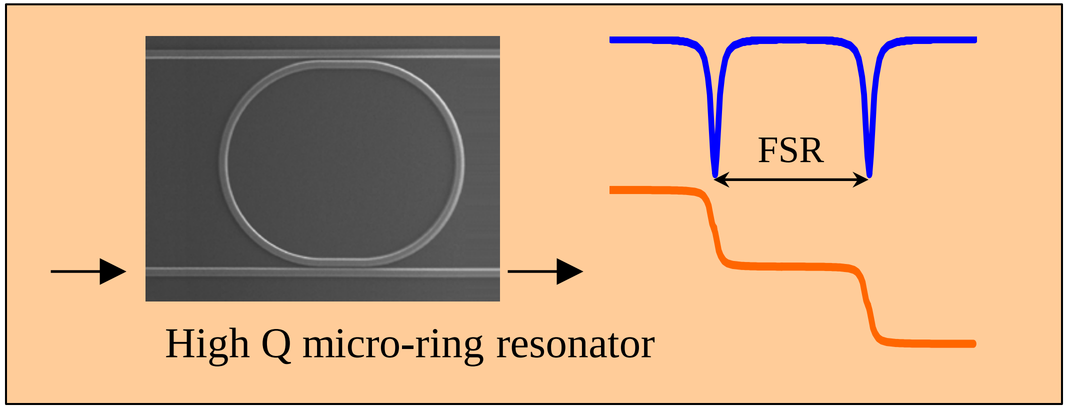
Practically, a Hilbert transformer can be implemented using a linear optical device with an ultra-narrow notch.





A photonic Hilbert transformer can be implemented using a phase shifted fiber Bragg grating (FBG) or a microring resonator（Ideal case，notch width is zero→ practical implementation using high Q ultra-narrow notch filter）





ARTICLES
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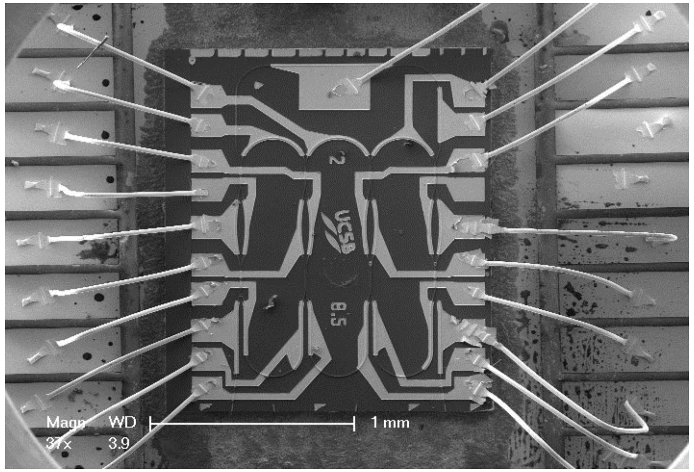
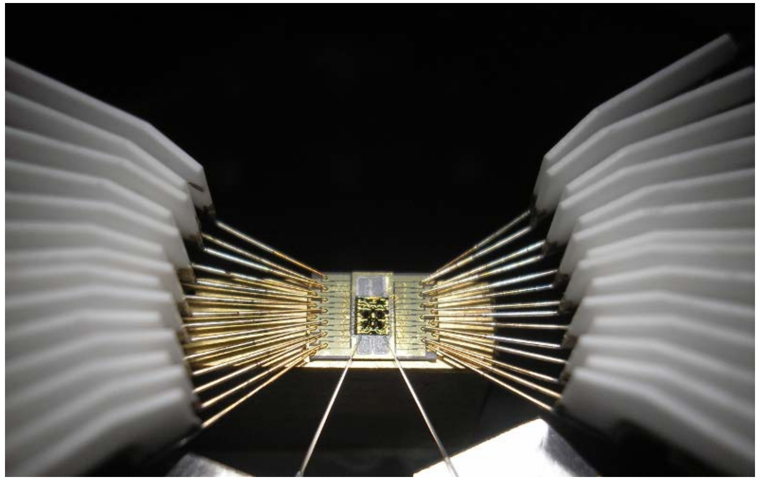
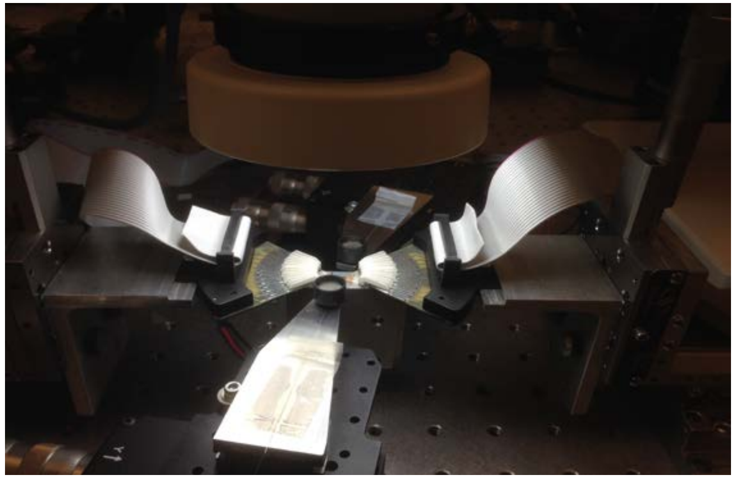
nature photonics

A fully reconfigurable photonic integrated signal processor

Weilin Liu[1‡], Ming Li[1†‡], Robert S. Guzzon[2‡], Erik J. Norberg[2], John S. Parker[2], Mingzhi Lu[2], Larry A. Coldren[2] and Jianping Yao[1*]

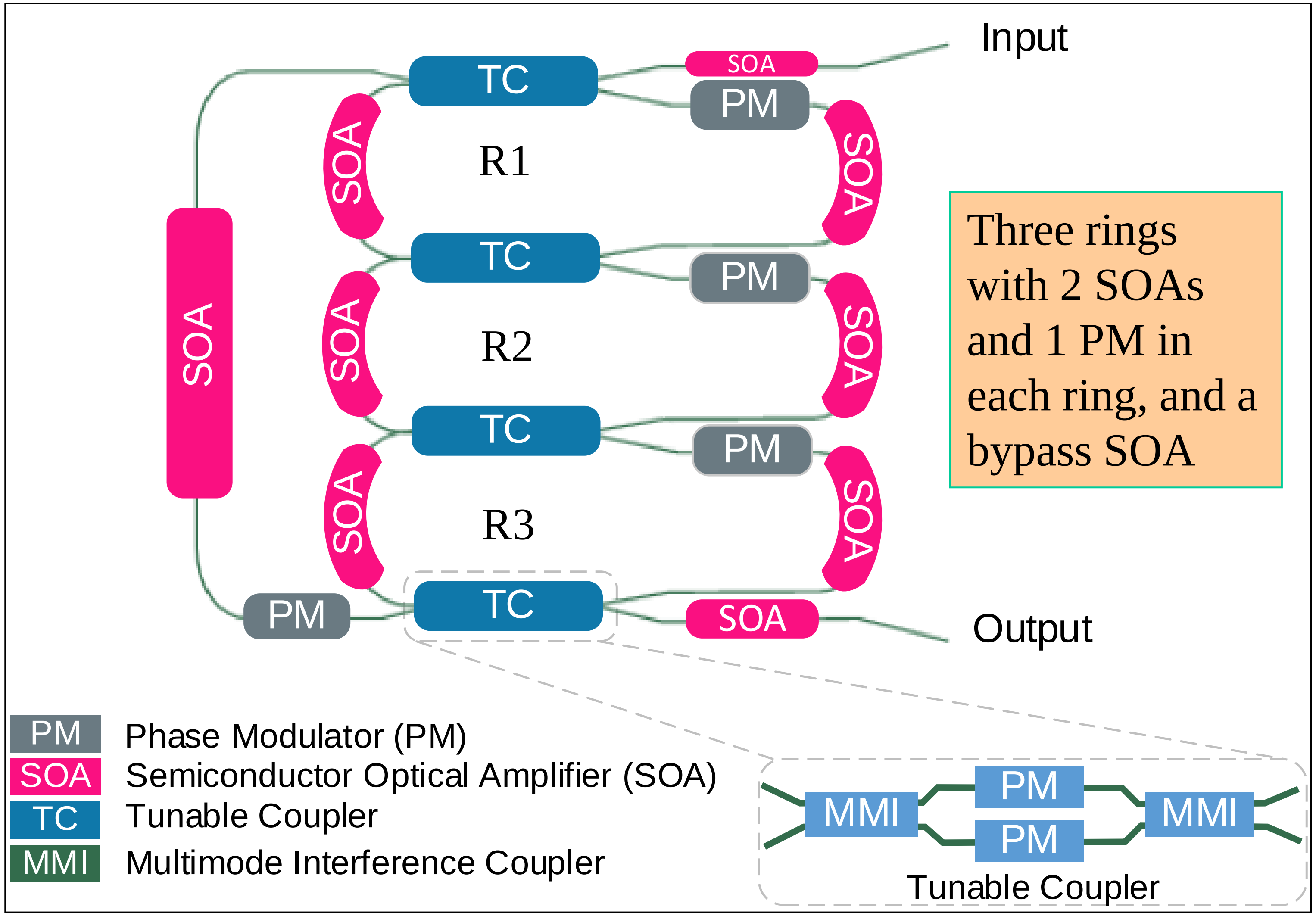




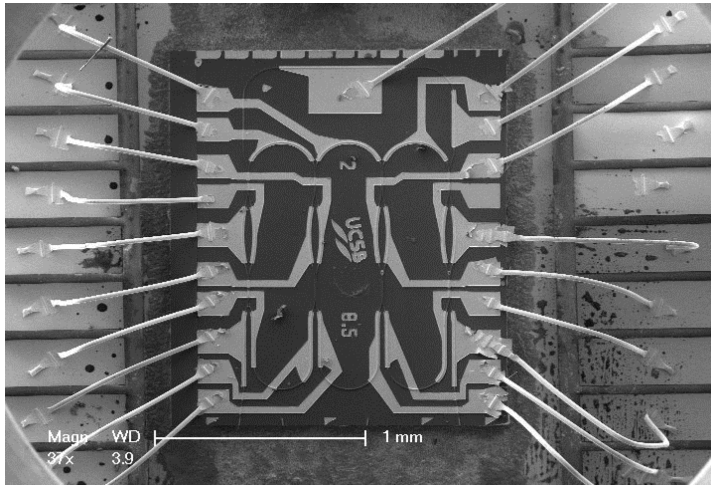


W. Liu, M. Li, R. S. Guzzon, E. J. Norberg, J. S. Parker, M. Lu, L. A. Coldren, and J. Yao, “A fully reconfigurable photonic integrated signal processor,” Nature Photon., vol. 10, pp. 190-195, Mar. 2016.

A fully reconfigurable photonic integrated signal processor



Reconfigurable - The reconfigurability is achieved by tuning the injection currents to the semiconductor optical amplifiers (9 **SOA**s) and current injection phase modulators (3 **PM**s) in the design, 4 tunable couplers (**TC**s).



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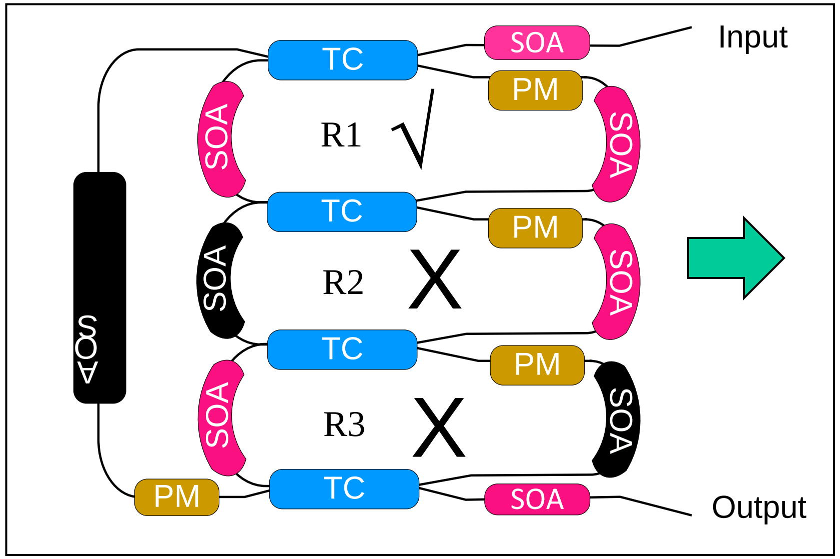
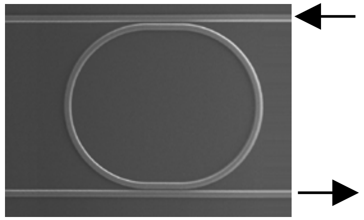
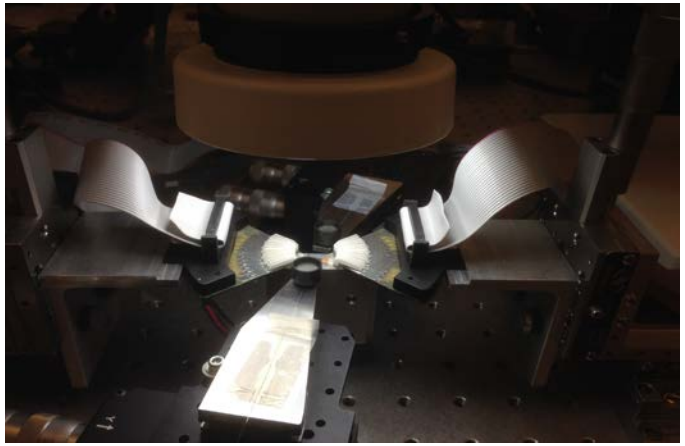
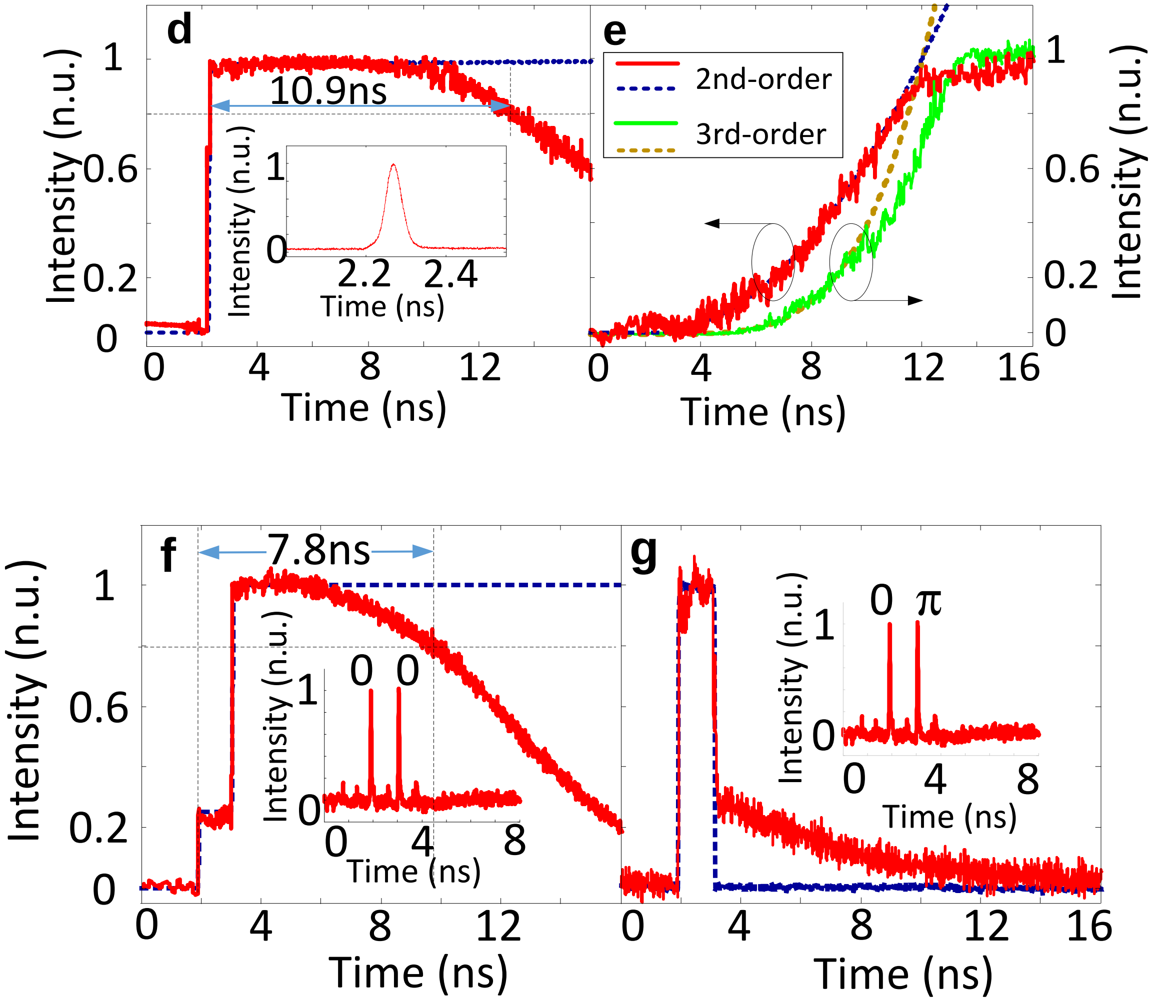
A fully reconfigurable photonic integrated signal processor – Integrator and results

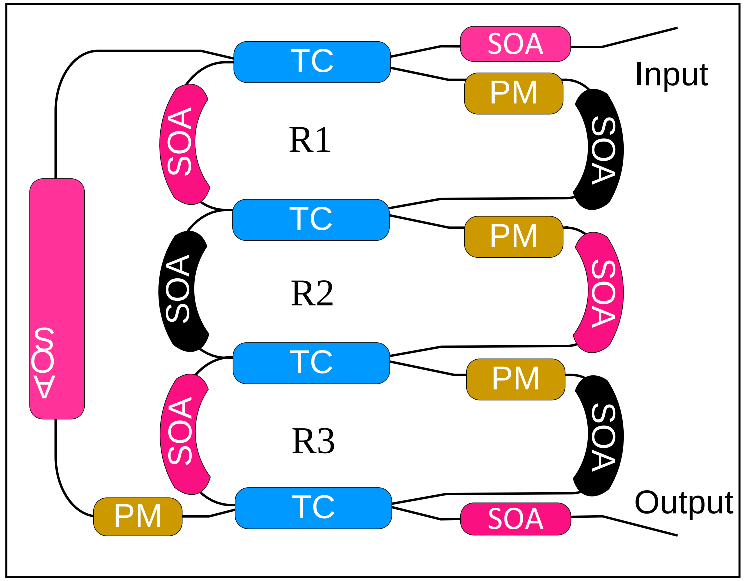


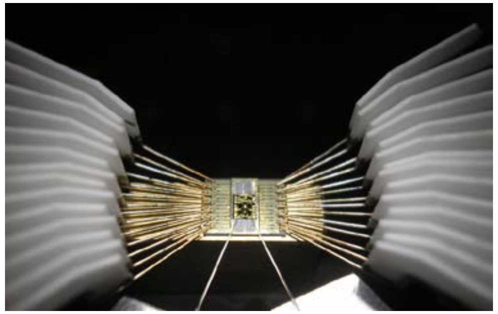


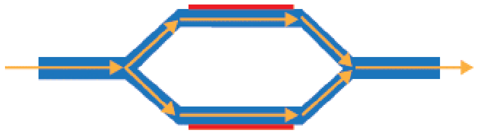




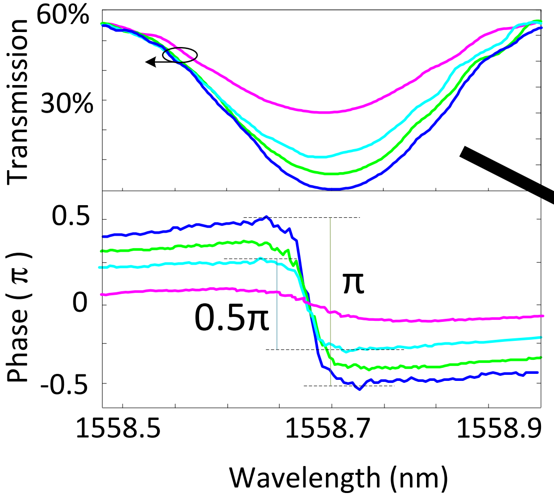
A fully reconfigurable photonic integrated signal processor – Differentiator and results



