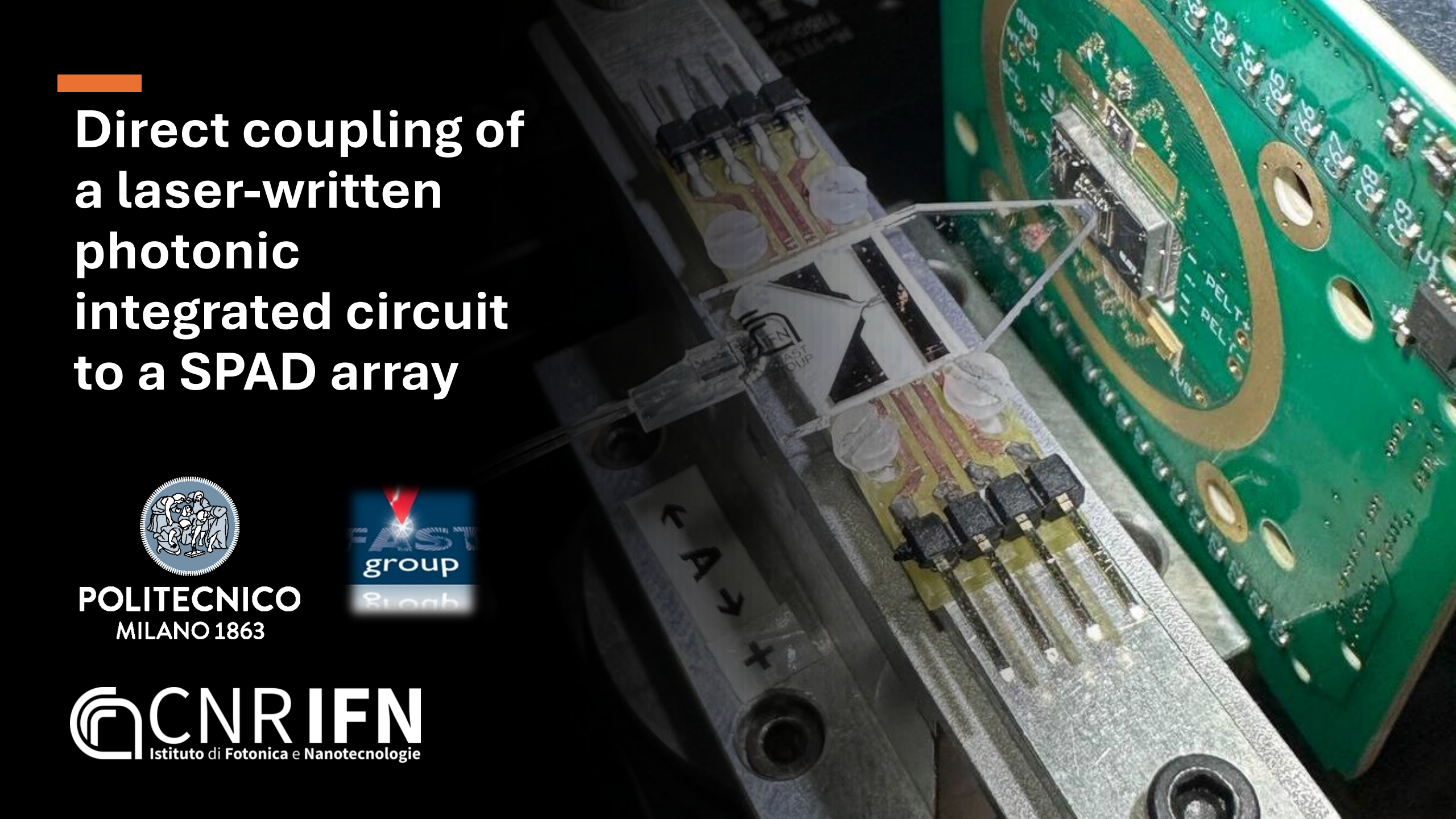
Direct coupling of a laser-written photonic integrated circuit to a SPAD array



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Quantum information processing

QUANTUM STATE GENERATION

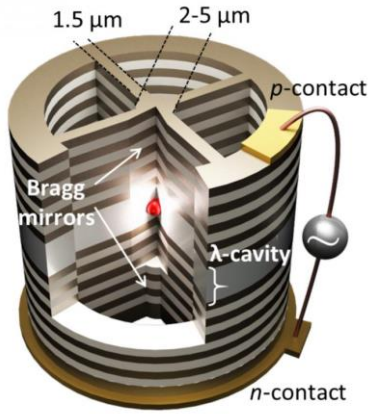
$|\Psi\rangle$

QUANTUM STATE MANIPULATION

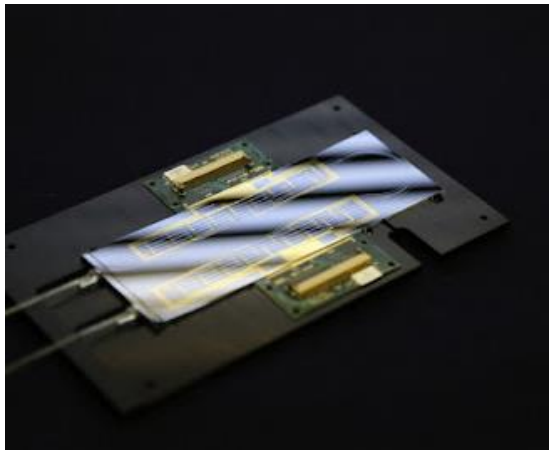
$U|\Psi\rangle$

QUANTUM STATE DETECTION

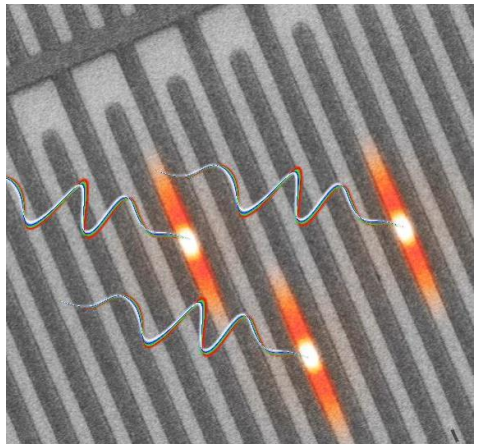
$\langle\Phi|U|\Psi\rangle$



Somaschi et al. *Nature Photonics* 10.5 (2016): 340-345.



Carolan et al. *Science* 349.6249 (2015): 711-716.



Cahall et al. *Optica* 4.12 (2017): 1534-1535.

