

Photon-number resolution with room-temperature detectors

Structured illumination microscopy with photon-number resolving detection

Daniel Scarbrough (Colorado School of Mines, Colorado, USA)

Matteo Moioli, Edoardo Mornacchi, Mireia Perera González (Swabian Instruments GmbH)

Photon detection is a fundamental and well-established capability in modern experimental physics, with applications in quantum optics, imaging, and communication. A key challenge is achieving photon-number resolution (PNR), the ability to precisely distinguish how many photons impinge on the detector. Superconducting nanowire single-photon detectors (SNSPDs) offer excellent PNR capabilities, but are expensive and require cryogenic cooling.

Here, we demonstrate PNR with room-temperature detectors, silicon photomultipliers (SiPMs) and hybrid photodetectors (HPDs), thanks to the picosecond-level precision of Swabian Instruments' Time Taggers.

EXPERIMENTAL SETUP AND METHODS

Figure 1 illustrates the experimental scheme employed for PNR measurements. An ultrafast pulsed laser source centered at a wavelength of 1035 nm (ThorLabs FSL1030-X1) is directed through a 4f Martinez grating pair system to compensate for pulse dispersion. The beam is guided into a structured illumination microscopy (SIM) system employing the spatial frequency modulation imaging (SPFI) technique [1] where the sample is positioned at the objective focus. Under excitation from the pulsed laser, the sample exhibits two-photon excitation fluorescence (2PEF) with a distinct fluorescent lifetime. The fluorescent light is collected with SiPM and HPD detectors, and their output is acquired with a Swabian Instruments' Time Tagger X (TTX).

To address the lack of temporal correlation between light emission and detector signals from incoherent 2PEF sources, two PNR analysis methods are developed based on Ref. [2]: *pulse-width* and *slope*. Signals are acquired with direct wiring and two- to four-way splits to compare our methods against the standard threshold-crossing approach, which differentiates the n and $n+1$ photons based on crossing a set voltage.

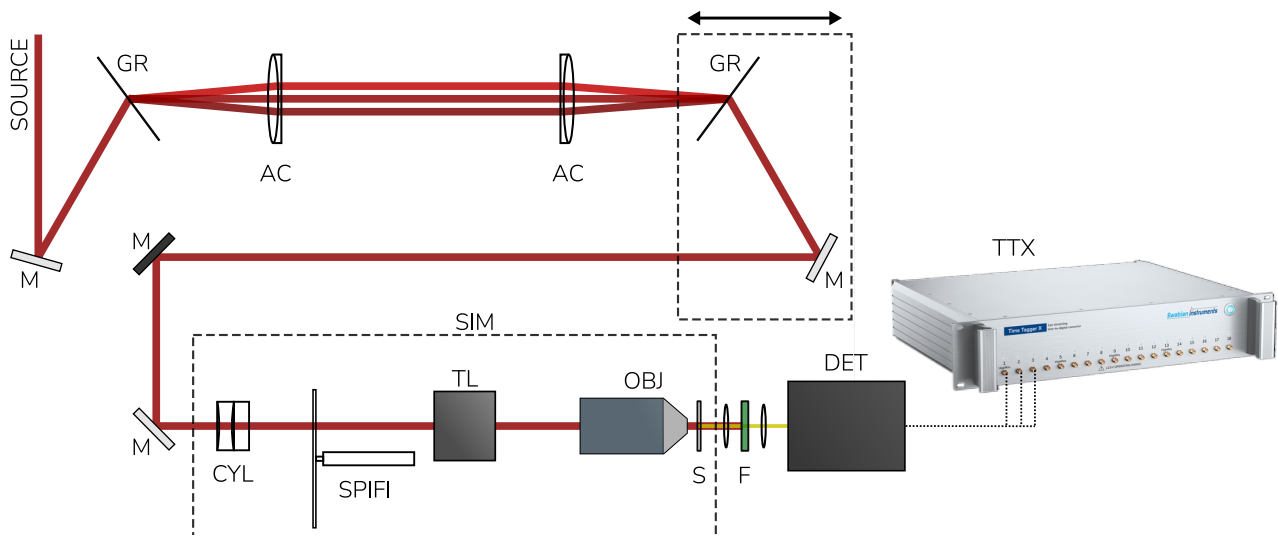


Fig. 1: Diagram of the structured illumination microscopy (SIM) system used for examining PNR with the Time TaggerX. The second grating and subsequent mirror can be shifted along the indicated axis to compensate for dispersion [1]. M: mirror; GR: grating; AC: achromatic lens; CYL: achromatic cylindrical lens; SPFI: modulation mask (not used during this experiment); TL: tube lens; OBJ: objective lens; S: sample; F: filter; DET: detector; TTX: Swabian Instruments' Time Tagger X.