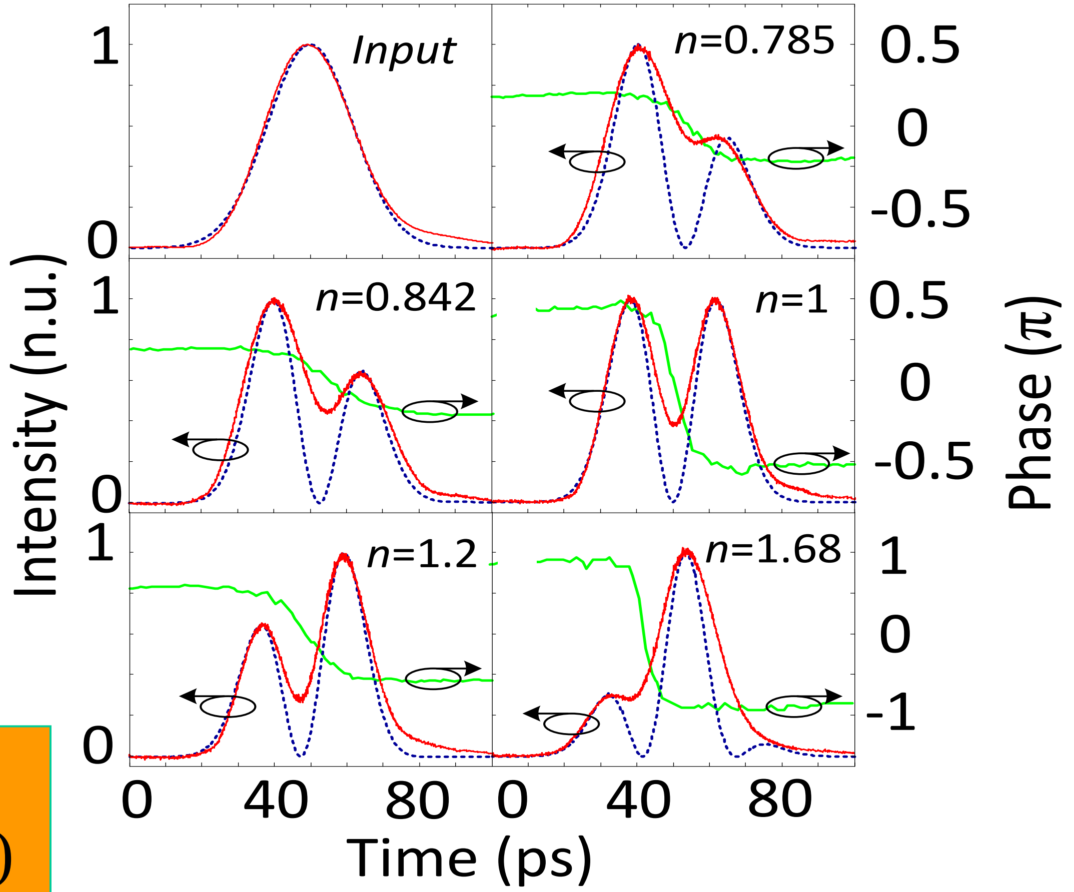




MZI

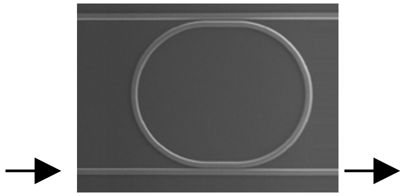


Different coupling ratio → different depth (phase jump) → different differentiation order

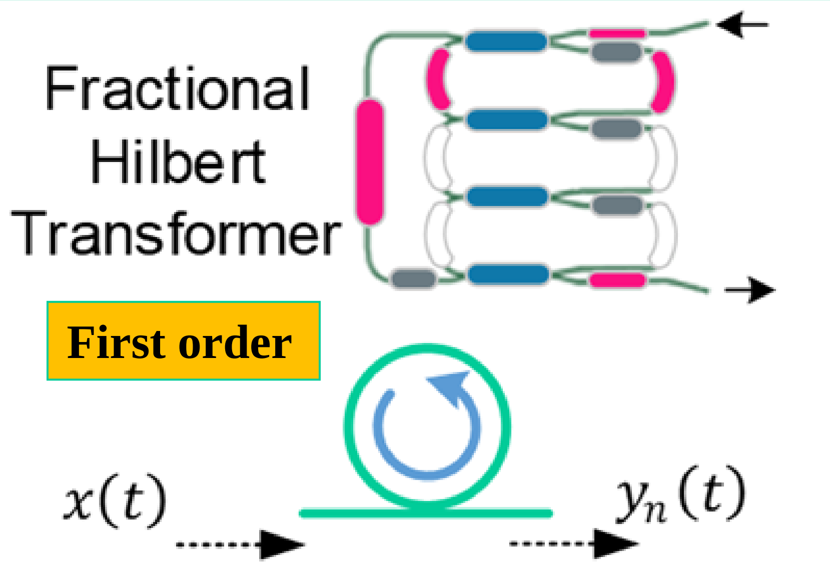


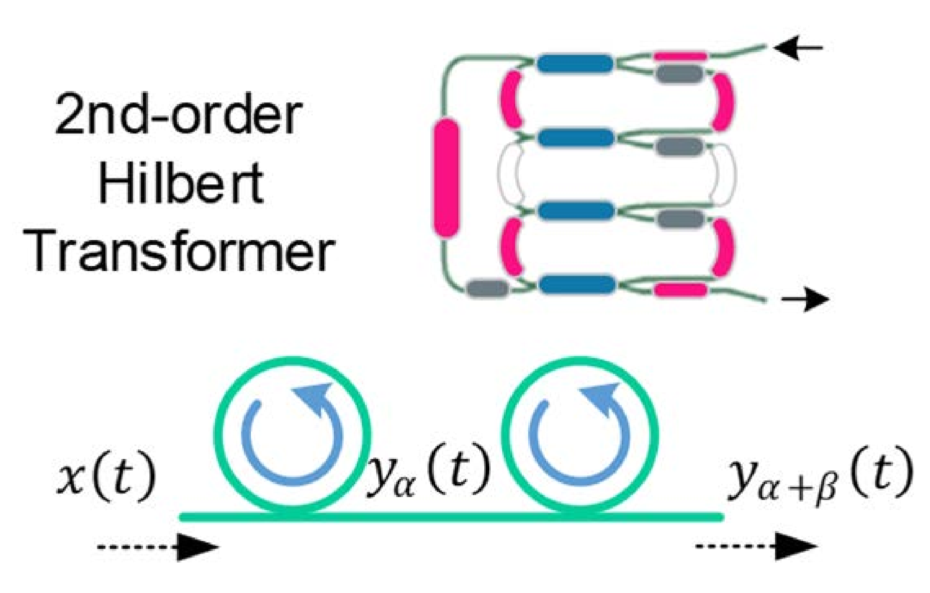
Output with different differentiation order

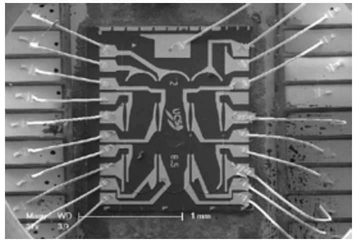
A fully reconfigurable photonic integrated signal processor – Hilbert transformer

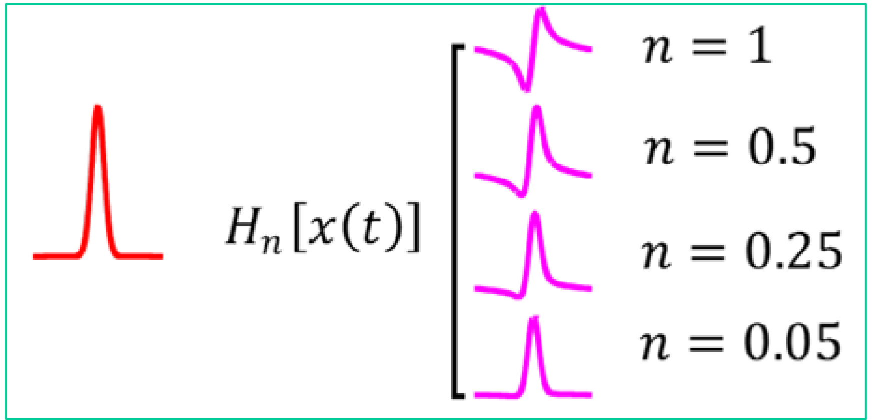


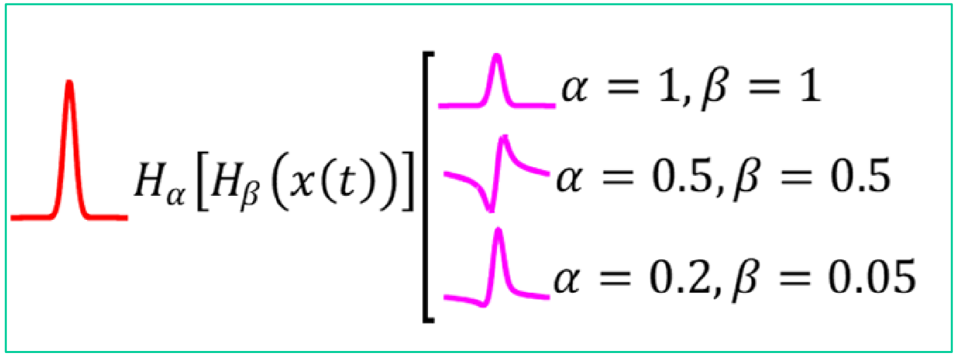
High Q micro-ring resonator 高Q值微环谐振腔



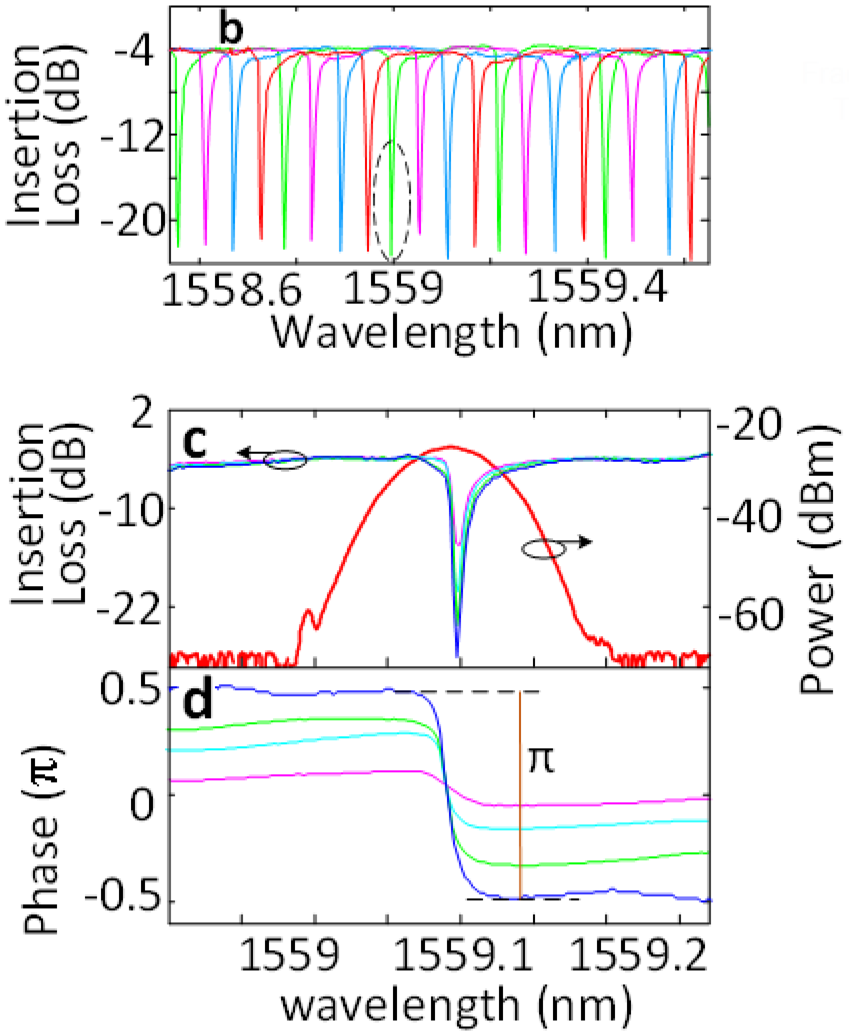


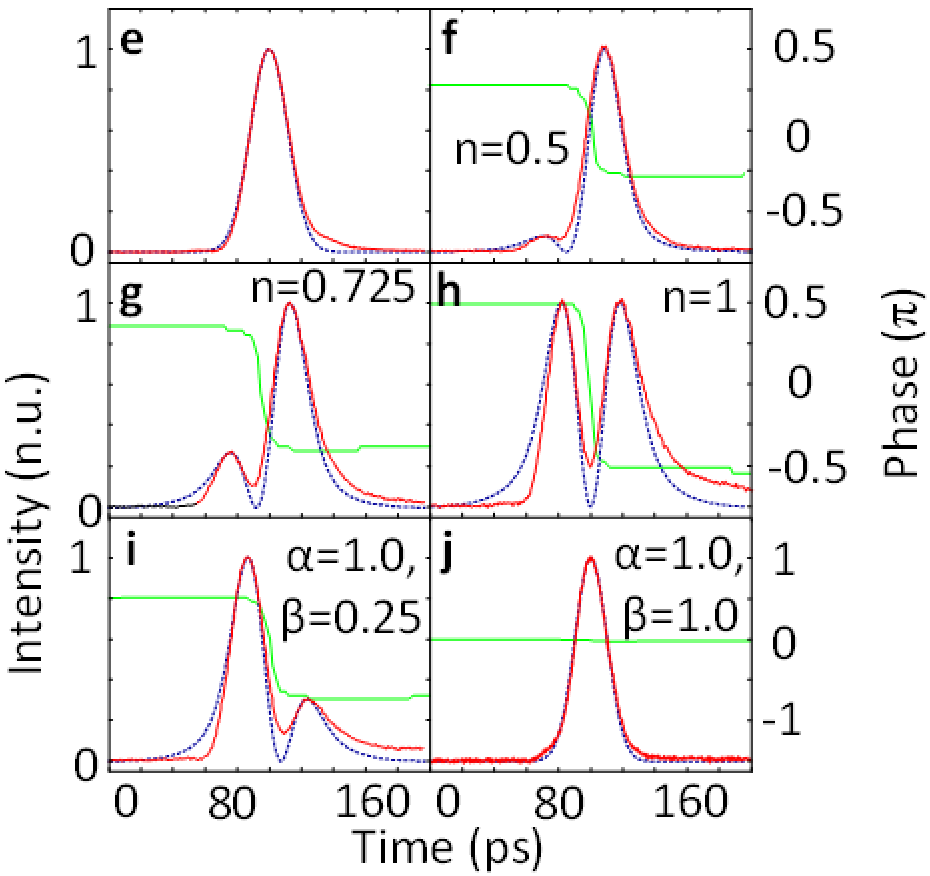




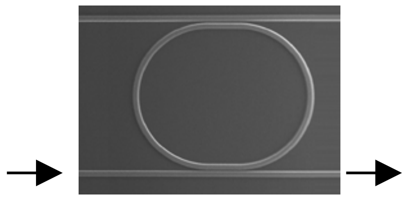


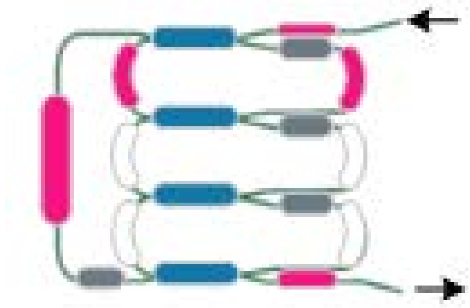
A fully reconfigurable photonic integrated signal processor – Hilbert transformer



