PHOTONICS RESEARCH GROUP

The Wavelength Dimension in Photonic Reservoir Computing

Emmanuel Gooskens – 28 May 2024
Promotors: Peter Bienstman, Joni Dambre

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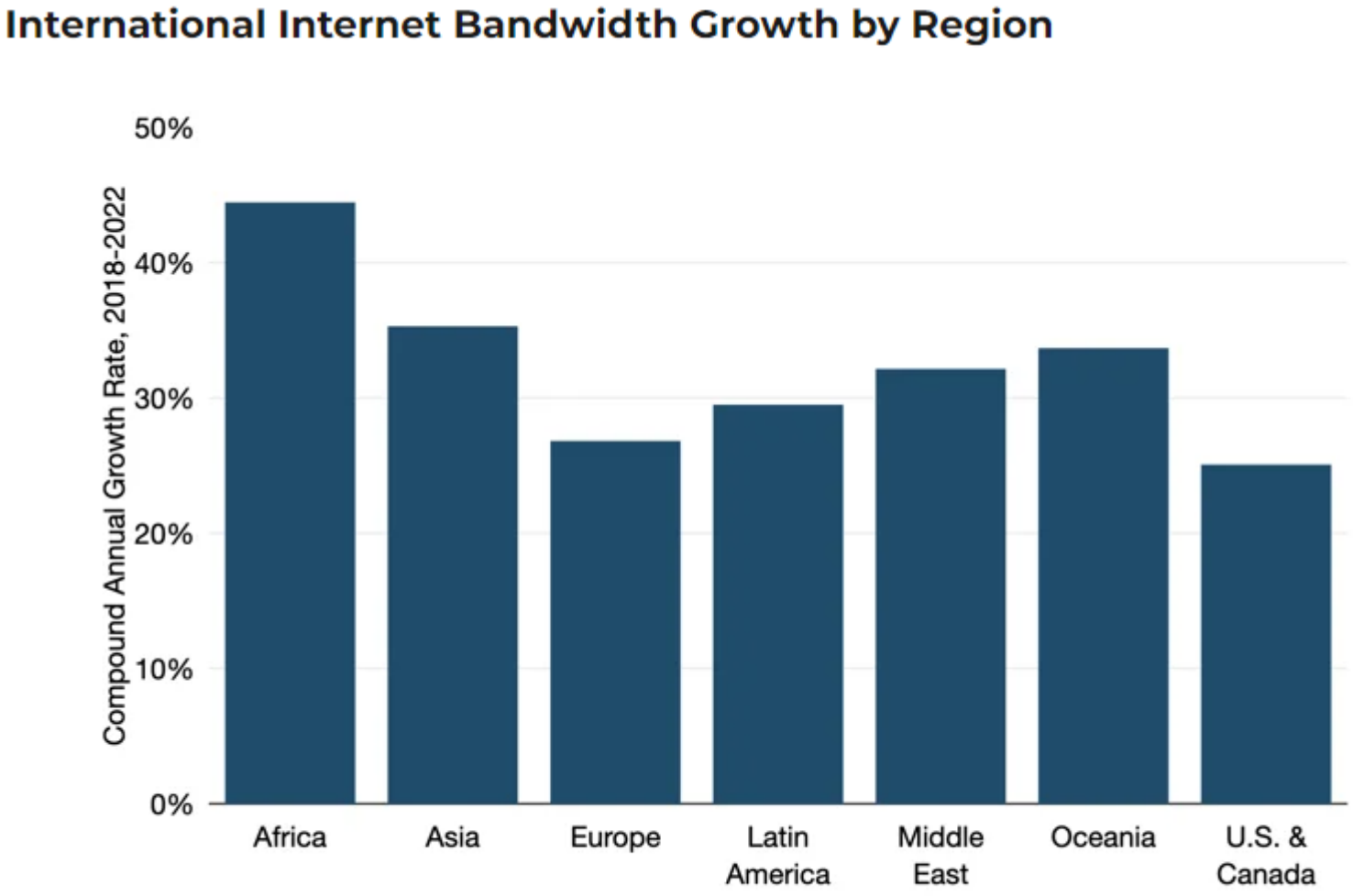
imec
embracing a better life

Overview

- Background
- Machine learning, neuromorphic and reservoir computing
- Reservoir computing with multiple wavelengths in parallel
- Reservoir with extra amplifier components
- European project: design of a wavelength demultiplexer for a matrix vector multiplication accelerator
- Conclusions

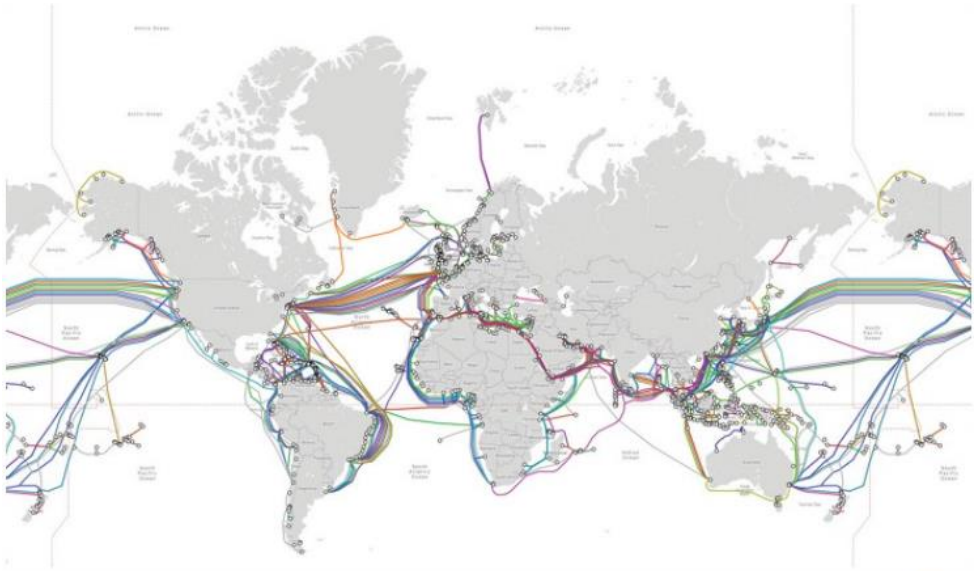
THE INTERNET, WE LOVE IT!



Between 2018 and 2022, global data bandwidth nearly tripled with an increase of 28% in 2022 alone.

DATA TRANSMISSION IS (OFTEN) OPTICAL

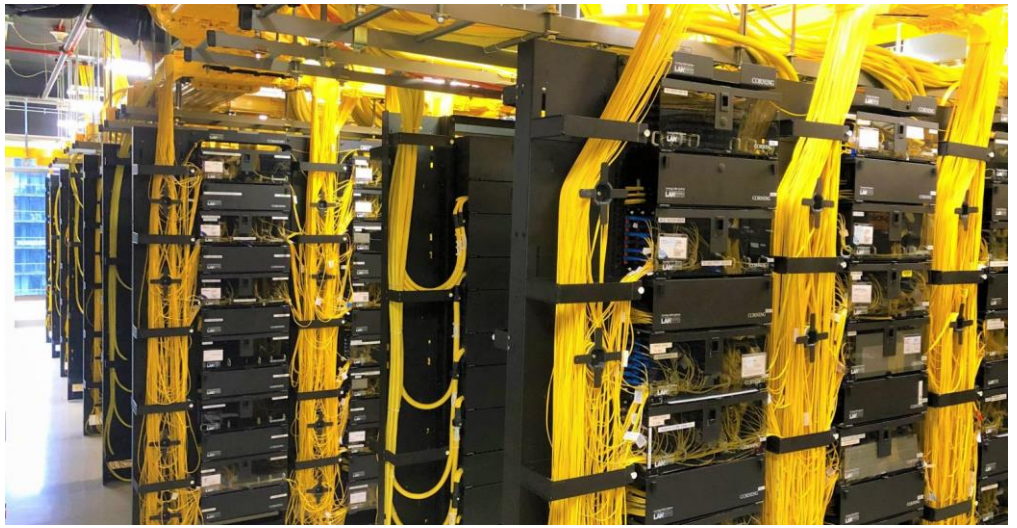
Around the world…



Credit: PriMetrica

A network of undersea fiber-optic cables crisscrosses the globe, carrying the world's telecommunication signals. Circles indicate landing points, where cables start and end; colors indicate individual cables.

…and in the datacenter.



Source: https://www.datacenterknowledge.com/

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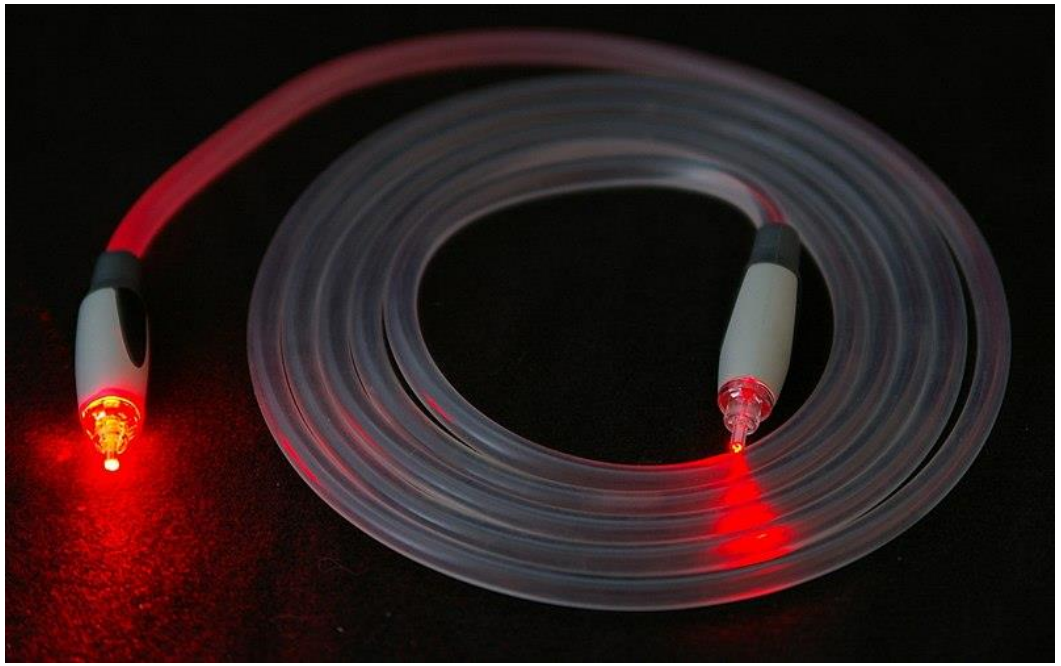
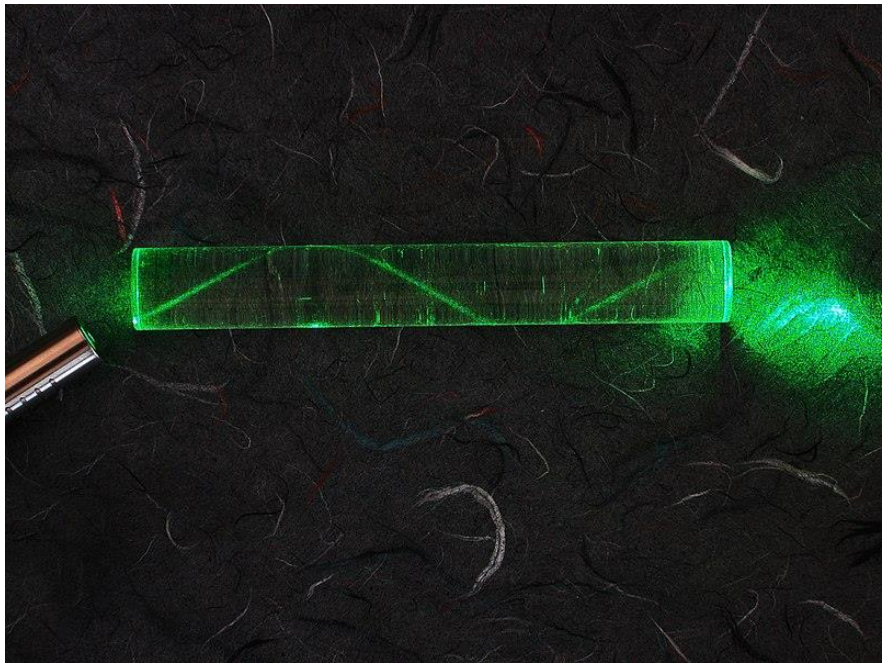
OPTICAL DATA CARRIED BY FIBER