Focus on scalability

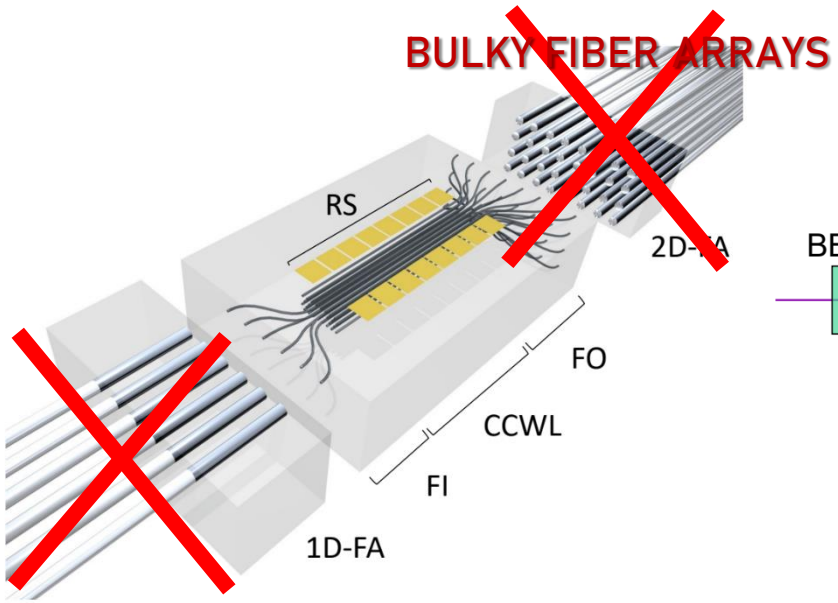
Scalability is critical to enable increasingly complex algorithms

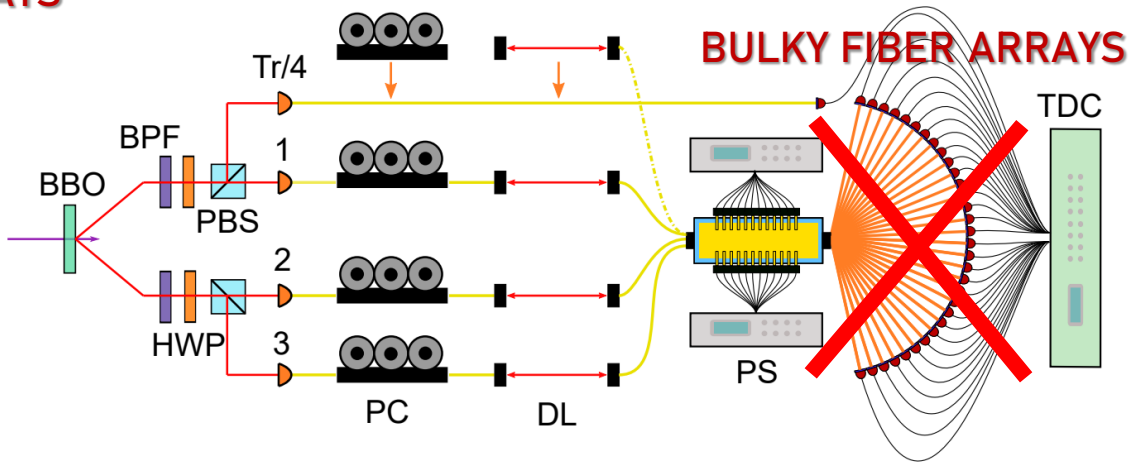
Up to date obstacles to scalabilty:

- Detector operating at cryogenic temperature (huge footprint and high power consumption)
- Bulky interconnections between manipulation and detection part

INTEGRATED SYSTEM
- room temperature
- high system efficiency

Superconduction Single Photon Detection Cryostat



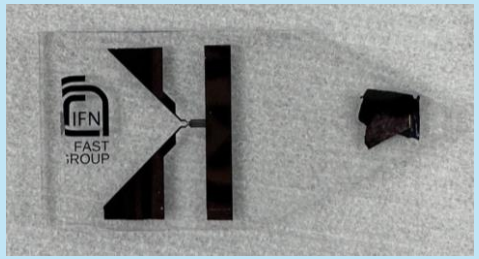


Hoch et al. *npj Quantum Information* 8.1 (2022): 55.

Hybrid Integration

Photonic Integrated Circuit (PIC)

Femtosecond Laser Writing (FLW) on GLASS



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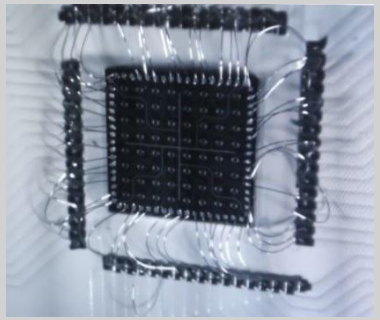
Single Photon Avalanche Diode Arrays (SPADs)

Custom silicon technology



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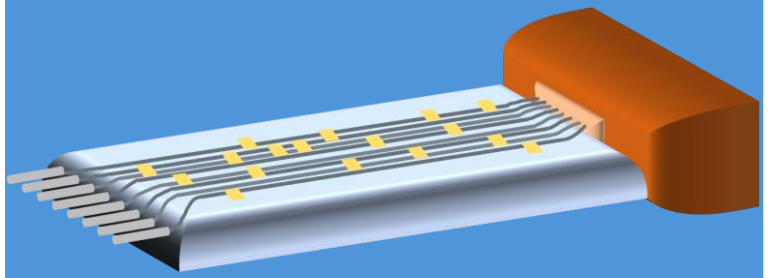
HYBRID INTEGRATION



Direct coupling

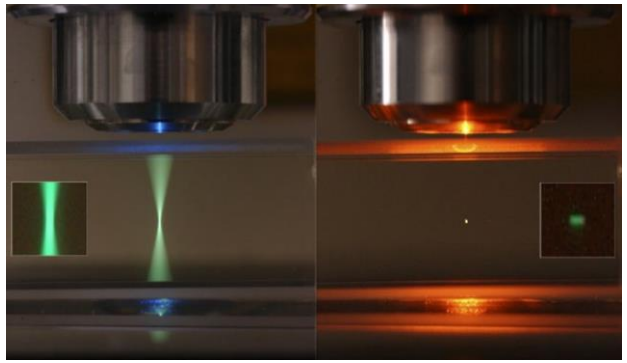
Custom technology to deliver state-of-the-art performances for the intended technology

→

Compact system without compromising on efficiency

Femtosecond Laser Writing

High energy pulses trigger non-linear absorption process that induce a permanent modification in the transparent material

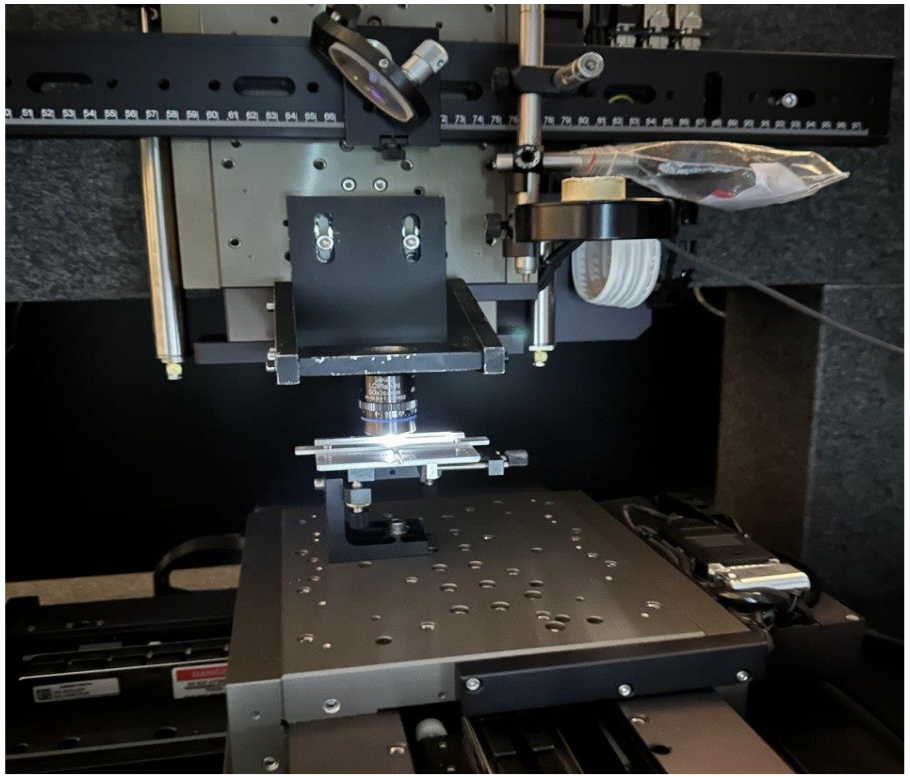


Linear absorption

Non-linear absorption

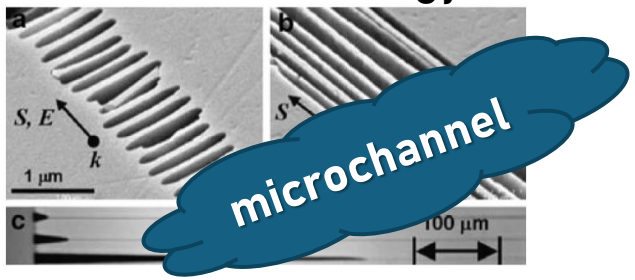
In the non-linear process the absorption occur only in the focal volume

