Conceiving and designing high-performance TCSPC systems for biological and quantum imaging

P2-10

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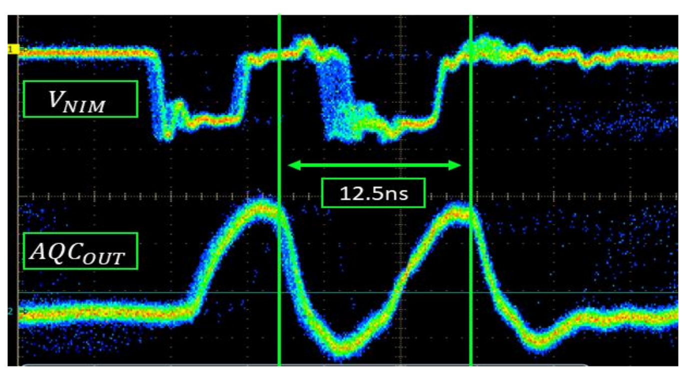
Surpassing TCSPC pile-up

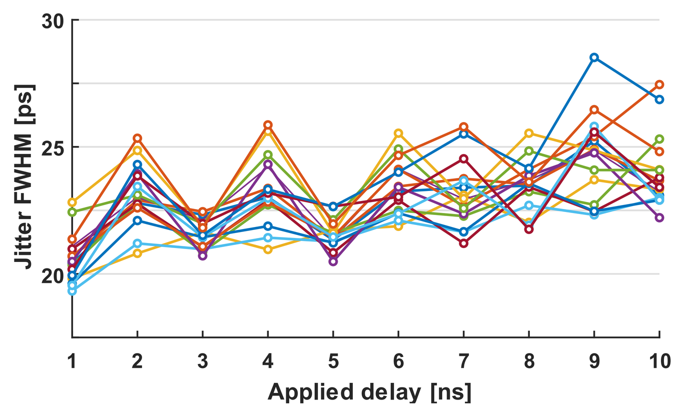
Background

In a typical TCSPC experiment, pile-up distortion is limiting the maximum acquisition rate to few percent (1-5 %) of the laser excitation rate. Due to the intrinsically repetitive nature of TCSPC experiments, a long acquisition time is needed for each single measurement. An increase in the overall acquisition rate would therefore pave the way to new advanced and real-time imaging techniques.

New approach

Based on theoretical studies and simulations, we demonstrated that it is possible to overcome pile-up limitation by matching the detector dead time to an integer multiple of the laser period. To this aim, we implemented the first system capable of applying the new technique.





SPAD Detection Module

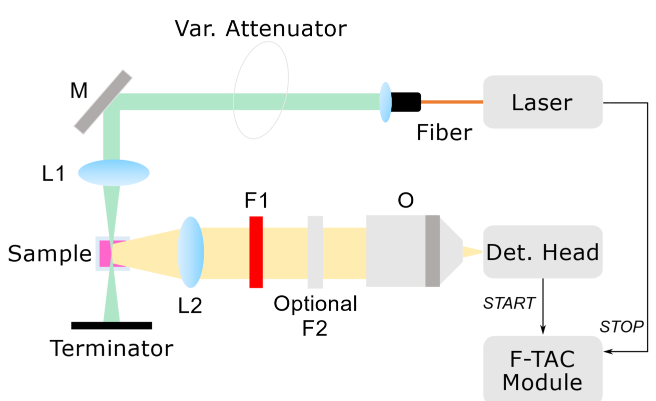
- Differential cell of thin SPADs
- Dead time matching (e.g. 12.5 ns) with tunable active quenching circuit (AQC)
- Transimpedance amplifier for avalanche current readout
- Jitter of 45-55 ps FWHM

TCSPC Timing Module

- Interleaved time-to-amplitude converter
- High-performance ADC and FPGA
- 1 ch at 80 MHz or 16 ch at 5 MHz
- USB3 communication
- Jitter of 20-25 ps FWHM
- DNL 0.85 % LSB rms

Results

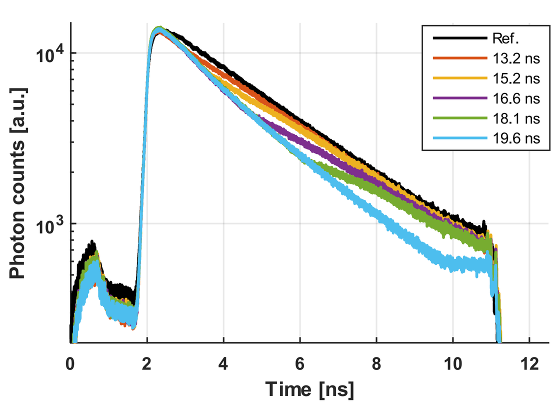
To validate the proposed technique, we performed fluorescence lifetime measurements with a standard setup and with a single-pixel camera, comparing non-distorted waveforms and images at low photon rates with those at high photon rates both with matched and non-matched dead time. The dead time is swept thanks to the tunable AQC.