Optical fiber



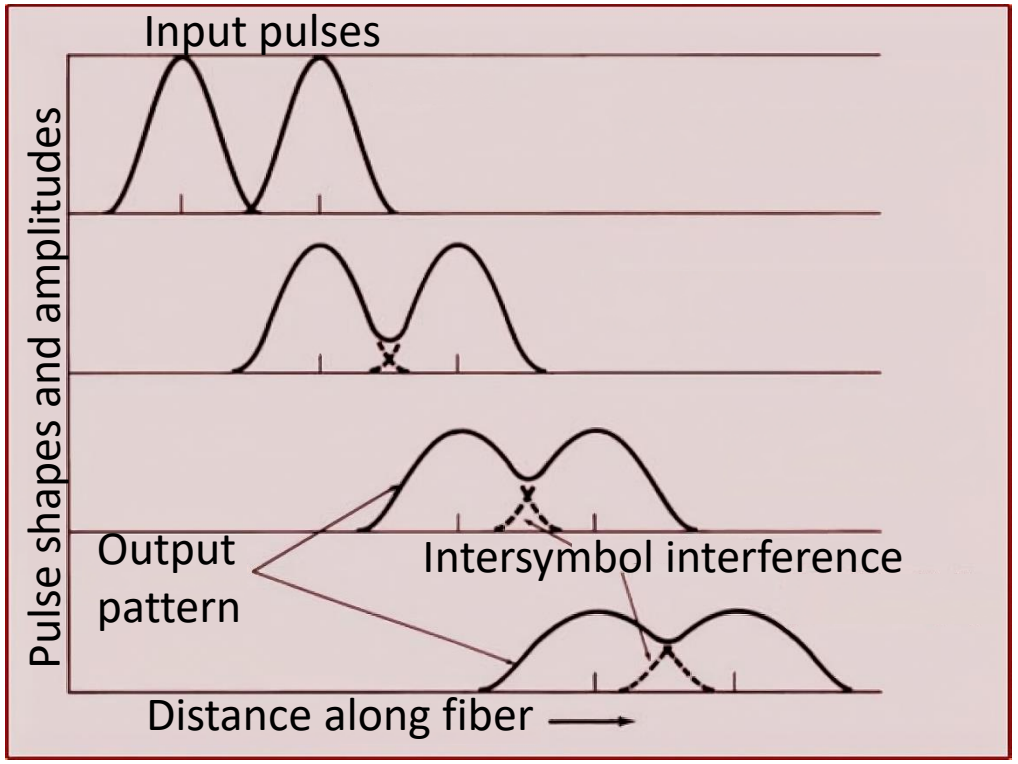
Source: Wikipedia Commons

Total internal reflection



Source: Wikipedia Commons

TRANSMITTED DATA NEEDS TO BE PROCESSED

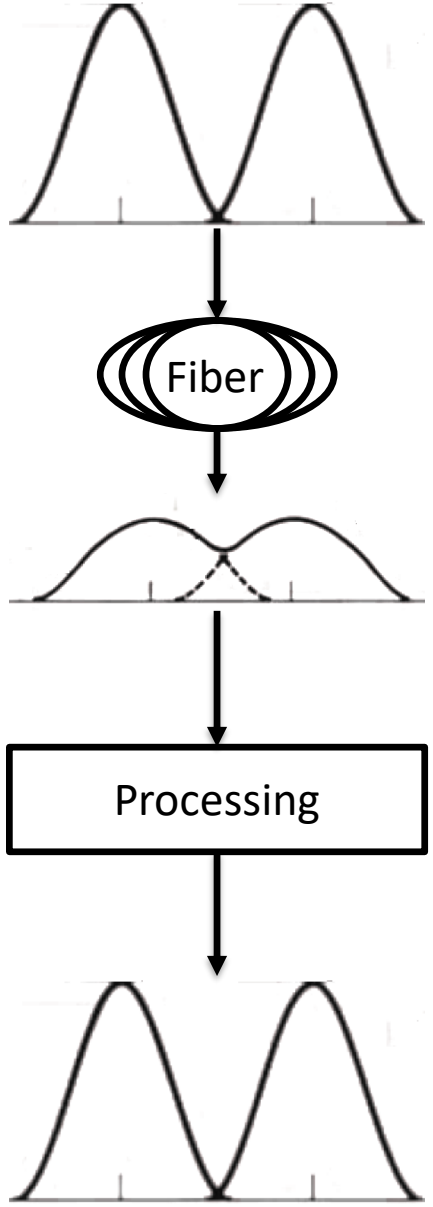


Separate pulses at start fiber

Distinguishable pulses further along

Barely distinguishable pulses

Indistinguishable pulses



Source:
https://stmarysguntur.com/wp-content/uploads/2019/08/lect4.pdf

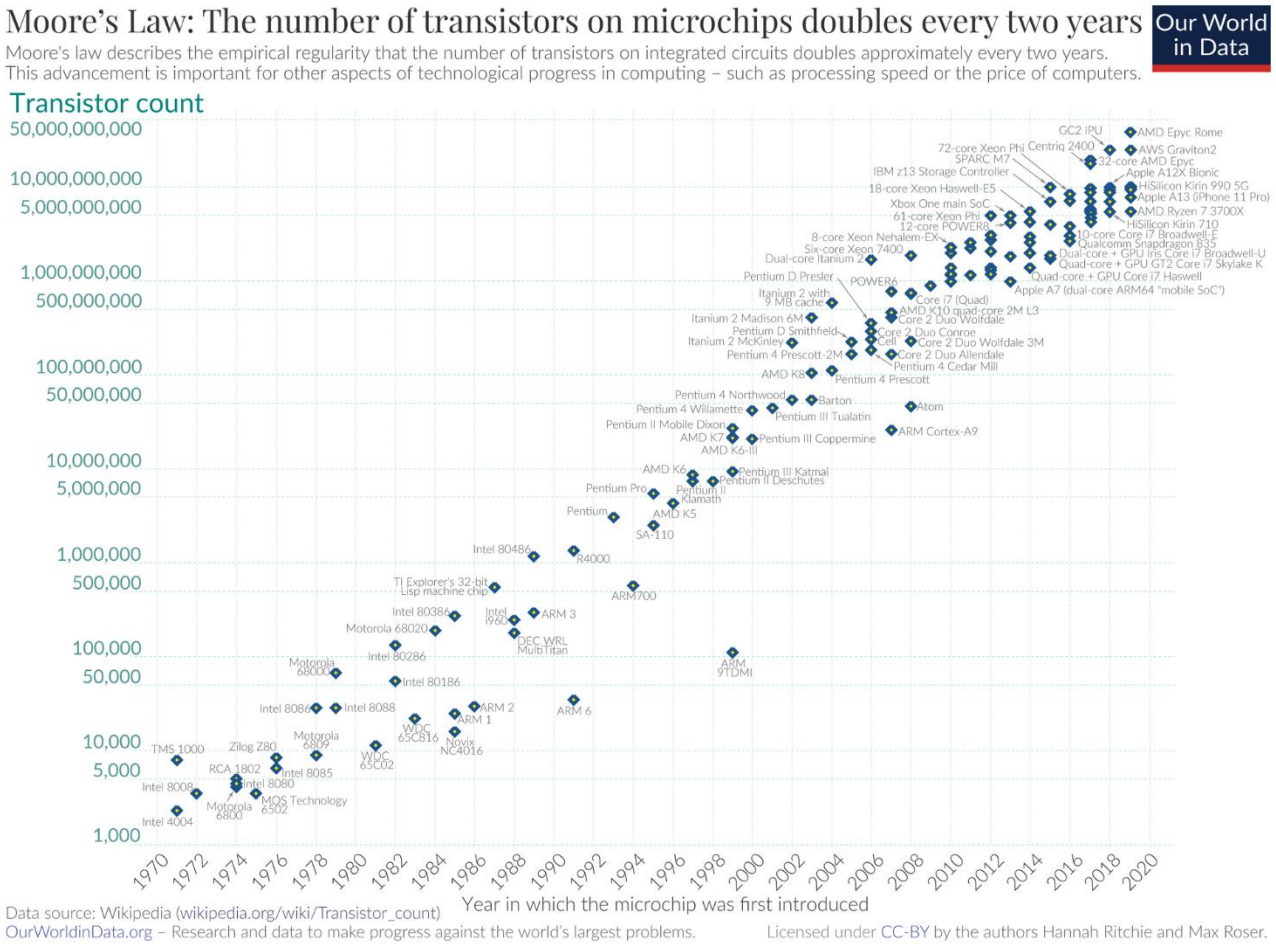
DATA PROCESSING IS (CURRENTLY) ELECTRICAL AND DIGITAL

Source:
https://www.linkedin.com/pulse/
dsp-chips-market-size-gaining-off-good-start-texas-analog-yeotikar/

Drawbacks:

- "Slow" (<20 Gbps)
- Power inefficient (electrical chips get hot)
- Lots of convoluted digital operations

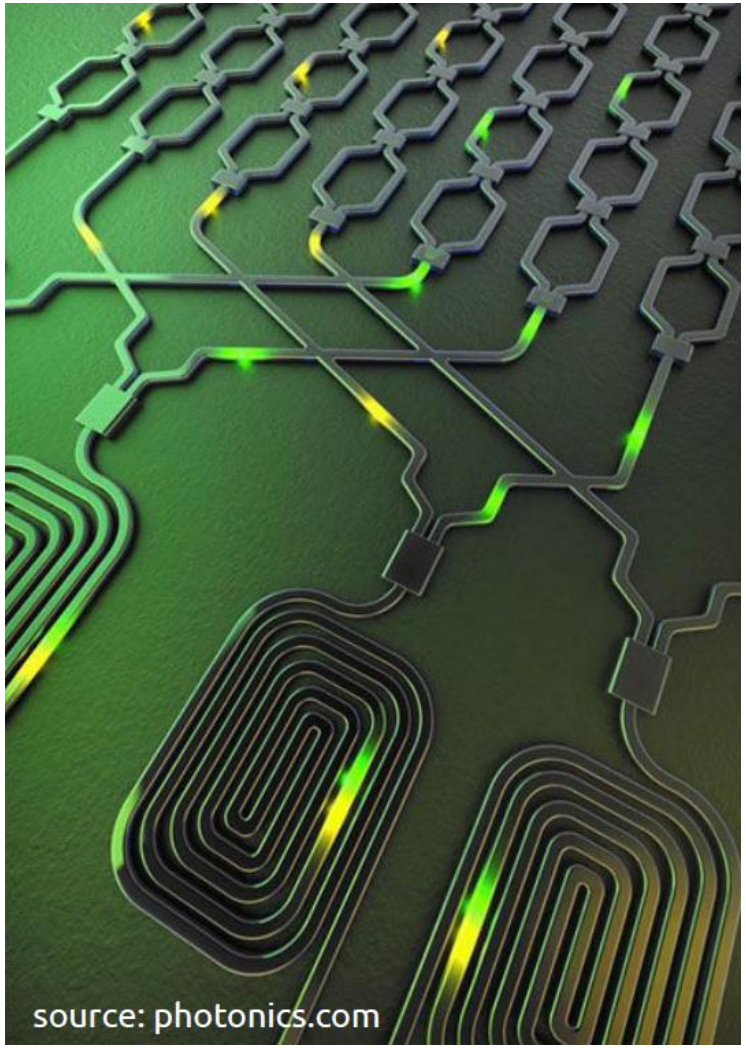
INTERMETTZO: MOORE'S LAW



Not bigger chips but smaller transistors.

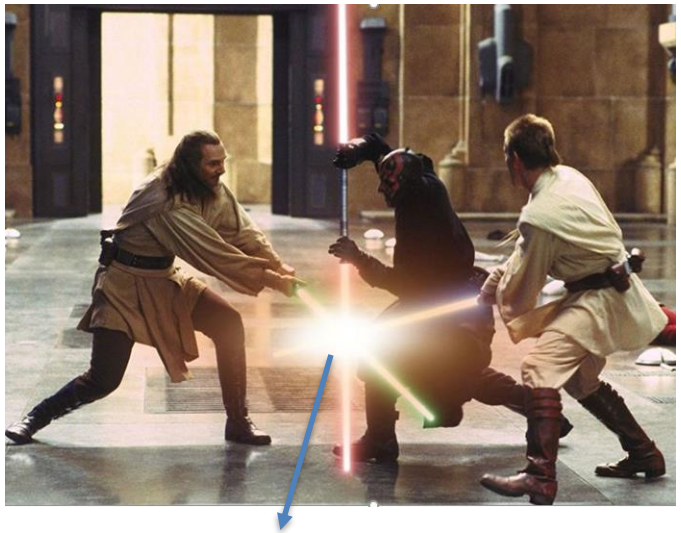
Size of transistor has lower limit
→ conventional way of improving computing power is running out.

ANALOG OPTICAL DATA PROCESSING IS (POSSIBLY) THE FUTURE



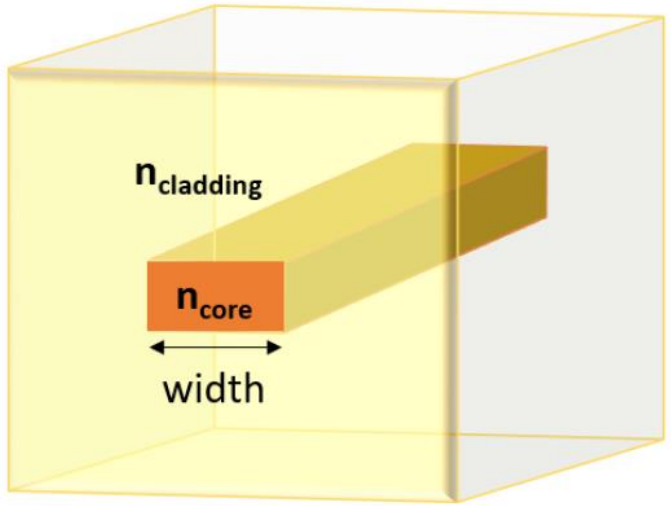
Advantages:

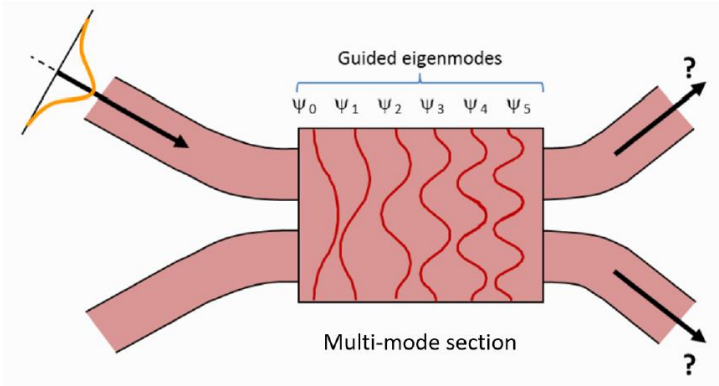
- Faster (potentially Tbps)
- Parallel information streams on parallel colors of light (wavelengths)
- Power efficient
- Information is processed continuously



NO

A PHOTONICS CHIP: LIGHT IS GUIDED AND MANIPULATED BY SMALL STRUCTURES





Source:
Multi mode interferometers.” https://docs.lucedaphotonics.com/picazzo/filters/mmi/

Silicon chips as in digital electronics.
→ “easy” for industry to make our idea.