3D

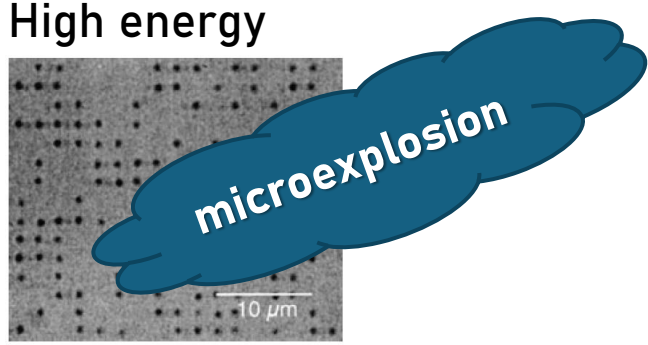


Low energy

Intermediate energy



High energy



Waveguide with FLW

- Low propagation losses
Around 0.1 dB/cm

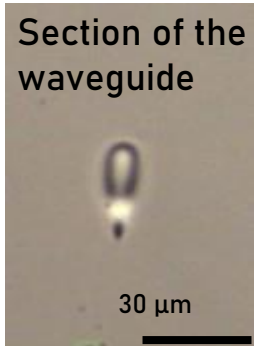
- Low Coupling losses
Around 0.2 dB

- 3D capabilities
Perfect for coupling to 2D arrays

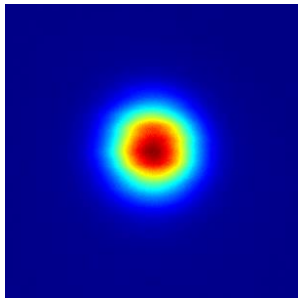
- Versatile tecnique
process a wide range of materials and for each we can optimize the process for every wavelenght

