Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

Monolithic Integration of SiON photonic-circuit and single-ph. detectors

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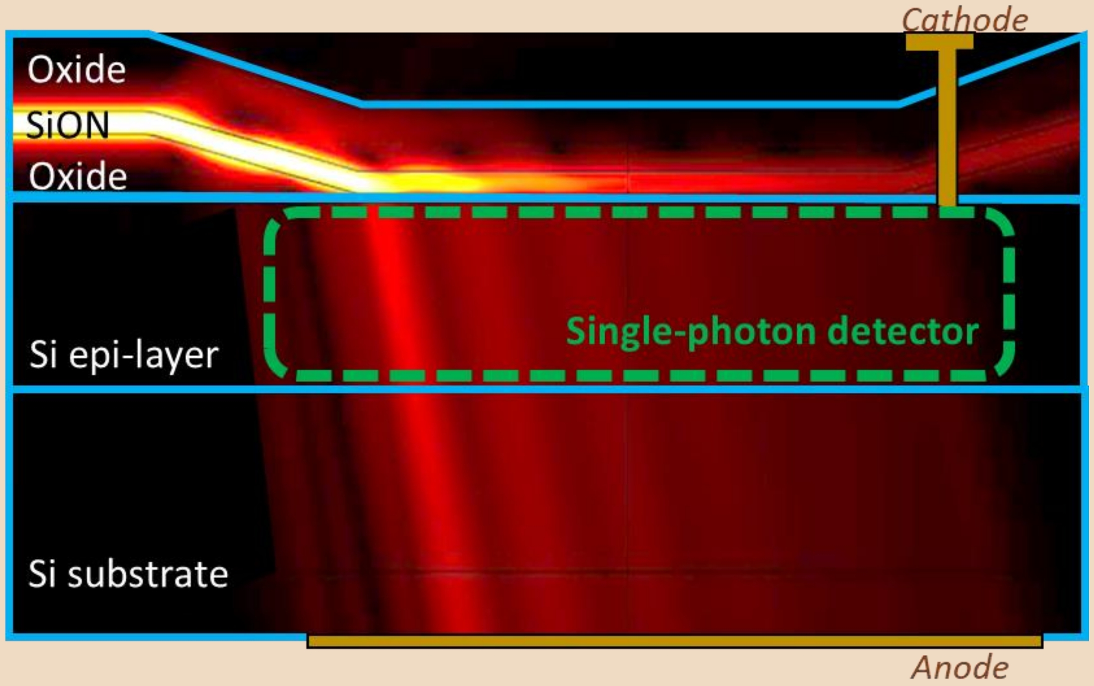

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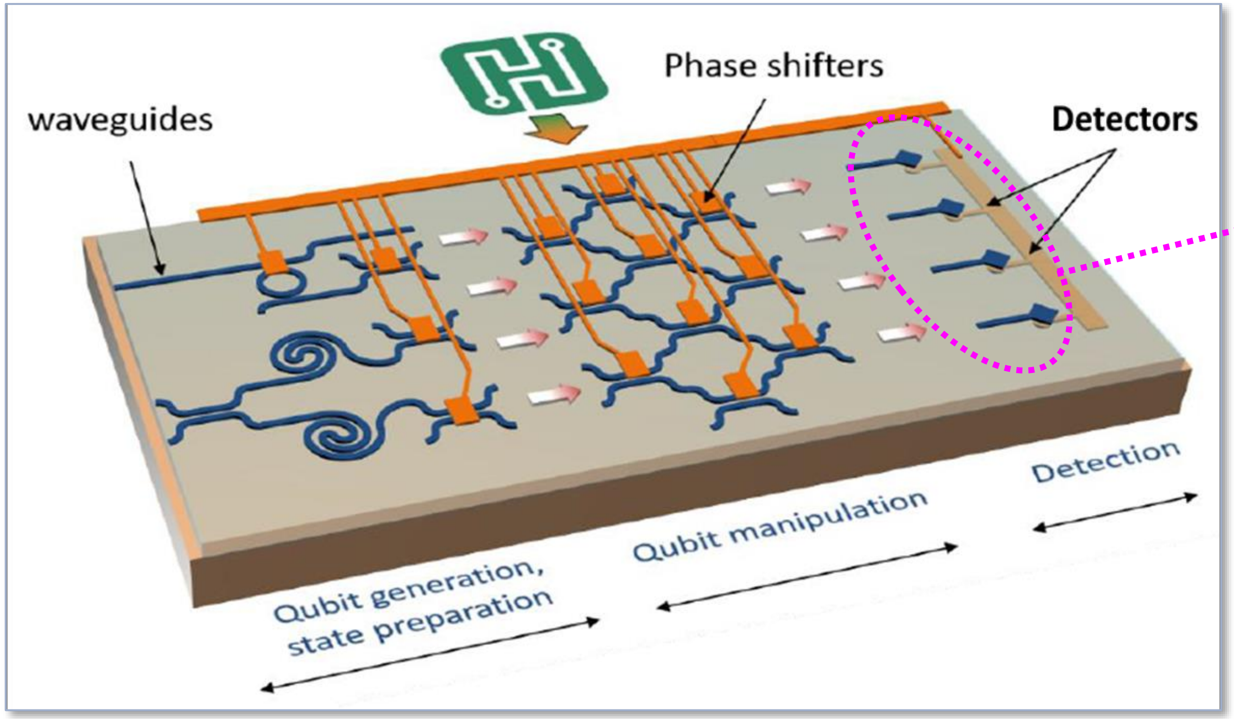
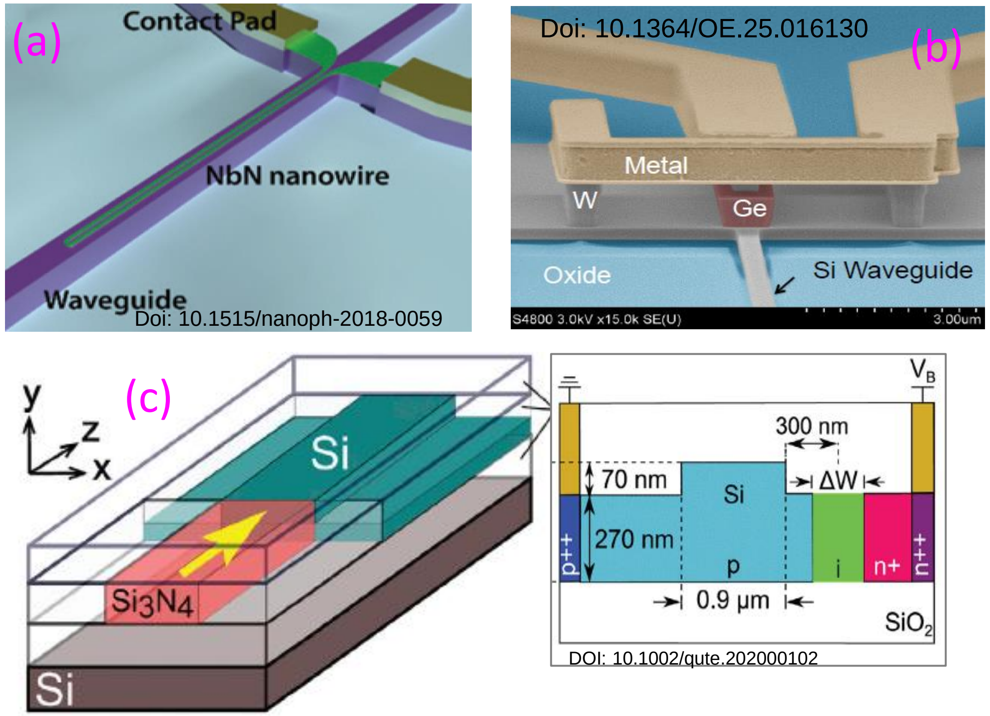
Introduction