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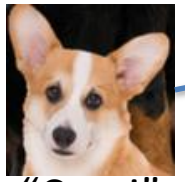
MACHINE LEARNING (AI): WHEN YOU KNOW THE SOLUTION BUT CAN NOT DEFINE IT

Flat snout Level of “fluffy” Drooping ears

Learning from Examples

“Labrador”

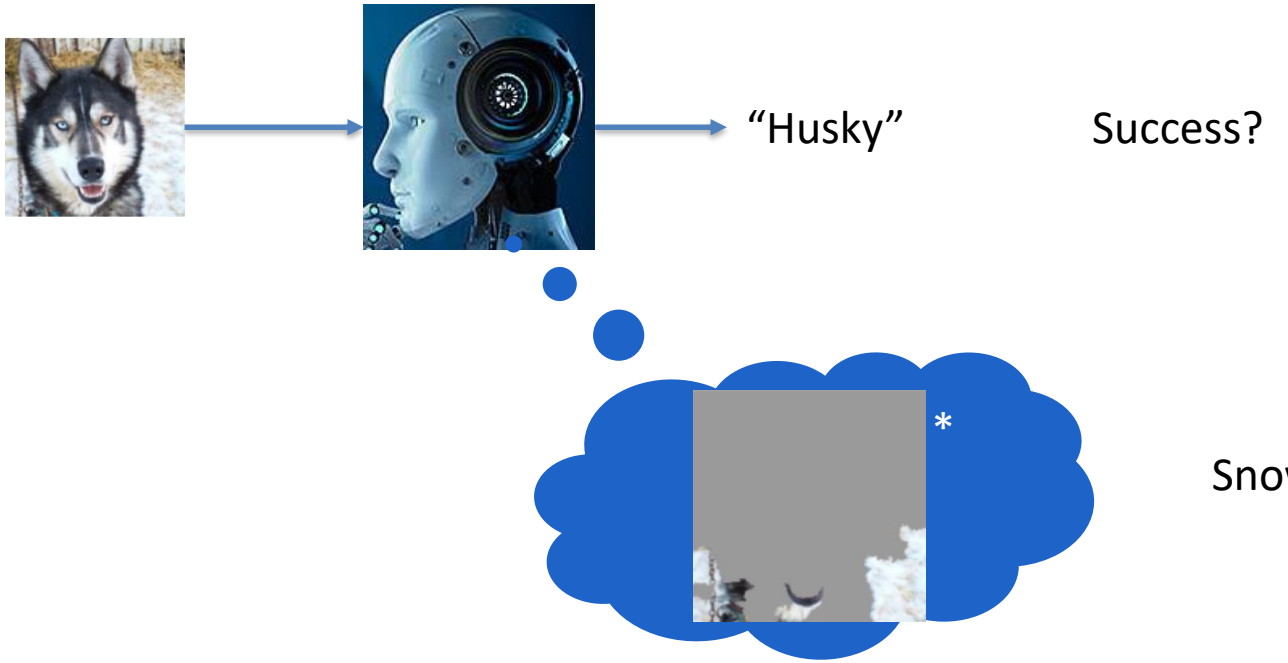


“Corgi”

...

CERTAINLY ARTIFICIAL BUT IS IT INTELLIGENT?

New unseen data



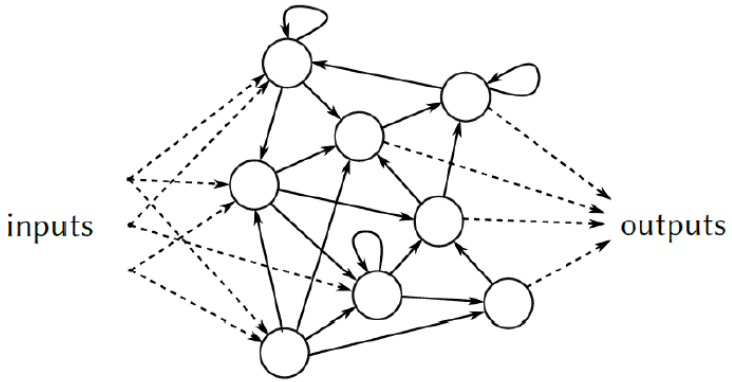
- (good) data
- A sufficiently powerful system
- A smartly designed machine learning algorithm
- A smart engineer

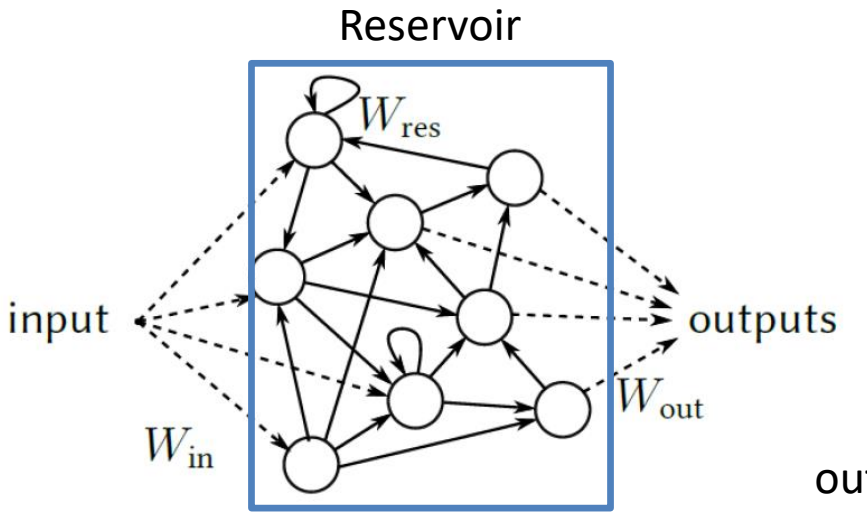
*Source: https://arxiv.org/abs/1602.04938

WHAT DOES THE SYSTEM LOOK LIKE? NEUROMORPHIC!

Source: XTREMERX, DREAMSTIME

Source: Alamy stock photo





$$y = \sum_{i=1}^{n} w_i x_i + w_0$$

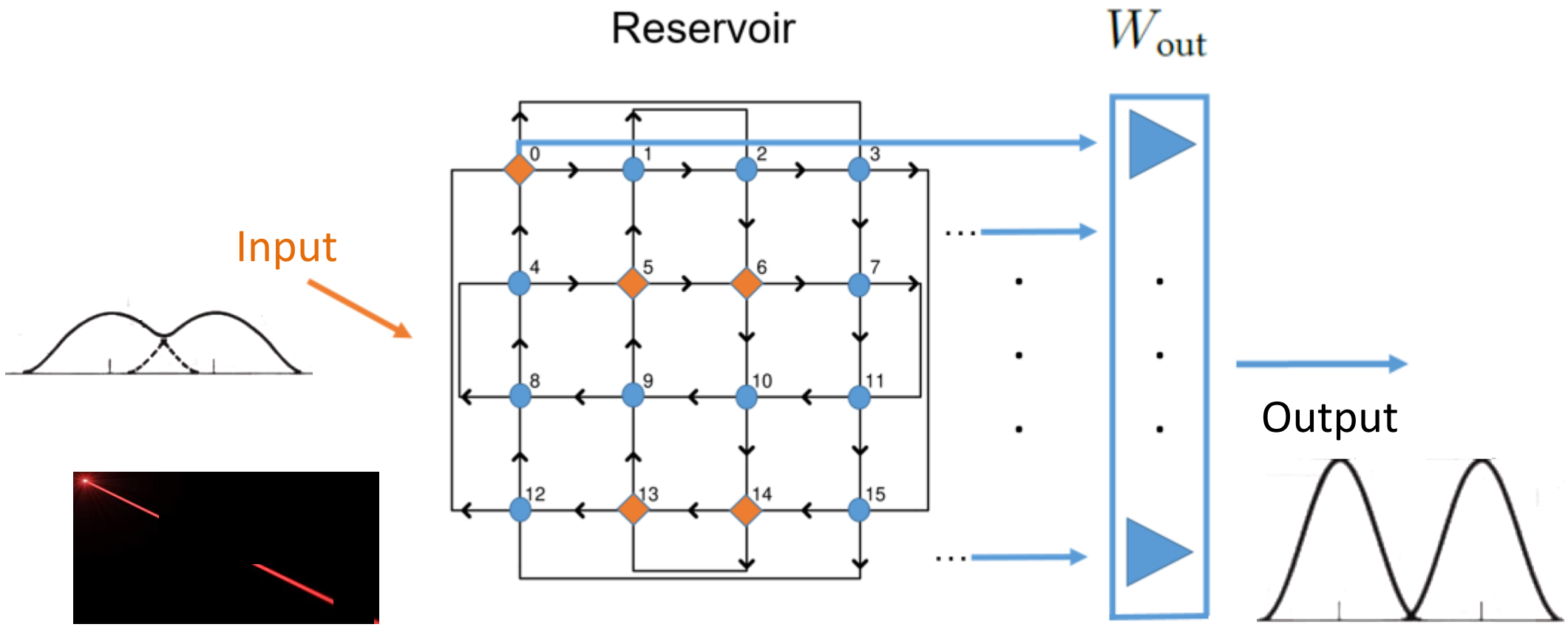
W_{out} weights

output

node signal

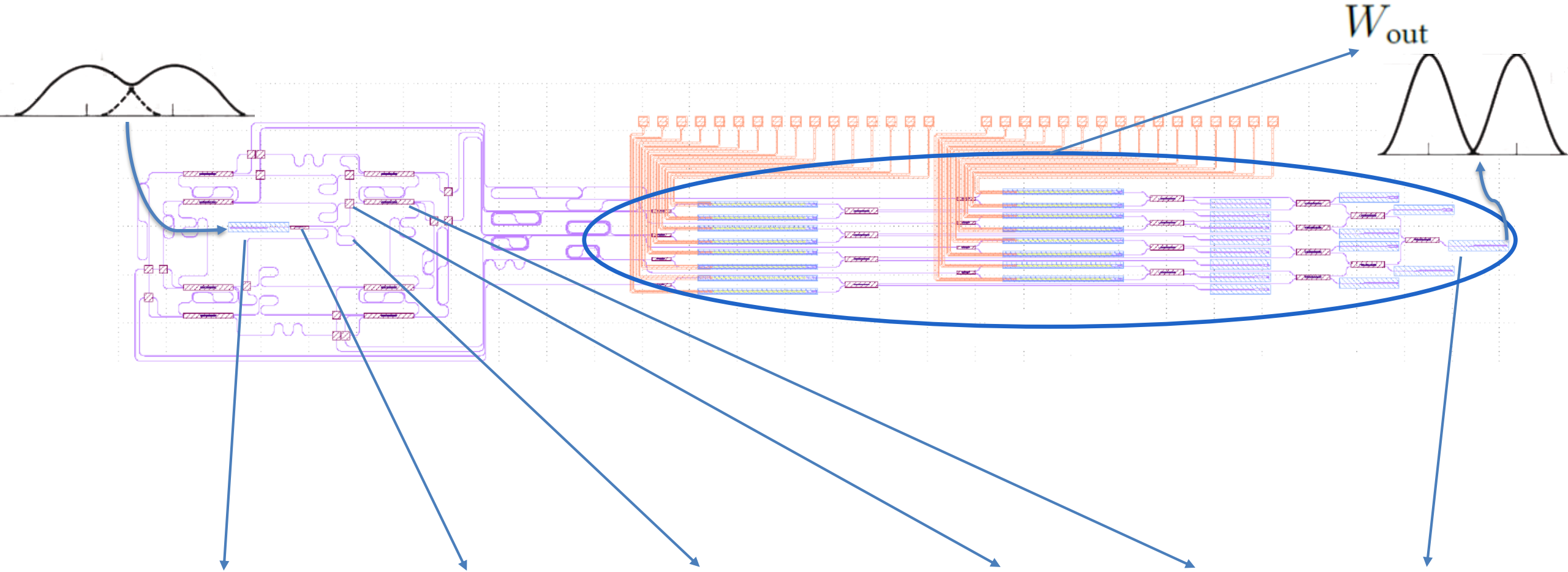
Source: F. Laporte, Novel architectures for brain-inspired photonic computers. Phd thesis

PHOTONIC RESERVOIR SCHEMATIC



Modulated optical signal,
“laser pulses”