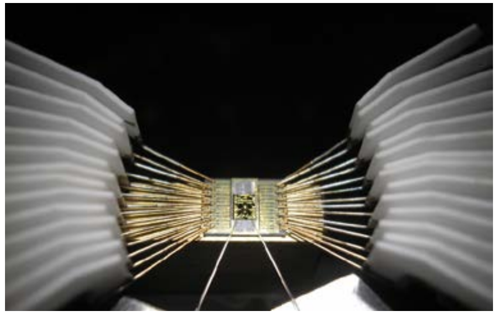


Output with different Hilbert transform order

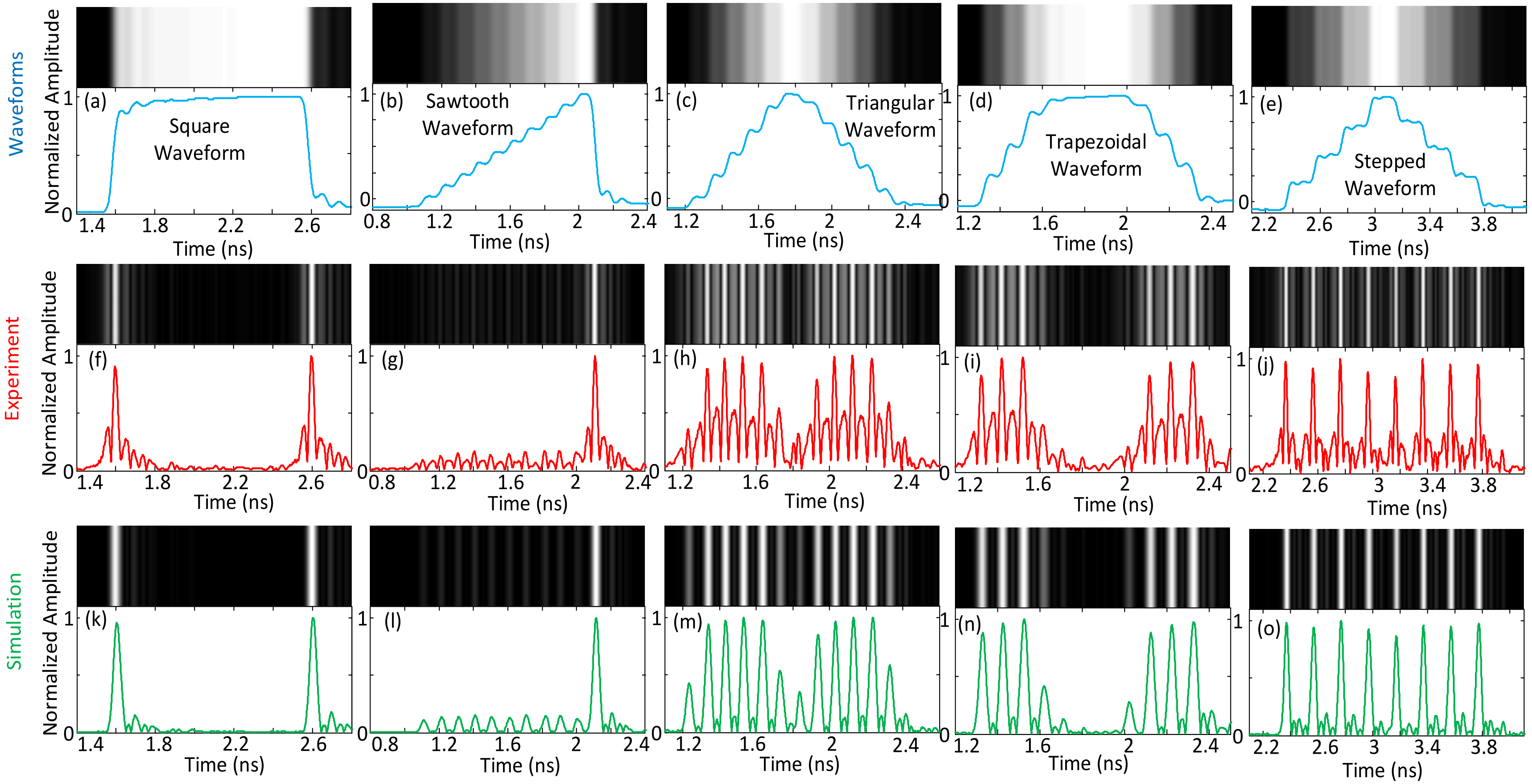




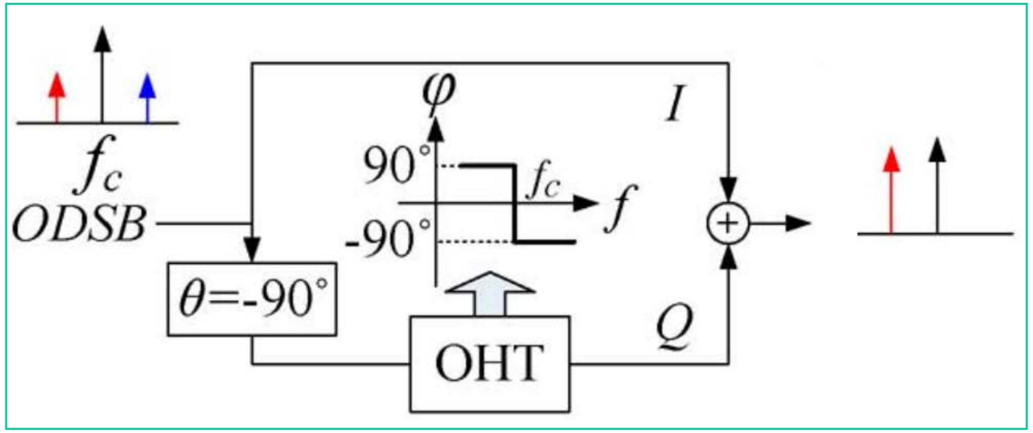
Fractional Hilbert Transformer



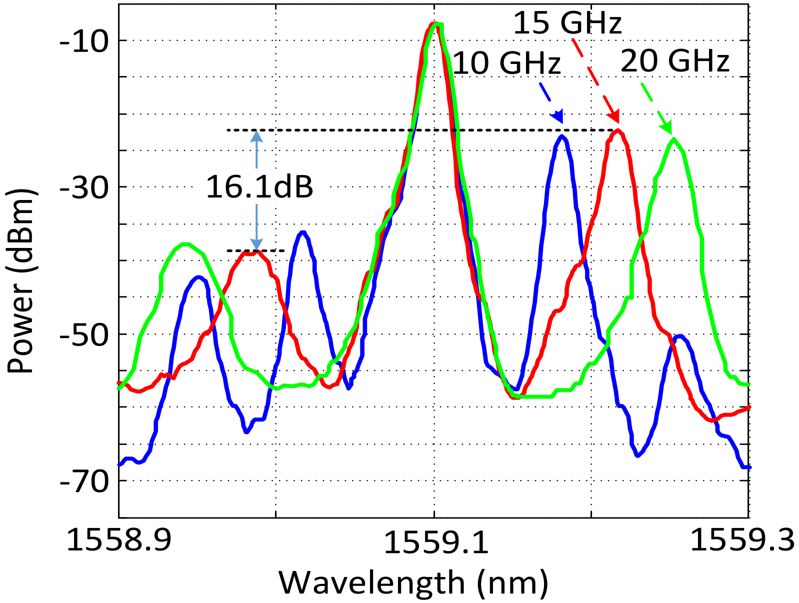
A fully reconfigurable photonic integrated signal processor – Applications

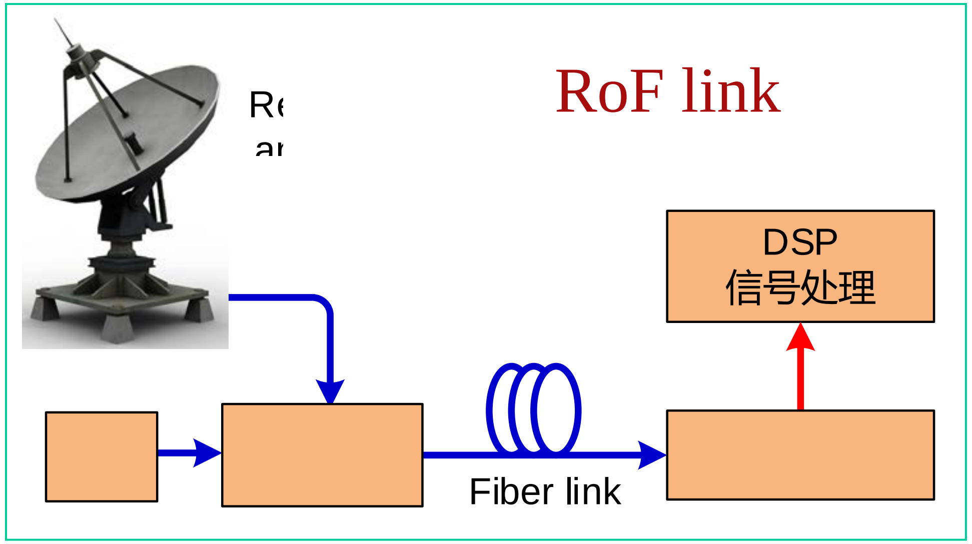


A fully reconfigurable photonic integrated signal processor – Applications



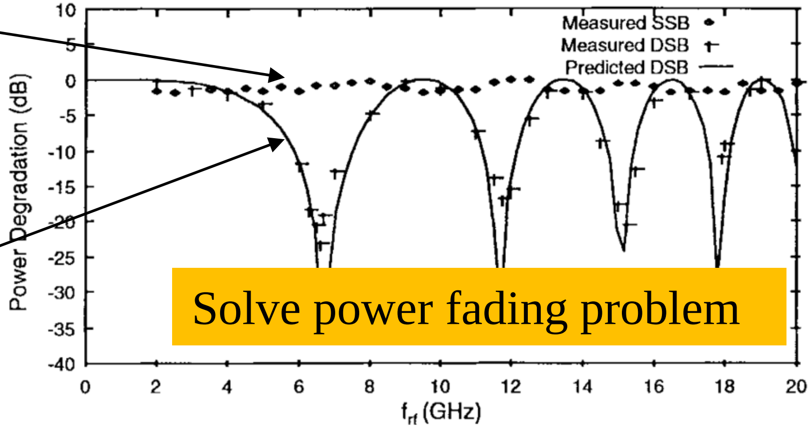
Single sideband (SSB) modulation based on Hilbert transform





SSB+C

DSB+C



Solve power fading problem

Article

Integrated lithium niobate microwave photonic processing engine

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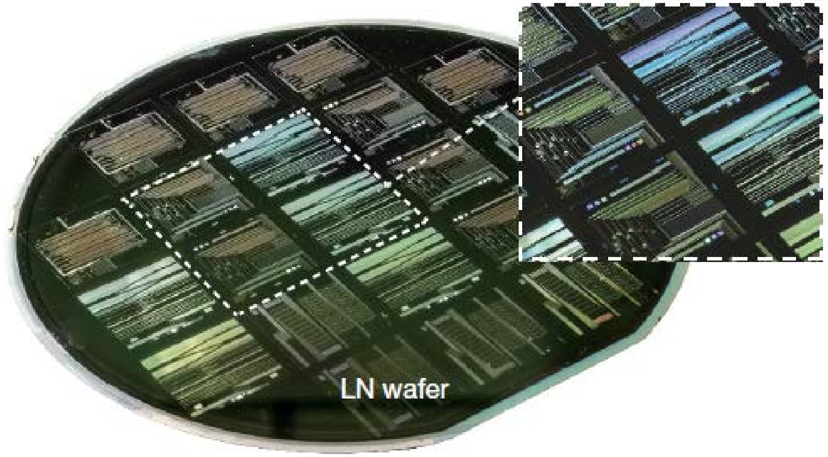
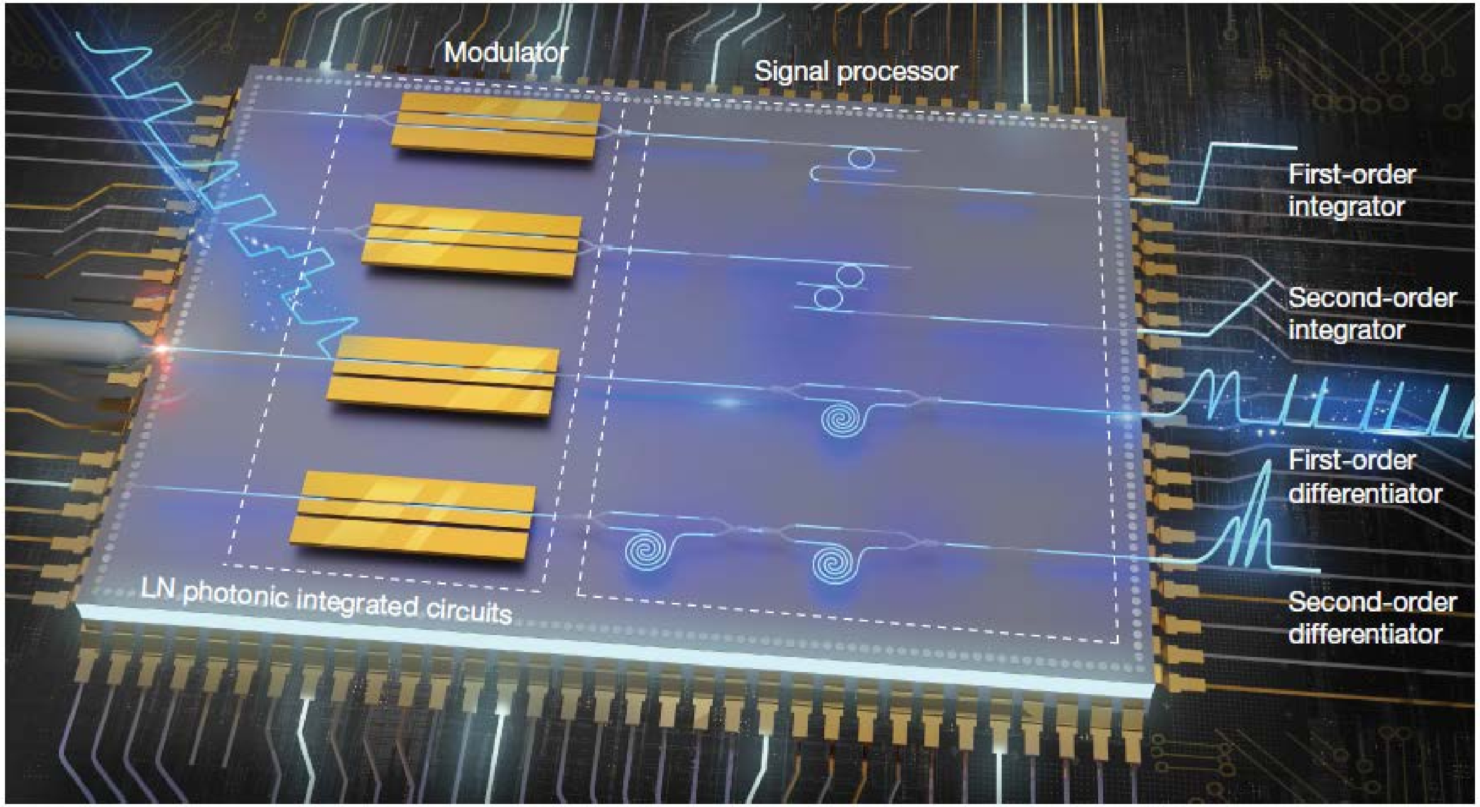
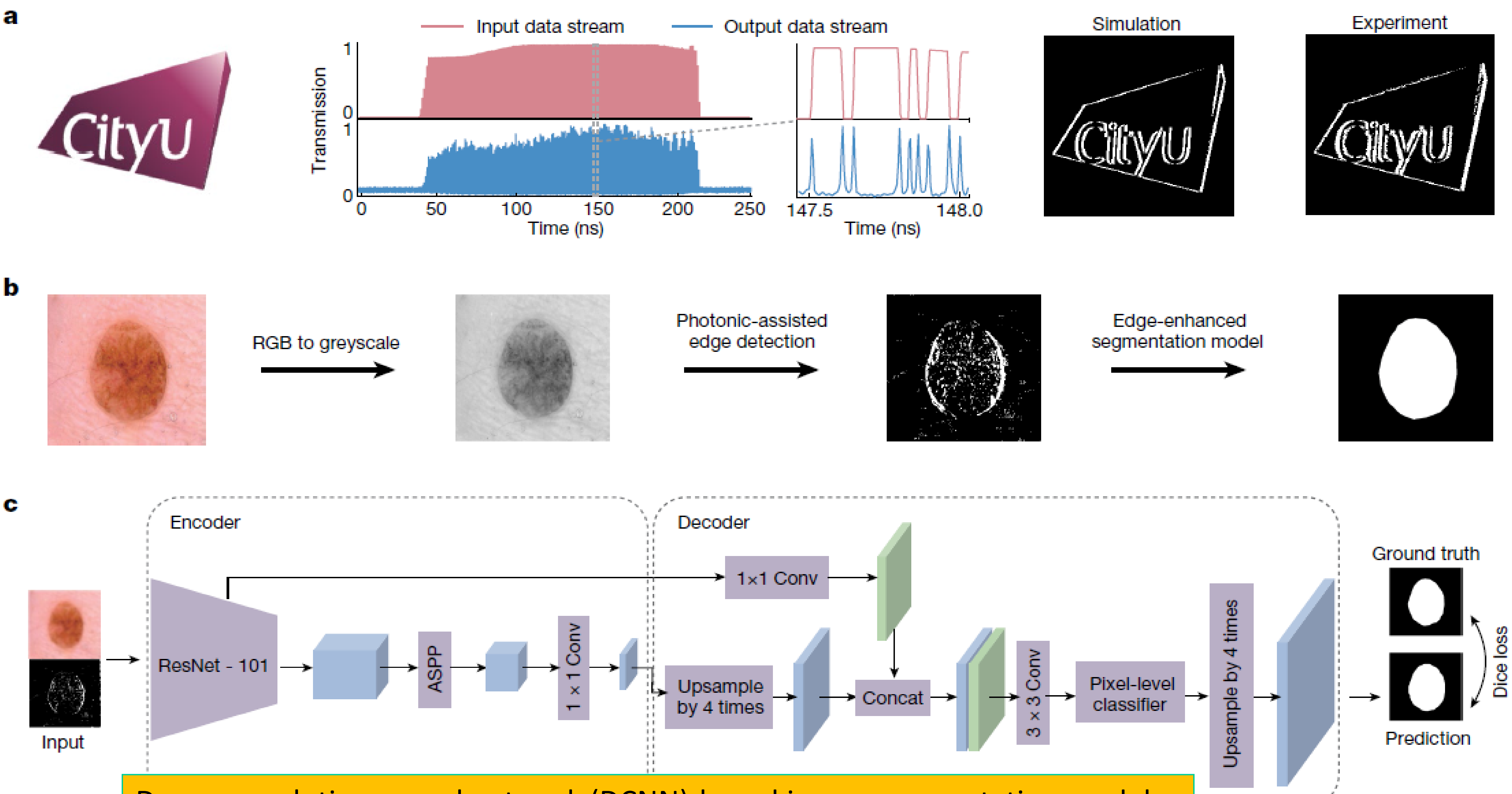




Feng, H., Ge, T., Guo, X. *et al.* Integrated lithium niobate microwave photonic processing engine. *Nature* **627**, 80–87 (2024).

uOttawa

High-speed photonic-assisted medical image segmentation

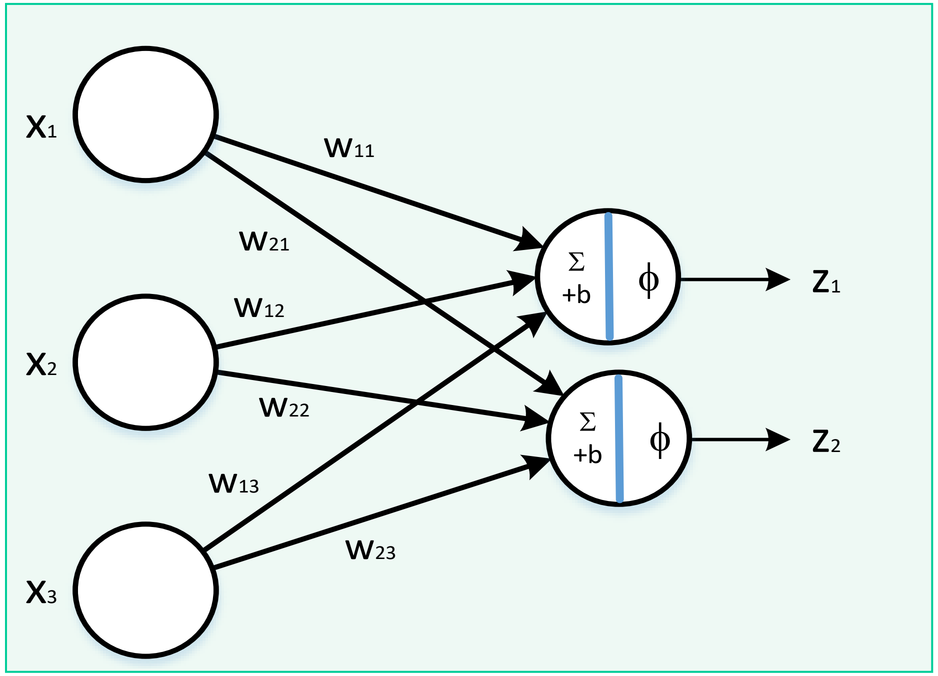


Deep convolution neural network (DCNN)-based image segmentation model

Outline

- What is MWP
- MWP and Optical Computing
- MWP and AI
- Convolutional Neural Network
  - Fiber-optic implementation
  - Photonic integrated implementation
- Optical Reservoir Computing
  - Fiber optic implementation
  - Photonic integrated implementation
- Conclusion