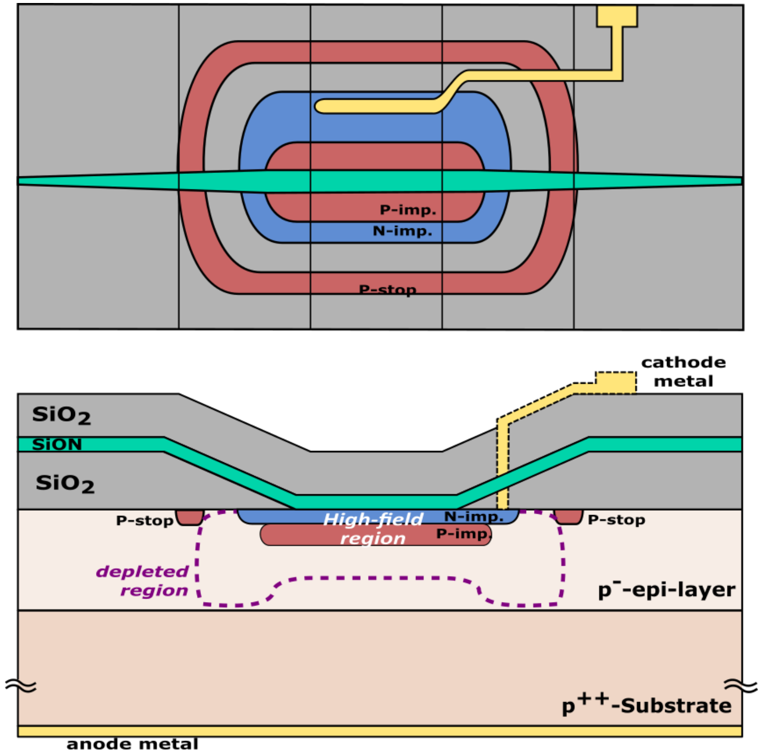


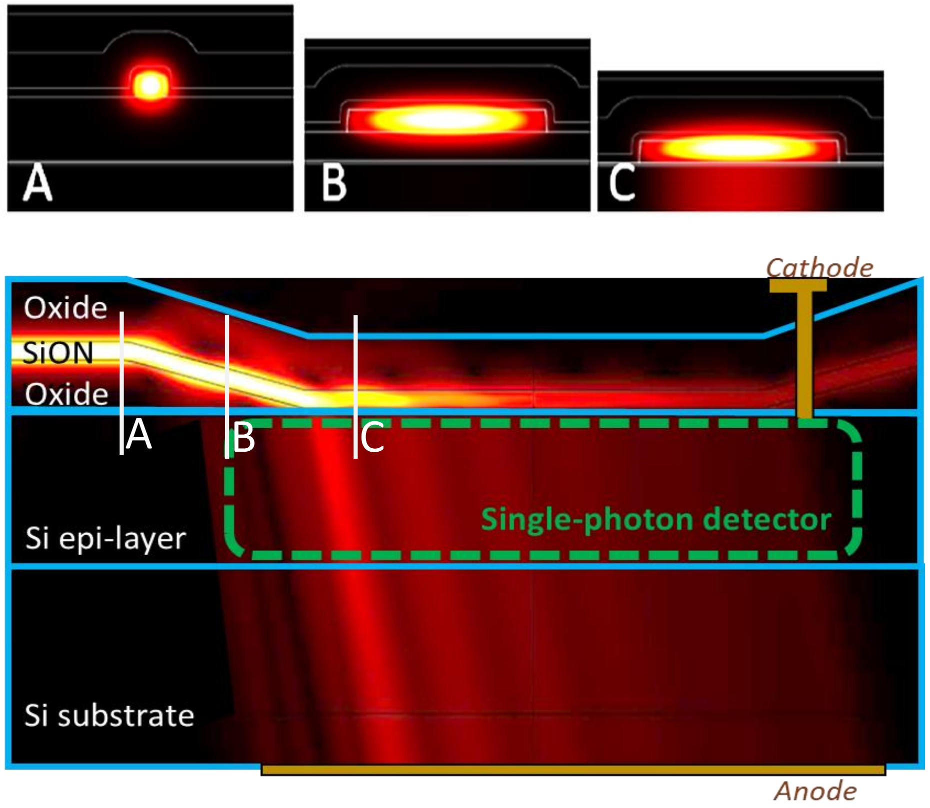
Detector integration in quantum PIC



- ***Important topic*** in quantum photonics → ***integration of photon source, manipulation and detection in the PICs***.
- Possible approach: - Si-based photonics (SWIR, e.g. 1550 nm) integrated with SNSPD, or with Ge-on-Si detectors;
  - SiN (or SiON) photonics (NIR, e.g. 850nm) integrated with Si detectors.
- ***FBK approach***: quantum PIC with SiN(SiON) waveguide monolithically integrated with Si-SPAD ***(CMOS compatible)***