PHOTONIC RESERVOIR COMPUTING



Input grating coupler

1x2 splitter

Waveguide interconnection

Waveguide crossing

3x3 MMI node

Output grating coupler

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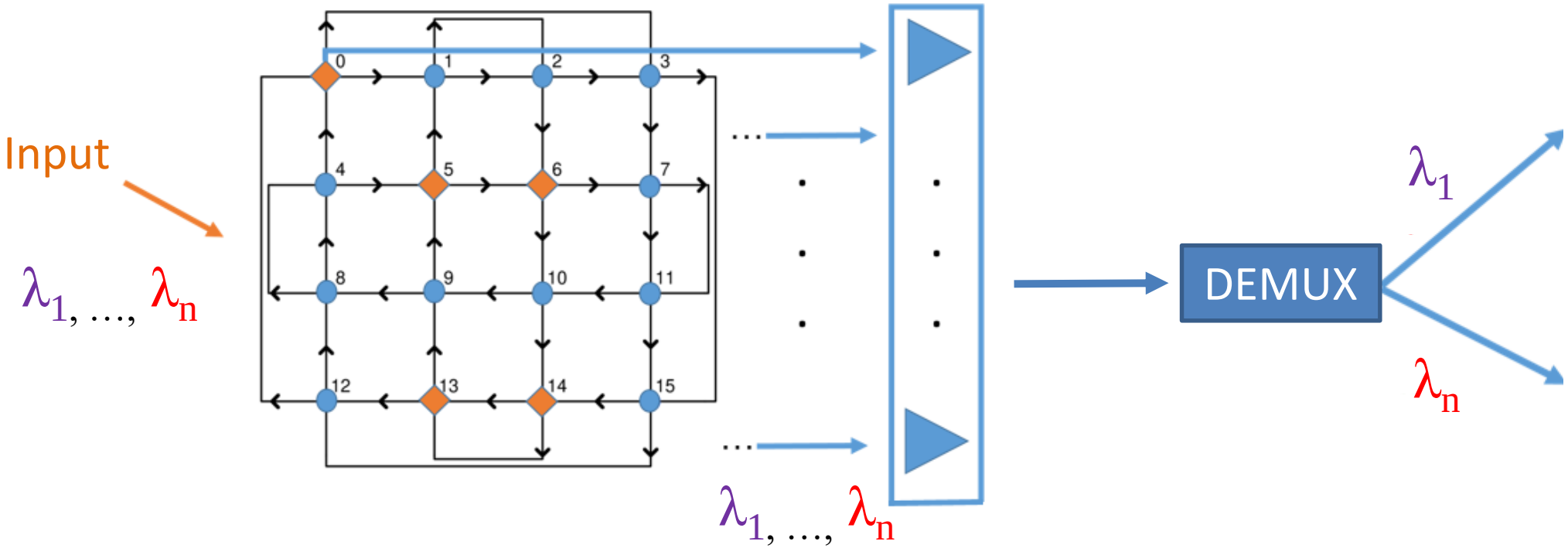
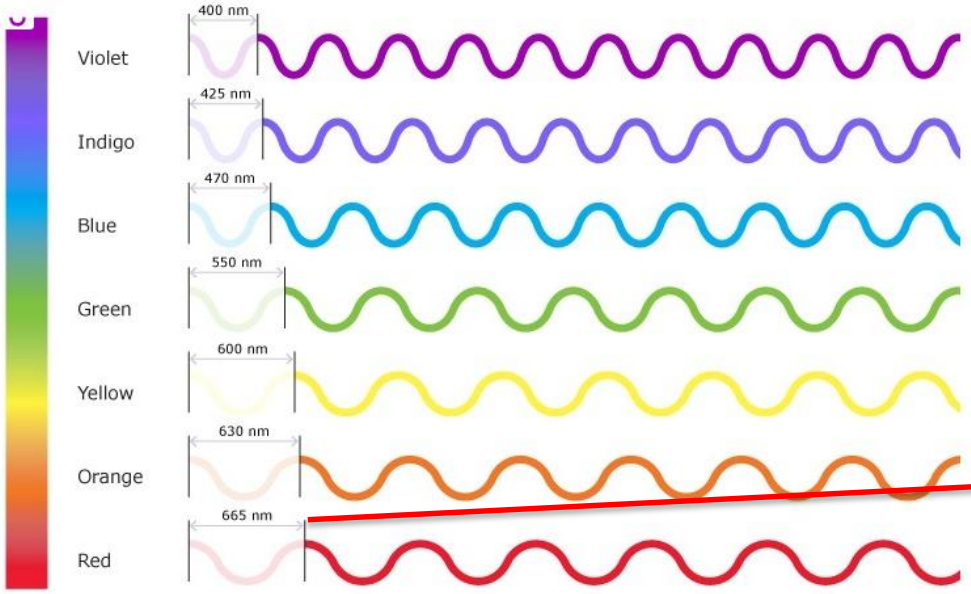
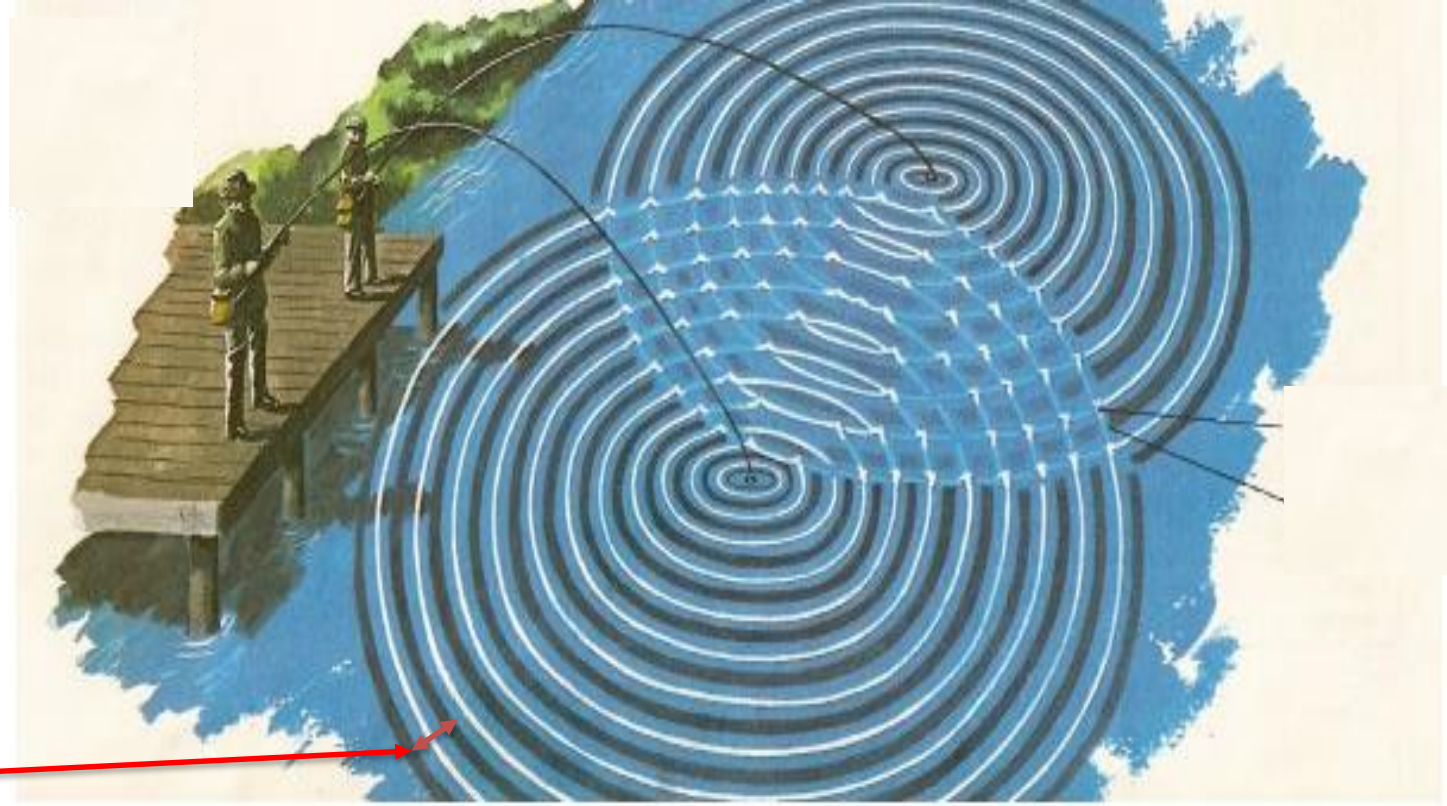
THE IDEA



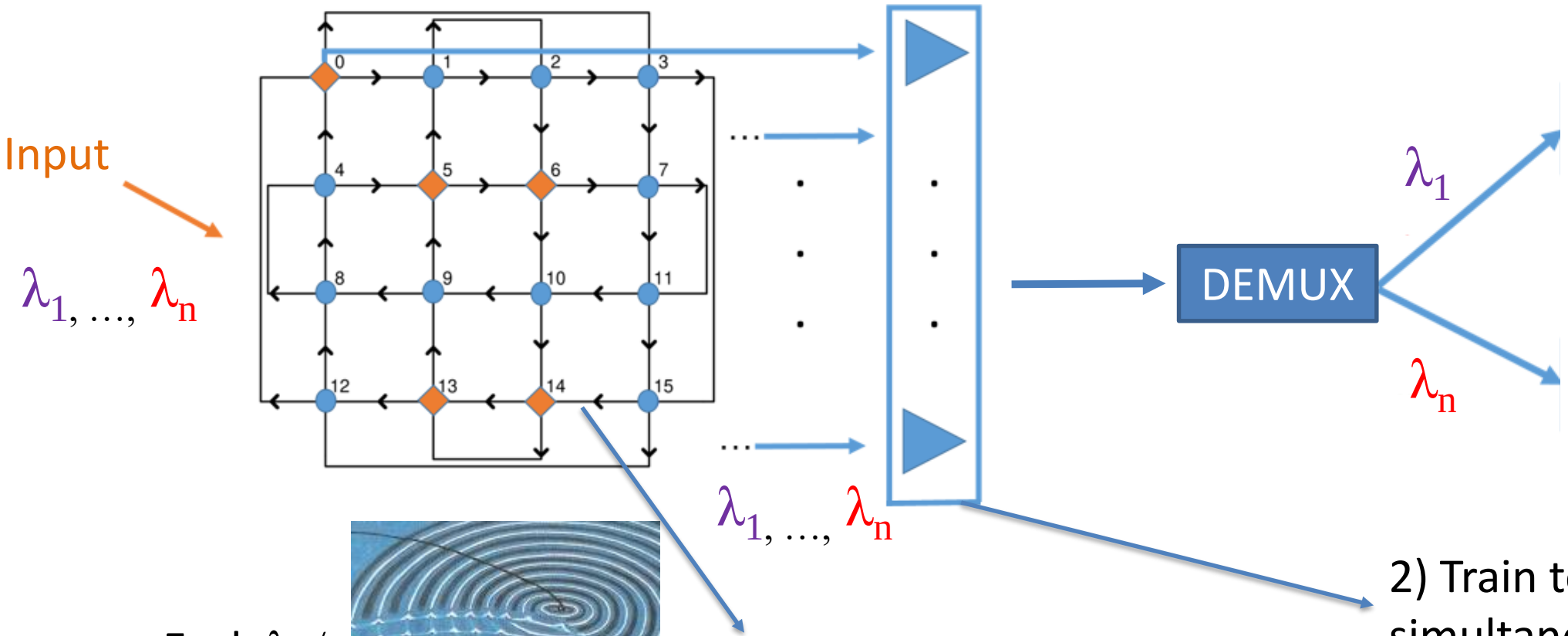
THE CHALLENGE: INTERFERENCE



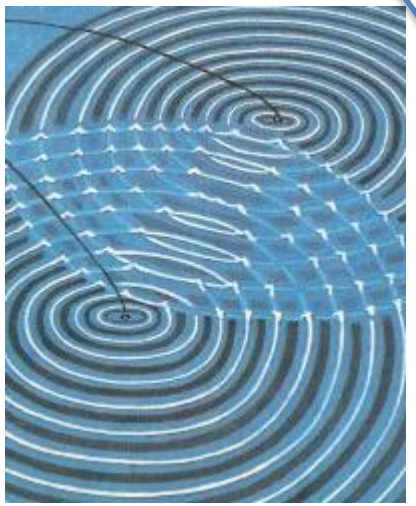


https://darkmattersalot.com/page/66/?themes_on_signup

THE 2 SOLUTIONS



Each $\lambda \neq$

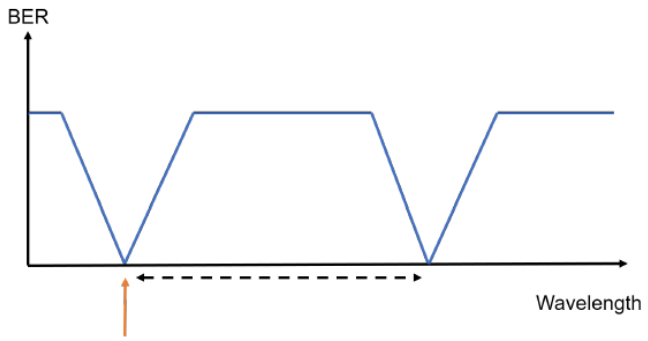


1) Engineer the interconnections so that $\neq \lambda$'s have = pattern

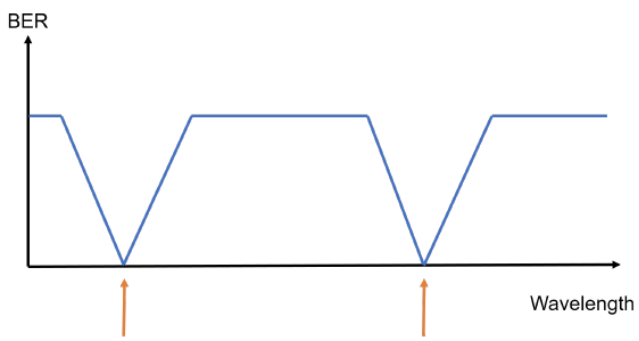
2) Train to handle $\neq$ patterns simultaneously