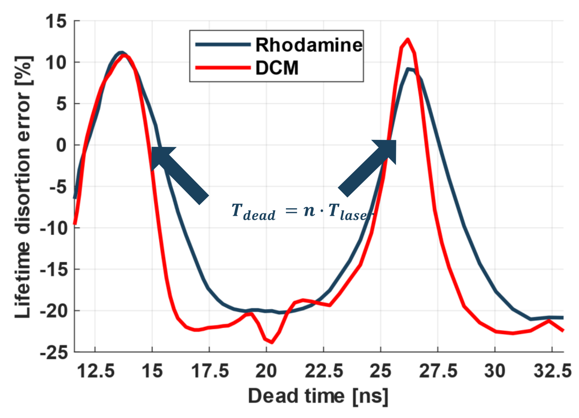


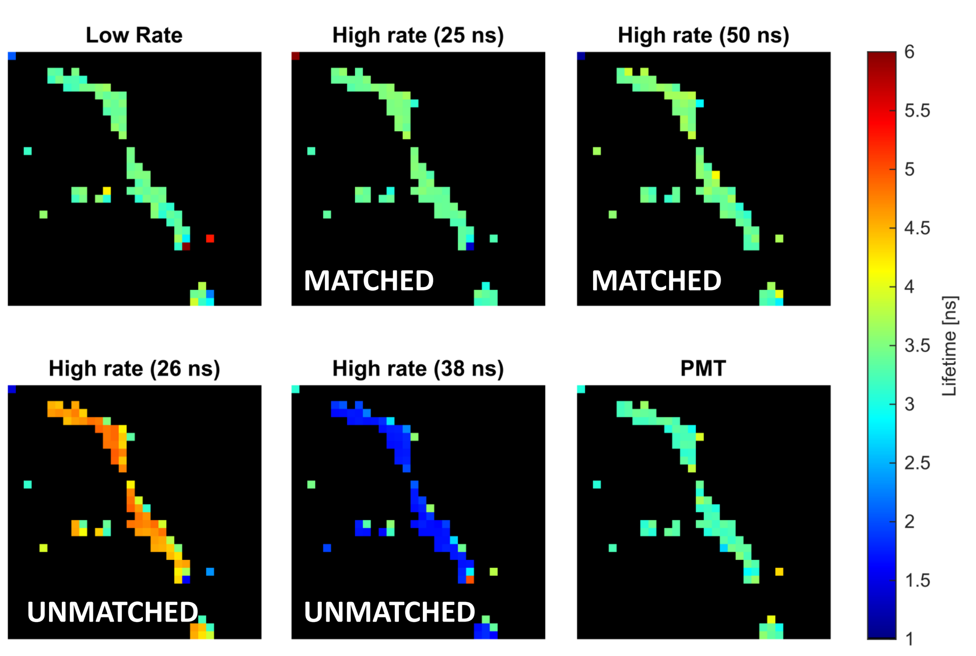
Bottom left:
- Black curve: reference curve at low photon rates, overlapped with matched dead time curves at high photon rates (12.5 ns and 25 ns)
- Other curves: distorted at high rates due to unmatched dead time

Bottom right:
- Lifetime distortion error versus dead time
- With matched dead time distortion error is negligible even at high photon rates

Top:
- Supercontinuum laser 80 MHz
- Variable attenuator to generate high and low photon rates
- Rhodamine B and DCM samples



