Ultra-fast Multipixel SNSPD Arrays with Photon-number Capabilities for Quantum Applications

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Abstract *We present a 14-pixel SNSPD array with a SDE of 90%, able to reach detection rates of 1.5 Gcps with an absolute SDE of 45%. We achieve a 2-photon fidelity of 74% and 57% for a 3-photon state, which represent state-of-the-art results for fibre-coupled SNSPDs.*

Since their inception[1], single-pixel superconducting nanowire single-photon detectors (SNSPDs) have had a profound impact in the field of optical quantum information processing and have demonstrated remarkable performances[2],[3]. However, a wide range of applications, from quantum-key distribution (QKD)[4], to integrated single-photon sources[5]–[7], would greatly benefit from detectors that could provide a considerably higher detection rate that what possible with conventional single-pixel SNSPDs, while maintaining a high efficiency. SNSPDs designs formed by parallel-connected pixels[8],[9] and based on spatial multiplexing have been explored, but their maximum detection rate is still limited to around ~ 100 Mcps[10]. Nonetheless, spatial multiplexing enables photon-number resolving (PNR) capabilities, a feature that is becoming increasingly important in several applications.

PNR capability is a critical requirement for linear optic quantum computing (LOQC)[11], Gaussian boson sampling (GBS)[12],[13], quantum networks based on quantum repeaters[14] and to achieve quasi-deterministic heralded single-photon sources[15],[16]. However, parallel SNSPDs can only resolve photon numbers with light pulse durations of up to a few hundred picoseconds at most[8], a limitation that could severely limit the use of such detectors.

Here, we will present an SNSPD array composed on 14 independent pixels, that is able to be operated in free-running mode and simultaneously deliver high performance in terms of system detection efficiency, jitter, recovery-time and maximum detection rate. The detector array demonstrates the ability to reach detection rates of 1.5 Gcps with an absolute SDE of 45%. When used in a QKD setup, the array can improve for the system performance, as it can enhance the detection count rate, perform quantum signal tracking tasks, and improve resilience against blinding attacks[17] by monitoring the coincidence clicks between the pixels[18]. A similar array, that we fabricated and characterized, has already been exploited to demonstrate high-speed QKD, with secret-key rates exceeding 60 Mbps over a distance of 10 km[4]. Moreover we will present a full analysis of the PNR capabilities of independent multi-pixel arrays and show a demonstration of operation with long light pulses, which is crucially still lacking in literature.

Results

The multi-pixel SNSPD array covers an area of roughly $200\,\mu m^2$, and is composed of 14 independent pixels arranged in a semi-interleaved geometry in order to guarantee a uniform light distribution, but also minimize the length of each pixel, as shown in Fig. 1.

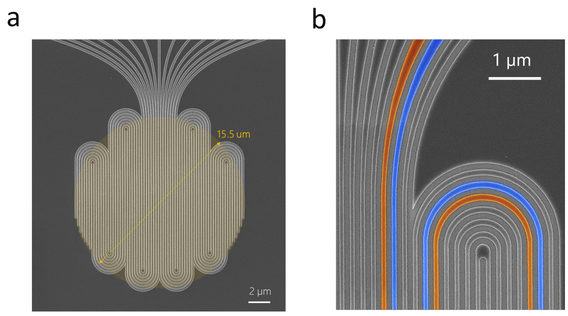

Fig. 1: 14-pixel SNSPD array. a, SEM image of the 14-pixel detector array. **b,** Recolored SEM image highlighting the path of two adjacent pixels.