THE SIMULATIONS

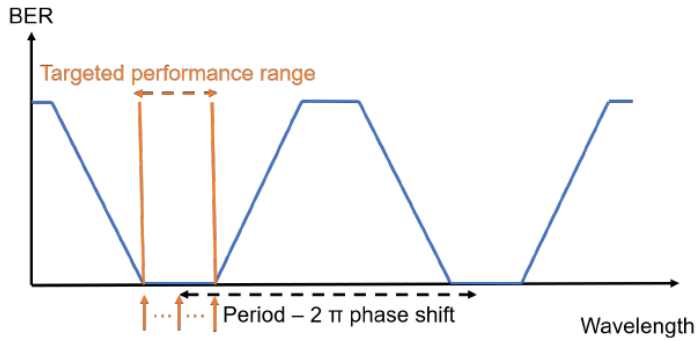
Solution 1

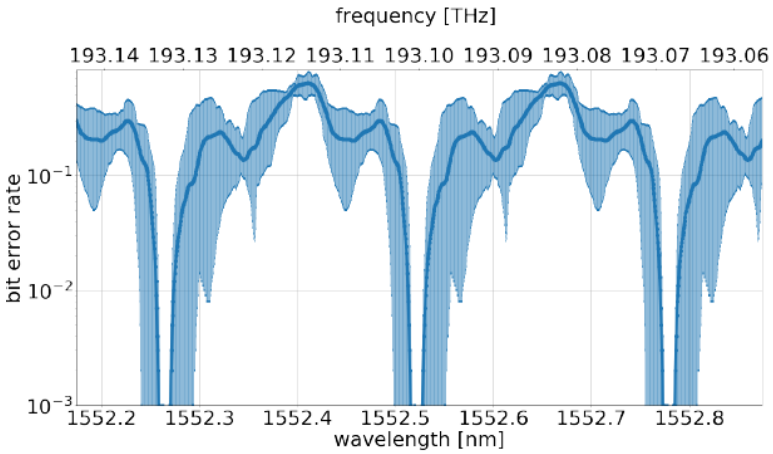


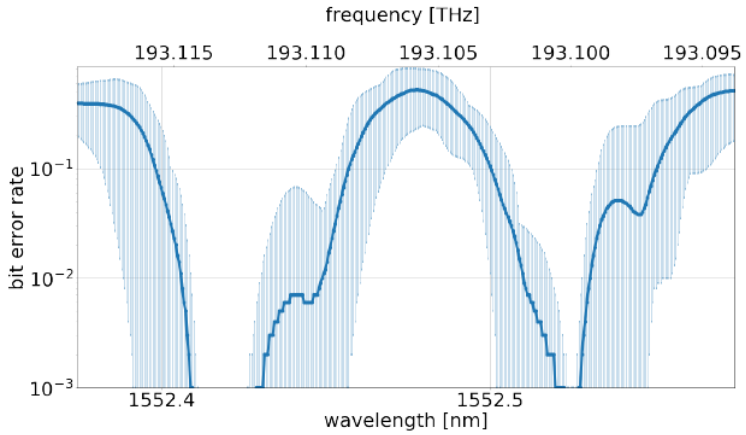
Solution 2

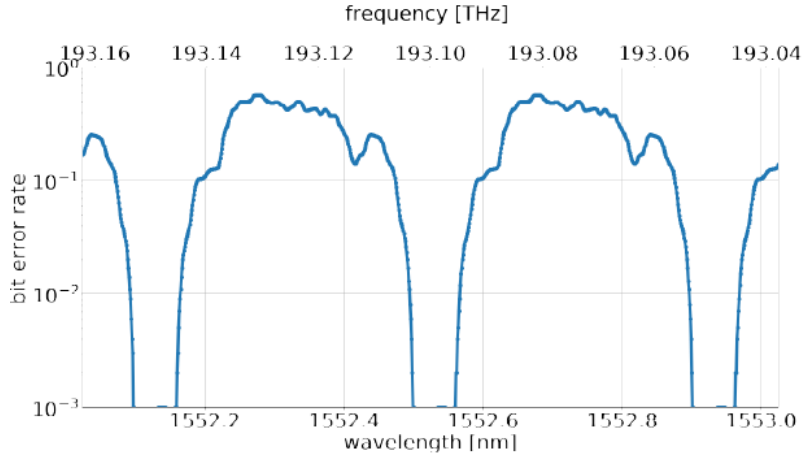


Combination









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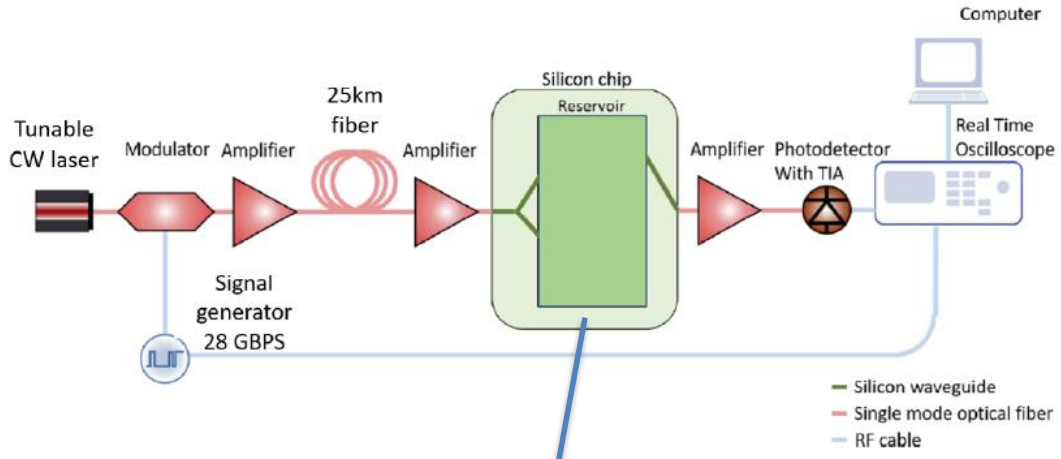
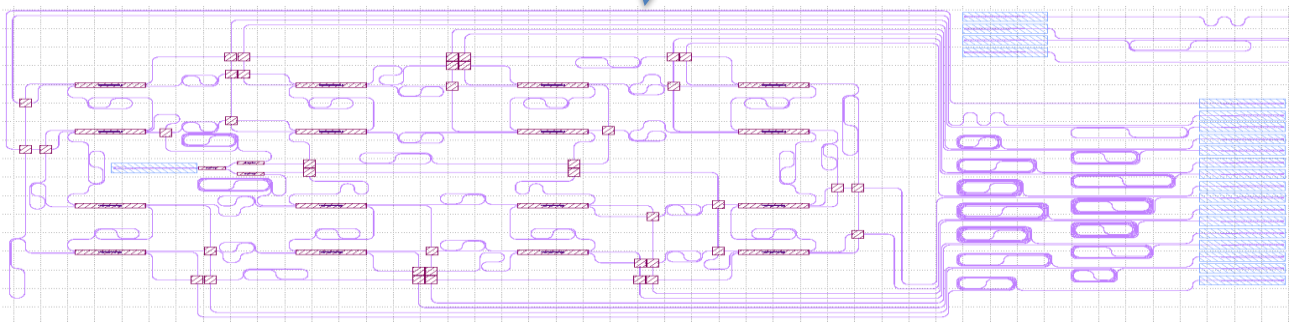
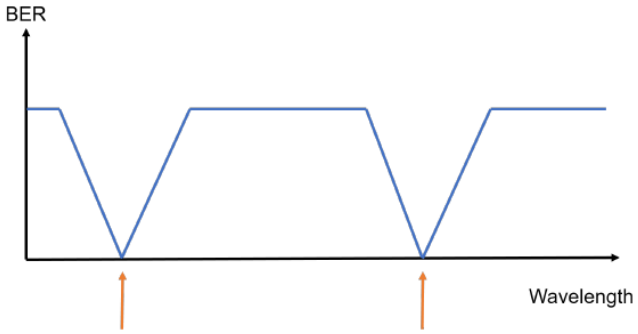
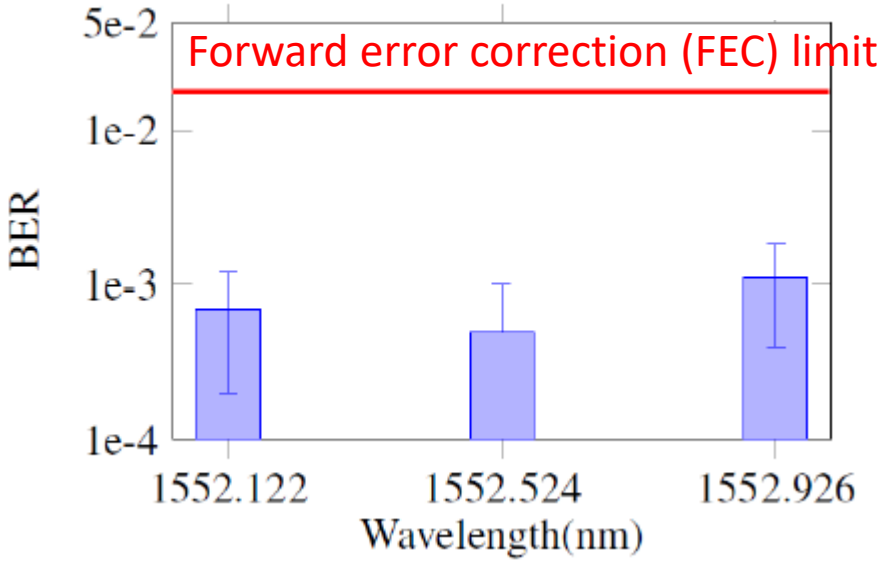
THE EXPERIMENTS: MULTIPLE λ NO INTEGRATED READOUT





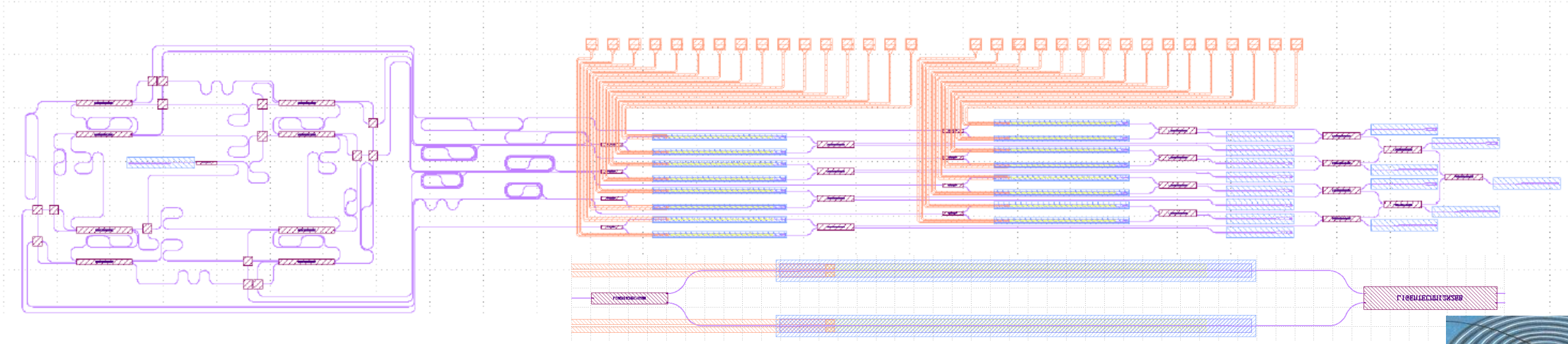
Non-integrated readout

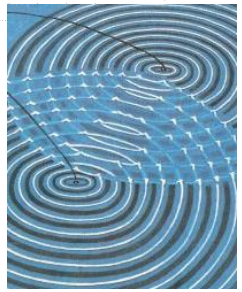




Success on **at least** 3 standard wavelengths with BER < 1.5 10^{-2}.

THE EXPERIMENTS: SINGLE λ INTEGRATED READOUT



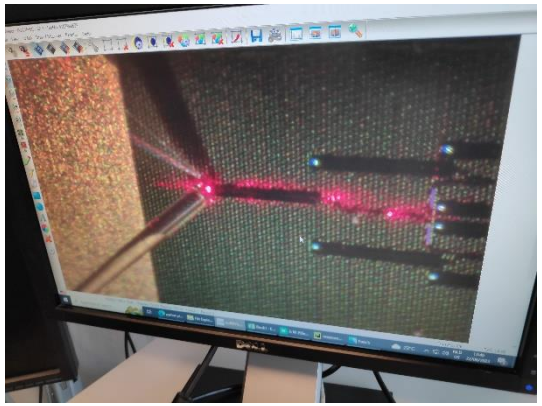


Many challenges remain but we already showed a factor 3 improvement compared to having no chip.

Thank you to Elger Vlieg and Alessandro Lupo!

MEASUREMENT LAB PHOTO'S

The reservoir chip



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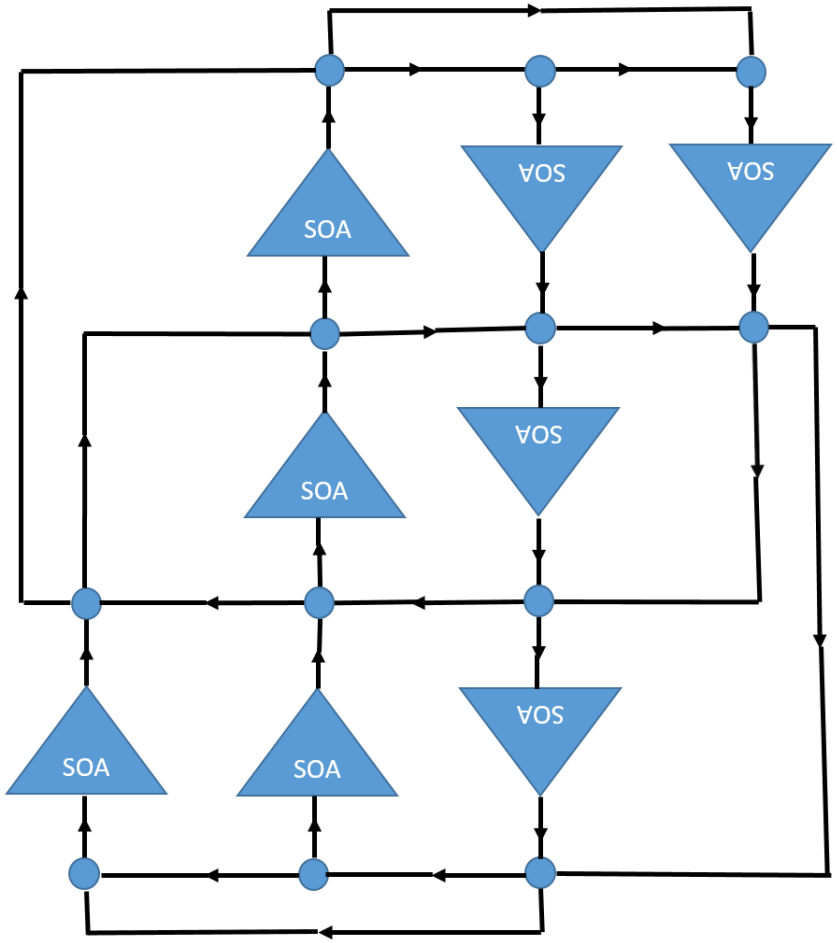
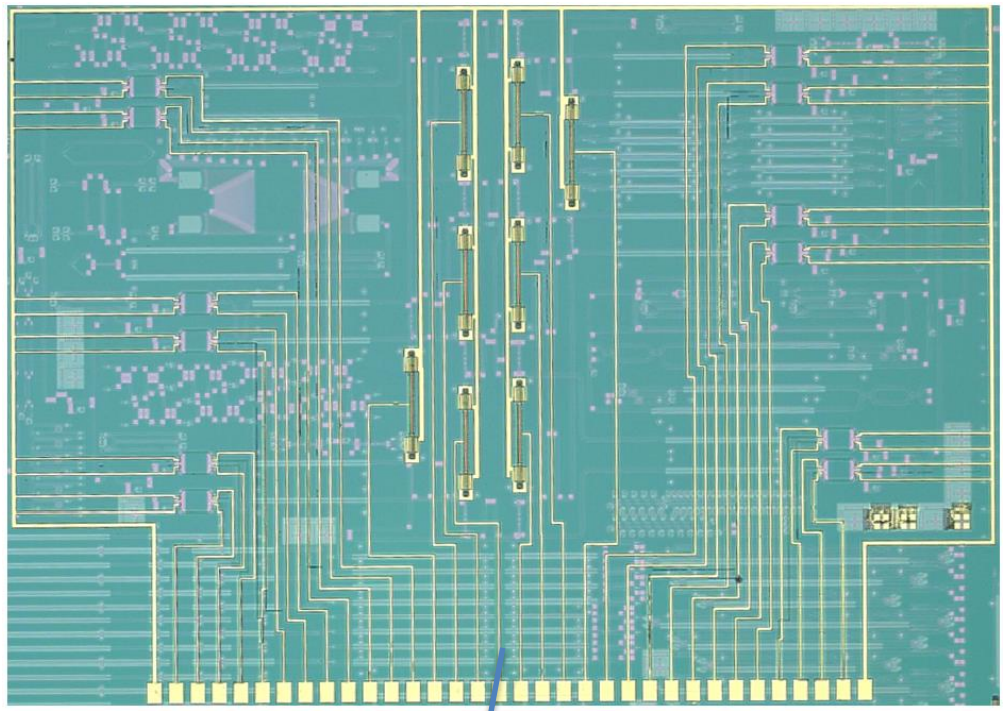
THE NEW RESERVOIR

SOA = semiconductor optical amplifier

Requires electricity to work!