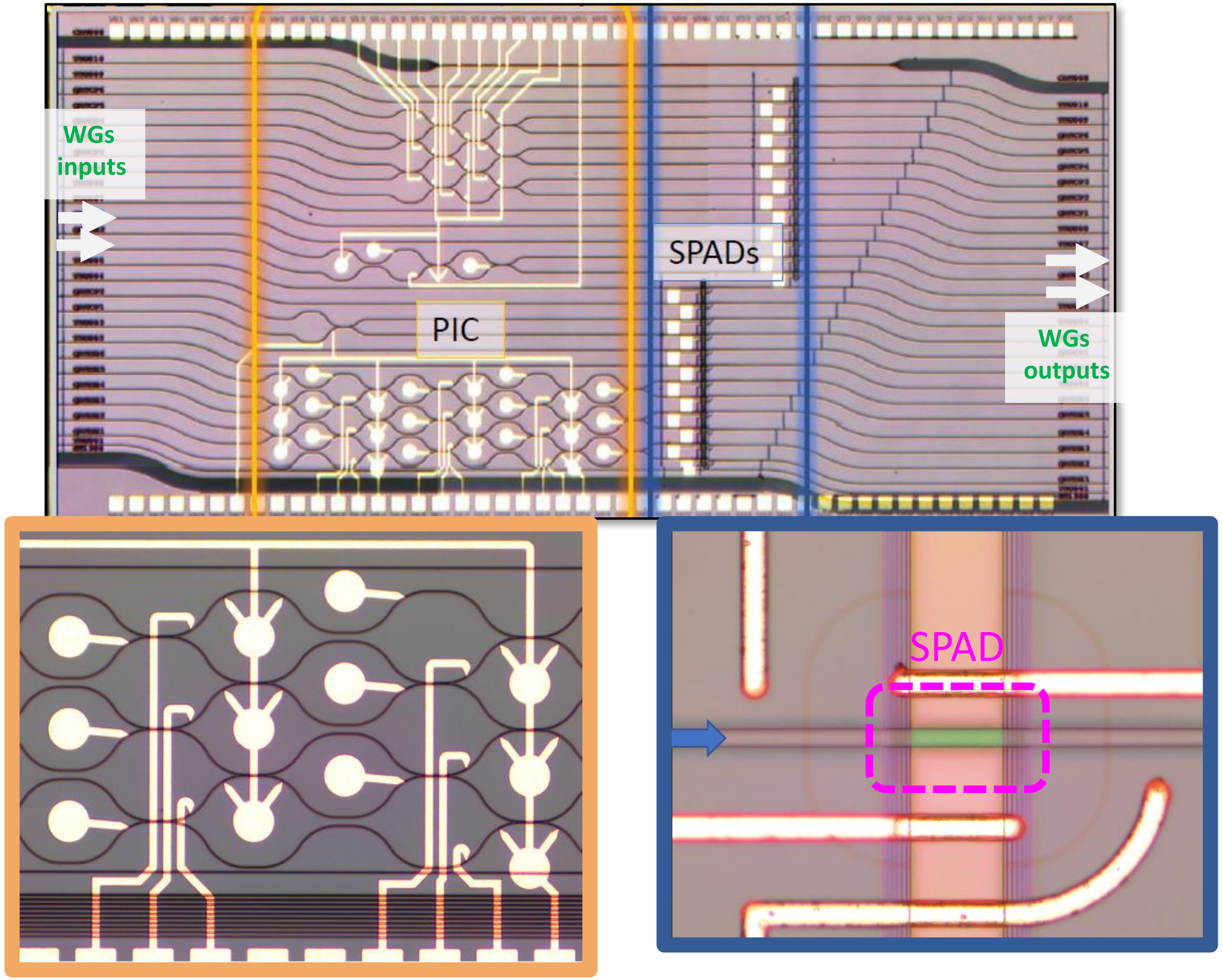
FBK photonic/electronic top-down coupling approach





- ***New efficient top-down evanescent coupling approach***
- ***based on shaping of WG and cladding thickness.***
- Advantages:
  1. materials all CMOS compatible (already used in CMOS);
  2. not require alignments, butt coupling, …etc…;
  3. it operates at room temperature;
  4. SPAD design does not have particular constraints.

Test chip: PIC+SPADs → *photon manipulation and detection*



- First implementation: *test chip developed within previous projects.*
- Several waveguides:
  - Inputs and outputs on opposite facets,
  - Each WG coupled to 1 SPAD
- Manipulation:
  - MZI, based on heaters
- Detection:
  - Si SPADs
  - FBK "RGB" Technology (n-on-p junction type)

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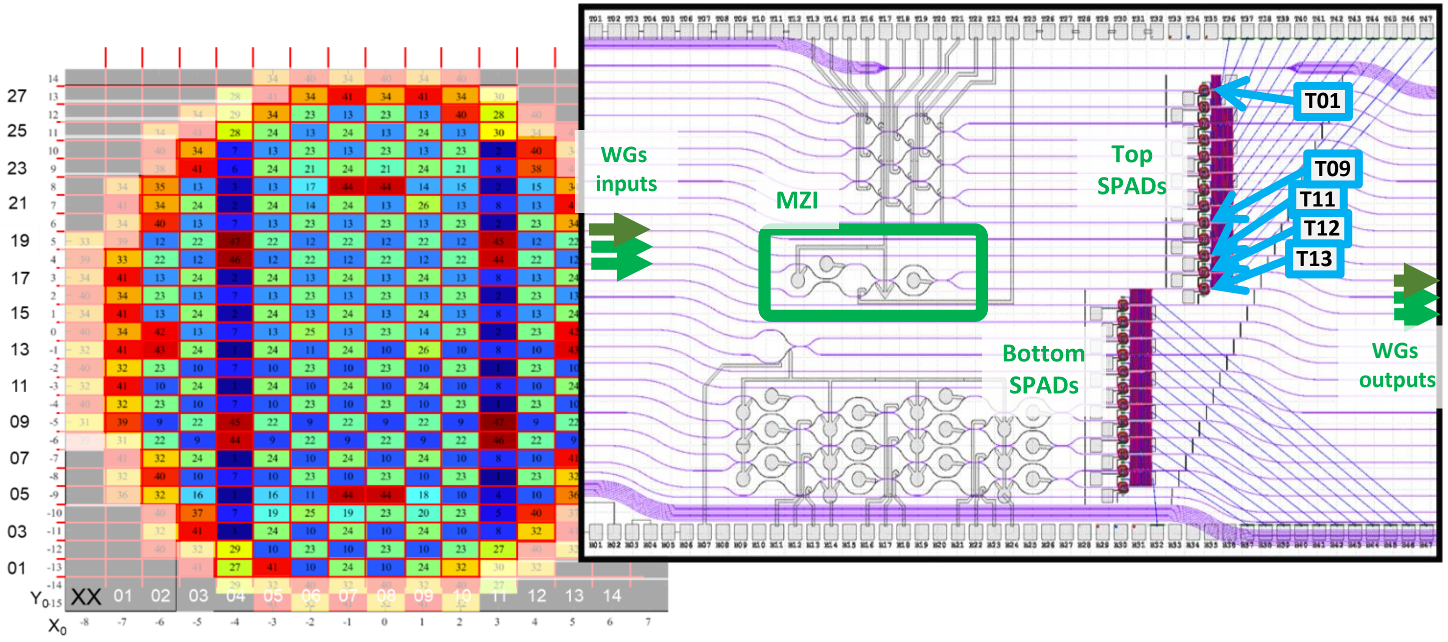
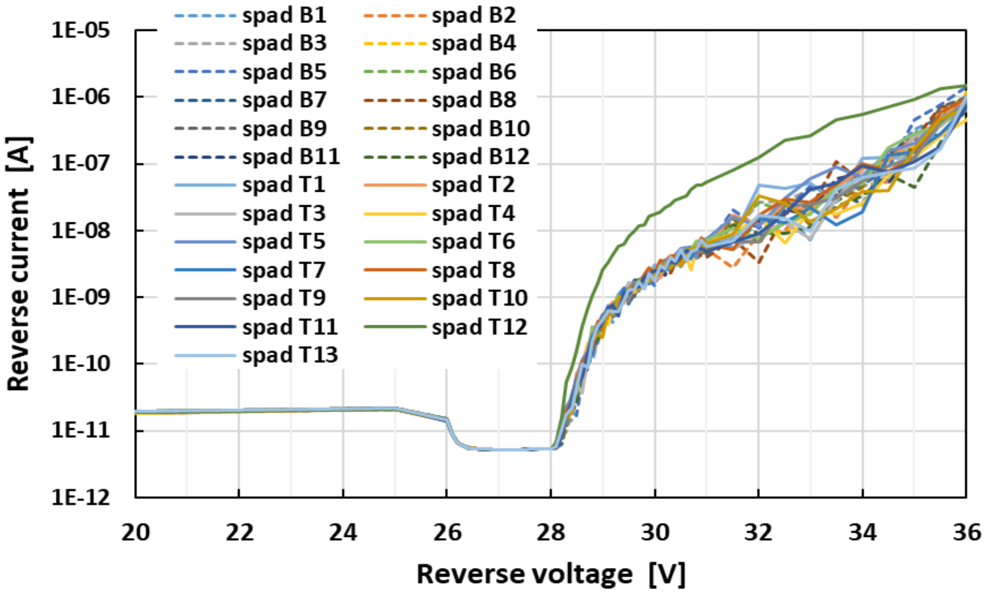
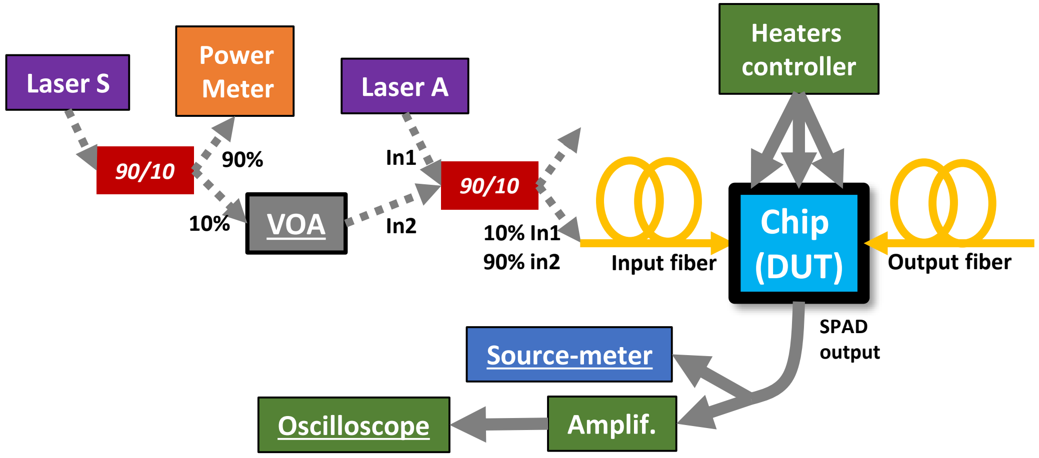
Electrical characterization