Artificial Intelligence – Neural Networks



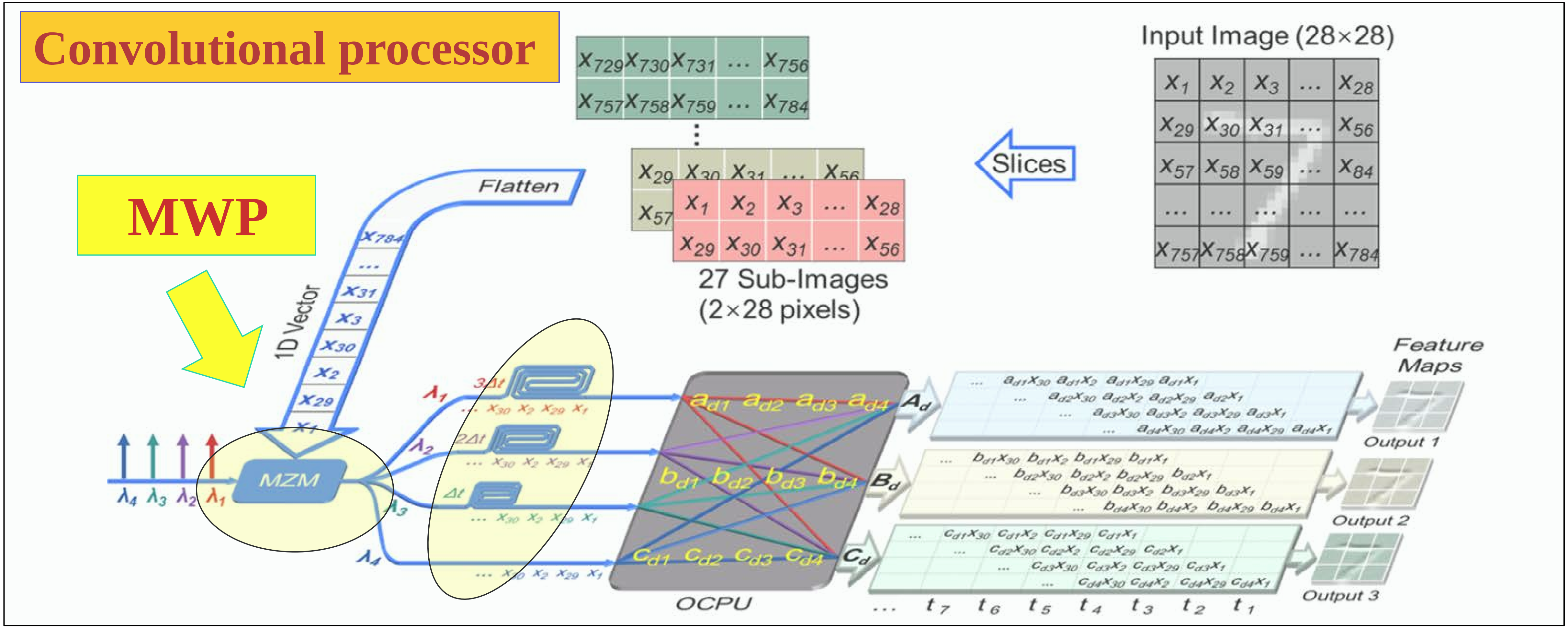
Single layer NN

$$z_1 = \varphi\left(x_1 w_{11} + x_2 w_{12} + x_3 w_{13} + b\right)$$
$$z_2 = \varphi\left(x_1 w_{21} + x_2 w_{22} + x_3 w_{23} + b\right)$$
$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \varphi \begin{bmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \varphi \begin{bmatrix} b \\ b \end{bmatrix}$$

ANNs involve heavy calculations, especially matrix operations (**Multiply–Accumulate（MAC) operations**) – we may use optical processors (pass and done)。

Advantages of optical processing：
- **High speed** (pass and done)
- **Parallel**

MWP and AI 微波光子学与人工智能的关系



MWP: microwave modulation, true time delay, etc

Meng, X., Zhang, G., Shi, N. *et al.* *Nat Commun* **14**, 3000 (2023)

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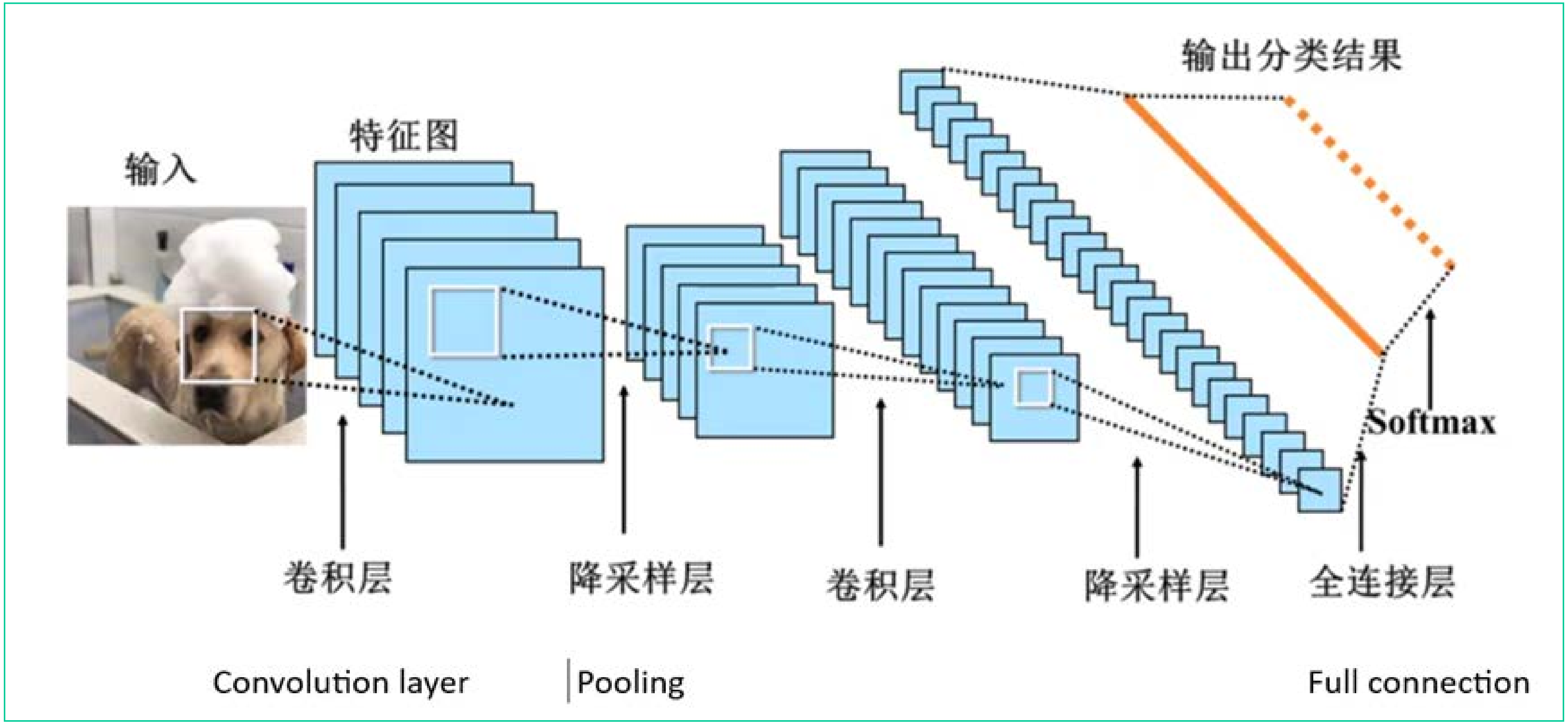
MWP and AI – Convolutional Neural Networks (CNNs)



CNN: three functions convolution, pooling (down-sampling) and activation (nonlinearity).

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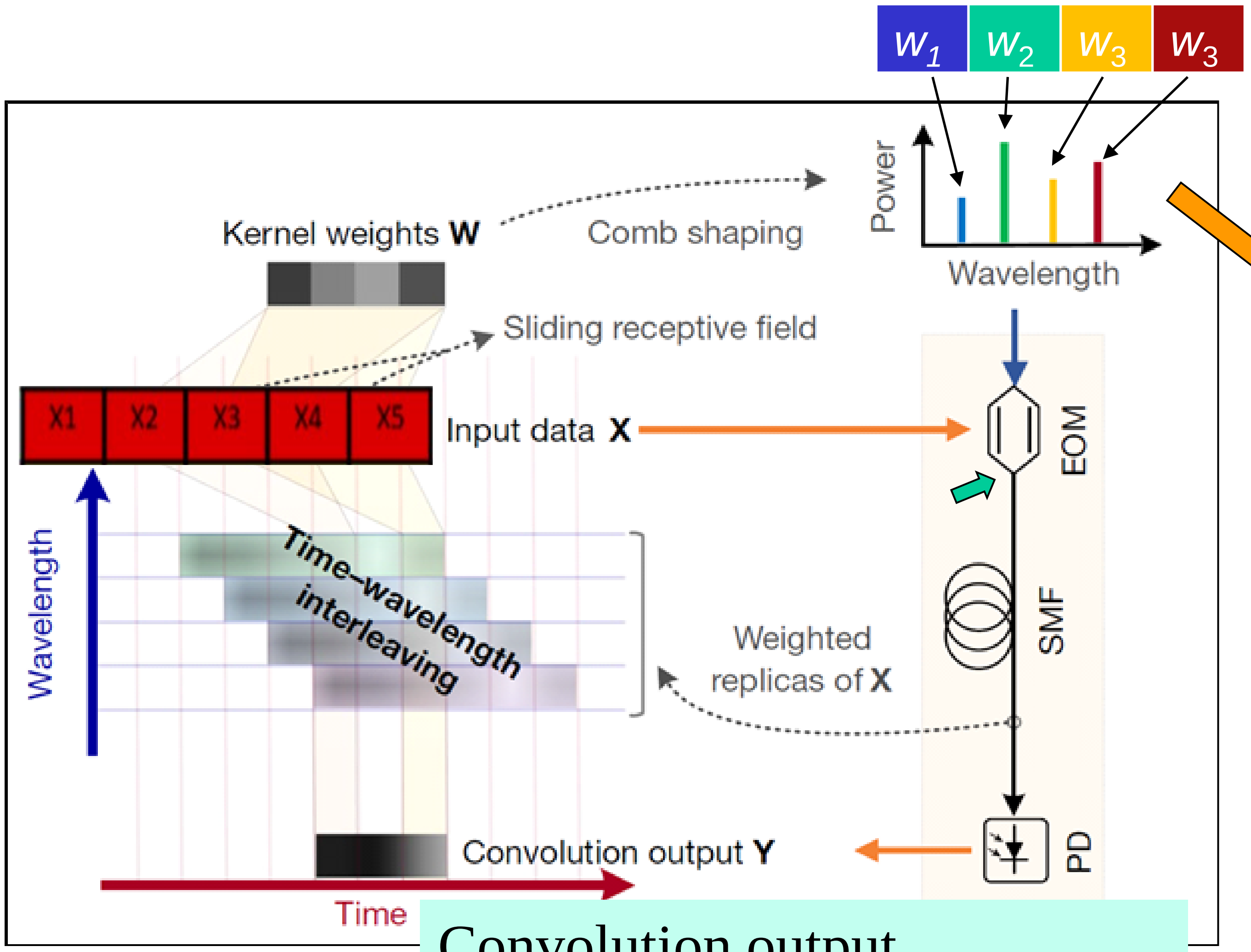
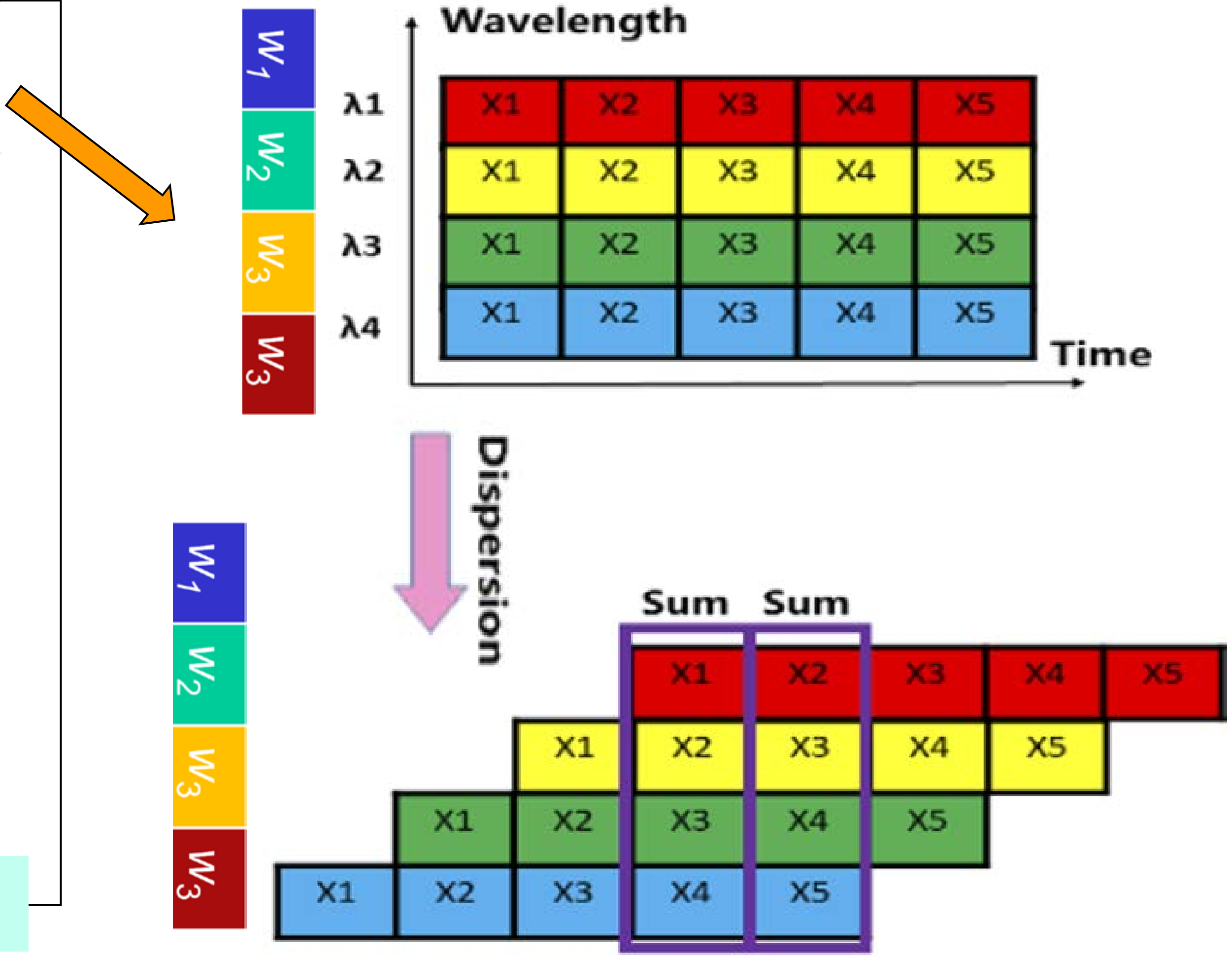
Photonic convolutional accelerator – fiber optics based

Weights (Kernel)





Convolution output

Xu, X., Tan, M., Corcoran, B. *et al.* 11 TOPS photonic convolutional accelerator for optical neural networks. *Nature* **589**, 44–51 (2021)

3892 Vol. 47, No. 15 / 1 August 2022 / Optics Letters Letter

Optics Letters

Optical processor for a binarized neural network

Long Huang and Jianping Yao*

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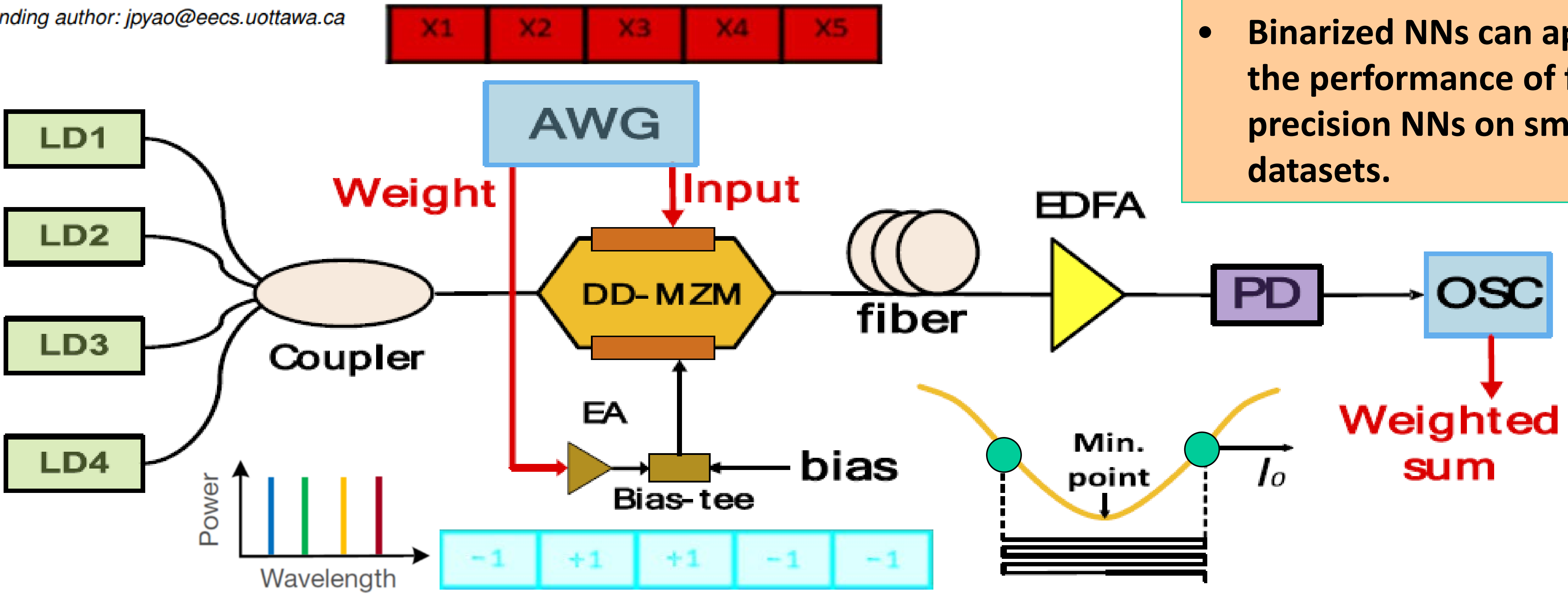
*Corresponding author: jpyao@eecs.uottawa.ca

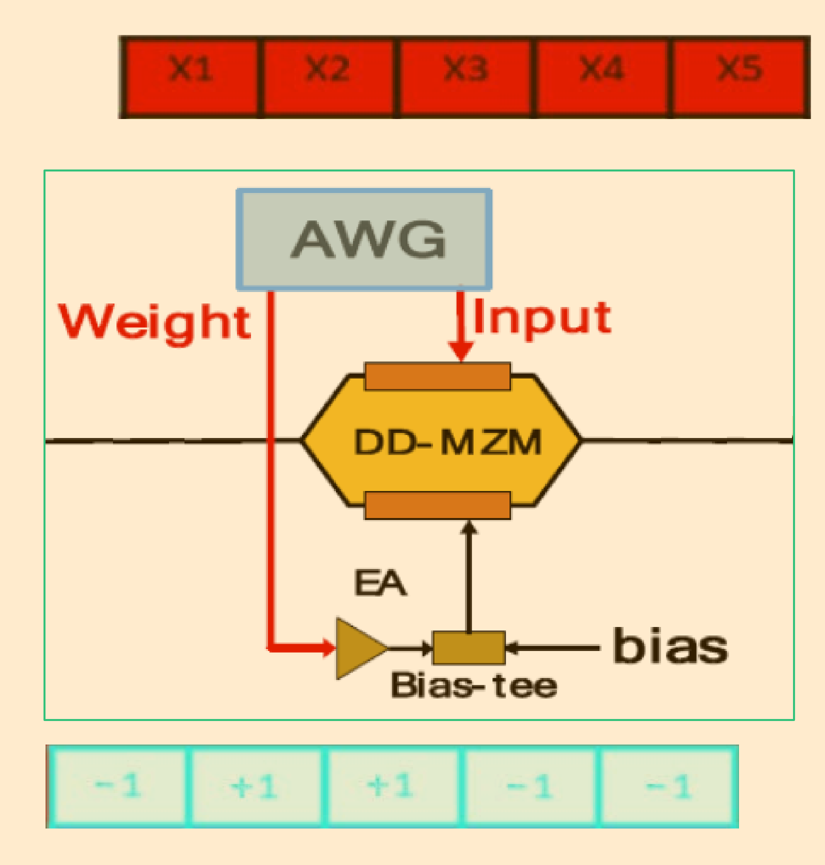


- Binary weights are introduced to simplify the implementation of NNs.
- Binarized NNs can approach the performance of full-precision NNs on small datasets.