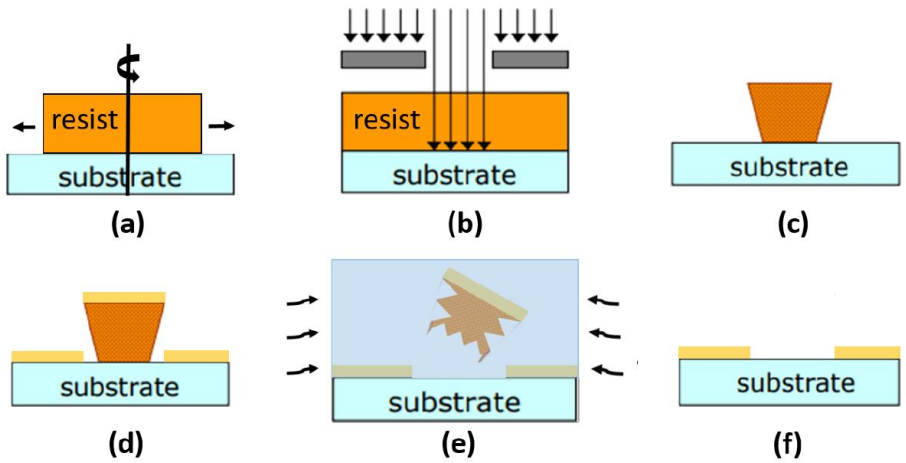


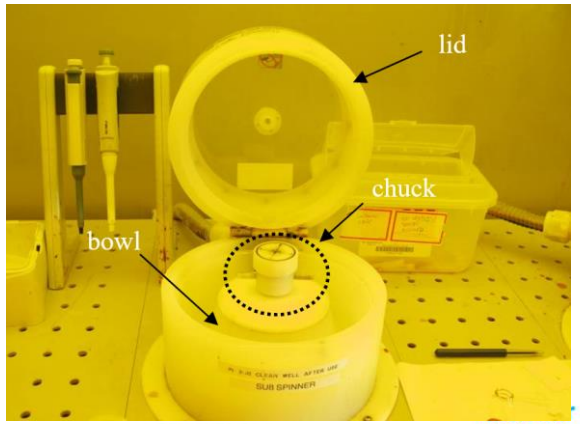


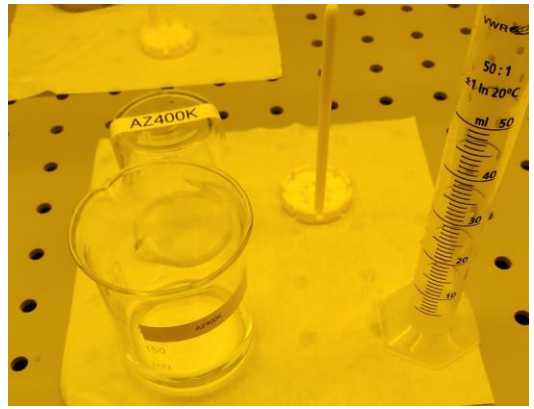
Gold electrical conductors

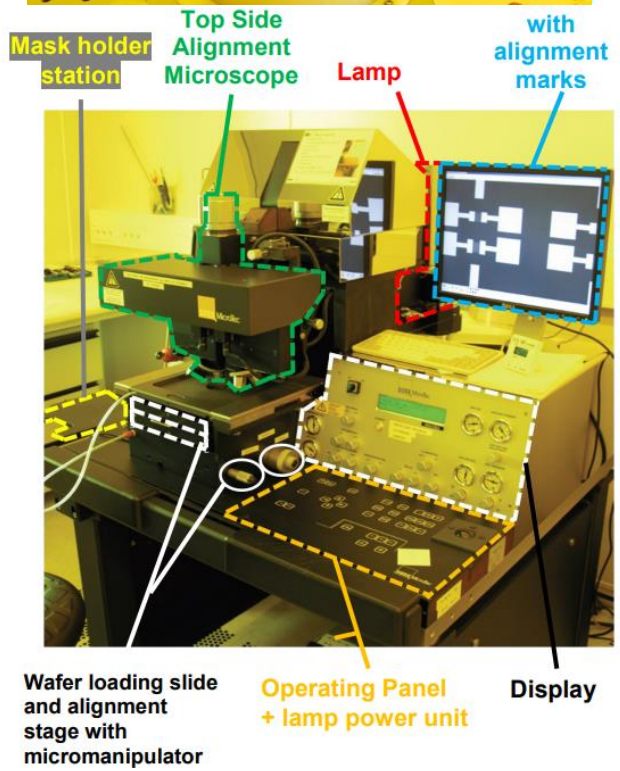
MAKING THE CHIP IN THE CLEANROOM

Lift-off process









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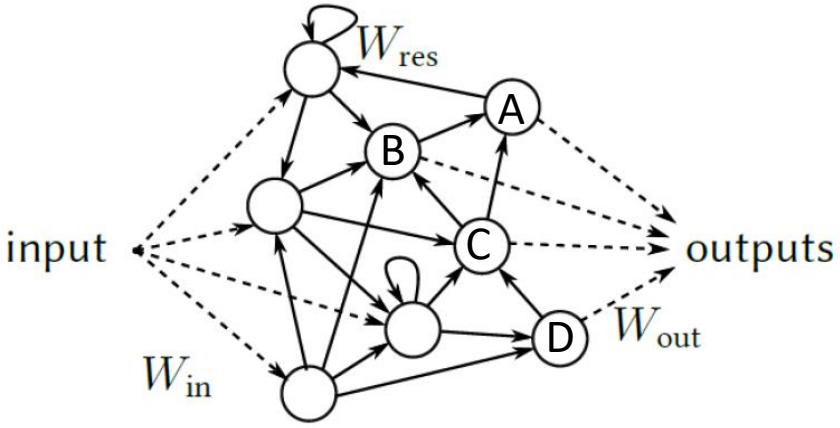
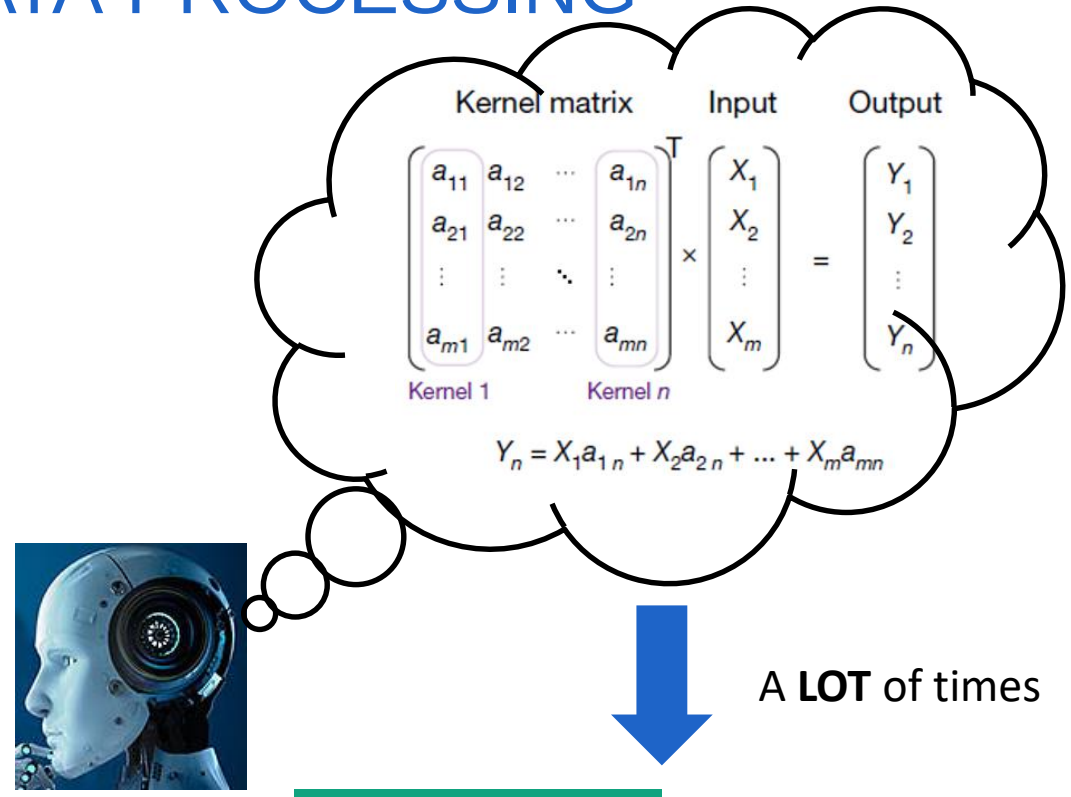
MATRIX VECTOR MULTIPLICATION ACCELERATOR: A DIFFERENT TAKE ON OPTICAL DATA PROCESSING



Output = $W_{out1}A + W_{out2}B + W_{out3}C + W_{out4}D$

Very common mathematics for machine learning!



A **LOT** of times

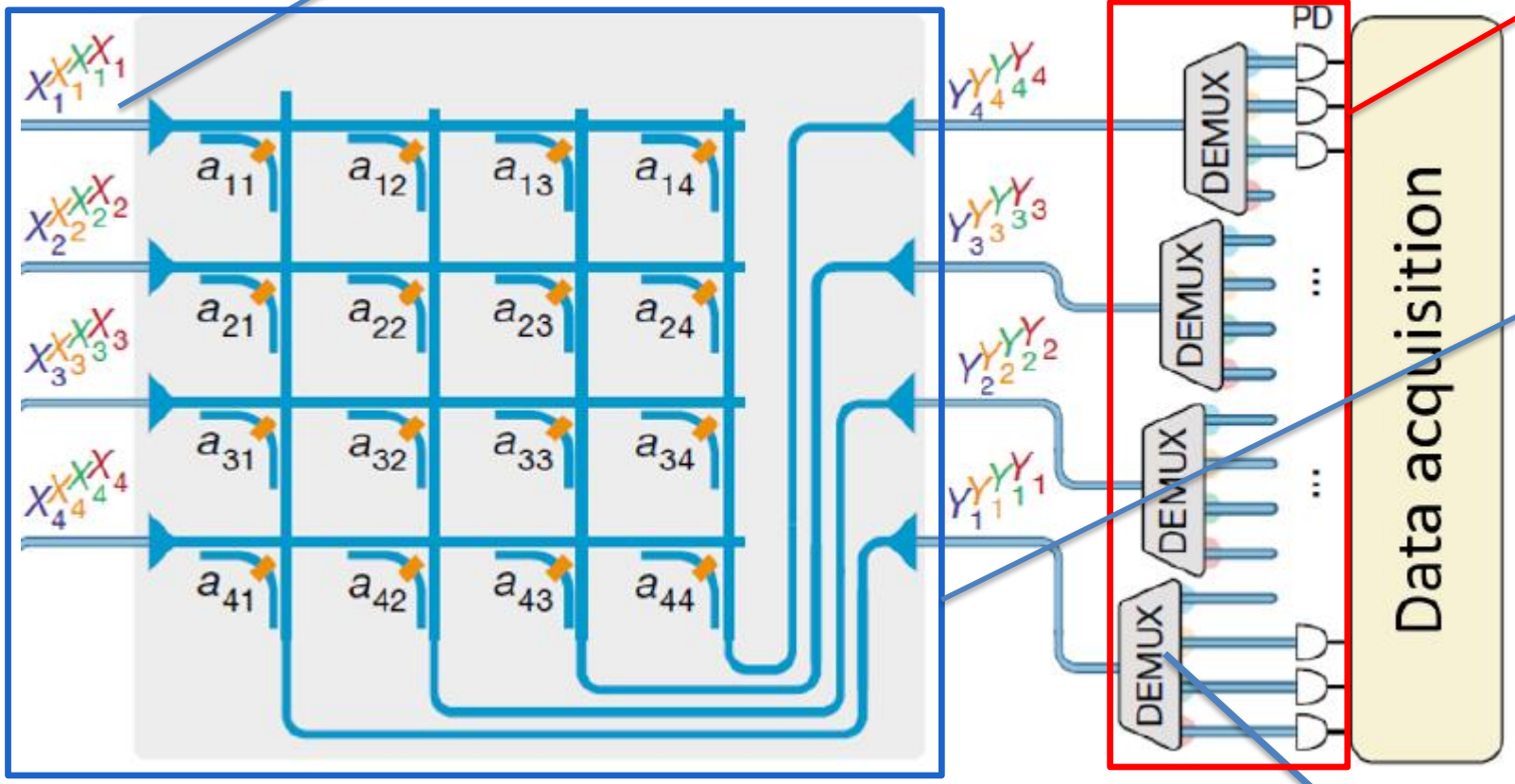
ChatGPT

Bing AI

AGAIN WE EXPLOIT WAVELENGTH MULTIPLEXING

NO

Lots of colors fit at same time because:



My part

UNIVERSITY OF OXFORD

Bhaskaran Lab

Universität Münster

Prof. Wolfram Pernice

At the end we split of our colors again using a demultiplexer.