- Small volume capability
fabrication of a few chips at a time

- Low change in refractive index
Around $\Delta n \sim 10^{-3}$

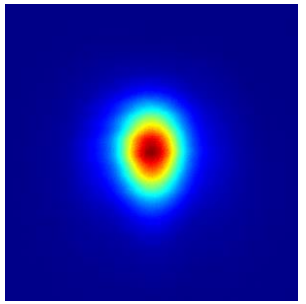


Fiber SM 450 @532nm

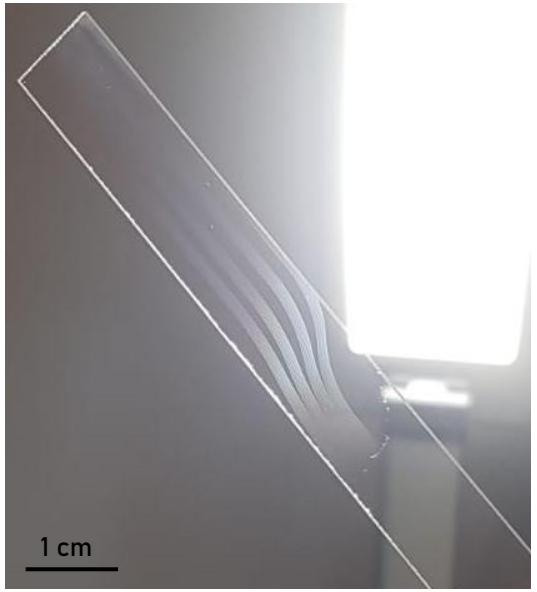


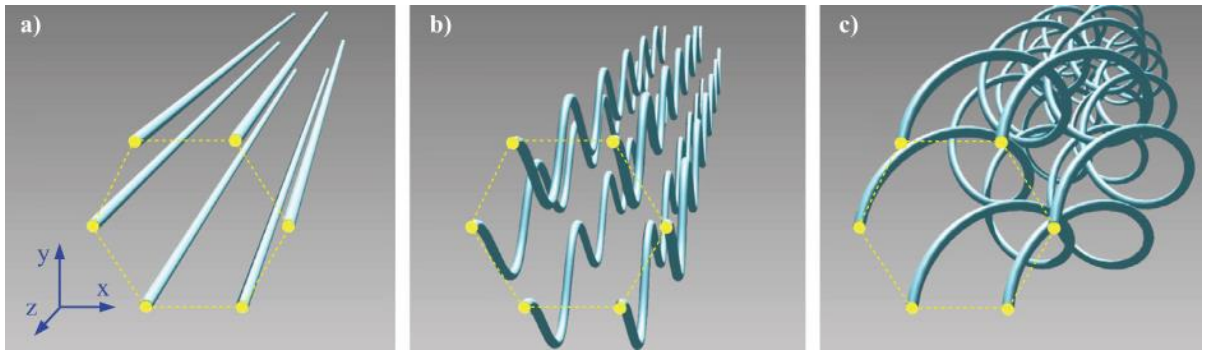
Dx=3.13 µm
Dy=3.13 µm

Waveguide



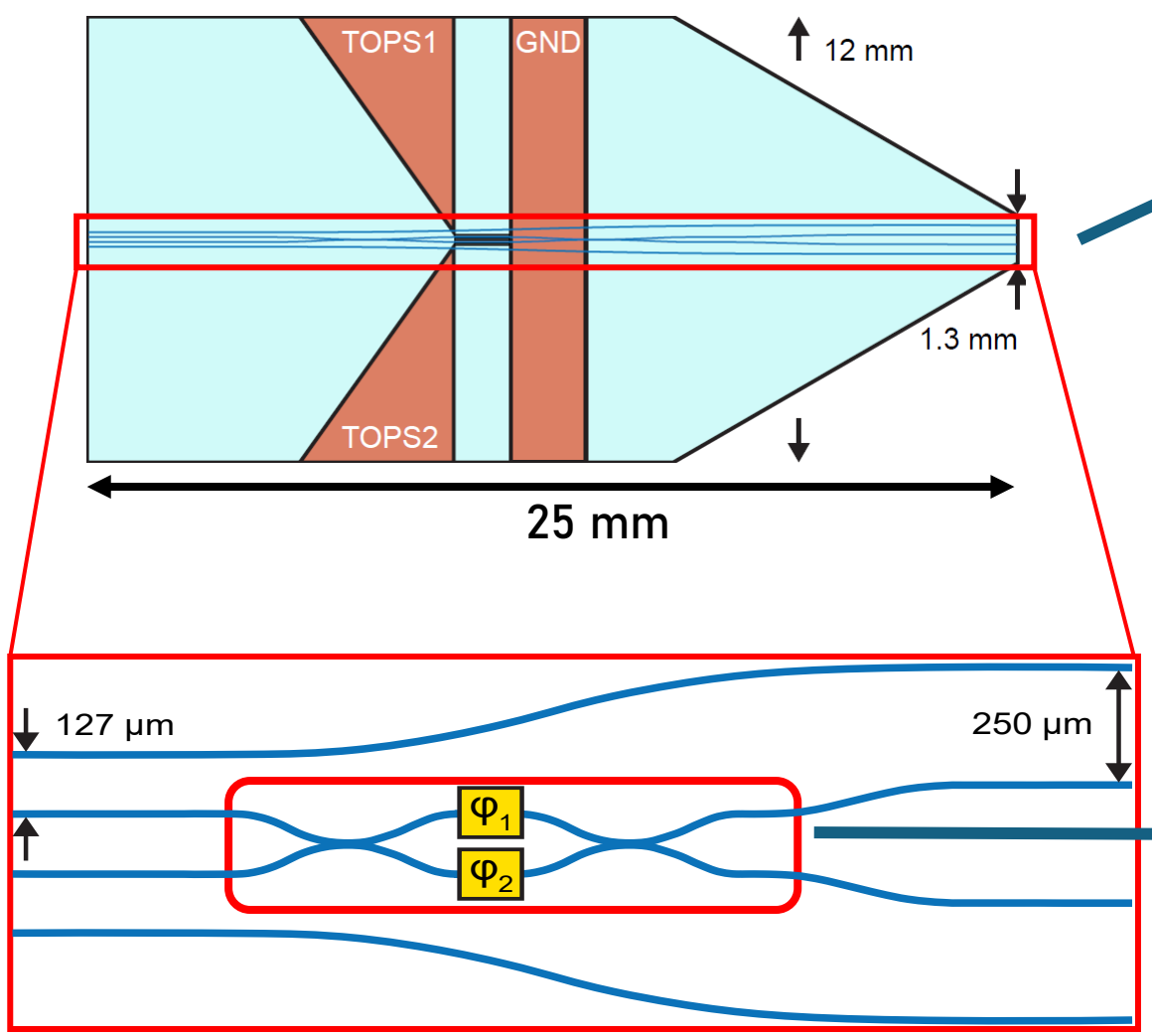
Dx=2.59 µm
Dy=3.25 µm



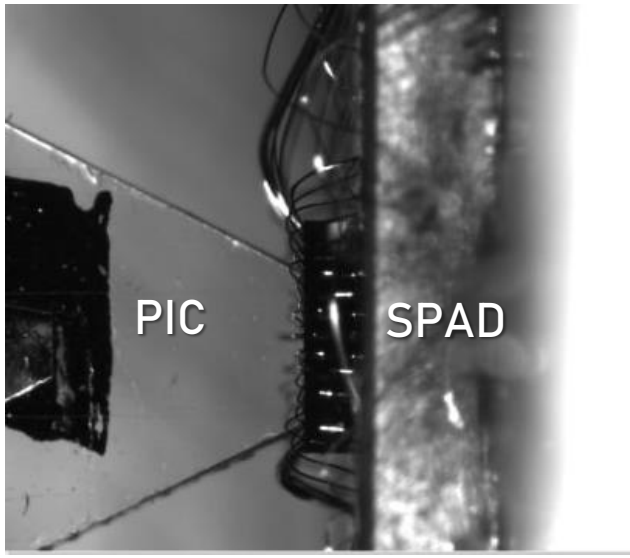


A. Crespi *et al* 2013 *New J. Phys.* 15 013012

Design of the PIC



Pointed shape for coupling with the SPAD



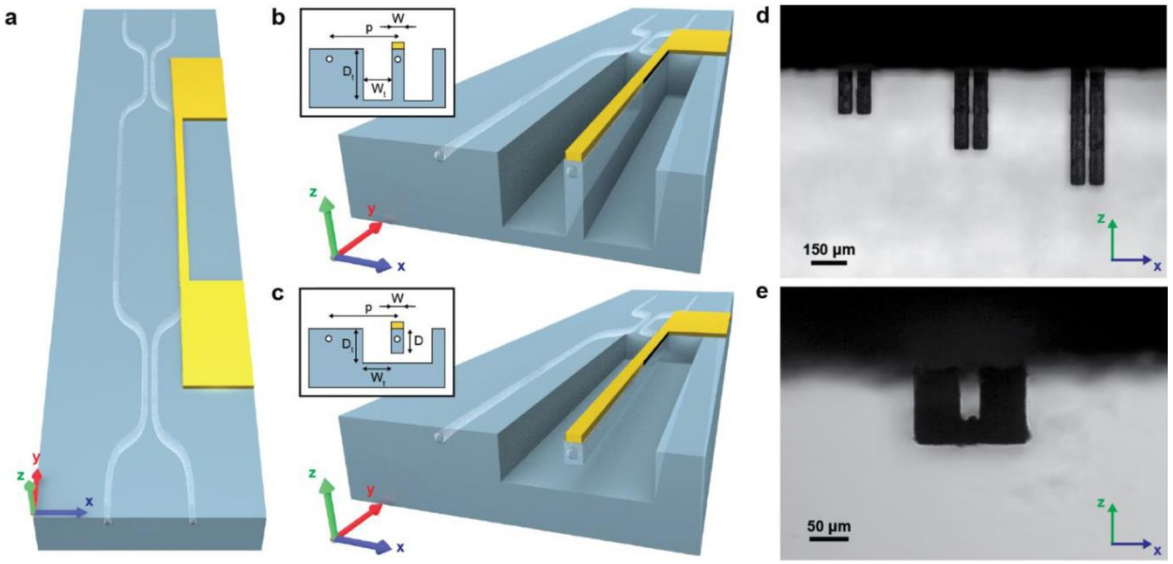
A reconfigurable MZI implemented through two thermo-optic phase shifters (TOPSs).

Building block to realize Universal Photonic Processor (UPP)

Trench and resistor fabrication

Thermal Isolation

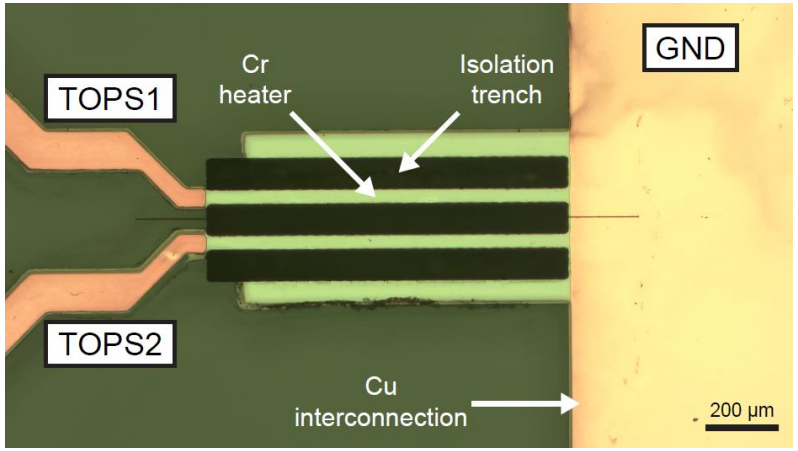
- Reduce the working power of the TOPS
- Reduce the thermal cross talk