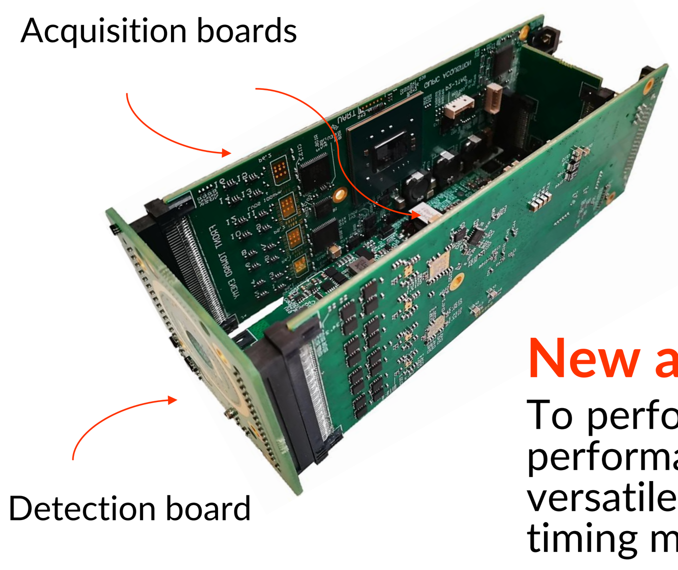




Single-pixel camera:
- High photon fluxes available on a single-pixel detector
- Structured light illumination with digital micromirrors devices (DMD) and image reconstruction from frequency to spatial domain
- High rate image with matched dead time in good agreement with low-rate and PMT-based instrument

Farina et al., Optics Letters 47.1 (2022) ; Farina et al., Review of Scientific Instruments 92.6 (2021);
Cominelli et al., Review of Scientific Instruments 88.12 (2017);

Exploiting more channels



Background

Many advanced TCSPC experiments require the usage of timing and counting systems with several channels to perform multidimensional imaging, for example in time, in space or in wavelength. These systems are based on array of detectors and typically require low jitter and low DNL.

New approach

To perform a high variety of experiments with a single high-performance system, we propose a ready-to-use and versatile module, embedding both the detection and the timing modules in a single compact case.

The system is based on plug-and-play exchangeable boards, with easy reconfigurable solutions:

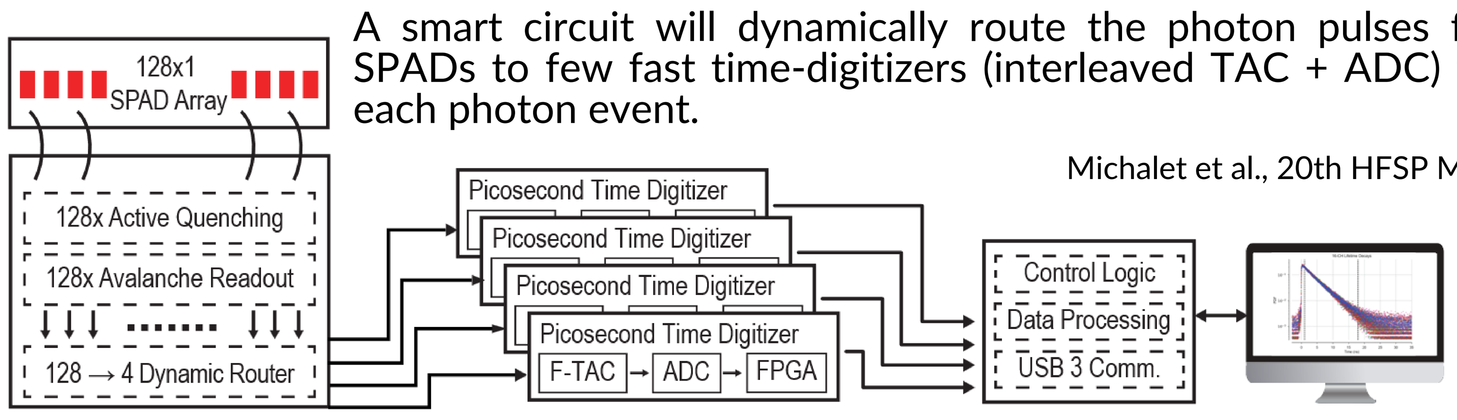
- Detection board: different array size (e.g. 32x1 or 8x8) of SPADs and their quenching circuits
- Acquisition board: two 16-channel boards with TAC, ADC and FPGA, and USB3 communication. The maximum number of available channels can be enhanced through router-based solutions.
- Power board: can support both Thin and Red Enhanced SPADs

Application example

In the framework of an HFSP project, the module will host a 128 Red Enhanced SPAD array with a detection efficiency >60% in the green and red and a timing jitter <100 ps FWHM.

A smart circuit will dynamically route the photon pulses from single SPADs to few fast time-digitizers (interleaved TAC + ADC) to time-tag each photon event.