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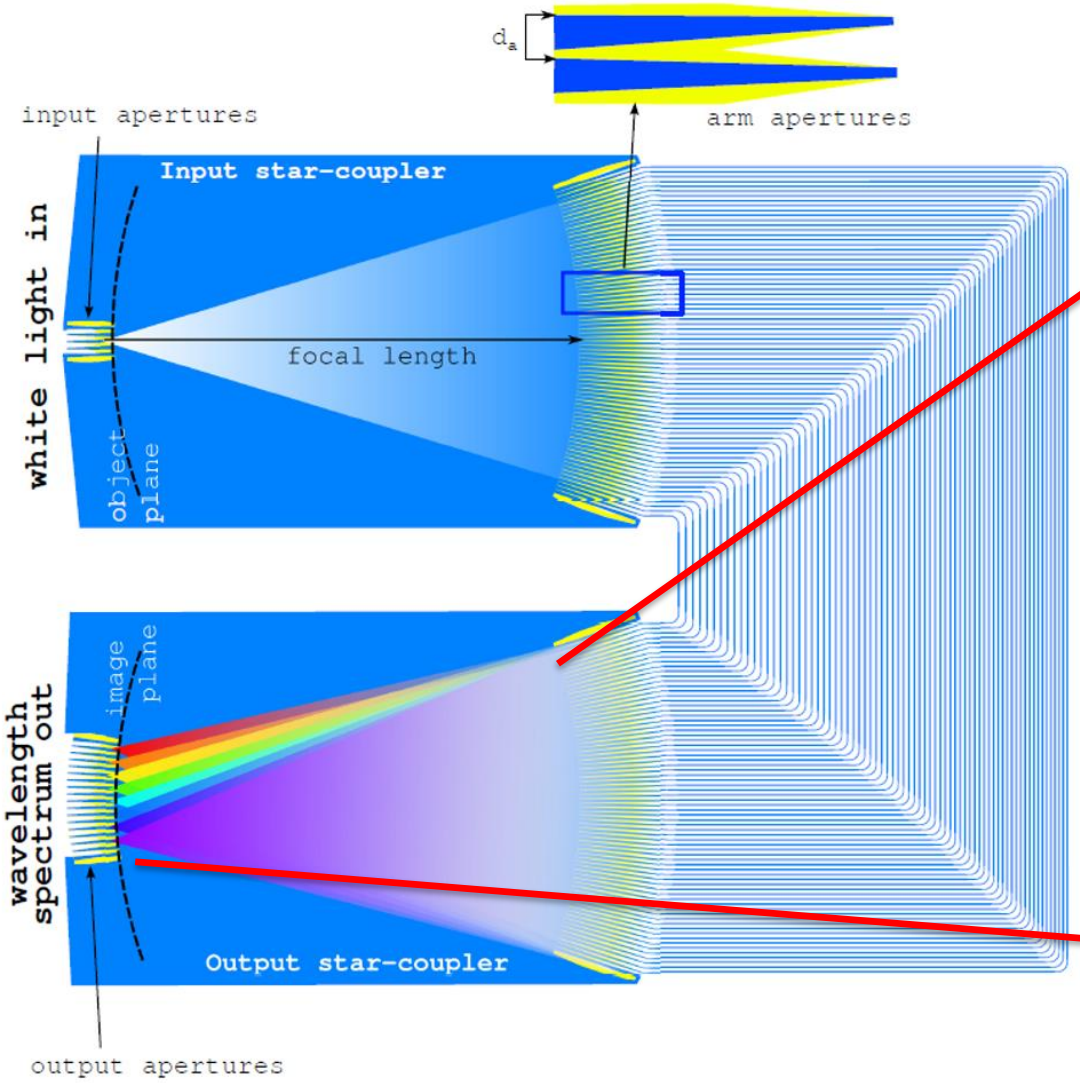
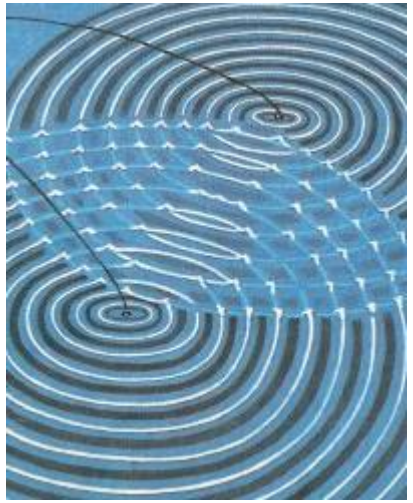
ARRAYED WAVEGUIDE GRATING DEMULTIPLEXER



Every waveguide outputs waves of light

Array of waveguides

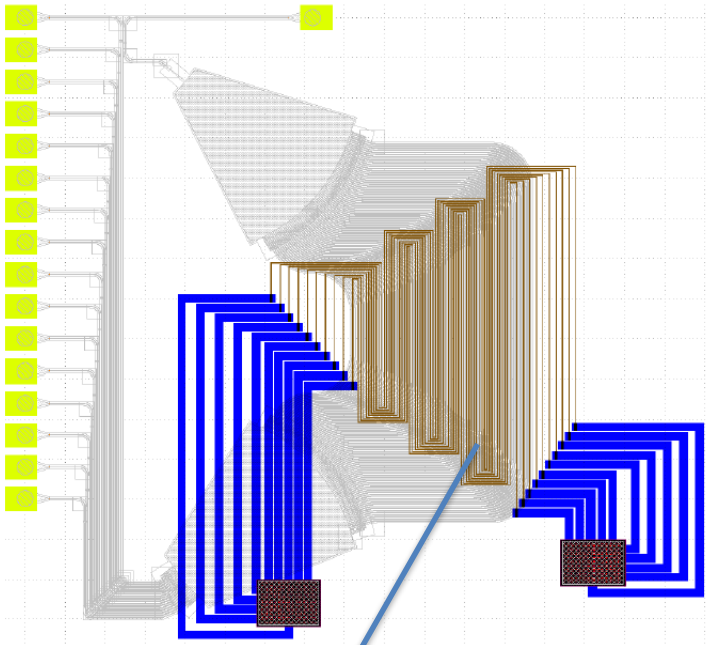
Each $\lambda \neq$

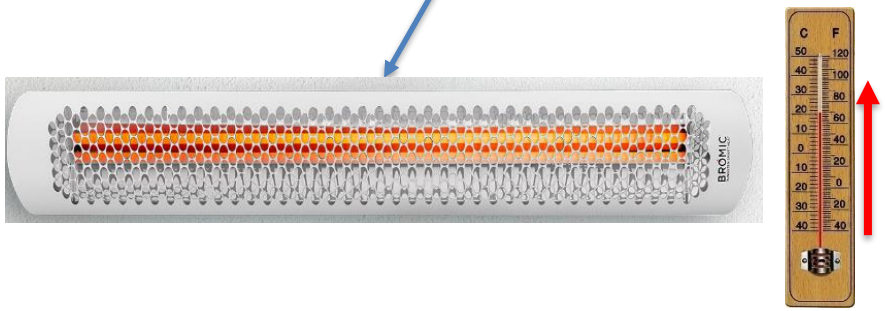


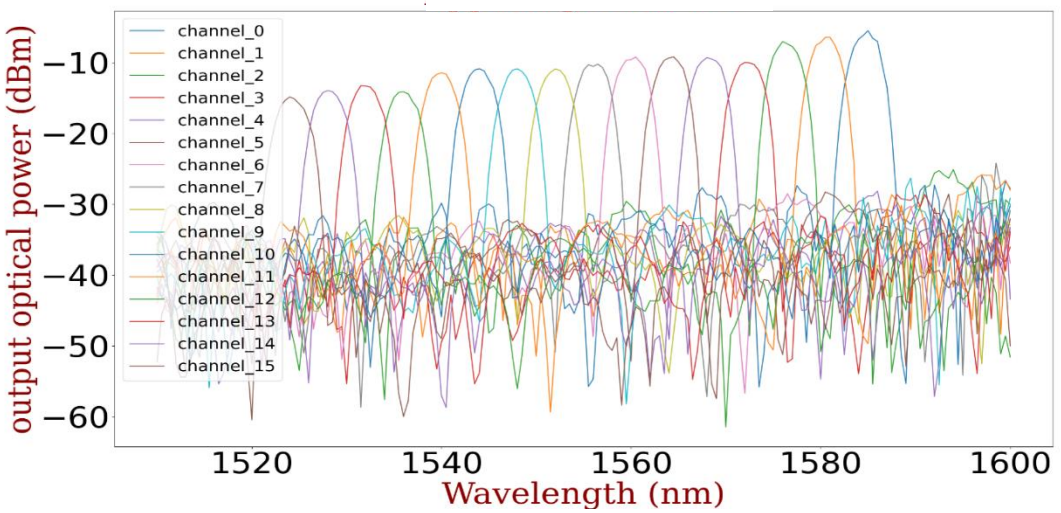
Light gets focused on the spot where the waves of all the waveguides overlap.

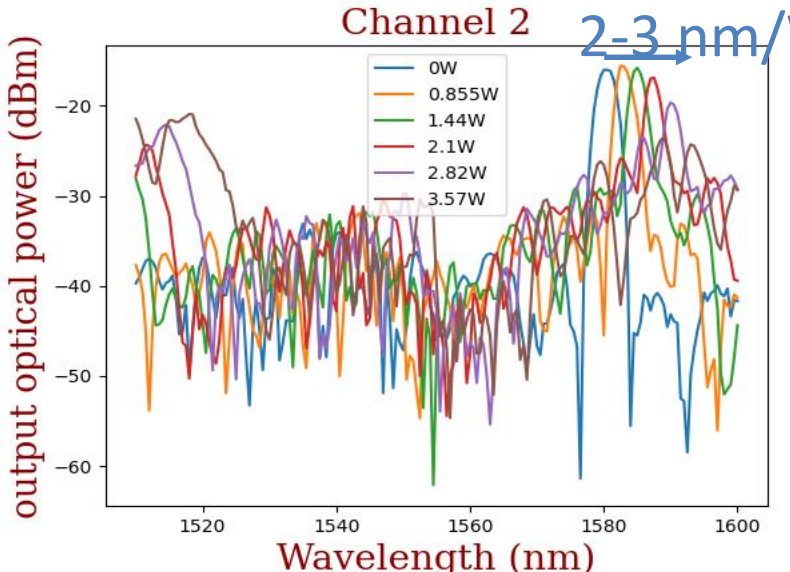
Different spot for $\neq$ wavelength/color of light!

DESIGN INCLUDES CHANNEL TUNING VIA HEATING









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Overview

- Background
- Machine learning, neuromorphic and reservoir computing
- Reservoir with multiple wavelengths in parallel
- Reservoir with extra amplifier components
- European project: design of a wavelength demultiplexer for matrix vector multiplication accelerator
- Conclusions

CONCLUSIONS

- Optical analog computing to meet growing data processing demands.
- Reservoir computing is one possible framework, photonic matrix vector multiplication accelerators are another framework.
- Parallel wavelengths/colors are key.
- Photonic reservoirs are sensitive to interference but can be made up to at least 3 wavelengths with BER < $1.5\ 10^{-2}$.
- Integrated readouts already achieve factor 3 improvement in early stage.
- Integration of active components offers potential improvements.
- Tunable arrayed waveguide gratings are potential wavelength demultiplexers.

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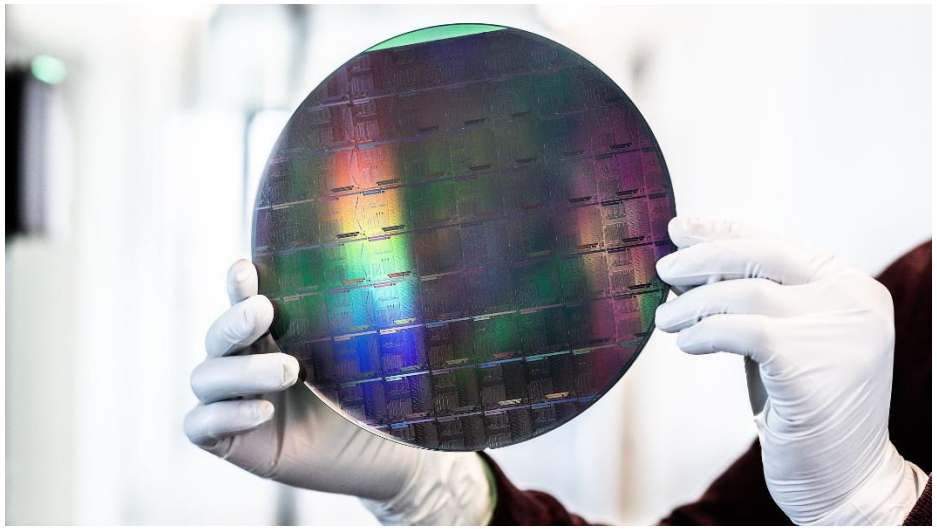