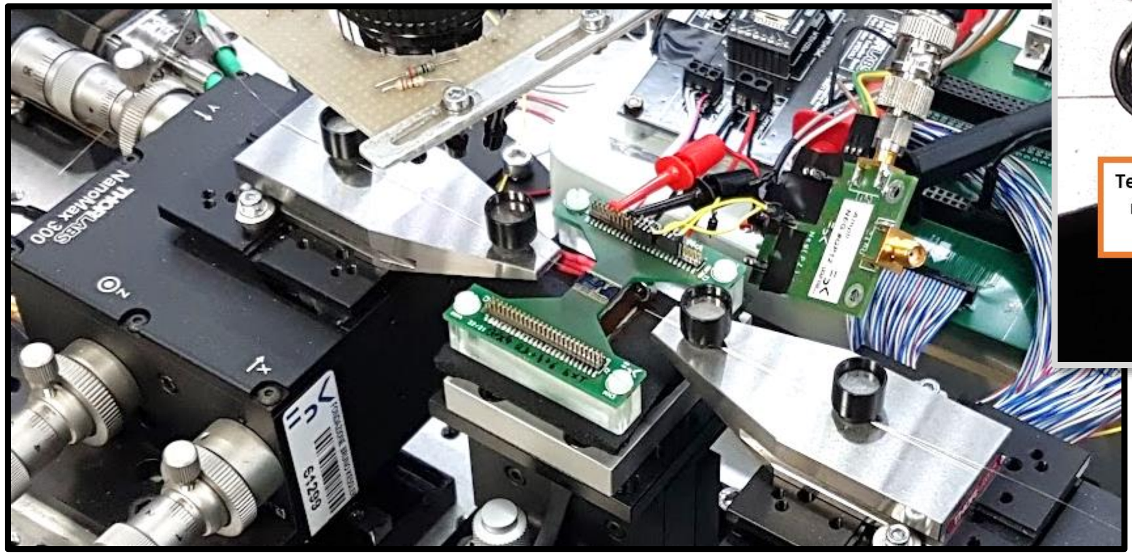


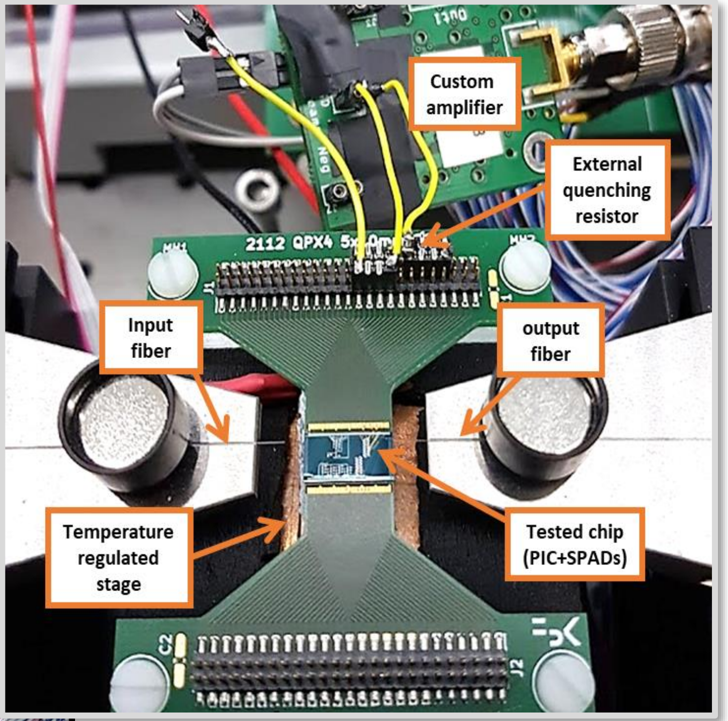


- ***Wafer level electrical testing → measurements of fw and reverse IV curves of diodes and SPADs***
  - Several chip tested
  - Good uniformity in breakdown voltage in the SPADs (~28V)
  - *Relatively low yield because of process-related issue → to be solved in future production*