Michalet et al., 20th HFSP Meeting (2021)



Attaining low jitter

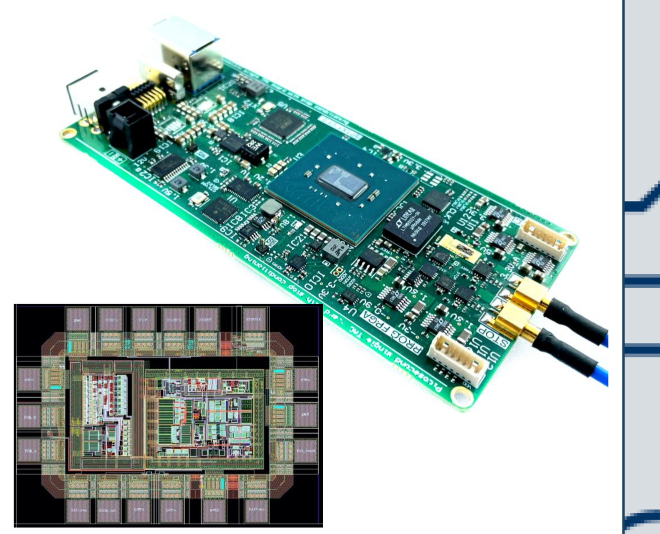
Background

In the last years, new sensors have emerged with extremely low timing jitter (<10 ps FWHM), namely Superconducting Nanowires Single-Photon Detectors (SNSPDs). Current commercial systems can reach low jitter only on a very small Full-Scale Range (FSR), being therefore unpractical for real applications.

New approach

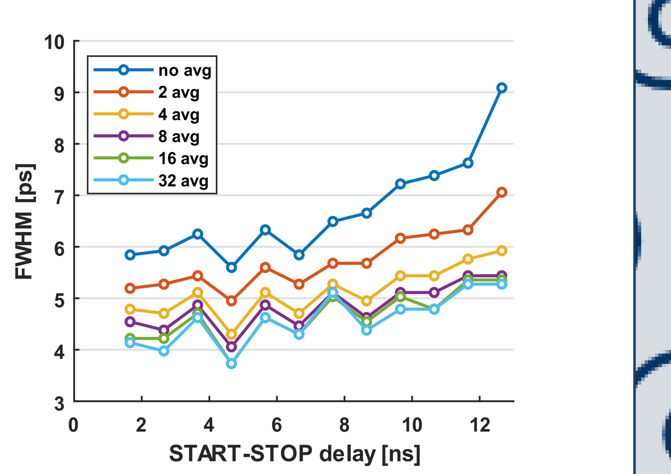
We propose a system capable to reach low jitter on a wide FSR, i.e. 12.5 ns. The main innovative elements consist in:

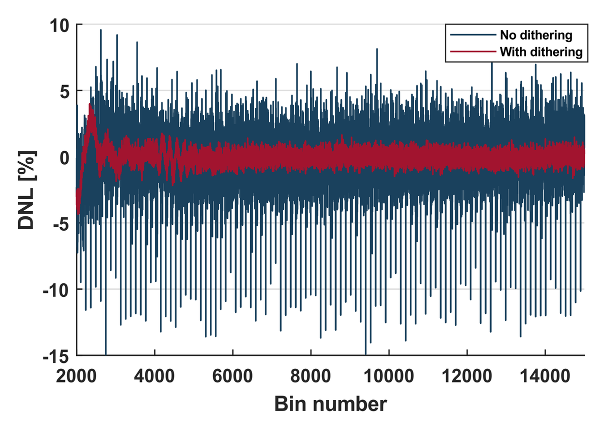
- New Time to Amplitude Converter with reduced jitter
- Low-jitter input comparator and high-performance ADC
- Improved signal and power integrity
- FPGA data memorization and USB3 communication



Results

FSR	Jitter FWHM 8 samples	Speed 1 sample	Speed 8 samples
12.5 ns	4.5 → 5.5 ps	12 MHz	7.2 MHz
25 ns	6.5 → 9 ps	10 MHz	6.4 MHz
50 ns	10 → 15 ps	7.9 MHz	5.5 MHz
100 ns	20 → 27 ps	5.4 MHz	4.3 MHz





- Lowest jitter at 12.5 ns (4.5 ps FWHM)
- Trade-off between lowest jitter and maximum speed due to averaging operation of consecutive samples
- DNL < 1.5 % LSB with dithering technique

Farina et al., IEEE Journal of Selected Topics in Quantum Electronics (2023);
Acconcia et al. IEEE Transactions on Instrumentation and Measurement (2023).

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