MWP-assisted binarized neural network

Accumulate (addition) using fiber (dispersion) and PD

Multiply using MZM



V

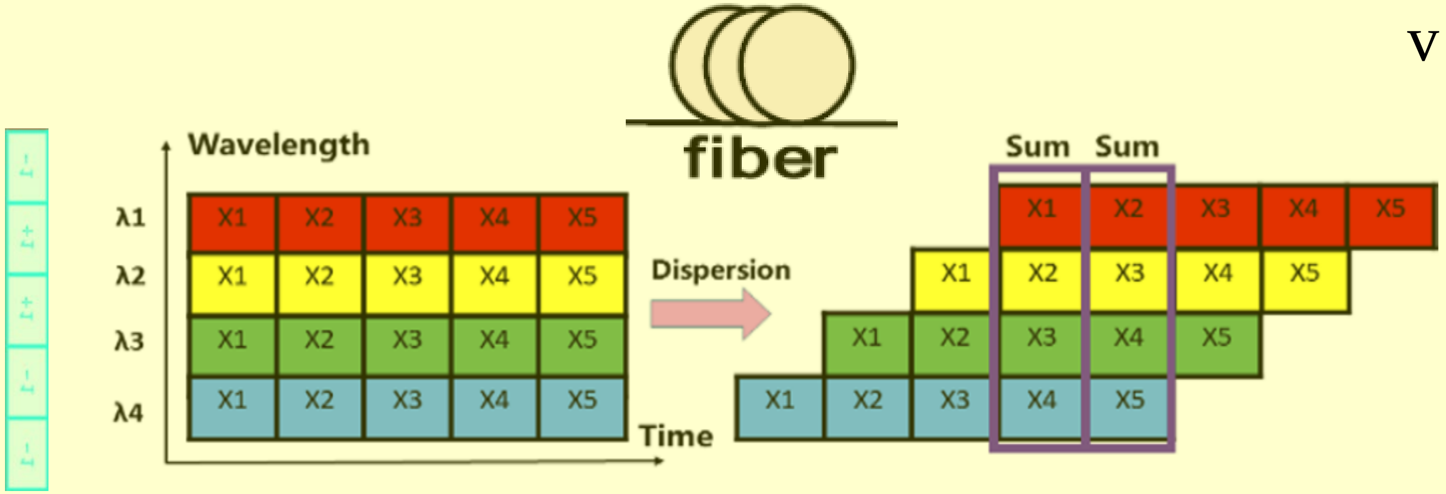
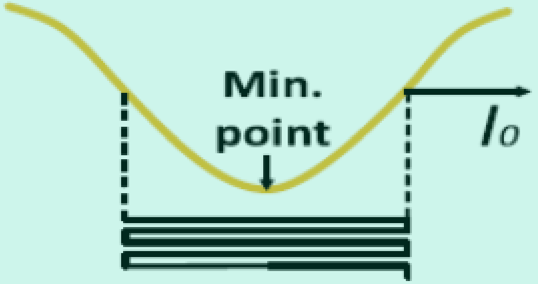


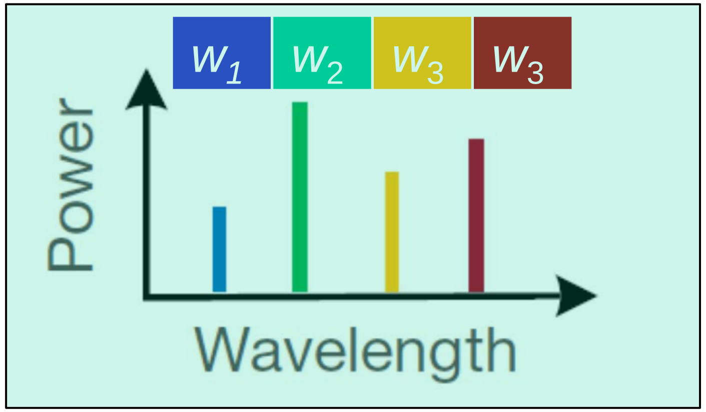
Fig. 2. Sum of the weighted input signal due the dispersion-induced time delay.



Weights control via bias switch – widely used by MWP

L. Huang and J. P. Yao, "An optical processor for a binarized neural network," Opt. Lett., vol. 47, no. 15, pp. 3892-3895, Aug. 2022.

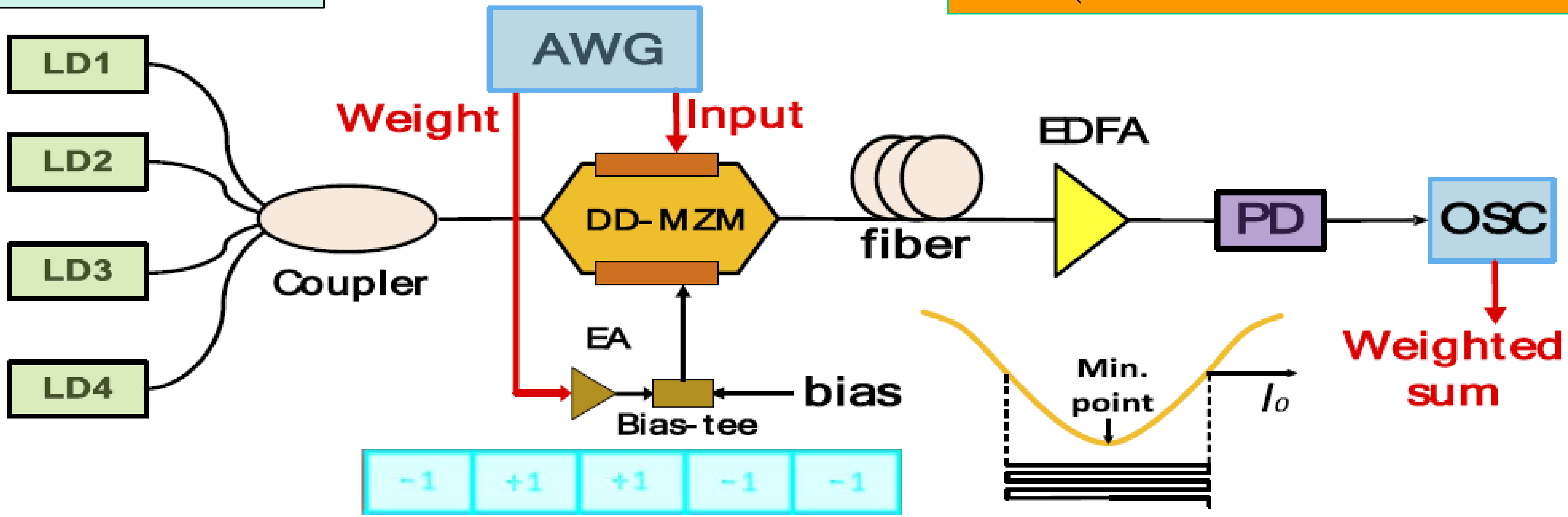
MWP-assisted neural network with real-valued weights



Weights (Kernel)

Real-valued weights

$$z_1 = \left(x_1 w_1 + x_2 w_2 + x_3 w_3 + x_4 w_4 \right)$$



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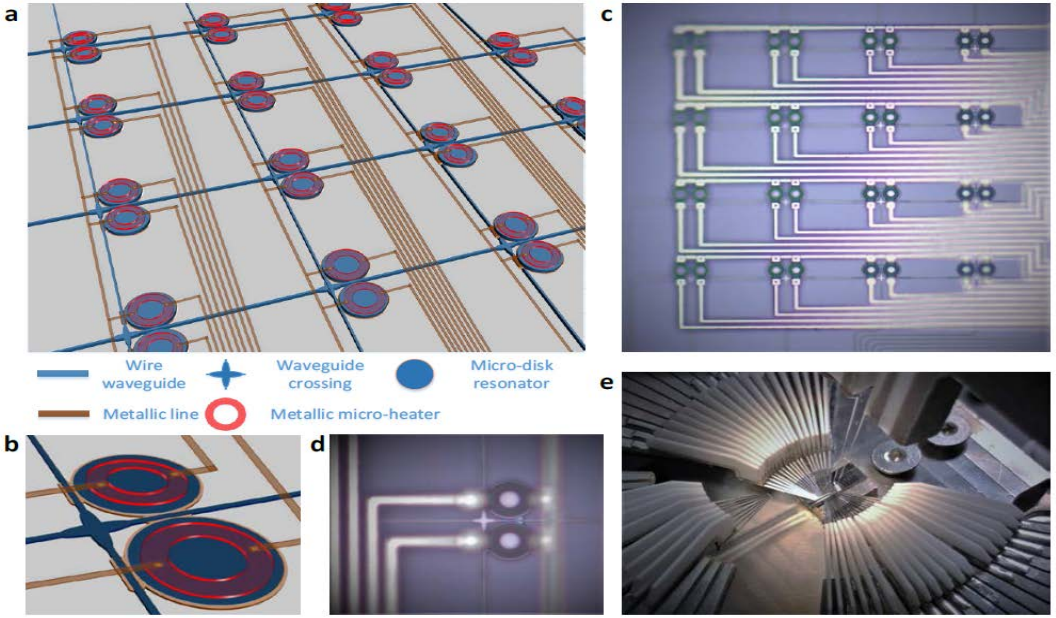
ARTICLE

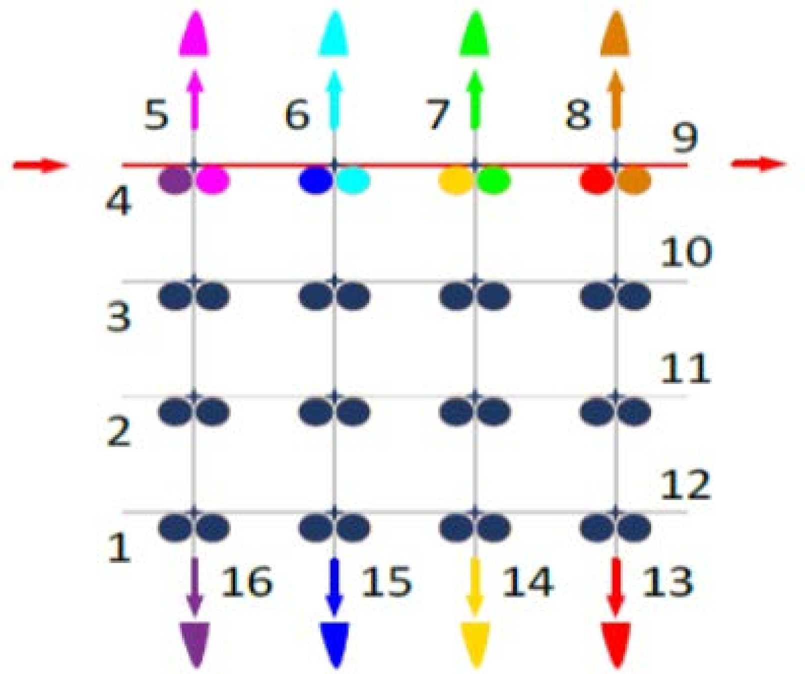
https://doi.org/10.1038/s41467-019-14249-0 OPEN

Photonic integrated field-programmable disk array signal processor

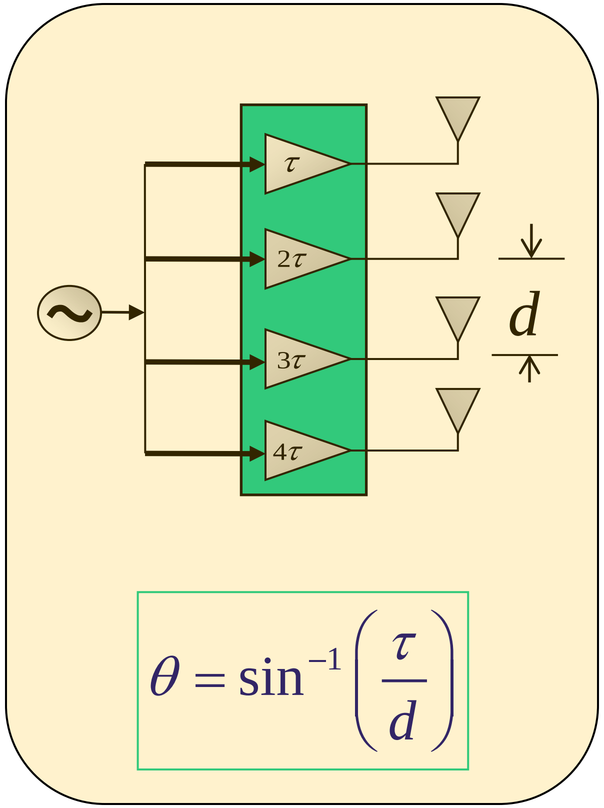
Weifeng Zhang[1] & Jianping Yao[1*]

Similar to an electronic FPGA





Photonic integrated field-programmable disk array signal processor



$$\theta = \sin^{-1}\left(\frac{\tau}{d}\right)$$

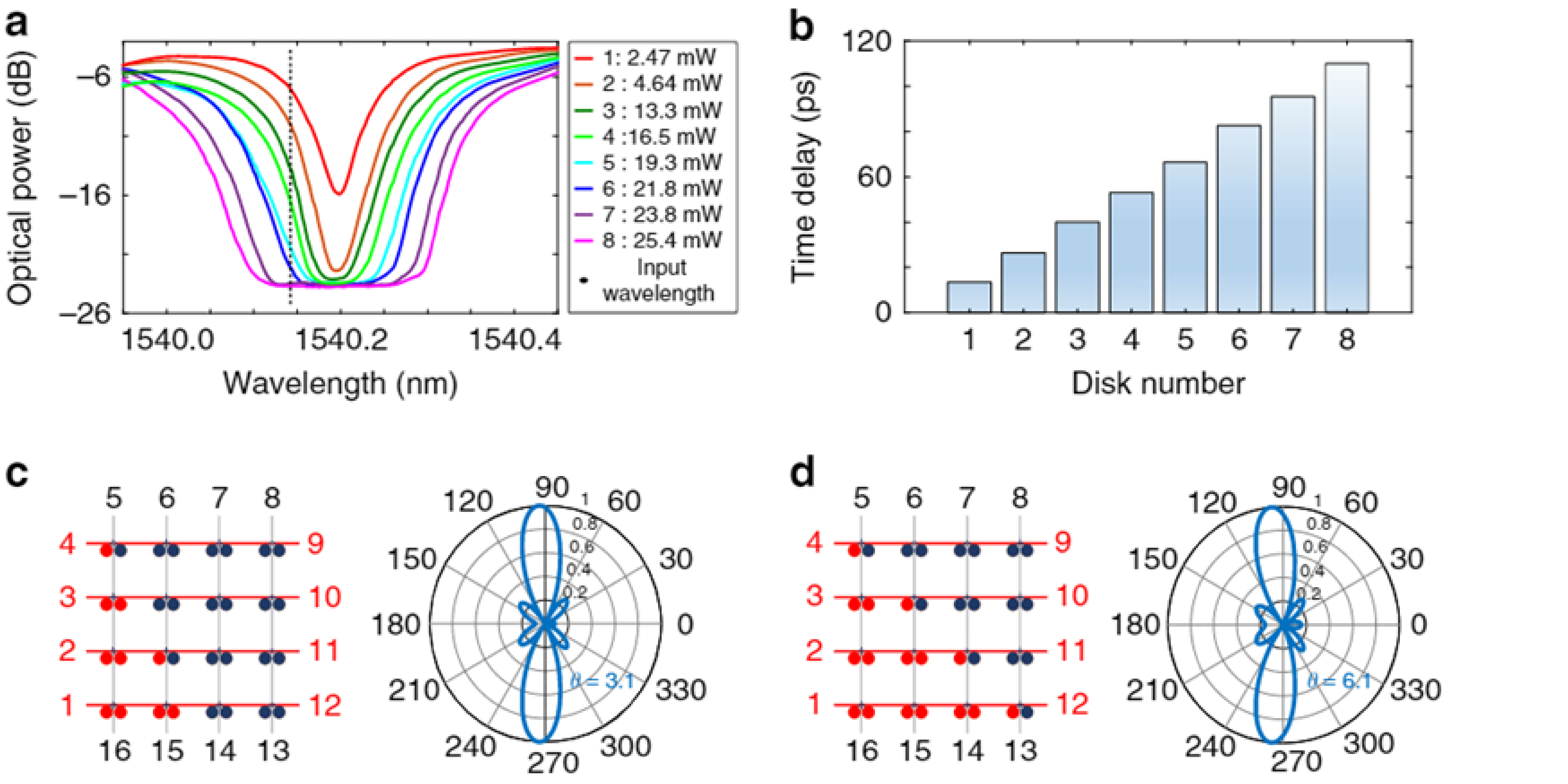
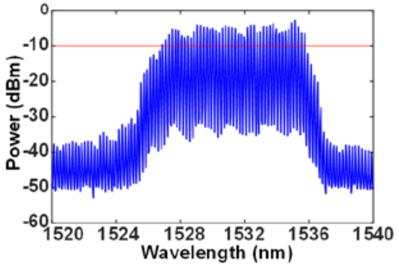
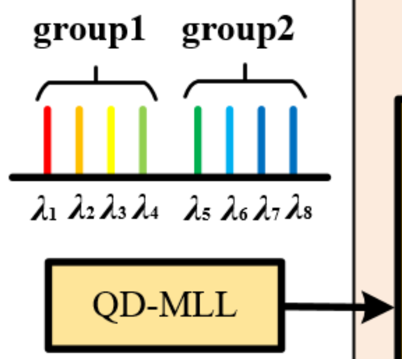
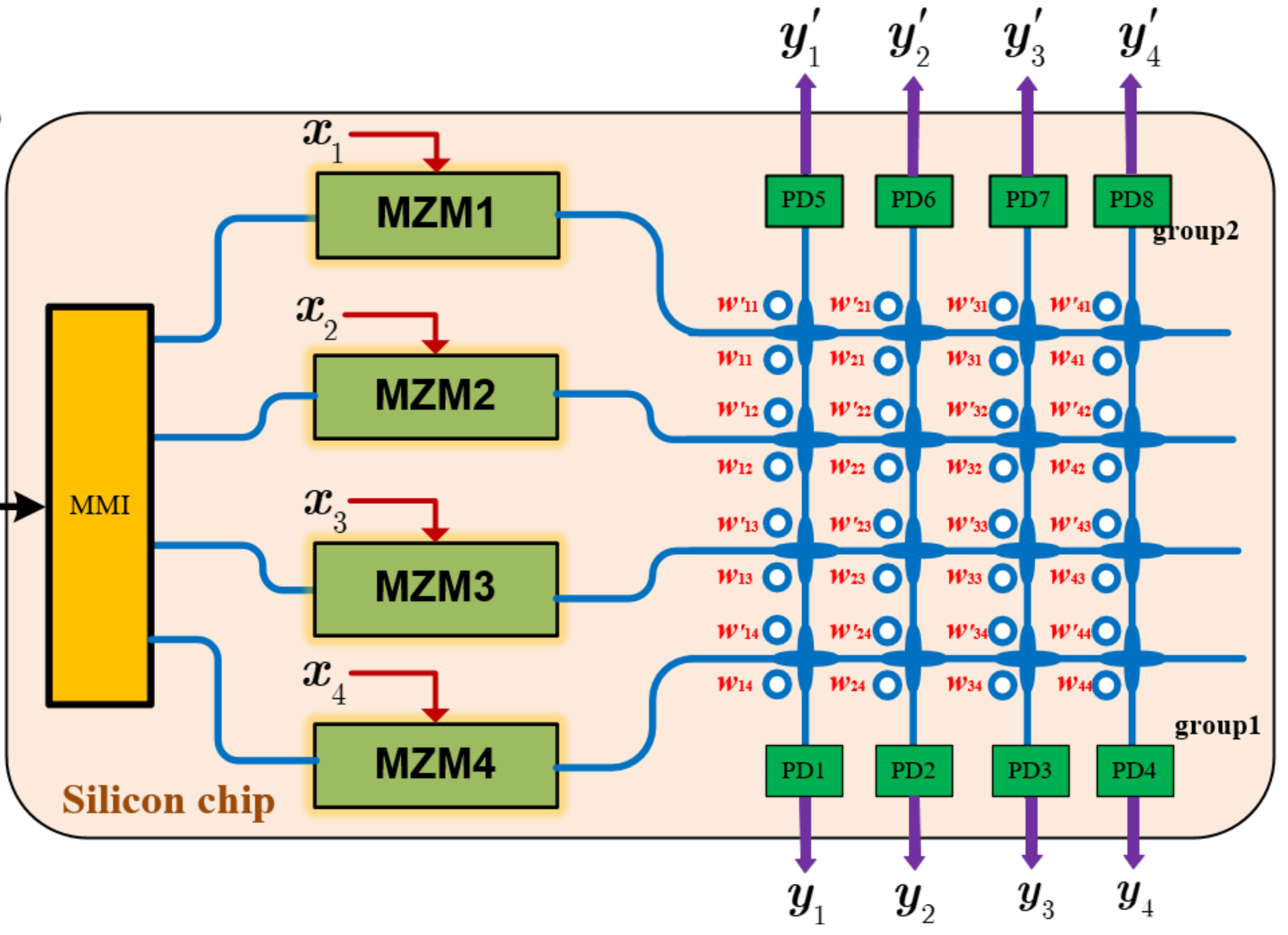


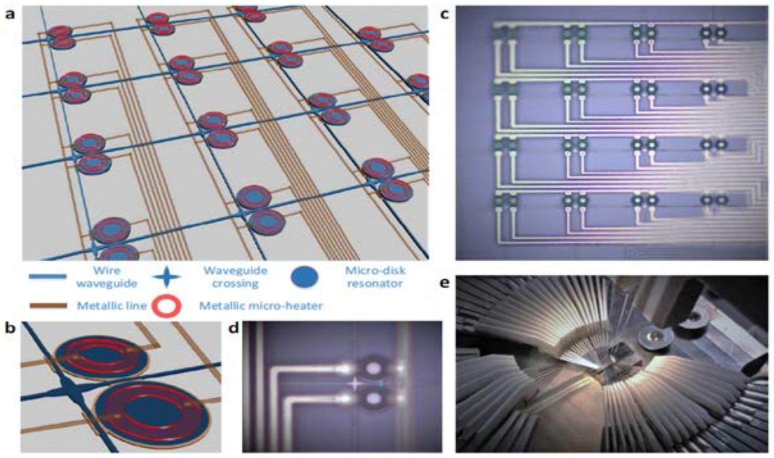
Fig. 4 Experimental results with photonic FPDA signal processor operating as optical beamforming network. a Measured transmission spectrum of the channel from port 4 to port 9 when the voltages are controlled to make resonance wavelength of each MDR aligned progressively. **b** Measured time delays with the number of the aligned MDRs increasing progressively. **c** Calculated array factors of a four-element linear PAA when the channel time delay is 13.5 ps. **d** Calculated array factors of a four-element linear PAA when the channel time delay is 26.4 ps.