We verify the performances of each individual pixel in terms of efficiency, recovery time, count rate, and jitter, as shown in Fig. 2. By summing up the maximum single-pixel efficiencies (presented in Fig. 2(a)), we estimate a total efficiency for the entire array of $\sim 89\%$. This estimation was then verified experimentally, as presented below in the abstract. Due to our semi-interleaved design, a slight misalignment between the fiber and the

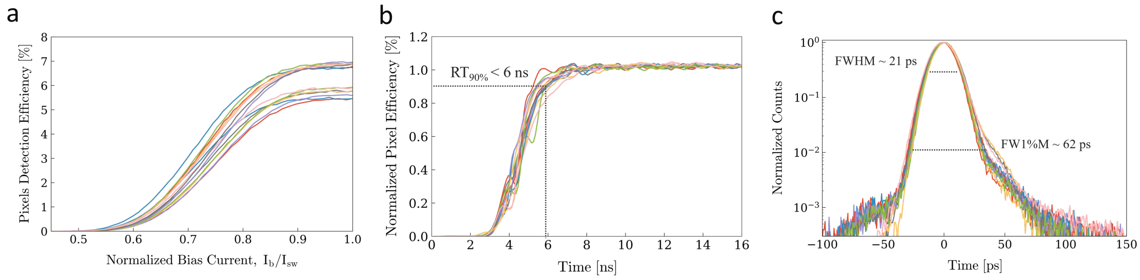

Fig. 2: Single-pixels characterization. a, Single-pixel detection efficiencies measured at 1550 nm as a function of the bias current. **b,** Recovery time measurement for the 14 individual pixels. The $RT_{90\%}$ is lower than 6 ns for all pixels. **c,** Jitter measurement for the 14 pixels.

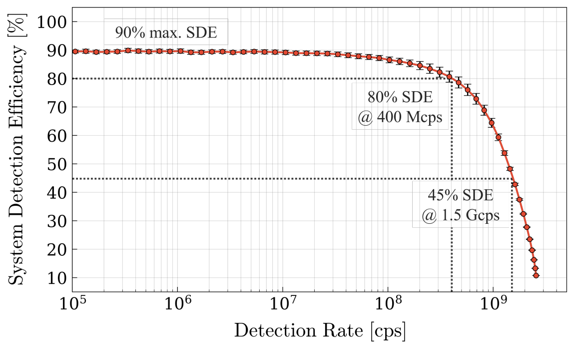

Fig. 3: SDE as a function of detection rate acquired with all 14 pixels active.

center of the array resulted in an uneven illumination of the detector, causing one set of 7 pixels to present a higher efficiency than the other set, as can be seen in Fig. 2(a). Since the detector covers the same area as a conventional single-pixel SNSPD, the length of each nanowire is greatly reduced, and so is its kinetic inductance (L_k), allowing for much faster operation, as can be seen from the ultra-fast recovery time (see Fig. 2(b)). Each pixel shows a full width at half maximum (FWHM) jitter of 21 ps (without any de-convolution) and an average full width at 1% maximum (FW1%M) jitter of 62 ps for currents close to I_{sw} (see Fig. 2(c)), which allows the time-precision needed for high-speed QKD.

After characterizing each pixel individually, we measure the performance of the array in terms of total system detection efficiency (SDE) and detection rate capability in free running mode, as shown in Fig. 3. As can be seen in Fig. 3, we measure a maximum SDE of $89.5\% \pm 0.7\%$ for detection rates up to 10 Mcps, with a SDE that remains above 80% up to 400 Mcps. The maximum count-rate (MCR) is determined as the detection rate at 50% of the maximum SDE, *i.e.* 45% absolute efficiency for our detector, and for which we achieved a MCR of 1.5 Gcps. Thanks to the latch-free operation, we can also operate the detector at even faster detection rates, and we obtain an average SDE photon of 27% at 2.1 Gcps.