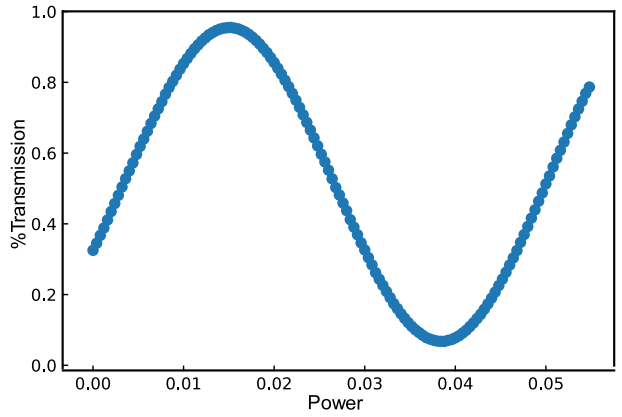


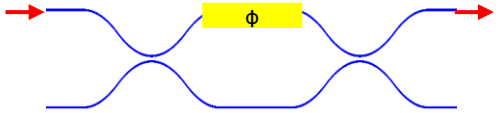
Ceccarelli et al. *Laser & Photonics Reviews 2020*
Low Power Reconfigurability and Reduced Crosstalk in Integrated Photonic Circuits Fabricated by Femtosecond Laser Micromachining

2-step photolithography

Cromium → high resistivity for higher heat dissipation
Copper → low resistivity for the interconnection



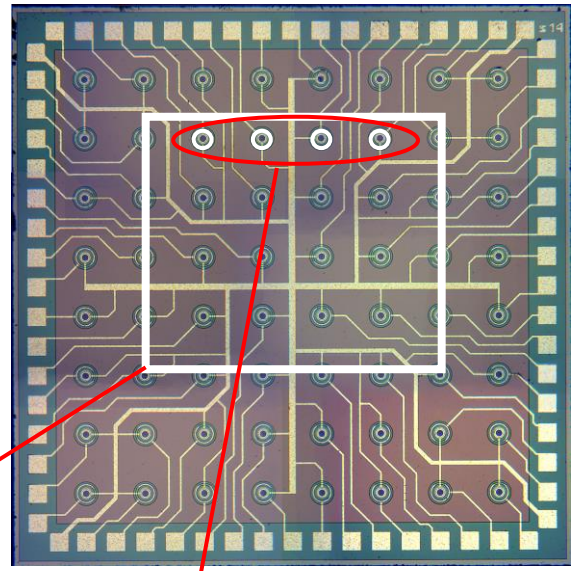


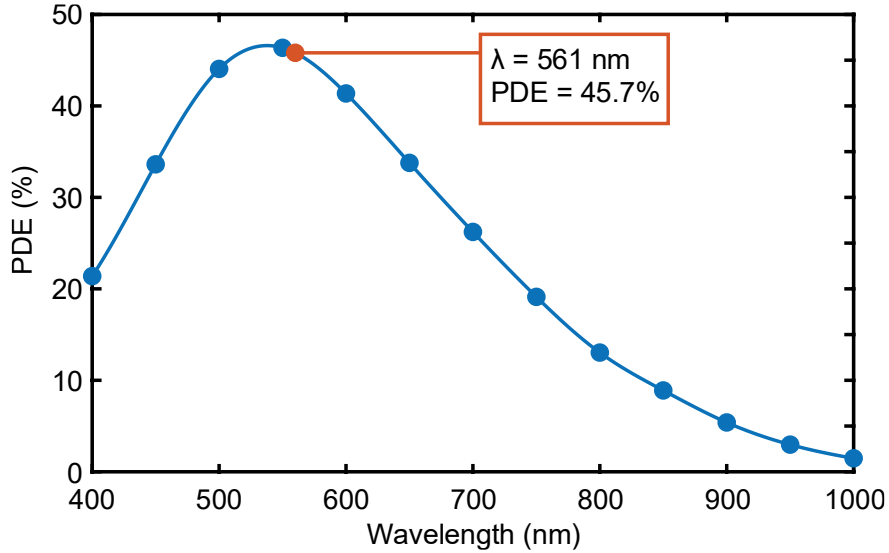


SPAD Array

CUSTOM-TECHNOLOGY THIN SPAD ARRAY

- Large pitch (250 µm)
- 20 µm single SPAD diameter
- Low number of pixels (64, only 4 will be actually used)
- High detection efficiency in the visibile range
- Relatively good DCR, afterpulsing, crosstalk, ecc.

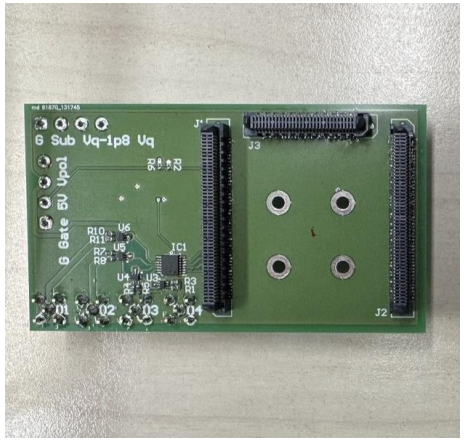




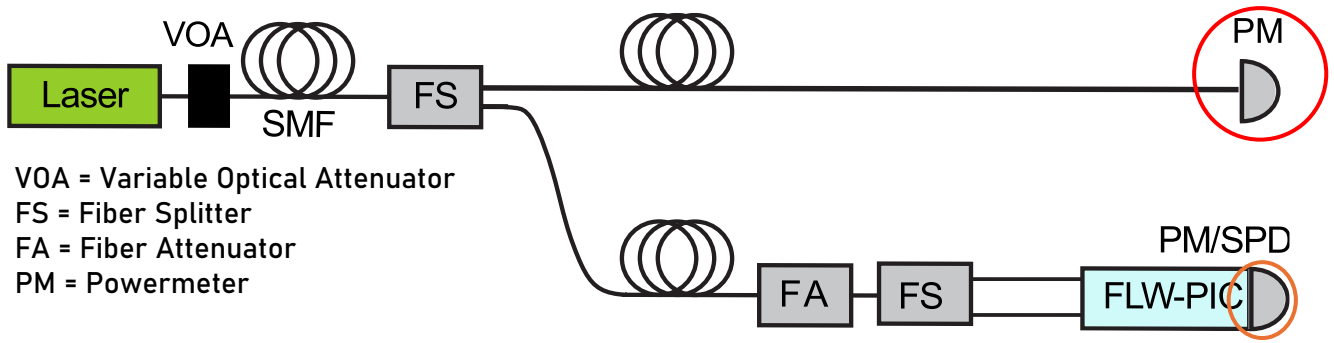
Footprint of the FLW-PIC (1.3 x 1 mm^2)

The four SPAD used in this experiment

The outputs of the selected active quenching circuits are buffered through an on-board circuit and made available by SMA connectors