Photonic/optoelectronic characterization







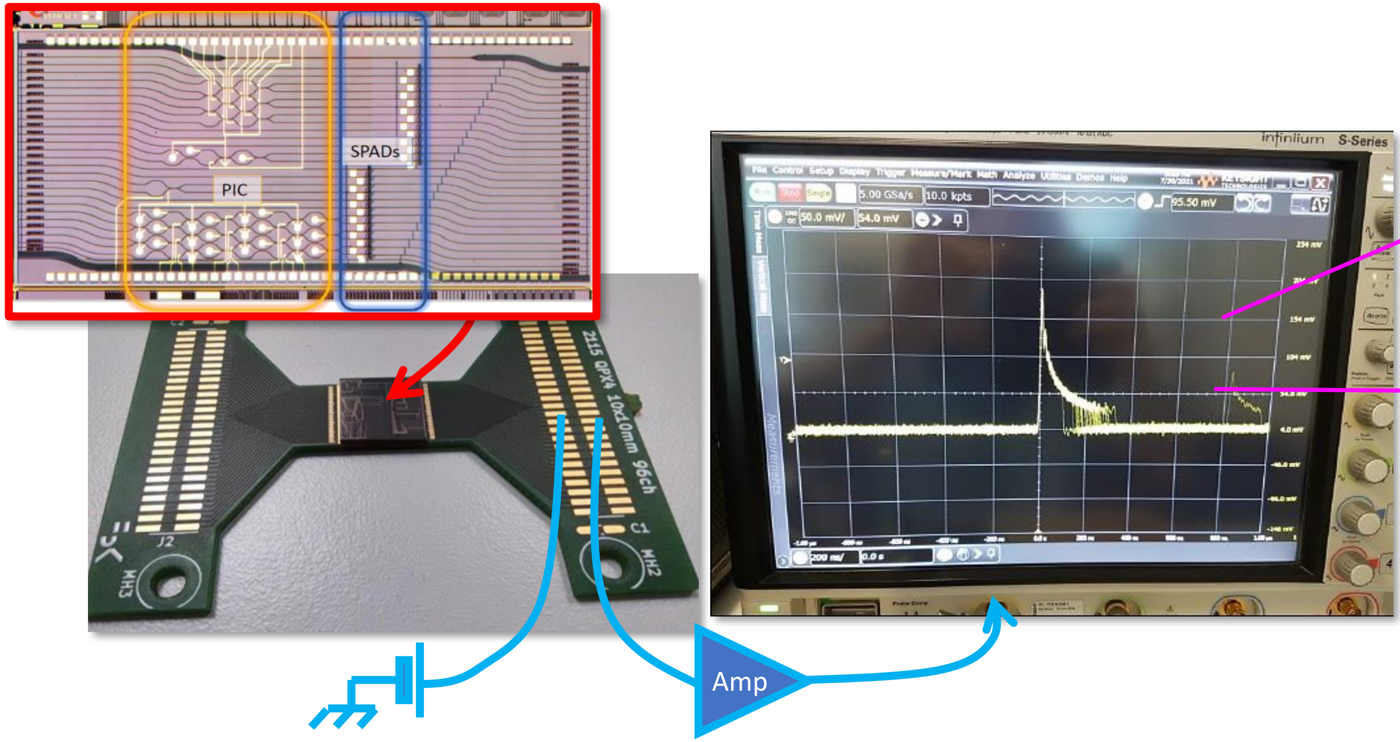
- Source laser (850 nm)
- Alignment laser

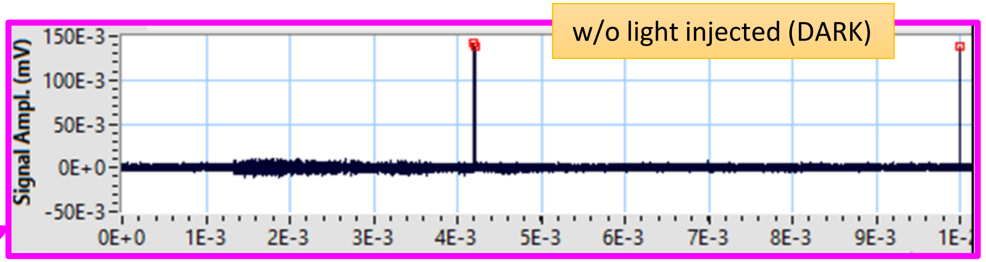
- Multiple variable optical attenuators:
  - Pre-calibration: with high light intensity
  - Use: to single-ph. Level

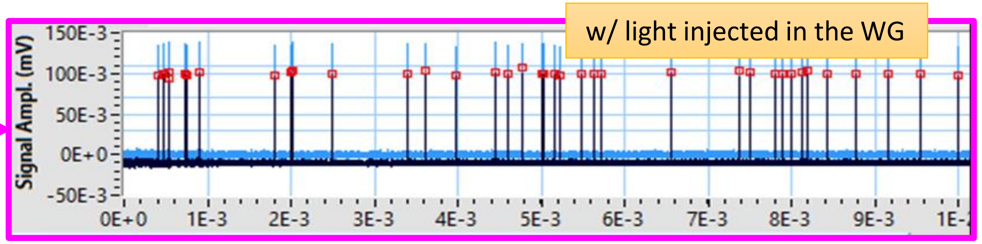
- TEC cooling

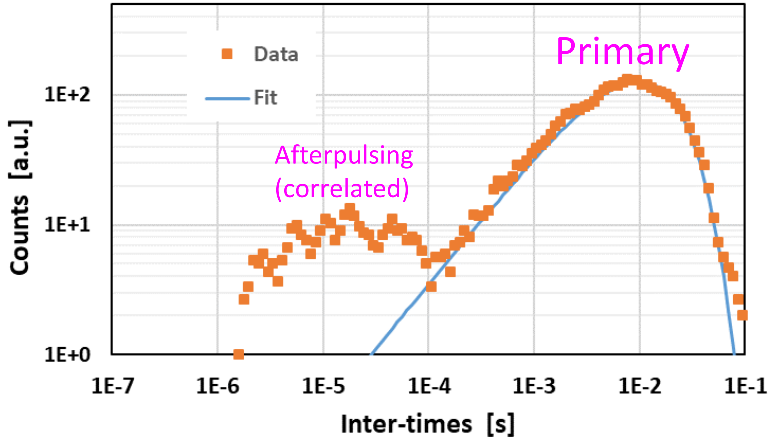
- SPADs:
  - External quench. resistors
  - Custom sig. amplifier