We finally illustrate the potential of our SNSPD array for use in quantum optics experiments, when operated as a photon-number resolving (PNR) detector, by measuring and reconstructing the photon statistics of long-pulses Poissonian light. Based on ref.[19] we estimated the photon fidelities of the array, *i.e.* the probabilities of correctly identifying n-photons when n-photons are sent. The detector has 2-photon and 3-photon fidelities of 74% and 57%, respectively, which represents a significant step forward with respect to the best reported values in literature for fiber-coupled SNSPDs, *e.g.* 48% for 2-photon fidelity and 9% for a 3-photon state[9]. As mentioned previously many promising protocols based on quantum repeaters require the use of heralded single photon sources along with quantum memories for storage of entanglement[20]. These systems require narrow bandwidth photons, corresponding to photons with long coherence times up to several nanoseconds[21],[22], which we refer to as the long light-pulse regime. Such a regime is also relevant for implementations of LOQC or GBS using squeezed states of light generated from cavity-enhanced SPDC[13] or SFWM sources[23]. As such, photon-number resolving detectors which can extract photon-number information from long light pulses is likely to become crucial in the implementation of these systems. However, parallel and series SNSPDs and impedance matching taper SNSPDs[24] can only operate with short light pulses (hundreds of picoseconds) due to their intrinsic detection mechanism. We tested the performance of our detector in the long light-pulse regime, by sending coherent light pulses of 10 ns produced by modulating a 1550 nm CW laser, see Fig. 4(a-d). Even in this regime, we were able to correctly reconstruct the input light statistics for μ up to 3.4, thus enabling the use of PNR SNSPDs in the long light-pulse regime.

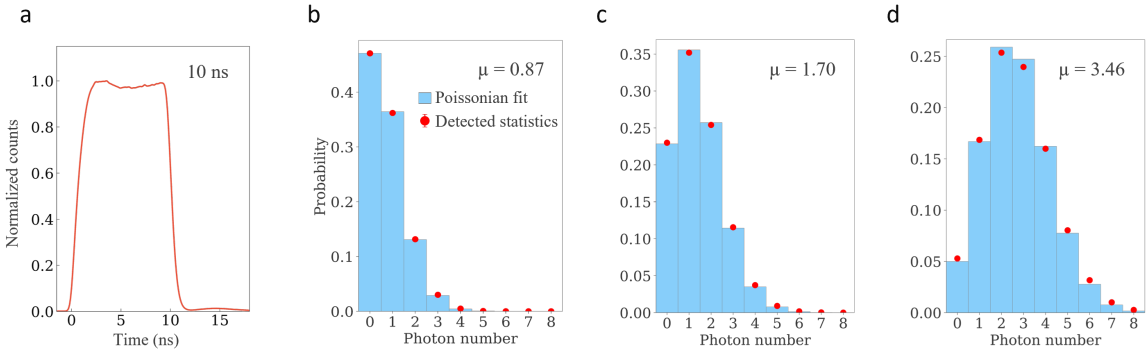

Fig. 4: Photon-number resolution and state reconstruction with long pulses of light. a Estimated profile retrieved from the counting histogram of a single pixel for $10\,\mathrm{ns}$ light-pulses. **b-d** Experimental and retrieved photon-counting statistics under Poissonian light illumination $10\,\mathrm{ns}$ light pulses.

Conclusions

Good luck with your submission! In conclusion, we will present a 14-pixel SNSPD array with a maximum system detection efficiency (SDE) of 90% that remains above 80% up to $400\,\mathrm{Mcps}$, and we demonstrate the ability to reach detection rates of $1.5\,\mathrm{Gcps}$ with an absolute SDE of 45%. Furthermore, we will explain how such device has been integrated in a QKD set-up and enabled high-speed QKD, with secret-key rates exceeding $60\,\mathrm{Mbps}$ over a distance of $10\,\mathrm{km}$[4]. Finally we will show that the detector is able to distinguish few-photon number states in an optical pulse with high fidelity, without posing strict limitations on the shape of the incoming light. We achieve a 2-photon fidelity of 74% and 57% for a 3-photon state, which represent state-of-the-art results for fiber-coupled SNSPDs. Such detectors could find immediate application in LOQC protocols where the capability to distinguish few photon-number states is sufficient – that is, either ‘1’ *vs* ‘more than 1 photons’[25],[26].

Acknowledgements

We acknowledge financial support from the Swiss NCCR QSIT, from the SNSF Practice-to-Science Grant No. 199084 and Grant No. 200020-182664 and from Innosuisse Grant No. 40740.1 IP-ENG. L.S. is part of the AppQInfo MSCA ITN which received funding from the EU Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 956071.

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