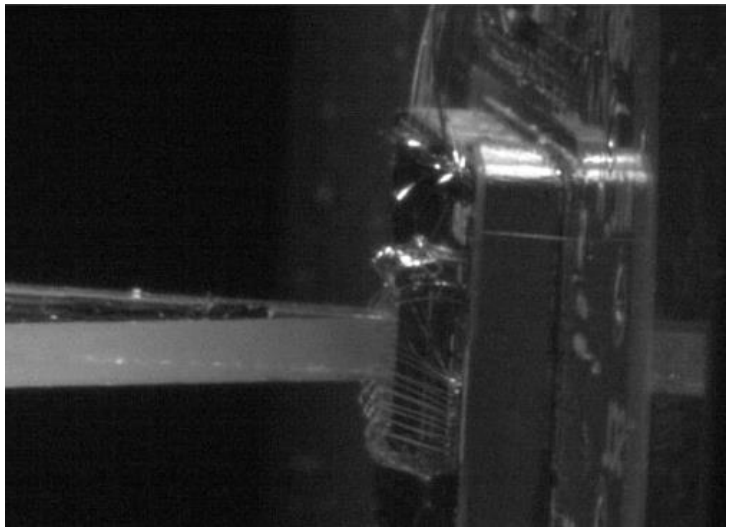


Measurement Setup

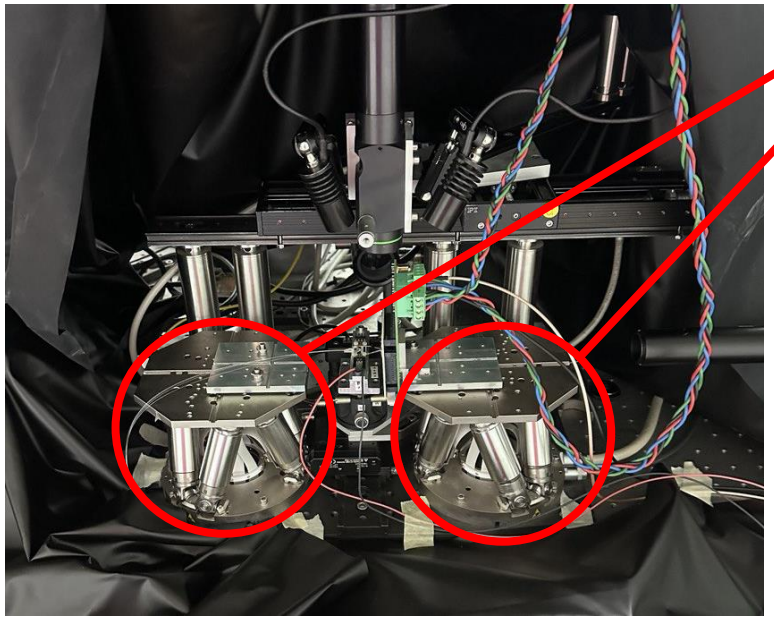


VOA = Variable Optical Attenuator
FS = Fiber Splitter
FA = Fiber Attenuator
PM = Powermeter

Setup adapted from T. Gerrits et al. Calibration of free-space and fiber-coupled single-photon detectors. *Metrologia*, 57(1):015002, 2020.



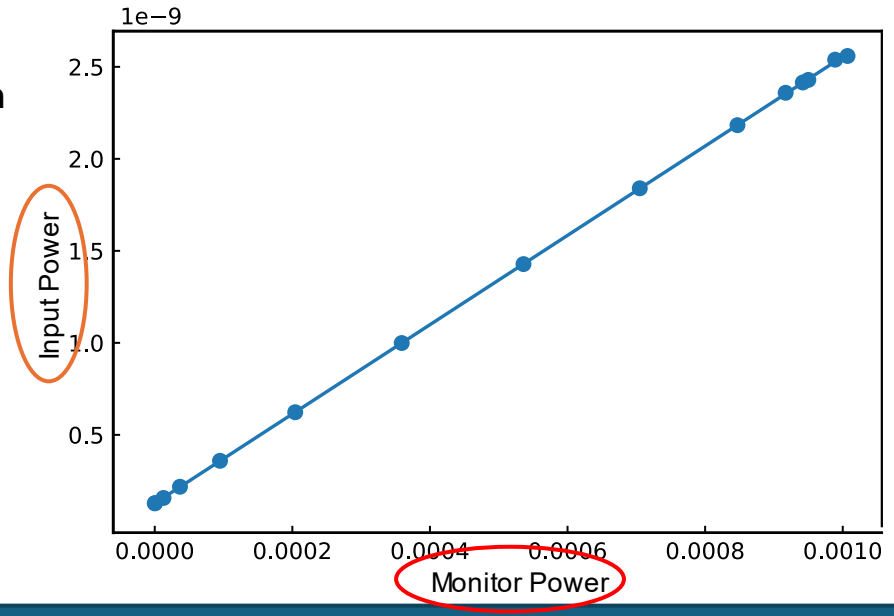
Measures inside black curtain



Hexapod

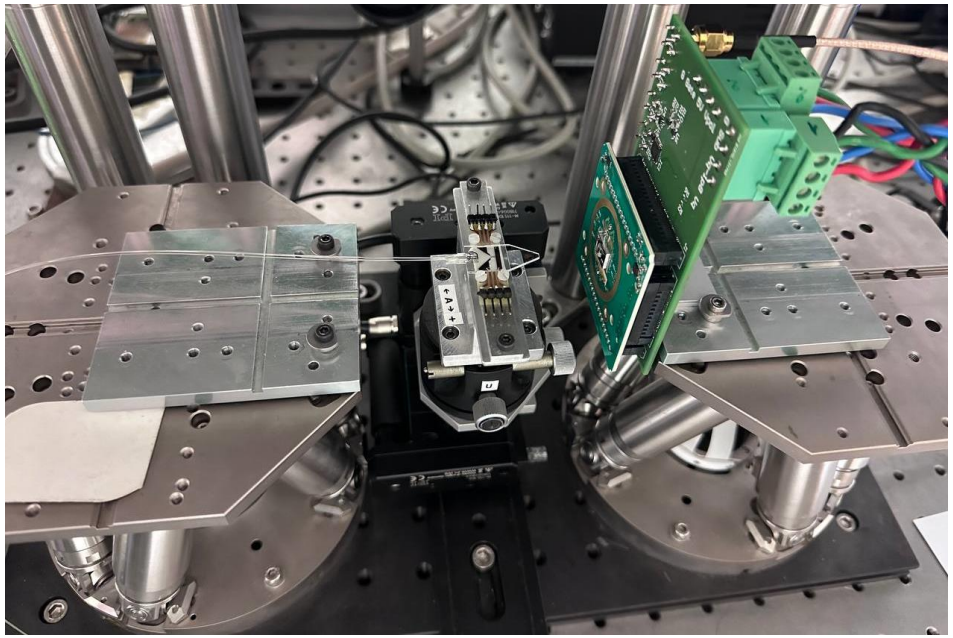
Thanks to the nanometer precision of hexapod we are able to achieve very precise coupling