Pulse-counting performance



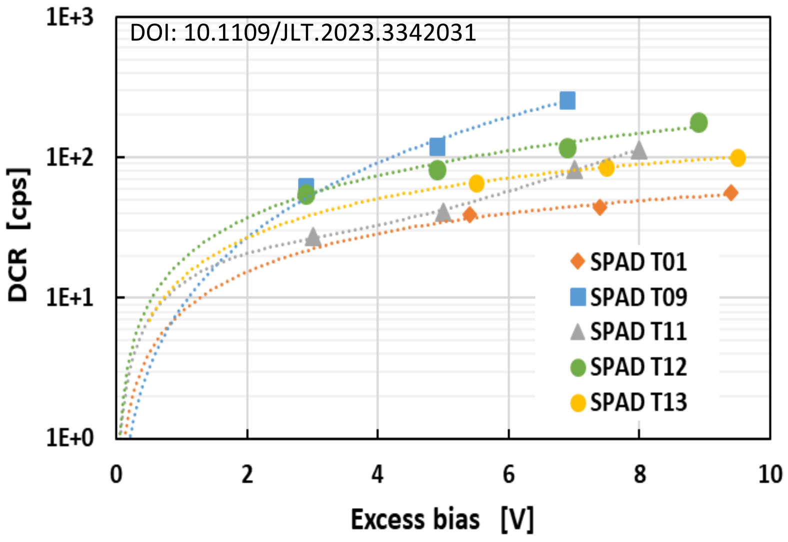


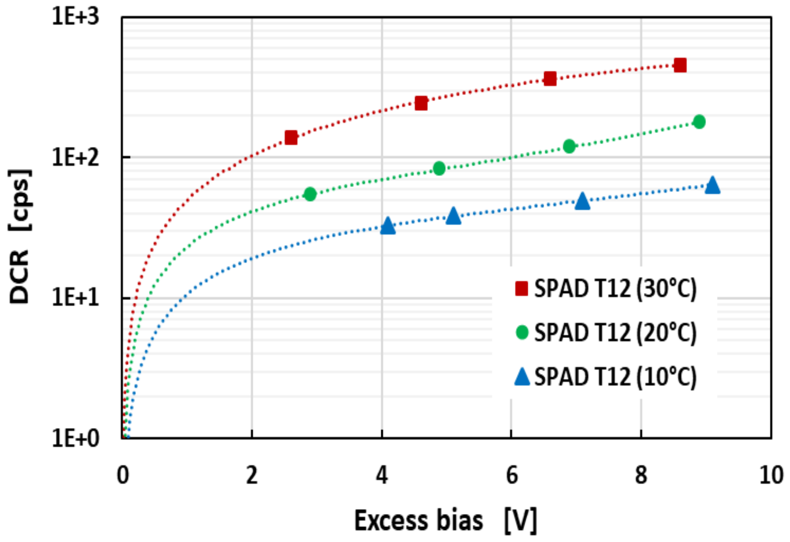


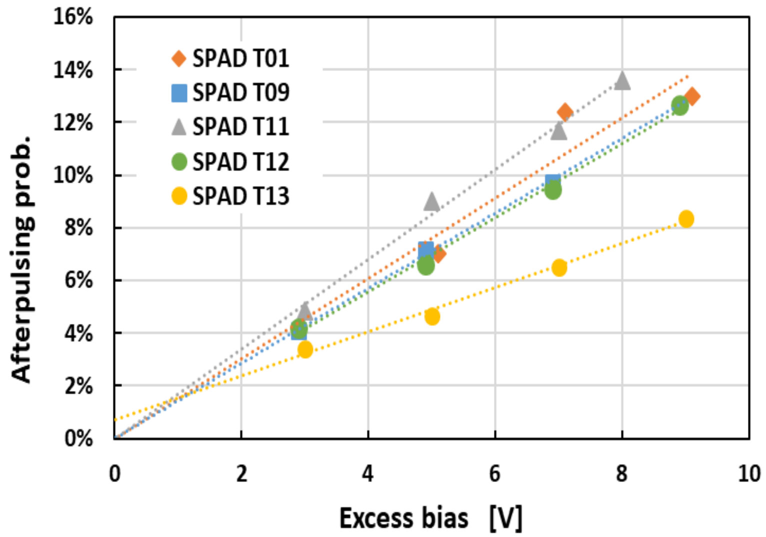


- SPAD pulse rate: proportional to the injected light intensity
- Inter-times between pulses → exponential statistics
  → extraction of primary and correlated events