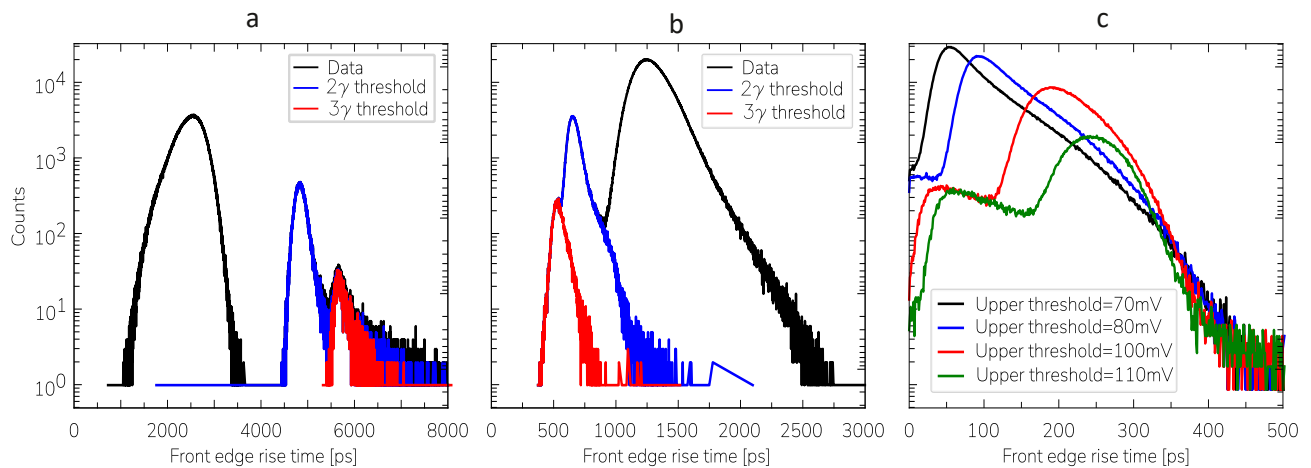


Fig. 2: Photon-number resolution with room-temperature detectors. (a-b) Signals from SiPM applying the pulse-width and slope method, respectively. The histograms obtained from the raw data (black) are compared with the ones where the time-tags are filtered out using thresholds corresponding to the amplitudes of the 2- and 3- photons peaks (in blue and red, respectively). (c) Signal from HPD using the slope method with the comparison of various upper thresholds.

PULSE-WIDTH METHOD RESULTS

In the *pulse-width* method, the Time Tagger records a pulse's rising and falling edges at a fixed trigger level to obtain the pulse-width and infer the number of photons contributing to the signal. SiPM detectors showed clear PNR, with well-separated 1-, 2-, and (3+)-photon peaks and a fidelity of 99.97%, 99.9% for the 1- and 2-photon peaks, respectively. Figure 2a compares raw and filtered data, where higher trigger levels isolated multi-photon events. The filtering was performed by parallel acquisition at voltages centered on the 2- and 3-photon peaks. HPD detectors, by contrast, showed less distinct peak separation with this method, making reliable photon-number assignment difficult.

SLOPE METHOD RESULTS

In the *slope* method, the detector signal is split into two channels with distinct trigger levels to obtain the slope of the signal from their time difference, and infer PNR. This method required better time resolution (hundreds of ps) but demonstrated PNR with SiPMs, with a fidelity of 99.9%, 75.6% for the 1- and 2-photon peaks, respectively, as shown in Figure 2b. HPDs performed better in combination with the *slope* method. Keeping the lower threshold level at 20 mV and adjusting the upper one between 70-110 mV, allowed the distinction of 1- and 2-photons. Figure 2c shows how increasing the threshold permits a better separation of the 1- and 2-photon components.

CONCLUSION

This application note demonstrates that SiPM detectors, combined with Swabian Instruments' Time Tagger, offer an effective, cryogen-free solution for PNR. In particular, the Time Taggers with their ability to acquire simultaneously from multiple channels, each with an independent trigger level and information on both the rising and falling edges of the signals, are essential for performing such experiments. The *pulse-width* method provides the best performance, particularly in combination with SiPM detectors, whereas HPDs delivered limited but promising results. While effective, the *slope* method requires an additional channel and offers slightly lower performance compared to the *pulse-width* approach.

REFERENCES

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- [2] G. Sauer, M. Kolarczik, R. Gomez, J. Conrad, and F. Steinlechner, *arXiv:2310.12472 [quant-ph]*