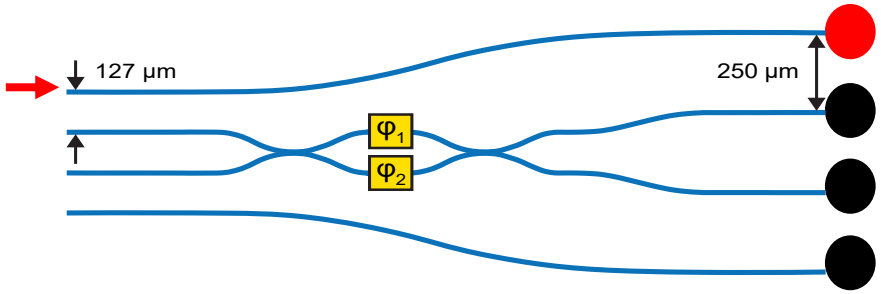
Attenuation = -56.15 dB



Linearity Measurement

Automated Measurement by scanning the intensity with VOA



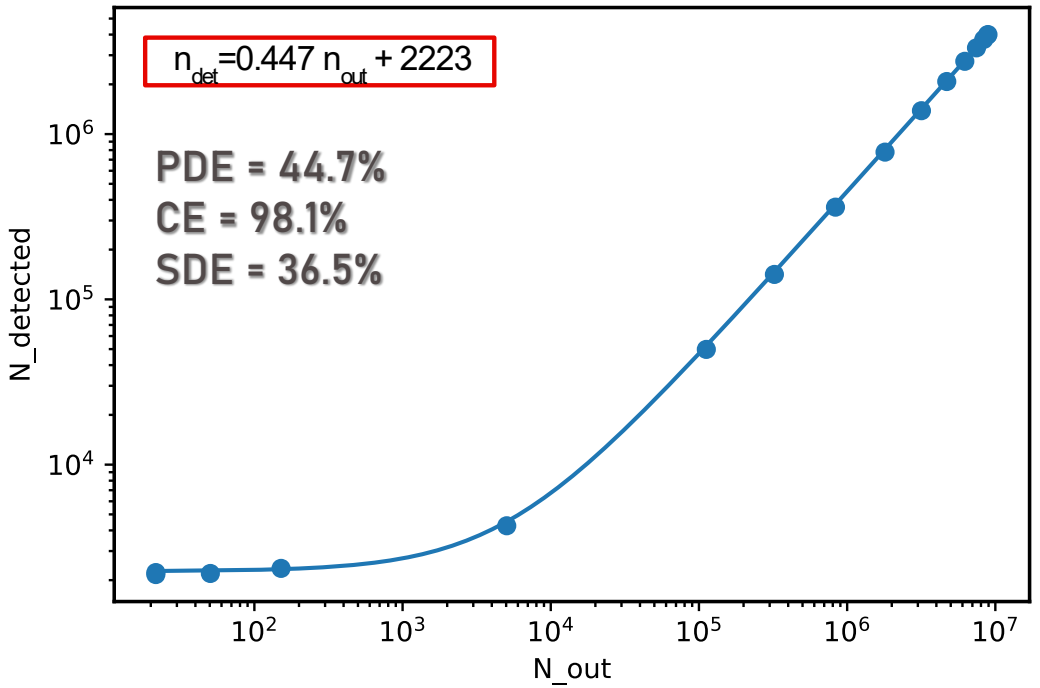


Measurement at 561 nm

PIC transmission = 81.6%

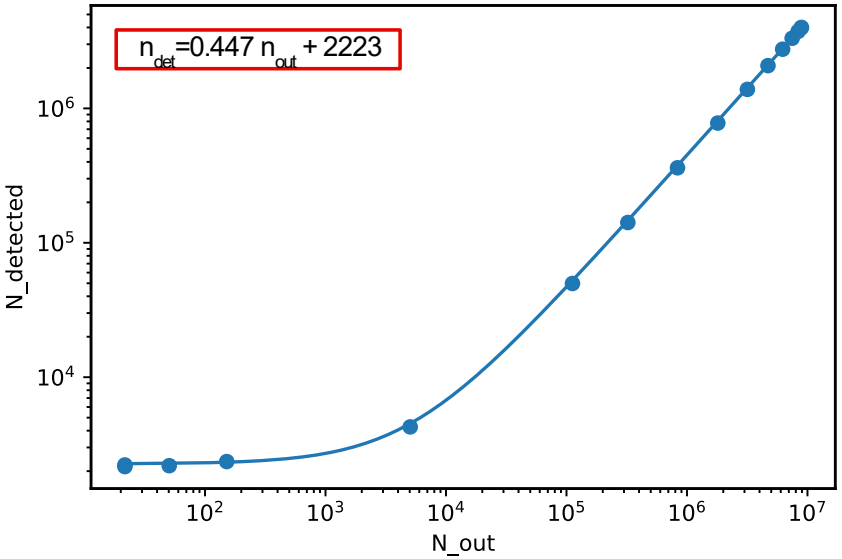
SPAD features

V_pol = 38.6 V
V_ov = 5 V
V_sub= 15 V
T_gate = 1 s
DCR = 2223
Dead Time = 55 ns



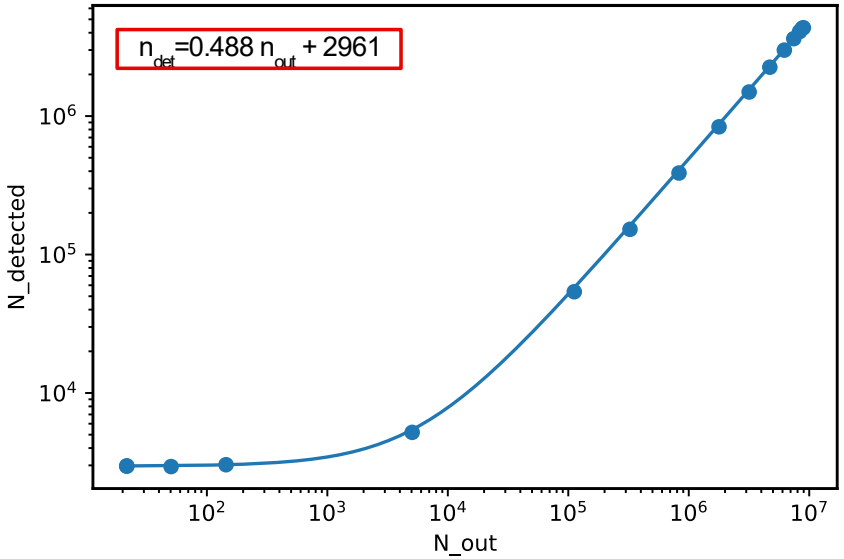
Efficiencies for Different Overvoltages

V_{ov}=5V



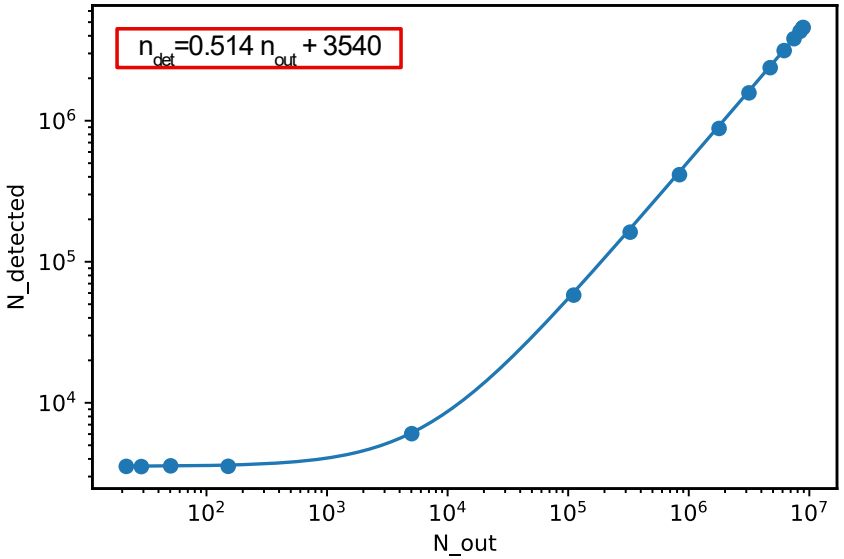
PDE = 44.7%
CE = 98.1%
SDE = 36.5%

V_{ov}=6V



PDE = 48.8%
CE = 98.1%
SDE = 39.8%

V_{ov}=7V

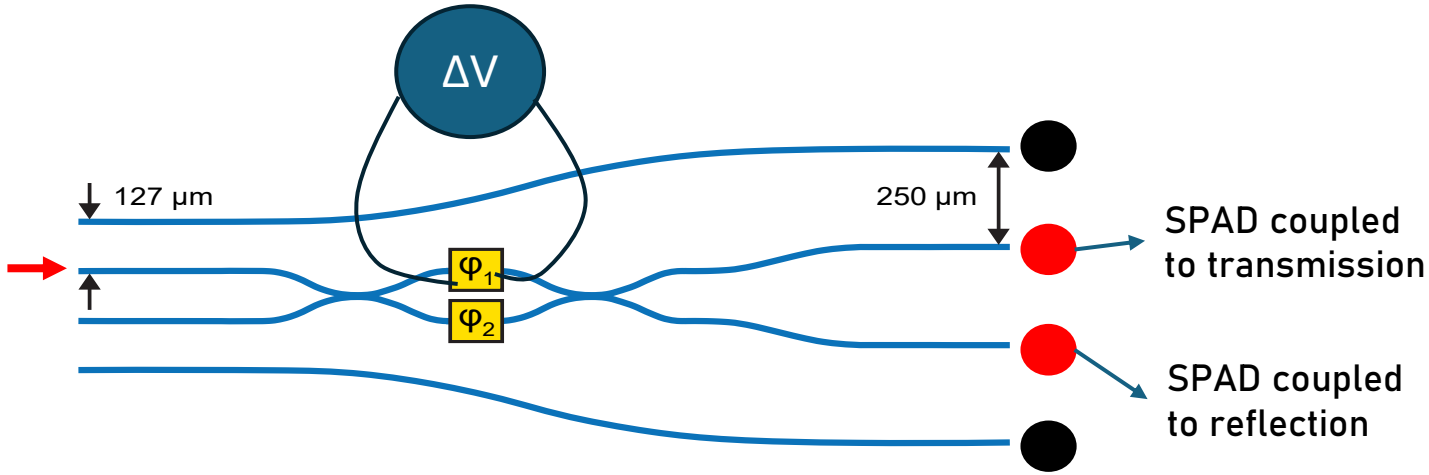


PDE = 51.4%
CE = 98.1%
SDE = 41.9%

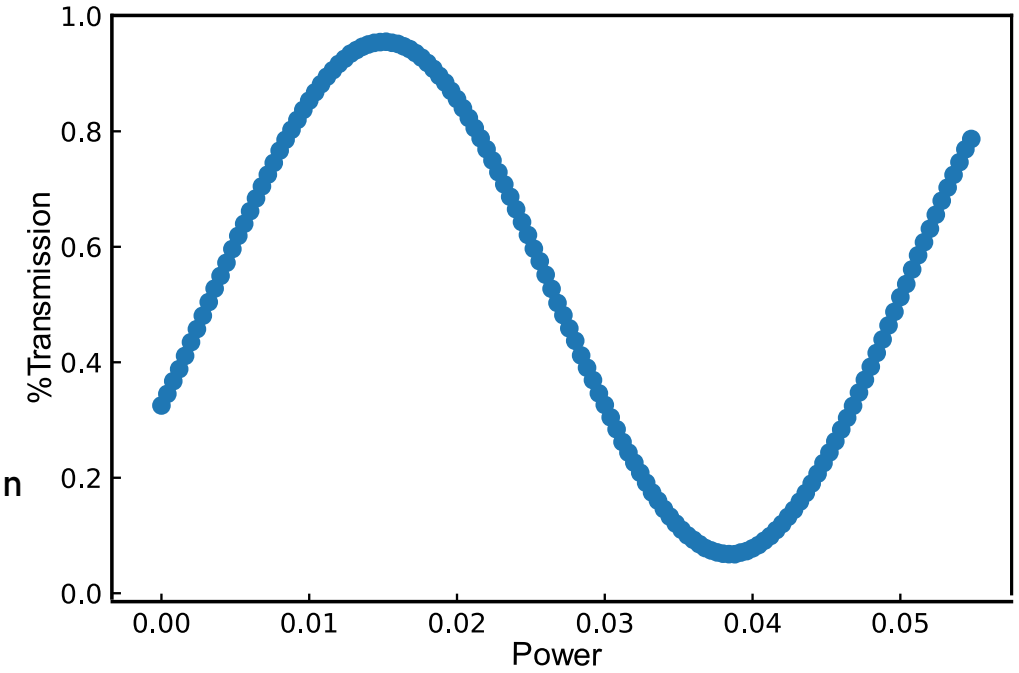
Phase Shift measured with SPAD

Measurement step

1. Tilt alignement using the 2 external straight waveguides
2. Change the input into the MZI and the relative SPAD
3. Simultaneous measurement of the two outputs
4. Normalization with respect the sum of the output