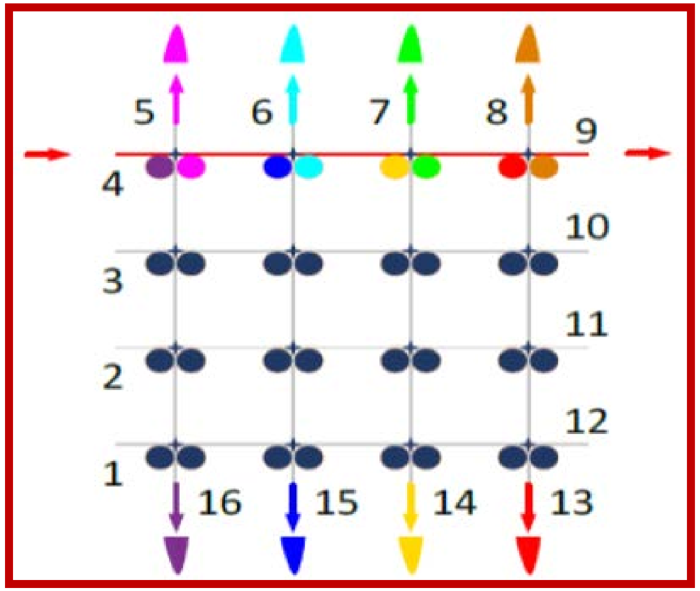
CNN based on a MRR crossbar array







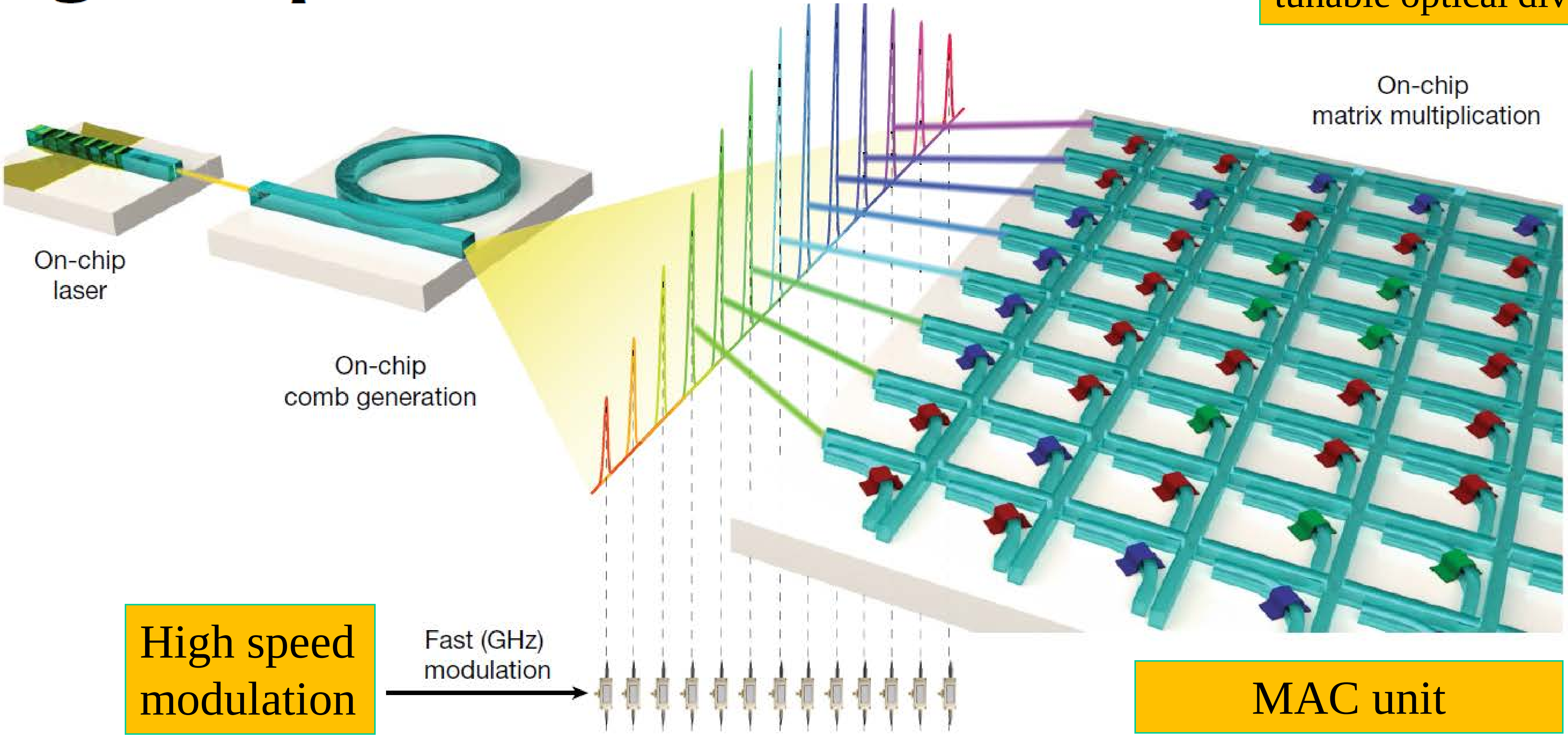




Article

Parallel convolutional processing using an integrated photonic tensor core

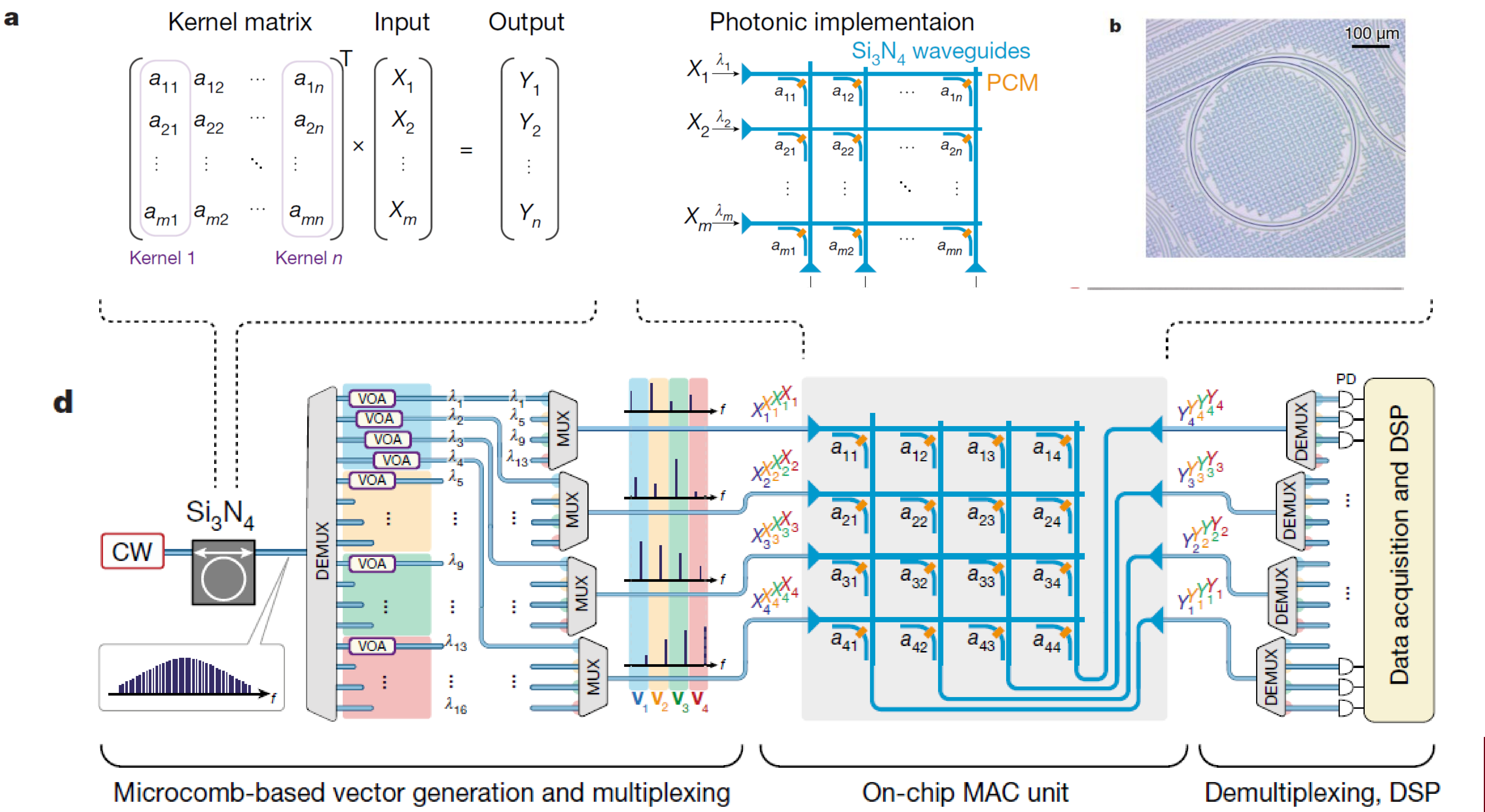
Phase Change Material (PCM) tunable optical divider



High speed modulation

MAC unit

Feldmann, J., Youngblood, N., Karpov, M. et al. Parallel convolutional processing using an integrated photonic tensor core. Nature 589, 52–58 (2021)



a
Kernel matrix
Input
Output
Kernel 1
Kernel n
Photonic implementaion
Si3N4 waveguides
PCM
b
100 µm
d
CW
Si3N4
DEMUX
VOA
MUX
PD
Data acquisition and DSP
Microcomb-based vector generation and multiplexing
On-chip MAC unit
Demultiplexing, DSP

 https://doi.org/10.1038/s41467-023-38786-x

Compact optical convolution processing unit based on multimode interference

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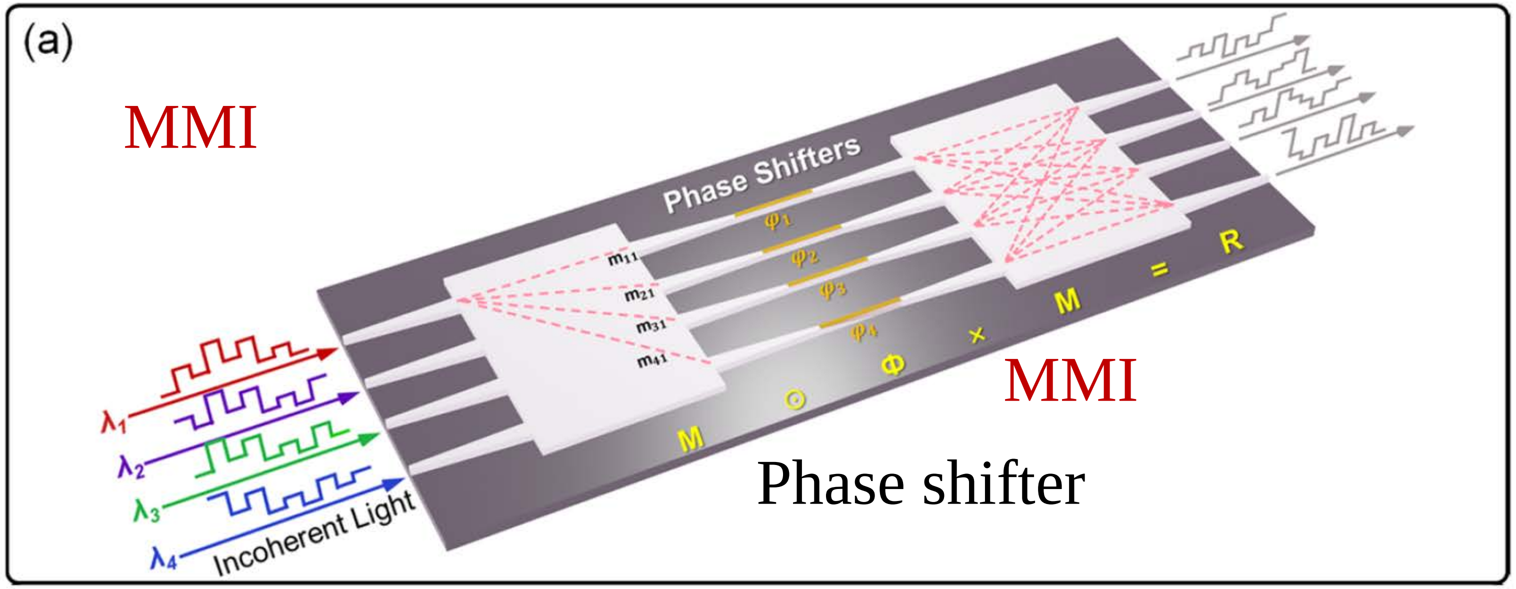
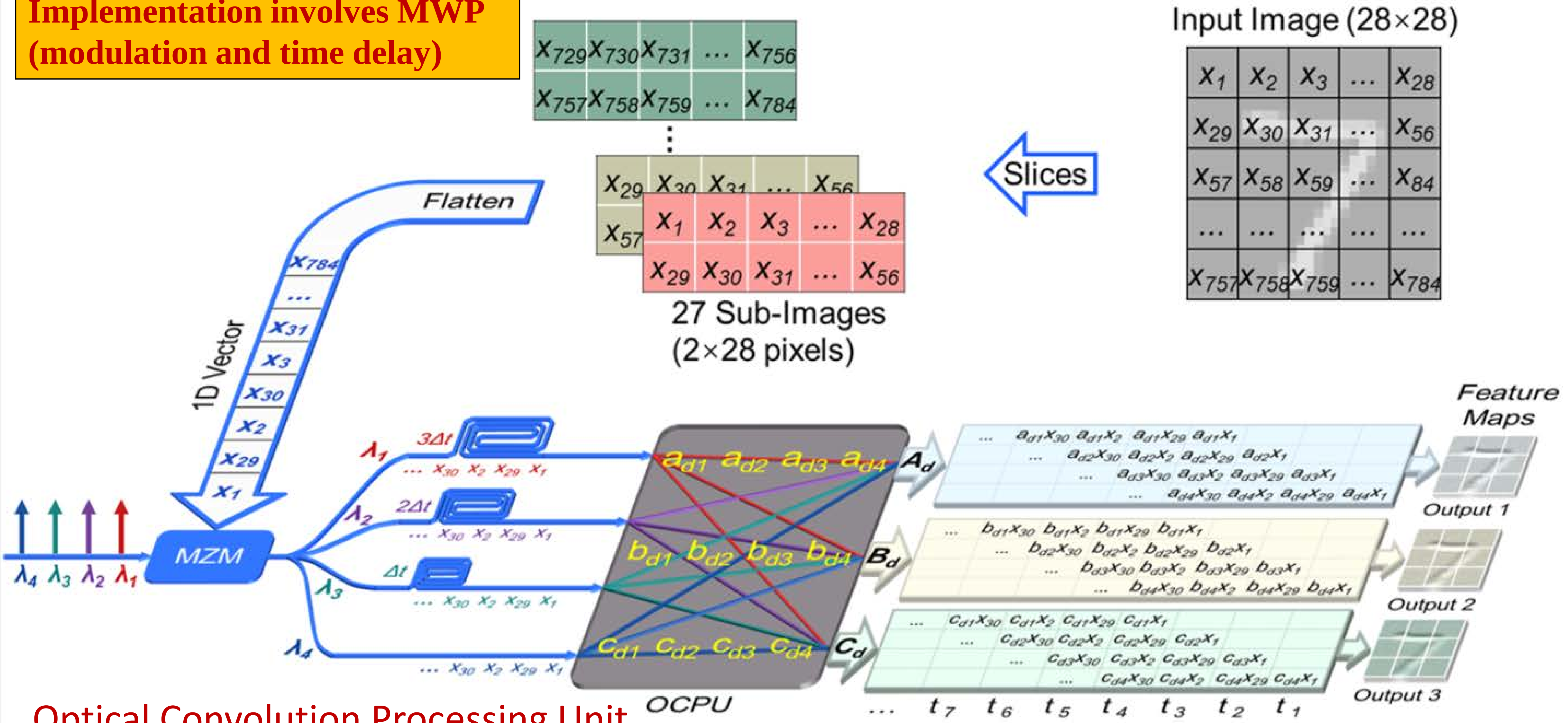


$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}, \Phi = \begin{bmatrix} e^{j\varphi_1} & e^{j\varphi_1} & e^{j\varphi_1} & e^{j\varphi_1} \\ e^{j\varphi_2} & e^{j\varphi_2} & e^{j\varphi_2} & e^{j\varphi_2} \\ e^{j\varphi_3} & e^{j\varphi_3} & e^{j\varphi_3} & e^{j\varphi_3} \\ e^{j\varphi_4} & e^{j\varphi_4} & e^{j\varphi_4} & e^{j\varphi_4} \end{bmatrix}, \quad (1)$$

$$R = (M \times (\Phi \odot M)) \odot (M \times (\Phi \odot M)) = \begin{bmatrix} |r_{11}|^2 & |r_{12}|^2 & |r_{13}|^2 & |r_{14}|^2 \\ |r_{21}|^2 & |r_{22}|^2 & |r_{23}|^2 & |r_{24}|^2 \\ |r_{31}|^2 & |r_{32}|^2 & |r_{33}|^2 & |r_{34}|^2 \\ |r_{41}|^2 & |r_{42}|^2 & |r_{43}|^2 & |r_{44}|^2 \end{bmatrix}, \quad (2)$$

X. Meng, G. Zhang, N. Shi, G. Li, J. Azaña, J. Capmany, J. P. Yao, Y. Shen, W. Li, N. Zhu, and M. Li, "Compact optical convolution processing unit based on multimode interference," Nature Comm., vol. 14, Article number: 3000, May 2023.