Pulse-counting performance



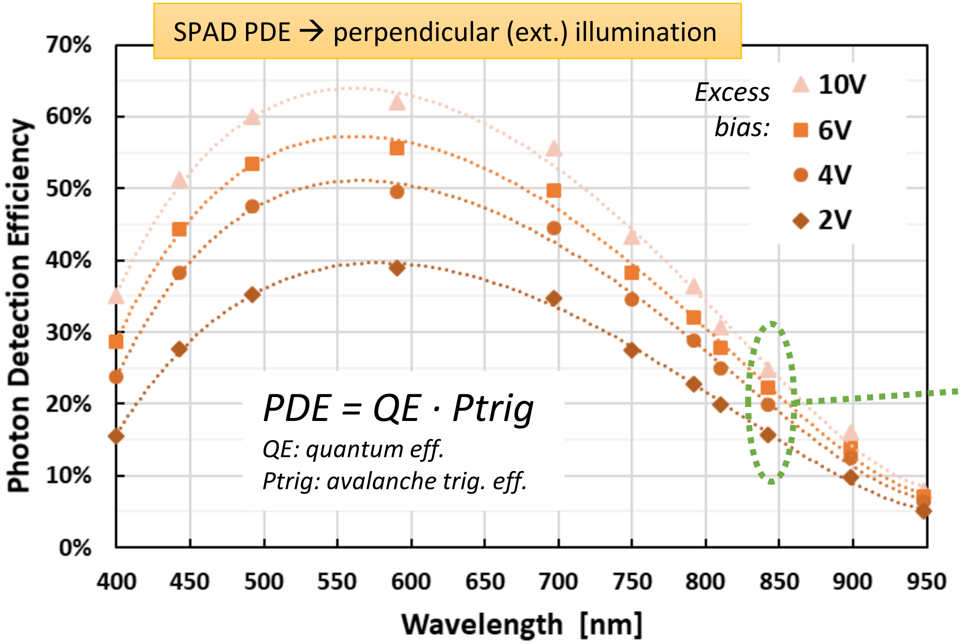


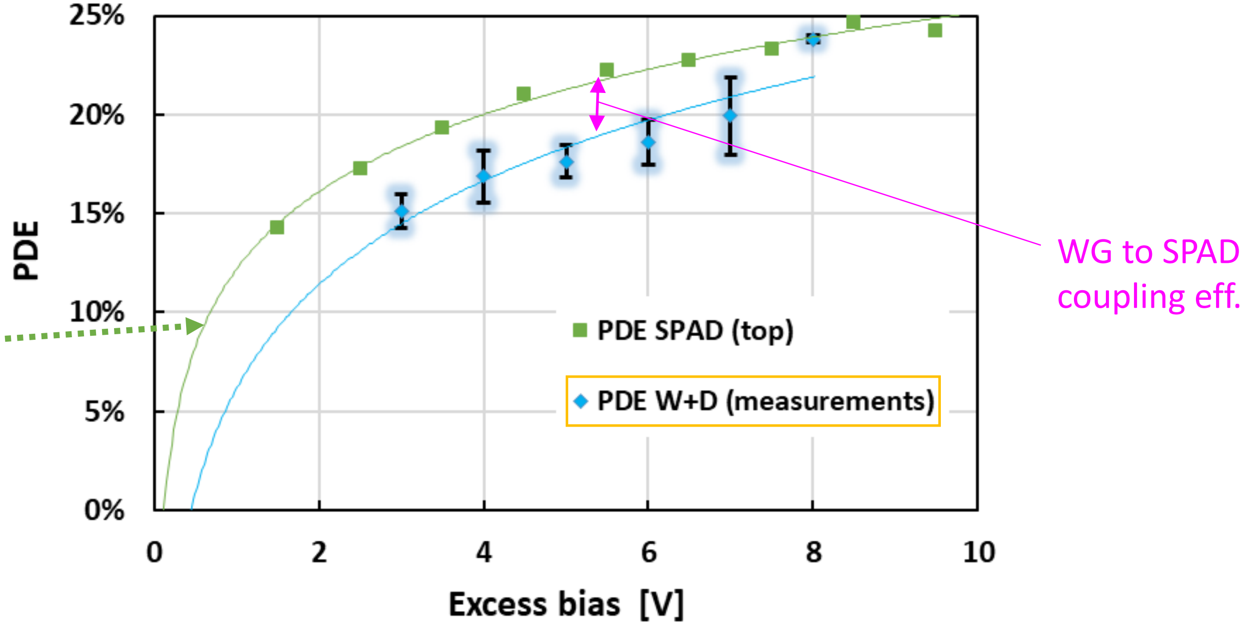


Excess bias: bias above the breakdown voltage

- Dark count rate (primary noise)
  - ~100 counts per second (cps) @ 20°C
  - in line with state-of-the-art Si-SPAD (commercial product)
- Temperature dependence: DCR halved about every 10°C
- Afterpulsing relatively high → *because of the external quenching (not optimized)(not the operative conditions)*

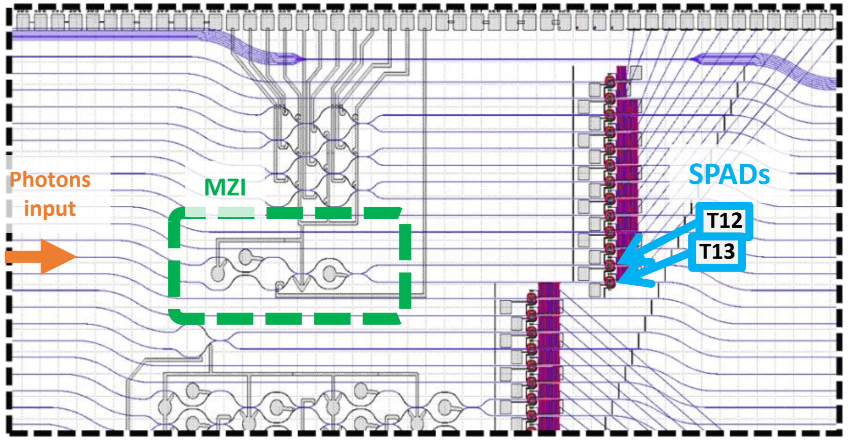
Detection efficiency and light-coupling efficiency

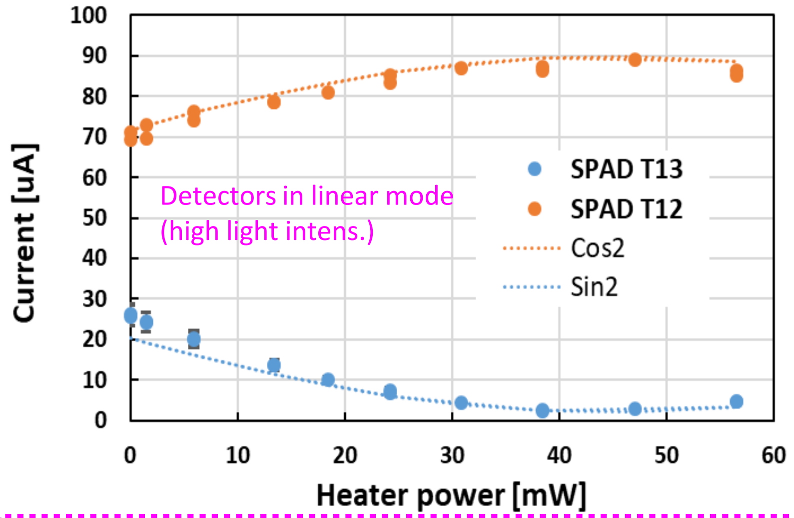


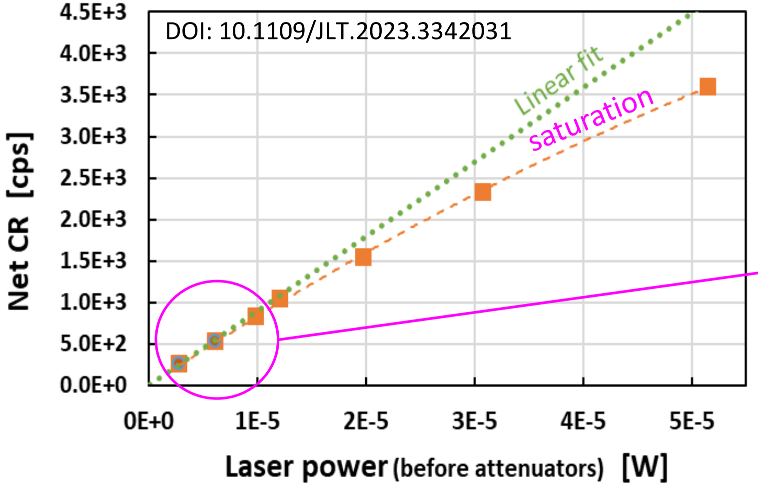


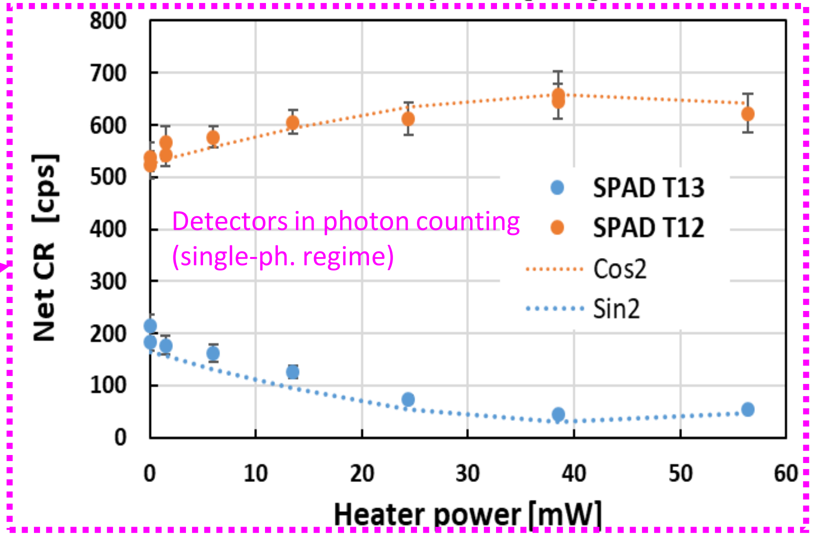
- Si-SPAD measurement with external light:
  - peaked in the green wavelength region; PDE= ~20% ÷ 25 % at 850nm
- laser light injected into WG + detection by SPAD:
  - *Detection efficiency= ~17% ÷ 20 % at 850nm* → *WG-to-SPAD coupling efficiency= ~ 76% ÷ 85%*