Transmission in function of the dissipated power in the microheater

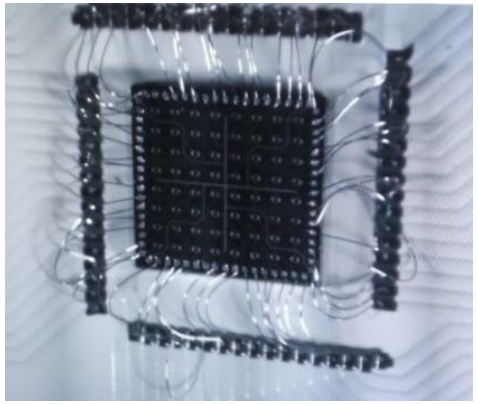


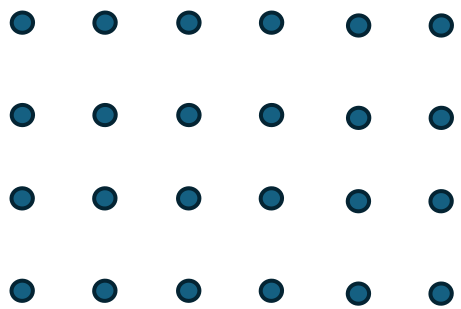
$$\% \text{ Transmission} = \frac{Phot_{Transmission}}{Phot_{Transmission} + Phot_{Reflection}}$$

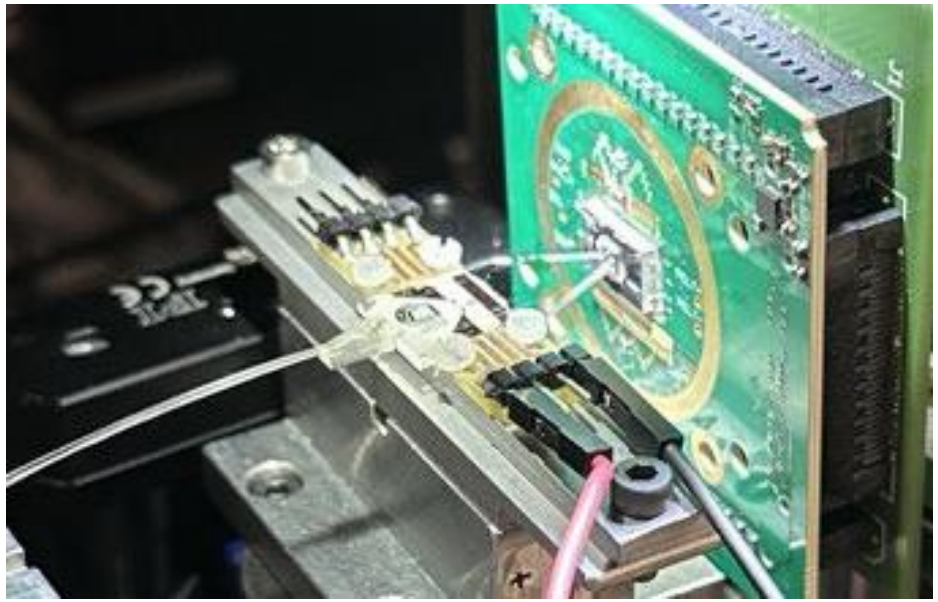
Conclusion and Future perspective

Compact system for the manipulation and detection of single photons

- Programmable PIC coupled with SPADs arrays
- Combines two custom technologies in order to optimize performance for each piece
- State-of-the-art performances at visible wavelength reaching $SDE_{@Vov7}$ = 41.9%







NEXT STEPS

- Test thicker SPADs arrays
- Exploit 3D FLW to couple 2D SPAD arrays
- Realize a portable setup

Thank you for your attention!

CNR IFN
Istituto di Fotonica e Nanotecnologie

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HI-LIGHT

Hybrid Integration of Laser-written Interferometers and sinGle pHoton deTectors

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