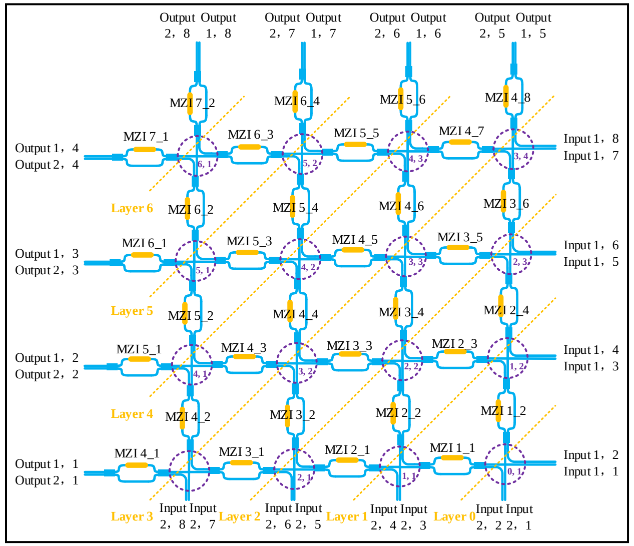
Implementation involves MWP (modulation and time delay)



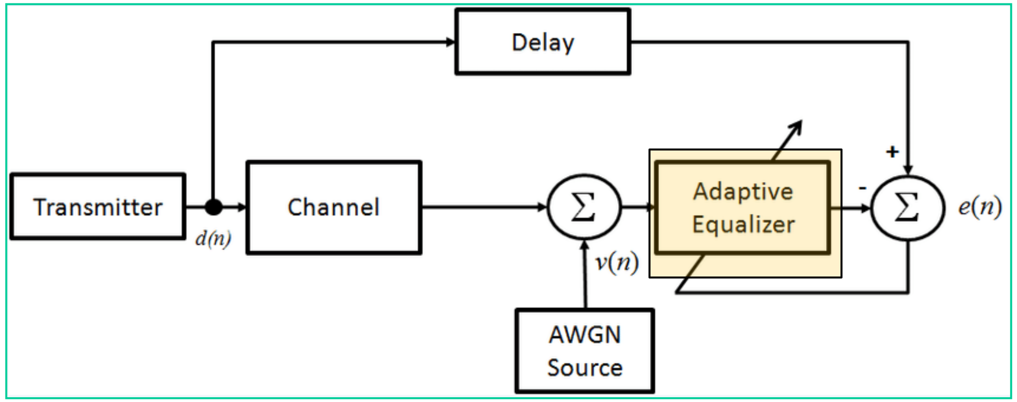
Optical Convolution Processing Unit

Meng, X., Zhang, G., Shi, N. *et al.* Compact optical convolution processing unit based on multimode interference. *Nat Commun* **14**, 3000 (2023)

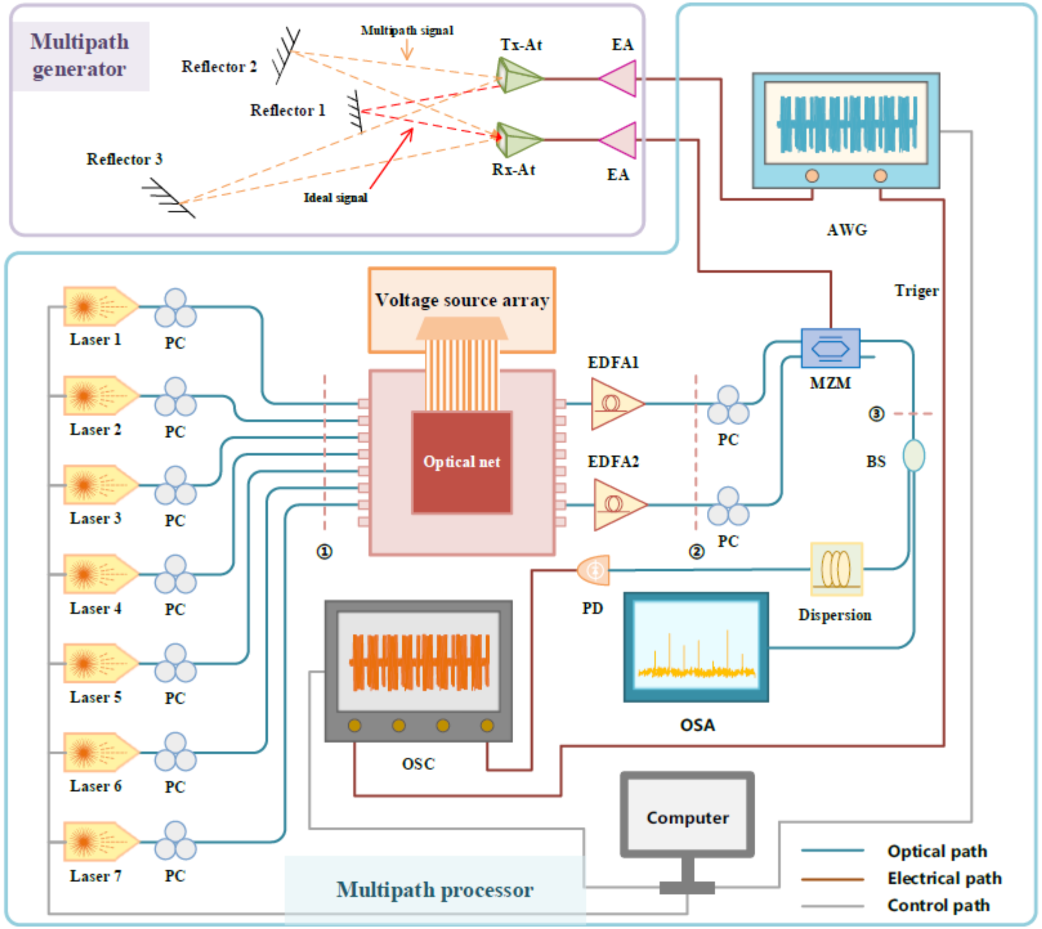
Optical on-chip signal processor based on matrix operations



Silicon photonic chip



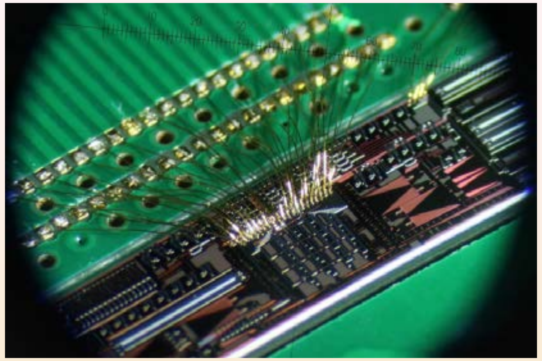
Channel equalization



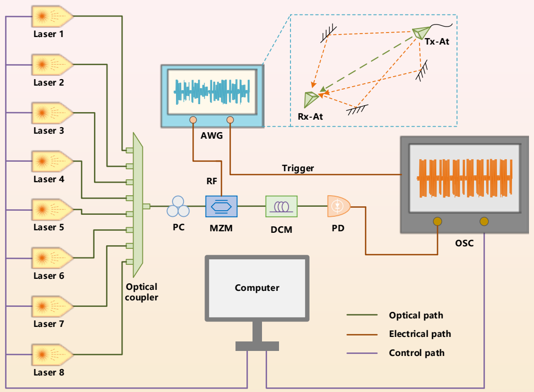
An MWP system - An adaptive delay line MWP filter to equalize the channel

Adaptive on-chip multi-path decoupling (implementation of an adaptive delay line filter to equalize the channel)

Optical on-chip signal processor based on matrix operations



Chip on PCB



Experimental setup

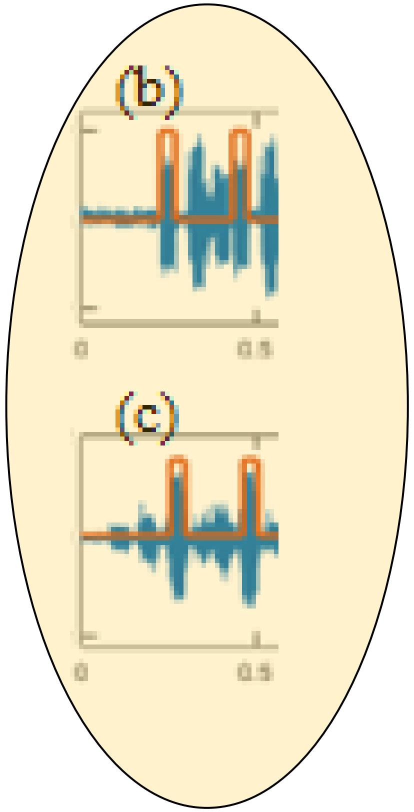
Matrix for decoupling:

$$\begin{bmatrix} y_{out1,1} \\ y_{out1,2} \\ y_{out1,3} \\ y_{out1,4} \\ y_{out1,8} \\ y_{out1,7} \\ y_{out1,6} \\ y_{out1,5} \end{bmatrix} = \begin{bmatrix} <-50 & <-50 & <-50 & -40.0 & <-50 & <-50 & <-50 & <-50 \\ <-50 & <-50 & -24.48 & -20.4 & -24.4 & -25.5 & -45.2 & -18.4 \\ <-50 & -19.7 & -31.4 & -30.8 & -30.4 & -38.9 & -19.9 & -27.9 \\ -22.26 & -17.4 & -16.8 & -18.3 & -27.2 & -25.48 & -19.7 & -34.46 \\ -46.9 & -45.2 & -40.0 & -39.2 & -46.3 & -46.2 & -25.7 & -9.25 \\ -13.96 & -21.88 & -14.07 & -26.0 & -21.9 & -27.9 & -17.05 & <-50 \\ -31.43 & -23.63 & -41.3 & -21.32 & -41.3 & -9.09 & <-50 & <-50 \\ <-50 & <-50 & <-50 & <-50 & -10.65 & <-50 & <-50 & <-50 \end{bmatrix} \cdot \begin{bmatrix} x_{in1,7} \\ x_{in1,5} \\ x_{in1,3} \\ x_{in1,1} \\ x_{in2,1} \\ x_{in2,3} \\ x_{in2,5} \\ x_{in2,7} \end{bmatrix}$$

(a)

(b)

(c)



Decoupling four interferences from 4 paths, carrier frequency 2.5GHz, bit rate 500MHz, 0 bit-error.

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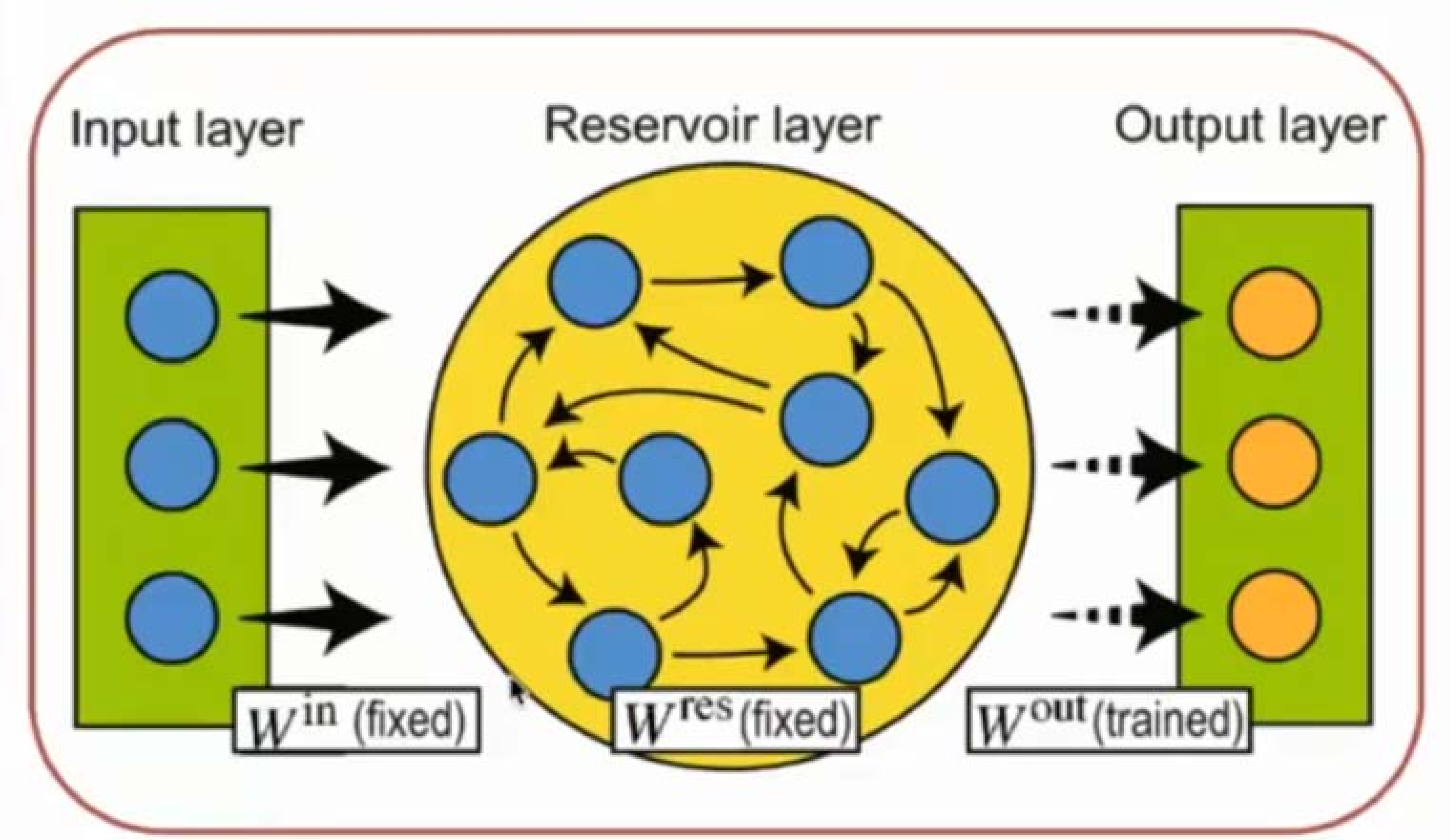
Optical reservoir computing



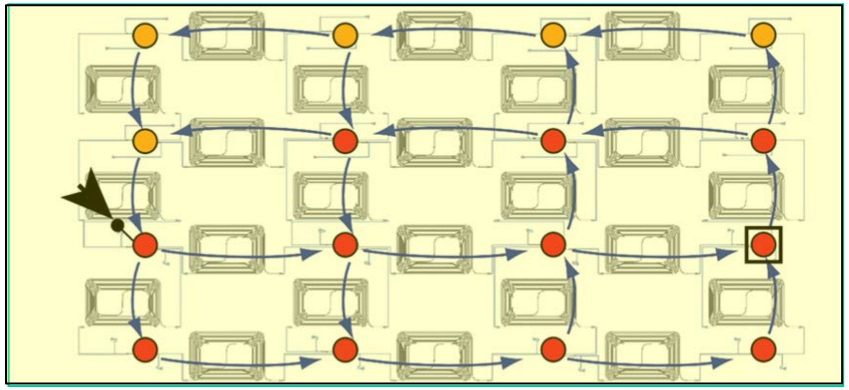
$$\boldsymbol{x}(t+\Delta t) = f_{NL1}\left[\mathbf{W}_i \boldsymbol{u}(t+\Delta t) + \mathbf{W}_{res}\boldsymbol{x}(t) + \mathbf{W}_{back}\boldsymbol{y}(t)\right]$$

$$\boldsymbol{y}(t+\Delta t) = \mathbf{W}_o f_{NL2}\left[\boldsymbol{x}(t+\Delta t)\right]$$

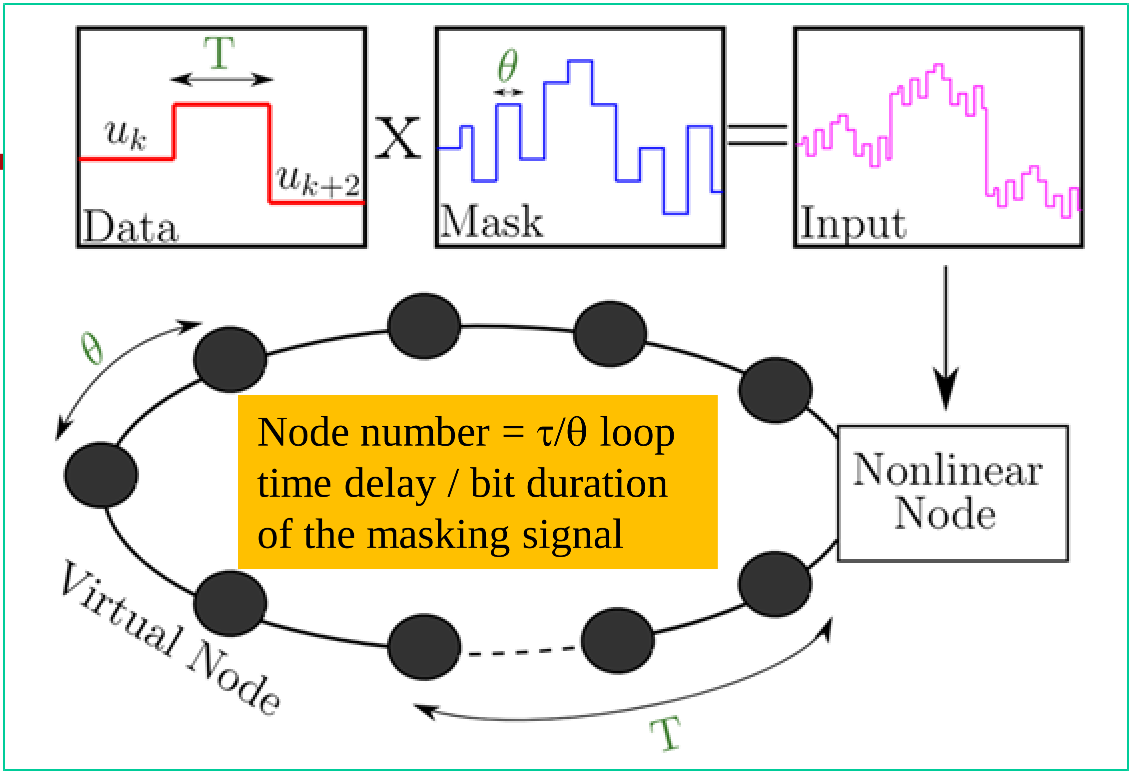
Training a reservoir NN, only the output layer *W*o needs to be trained, and the input layer *W*i and the internal interconnection weights *W*res can remain fixed.

The reservoir NN consists of three layers, the input layer, the middle layer, and the output layer. The middle layer is also called the reservoir.

Optical reservoir computing structure



Silicon photonic chip



Spatially Distributed RC (SD-RC) on a silicon photonic chip: The reservoir consists solely of on-chip low-loss waveguides, optical beam splitters, and optical beam combiners. Nonlinearity is introduced by the squared nonlinearity of the photodetectors.

Time-delayed RC (TD-RC) :

- Masking is done on each bit of an input signal.
- Mask is randomly generated. It determines the node interval （τ/θ） and determines the weights (binary or real-valued)
- The masked signal is applied to the nonlinear node (MZM).
- The response enters the delay line and is fed back to the nonlinear node after time τ, forming a closed loop.

Vandoorne, K. *et al.* Experimental demonstration of reservoir computing on a silicon photonics chip. *Nat Commun* **5**, 3541 (2014).