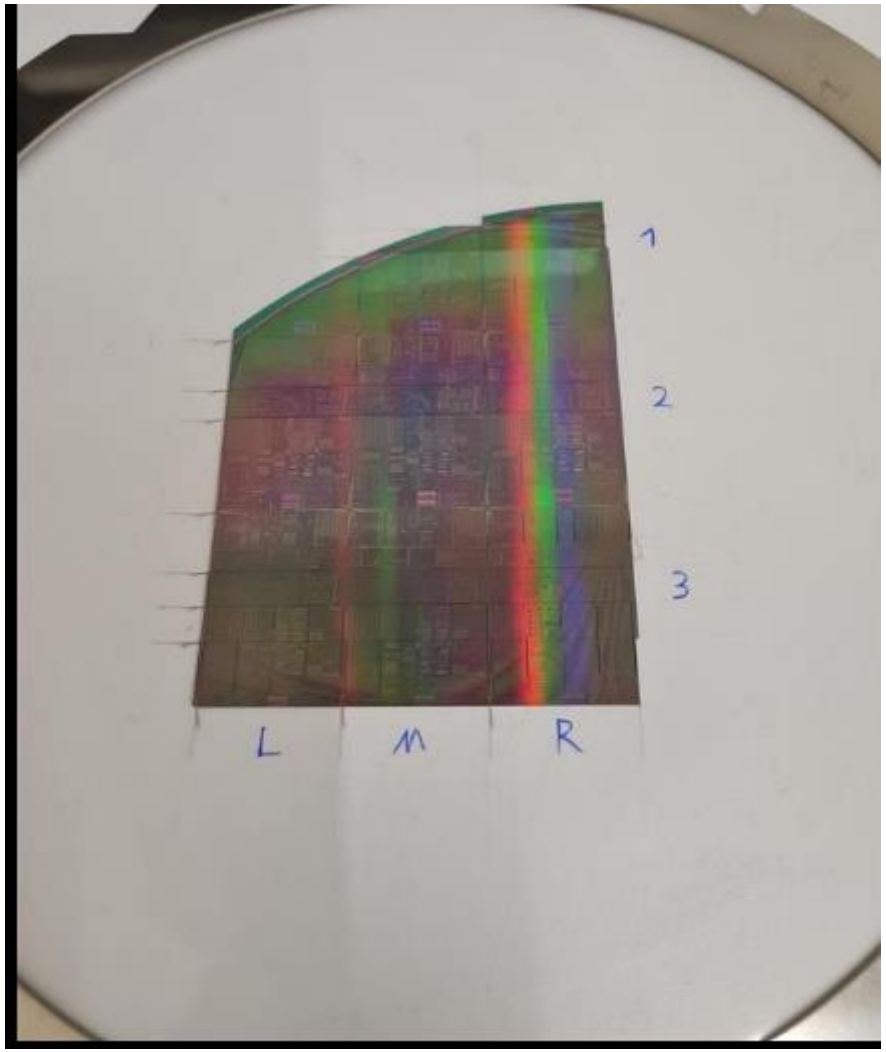
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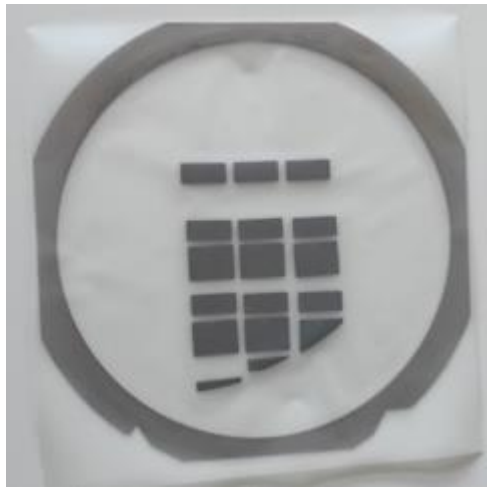

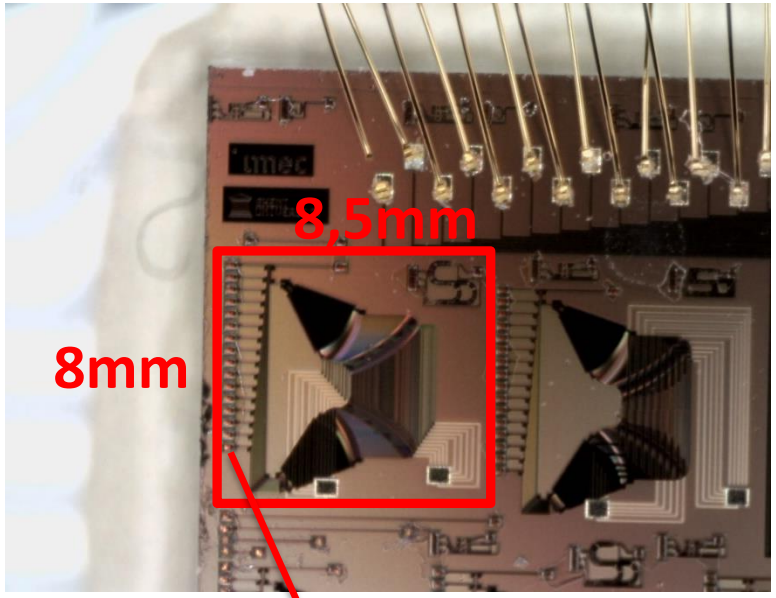

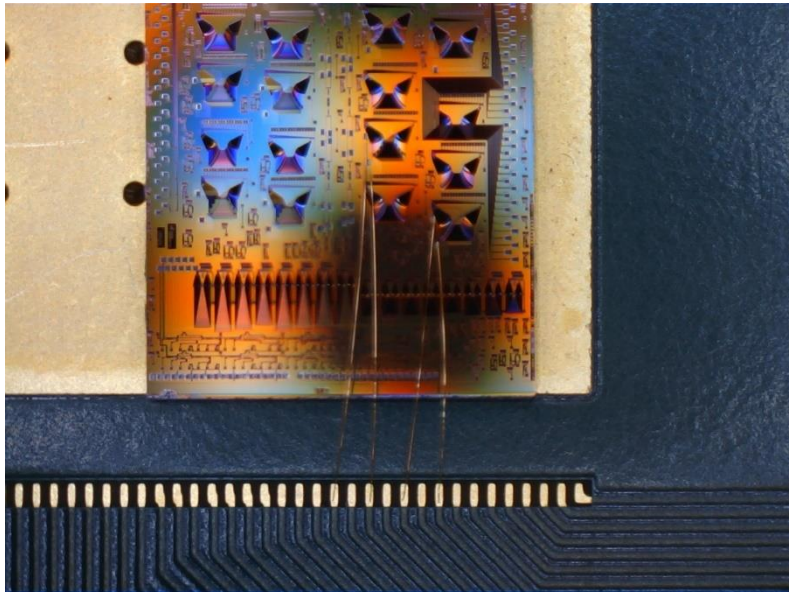

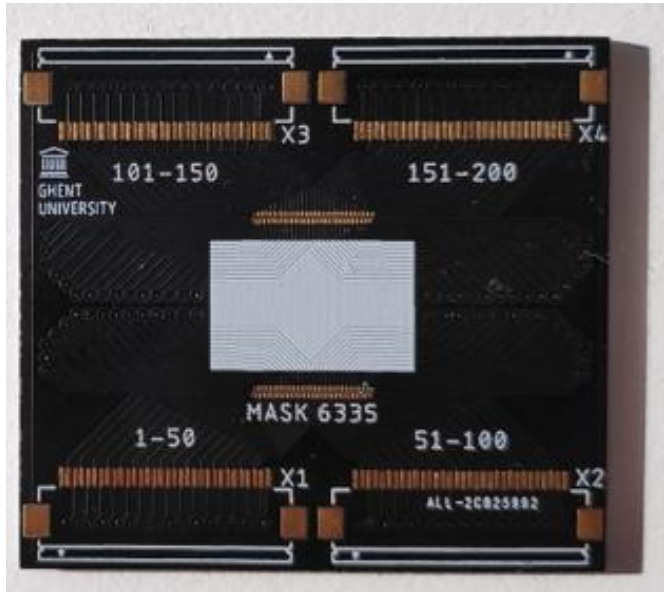

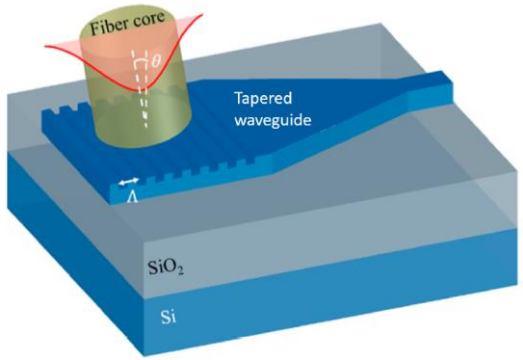

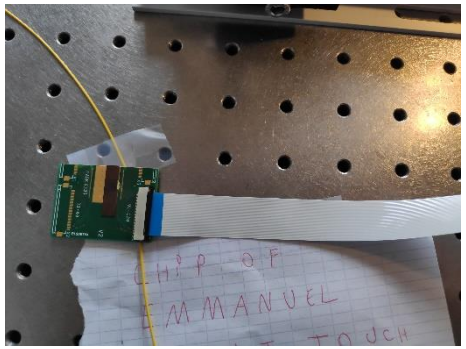

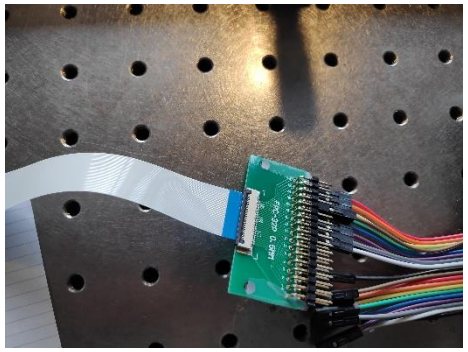

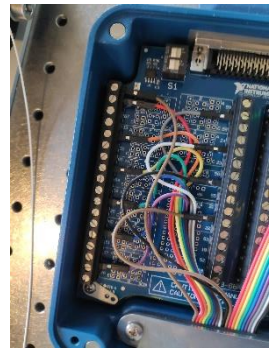

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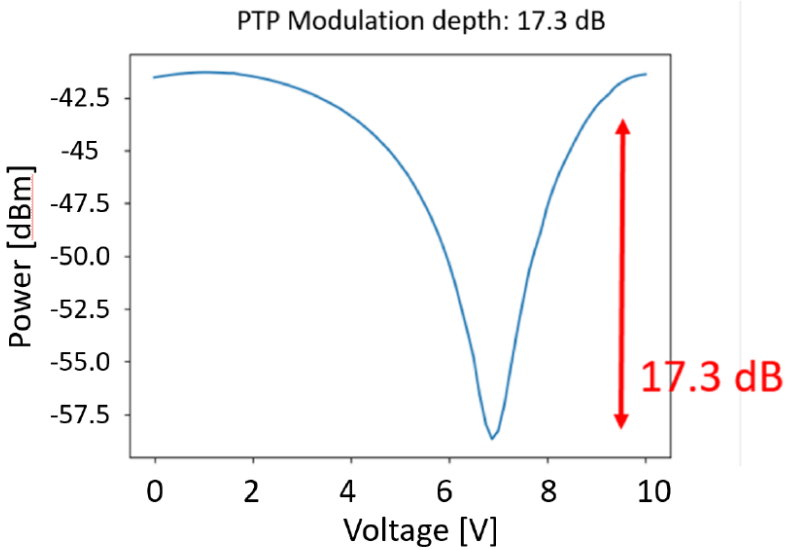
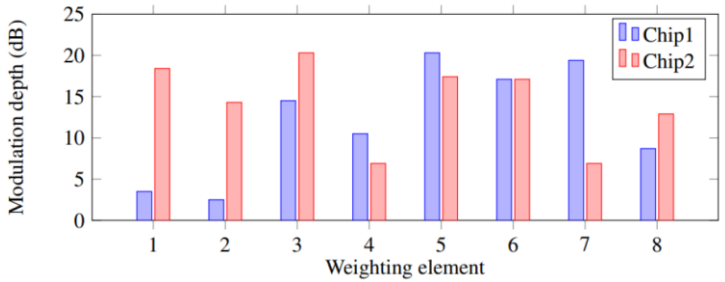
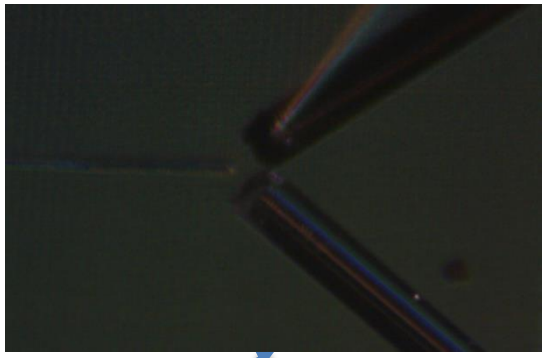
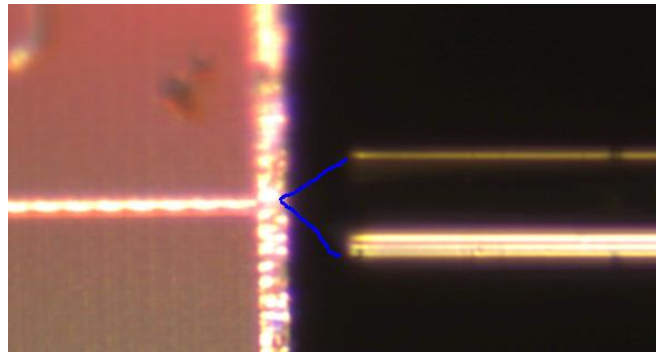
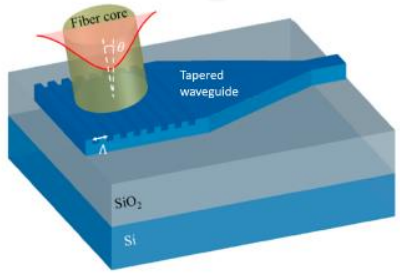
PROBEMS WITH INTEGRATED READOUT











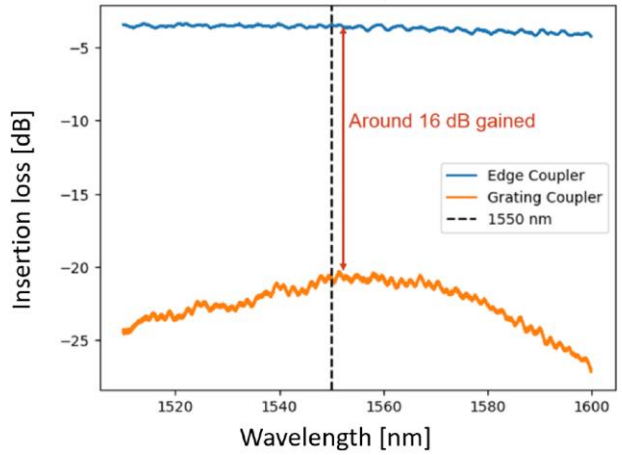


Figure 6.17: Transmission measurements of vertical grating couplers and edge couplers for the Ligentec SiN platform. Around 16 dB of power is gained, 8 dB per coupler, when comparing the edge coupler to the vertical grating coupler case.

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Experimental designs: more granular control over heating