Light modulation with MZI









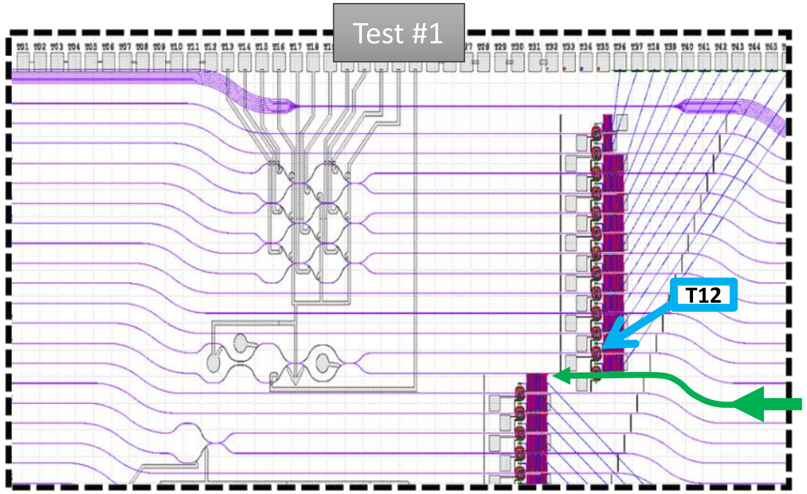
- ***Direct test of photon manipulation and detection***

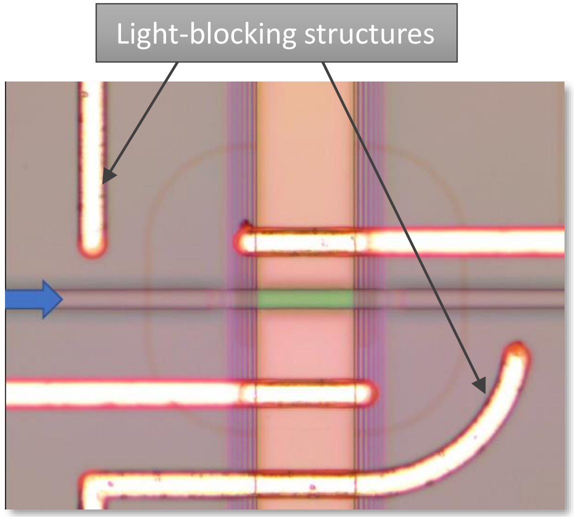
- Single photons injected.
- MZI (driven by heaters)
- 2 SPAD detectors

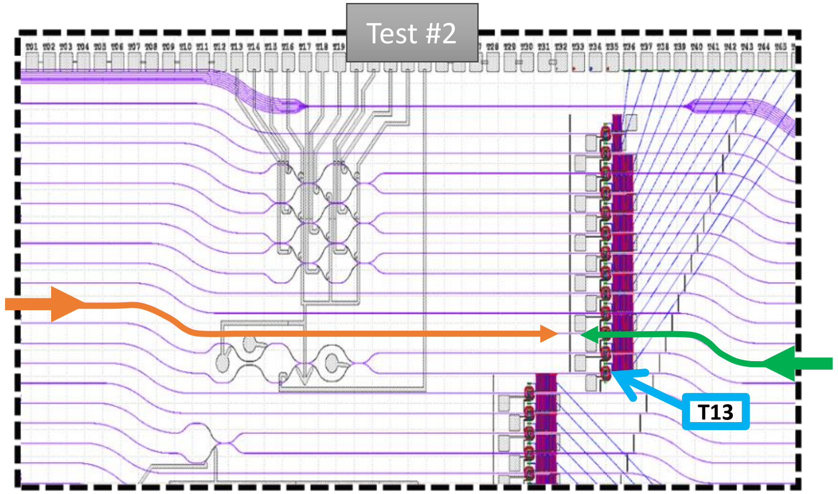
Procedure:

1. Selection of non-saturated power range
2. Heater power modulation
3. Count rate measurements (in the 2 SPADs)
4. *Good agreement: photon counting behavior vs linear-mode behavior*

Stray-light estimation







- Test #1: light from the right side WG associated to SPAD T13, monitoring SPAD T12.
  - we estimated a detection efficiency of about ***0.04%***.

- Test #2: light from left or right side of WG associated to SPAD T11, monitoring SPAD T13
  - detection efficiency around ***0.03%*** (first case) and ***0.16%*** (second case).

Conclusions

- New ***CMOS compatible top-down evanescent approach for monolithic electronic-photonic integration***
  - ✓ material all CMOS compatible,
  - ✓ it does not require alignments, butt coupling, or two waveguides made in different materials,
  - ✓ it can be operated at room temperature,
  - ✓ design of the SPADs does not have particular restrictions.

- Fabricated the first PIC based on SiON waveguide and with integrated silicon SPADs:
  - moderately low dark count rate
  - Good photon detection probability (improvable in future runs)
  - SPADs well appropriate for short gating pulses in a photonic quantum simulator.
  - system detection efficiency (i.e. PIC+SPAD), being between 17% and 20%
  - Waveguide-to-detectors coupling efficiency ~ 80%.

- Direct test of photon manipulation and detection:
  - Modulation of photons propagation between two adjacent waveguides and detection.

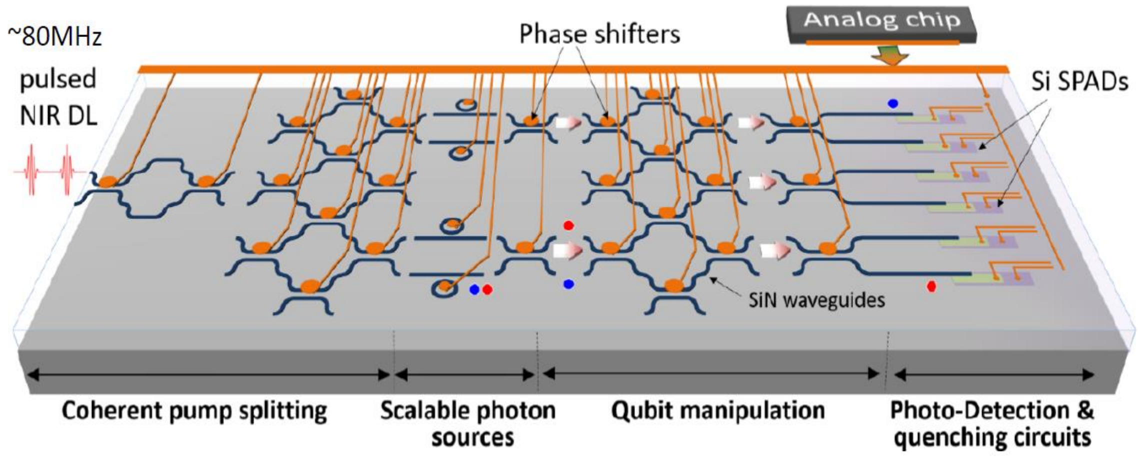
- Promising technology for future developments at FBK.

- Future runs: improvement of detection efficient (light trapping)

Acknowledgements

Electronic photonic integrated quantum simulator

EPIQUS



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Quantum Photonic Circuits with monolithically integrated Silicon Single Photon Detectors

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Integrated photonic electronic platform for quantum technologies

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