F. Köster et al., "Master memory function for delay-based reservoir computers with single-variable dynamics," in *IEEE Transactions on Neural Networks and Learning Systems, to be published*

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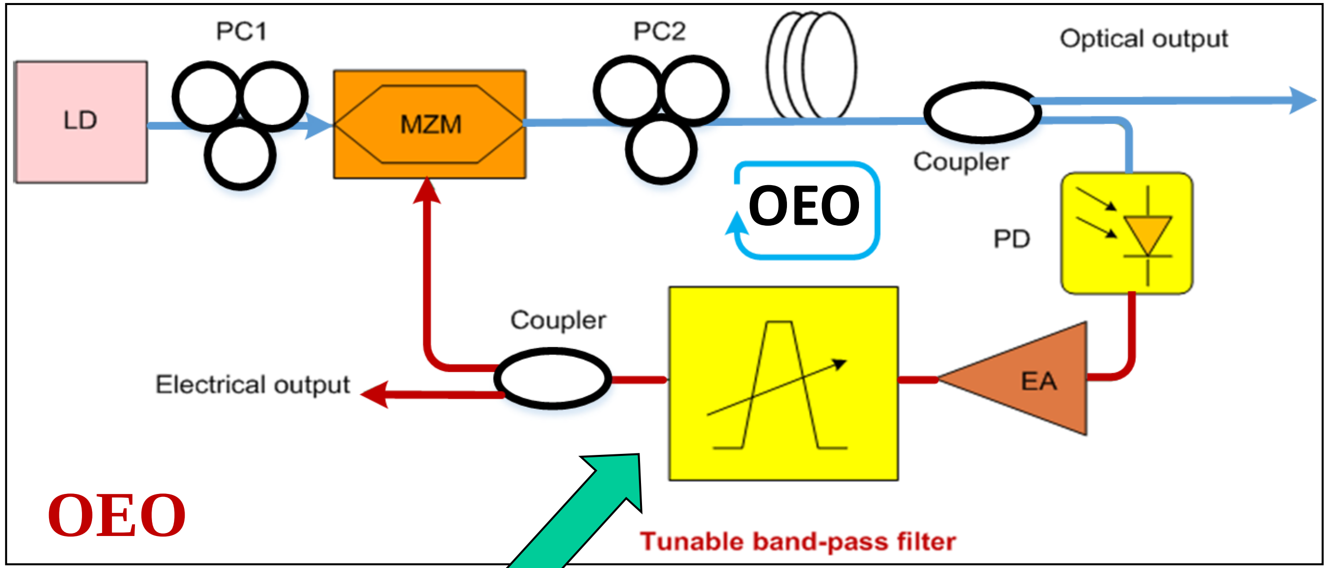
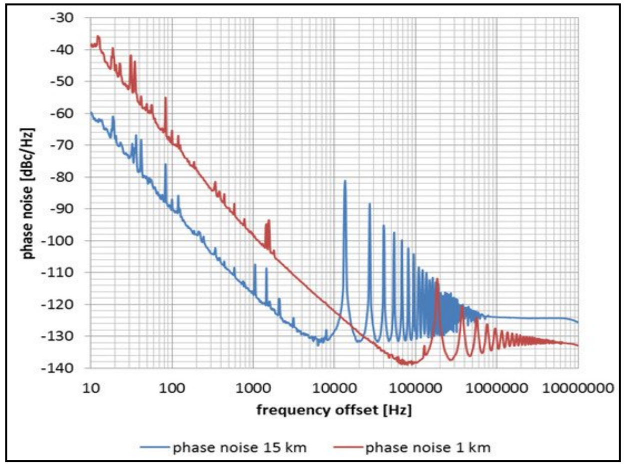
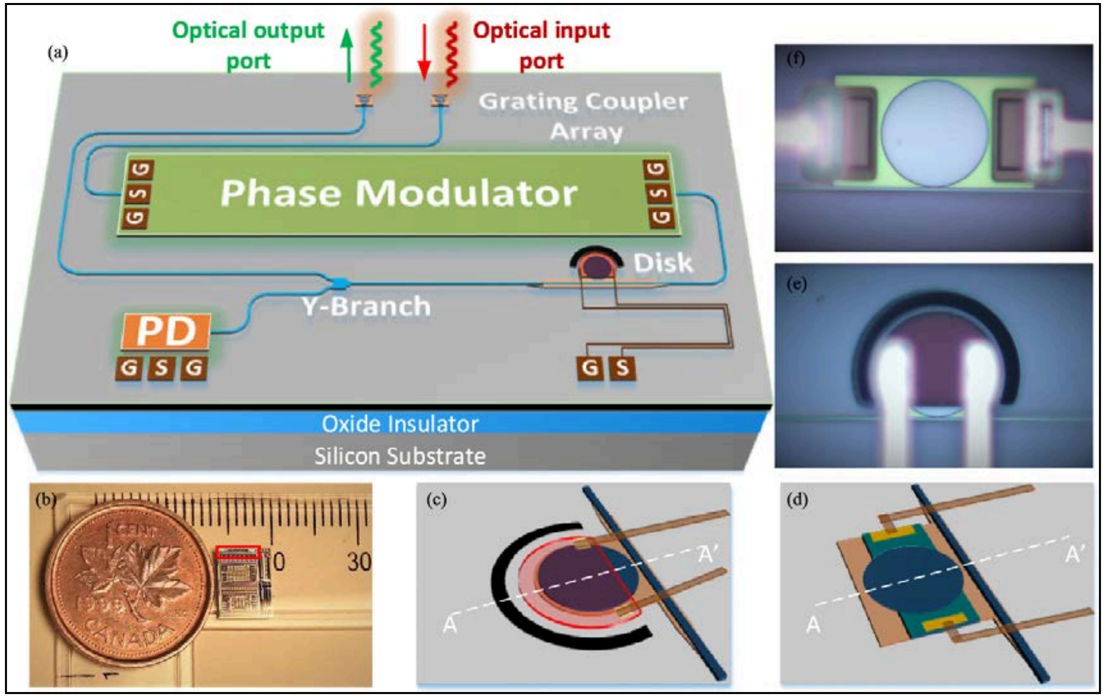
Optical Reservoir Computing- Microwave Photonic Implementation



Narrow-band tunable bandpass filter





Silicon photonic integrated optoelectronic oscillator (OEO)

W. Zhang and J. Yao, *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4655-4663, Oct. (2018 MWP special issue 2018)

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Optics Letters

Optical Reservoir Computing- MWP Implementation

Multi-task photonic time-delay reservoir computing based on polarization modulation

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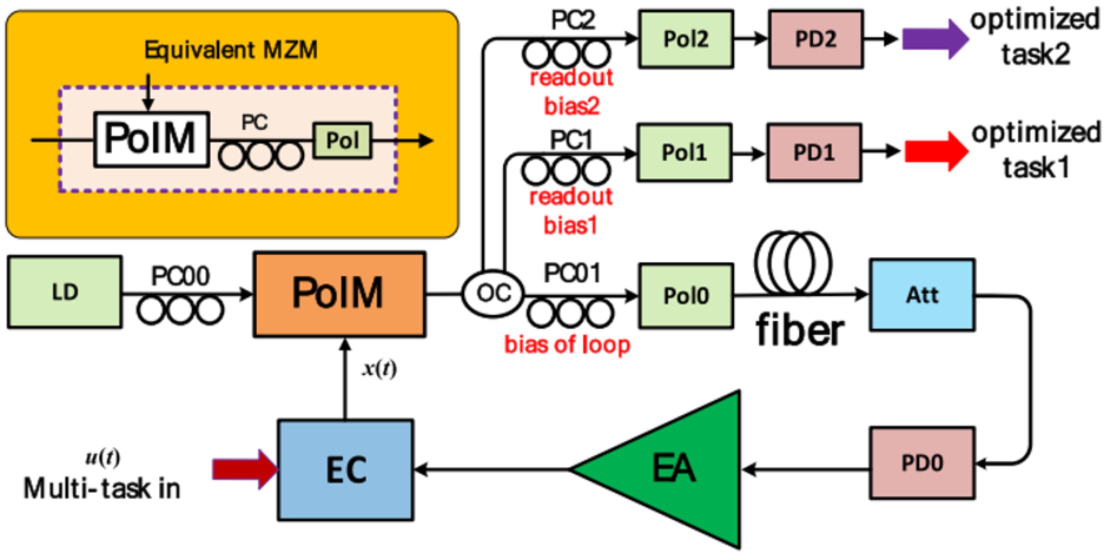
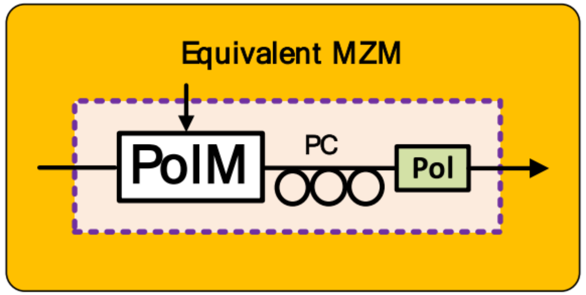
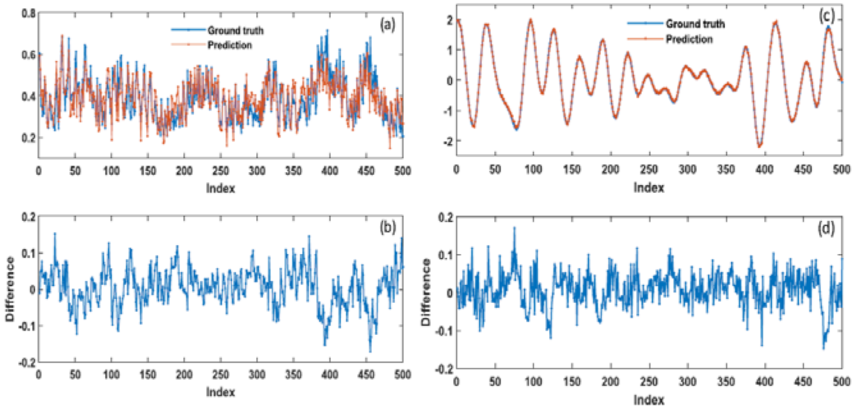




PolM+ PC + Pol = MZM, bias point can be adjusted by tuning the PC→adjustable nonlinearity

Task 1



Task 2

Fig. 6. Readout bias adjusted to minimize the NMSE of the IPIX radar signal prediction task. (a) True and predicted NARMA10 time series and (b) the difference between them. (c) True and predicted IPIX radar signals and (d) the difference between them.

The difference an RC from an OEO is that

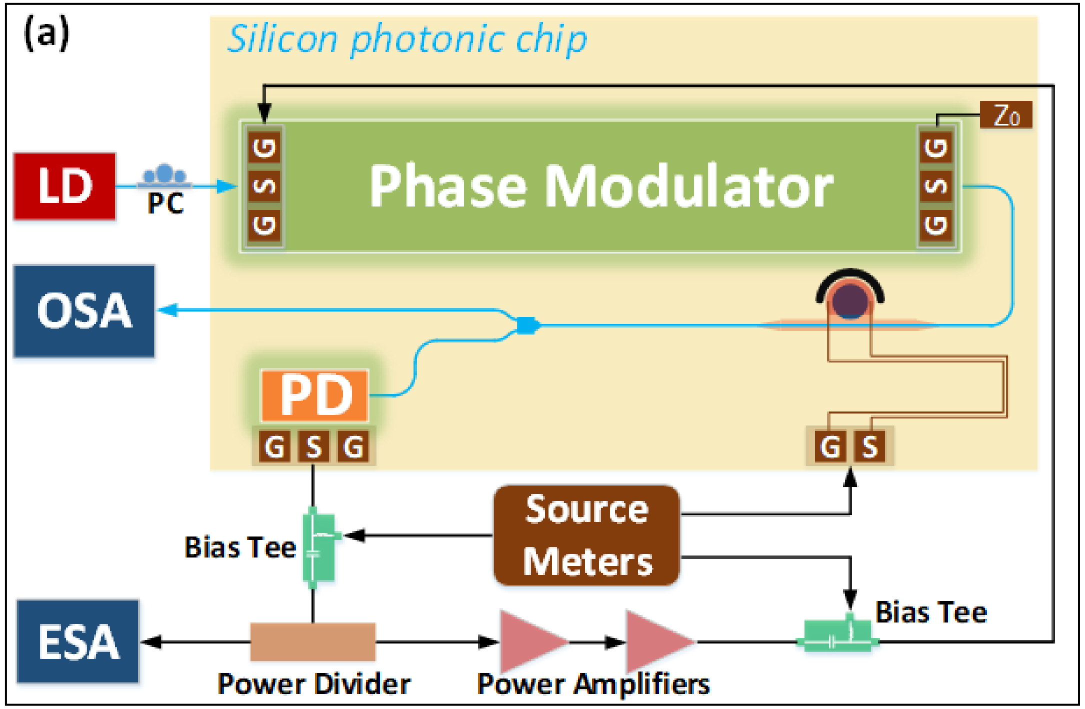
- **narrowband bandpass filter to be removed**
- **Net gain slightly smaller than 1**

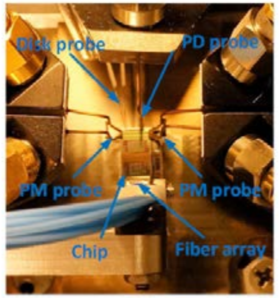
L. Huang and J. P. Yao, "Multi-task photonic time-delay reservoir computing based on polarization modulation," Opt. Lett., vol. 47, no. 24, pp. 6464-6467, Dec. 2022.

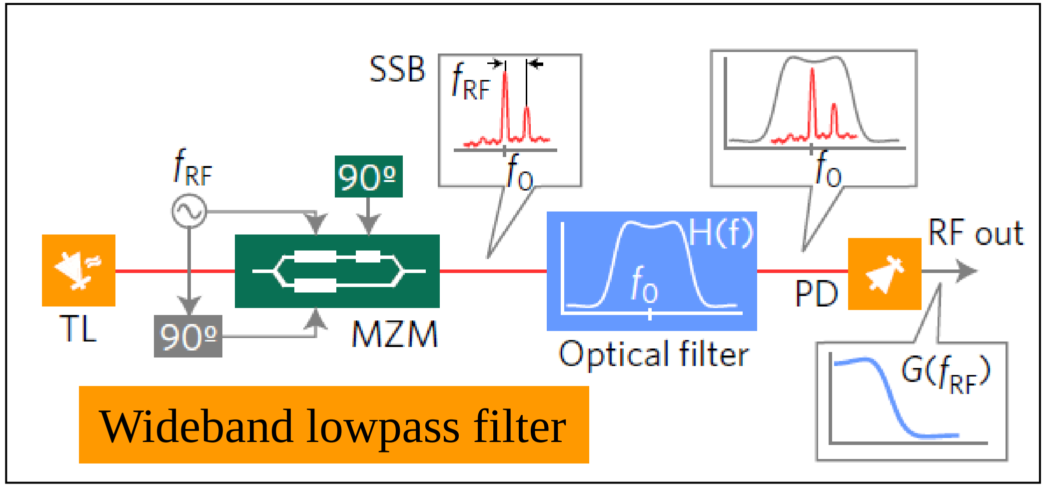
Outline

- What is MWP
- MWP and Optical Computing
- MWP and AI
- Convolutional Neural Network
  - Fiber-optic implementation
  - Photonic integrated implementation
- Optical Reservoir Computing
  - Fiber optic implementation
  - Photonic integrated implementation
- Conclusion

RC implementation based on PIC







An integrated OEO for microwave generation in which a narrow passband filter is employed for frequency selection

For optoelectronic reservoir computing, the bandpass filter should be changed to a wideband low-pass filter

PIC based RC: higher speed and better stability

Fandiño, J., Muñoz, P., Doménech, D. *et al.* A monolithic integrated photonic microwave filter. *Nature Photon* **11**, 124–129 (2017).

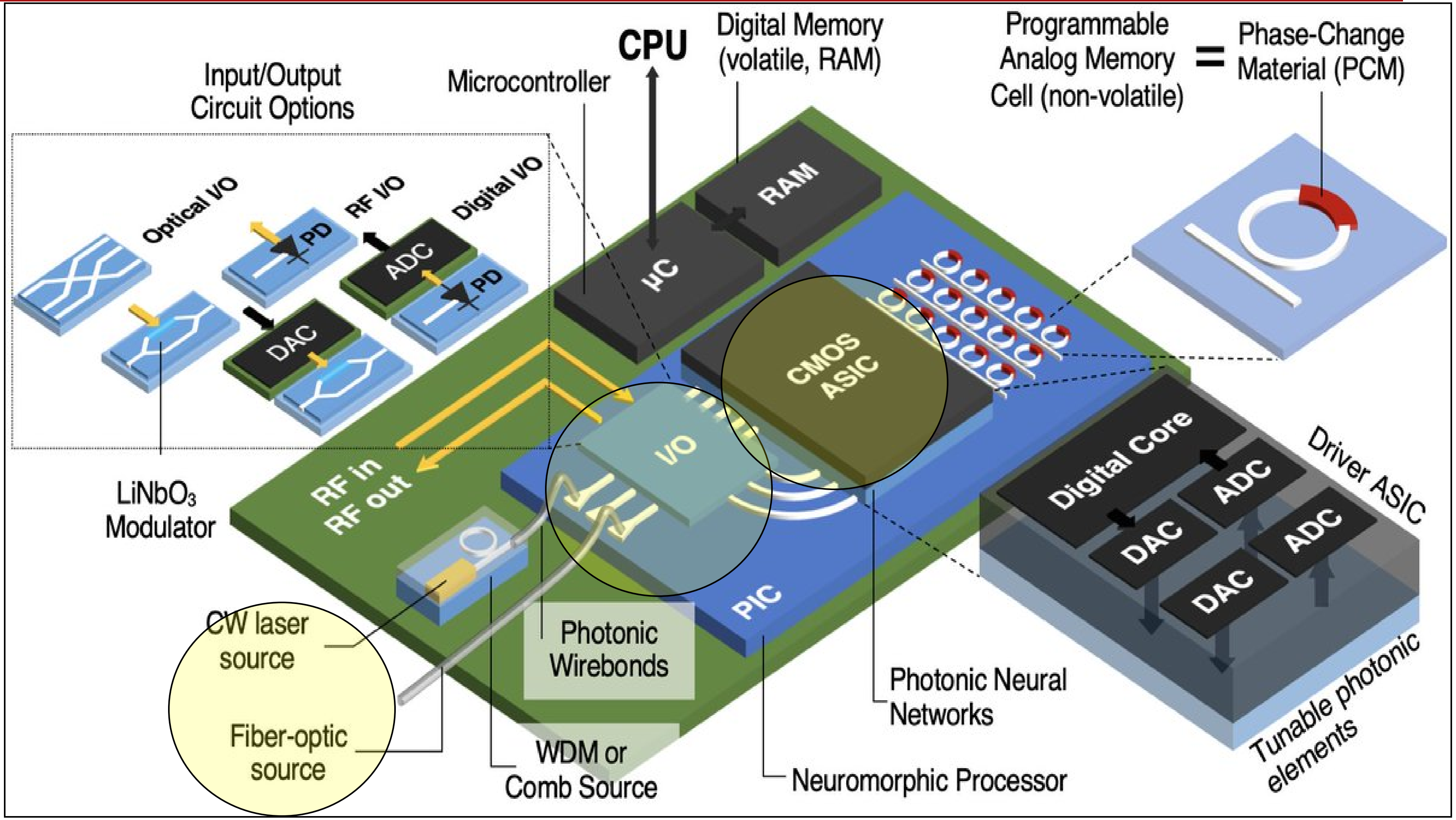
MWP and AI

Conclusion:

- Microwave photonics enables high-speed optical computing
- High-speed optical computing can assist AI implementation at high speed (especially for neural networks)
- A fully integrated signal processor should have ICs and PICs, Analog and Digital→ the architecture on next page

Shastri, B.J., Tait, A.N., Ferreira de Lima, T. et al. Photonics for artificial intelligence and neuromorphic computing. Nat. Photonics 15, 102–114 (2021).

Photon-assisted fully integrated signal processor architecture



Fully hybrid integrated signal processor:

- The light source is connected to the I/O chip through “optical wire bonding”
- The I/O chip includes a modulator and a detector (MWP part) I/O
- CMOS ASIC controls optical networks, including programmable analog optical memory units (composed of phase change materials) to complete high-speed computing

Shastri, B.J., Tait, A.N., Ferreira de Lima, T. et al. Photonics for artificial intelligence and neuromorphic computing. Nat. Photonics 15, 102–114 (2021).