Integrated Spectral-Correlator with Ultra-high Time-resolution and Efficiency (INSPECT)

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ABSTRACT

Optical sensing is a vast and rapidly expanding field, demanding future applications require revolutionary sensors with high detection efficiency, high time resolution, spectral resolution, and statistical analysis of light. There are however no detectors currently available offering all these features simultaneously. In INSPECT combines integrated photonics with superconducting detector technology to realize a micro-meter sized spectrometer combining the described functionalities, all at once. The detectors' high quantum efficiency, state of the art timing resolution, and close to unity coupling to nanosized waveguides allow for combining spectral analysis with direct measurements on higher order photon statistics.

1. INTRODUCTION

From visible to mid-infrared, superconducting nanowire single photon detectors (SNSPDs) have demonstrated excellent performances in terms of efficiency, temporal resolution and dark counts. These features make SNSPDs ideal candidates for photon detection in communication, computing, sensing, and light ranging and detection (LiDAR). However, it is difficult to extract spectral information about the measured signal, unless the detector is coupled with bulky and lossy wavelength-selective elements to allow for only a narrow spectral range of the signal to interact with the detector.

In INSPECT, we develop micrometer sized spectrometers in integrated waveguides by physical computation of the Fourier transform of light signals on-chip, with minimum losses and no moving parts. A schematic of the device is shown in Figure.1, our detector is classified as stationary-wave integrated Fourier transform spectrometry (SWIFT). The concept is more than 100 years old since the invention by Lippmann, which resulted in the 1908 Nobel Prize in Physics. The spectrometer is usually coupled to CCDs to perform spectral analysis for astronomical and medical applications, with limited time-resolution and restrictions on the central operating wavelength and bandwidth due to several physical and engineering challenges. In INSPECT we go beyond current demonstrated technologies regarding photonic design/fabrication to electronic driving circuits and data analysis software, all enabled by state-of-the-art technologies developed by KTH and SQ. In order to reconstruct the spectrum of the input signal, the Nyquest Shanon criteria must be satisfied. This requires several number of independently operated detectors on the same chip, each with its own readout. The task proves to be a difficult task, since aiming for hundreds of detectors requires similar number of coaxial lines to address each detector, which hinders the performance of the detectors and limits maintaining the superconductivity due to the temperature increase

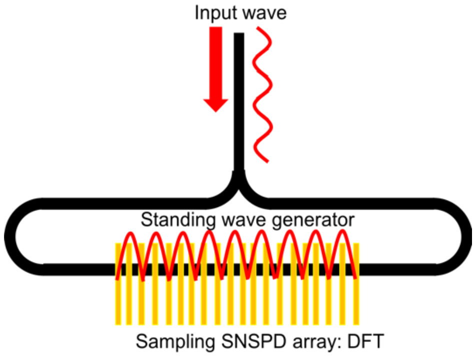

Figure.1 Standing wave integrated Fourier transform. The device consists of a SiN waveguide formed in a loop to interfere the input signal with itself generating standing waves. The standing waves will be sampled an array of superconducting single photon detectors.

In Inspect we performed dispersion engineering of the superconducting single photon detectors transmission line, to achieve slow RF signal propagation. This enabled time-division-multiplexing of single photon detectors on the same transmission line, thus enabling the usage of a single biasing and readout circuit for the multiple-detectors. The fabricated slow-RF coplanar waveguide provides a delay of 1.7 picoseconds per 1μm of propagation, corresponding to detection signal speeds of approximately 0.0019c, where c is the speed of light in vacuum. Additionally, the detectors show low dark counts with saturated internal efficiency, combined with high time resolution of 70 picoseconds without the need of any cryogenic amplification.

2. STATE OF THE ART

Superconducting single photon detectors (SNSPDs) with their close to unity detection efficiencies[1], wide detection range[1], sub 3 picoseconds timing resolution[2], and versatile integration with different photonic platforms[3], are central resources for quantum information technologies[4]. Optimization of SNSPD operation and understanding the physical limits of their performances have been extensively performed since their conception[5], the current aim is to realize large scale systems making use of this powerful detection technique[6]. A straight forward approach would be to include independent RF feedlines for each individual detector. This is challenging when aiming for thousands of detectors, in addition to the cooling power required to operate a large number of RF lines, other more sophisticated approaches include frequency-[7], amplitude-[8], and time-multiplexing[9-12]. Frequency multiplexing requires precise tone generation to address individual SNSPDs, coupled with the ability to fine tune individual detector resonance circuits (or the driving frequency), at will, placing practical limits on the complexity and number of detectors addressed. Amplitude multiplexing on the other hand, provides a simpler approach, but is more susceptible to noise and errors, that can limit the number of identifiable logic levels, a common challenge to amplitude modulation techniques. Time multiplexing has advantages in terms of operation simplicity, but two main challenges must be addressed: (1) individual detector jitter needs to be minimum, setting a lower limit on time-bin size. (2) The high on-chip RF propagation velocity places practical challenges on the devices dimensions to achieve the needed delay for time multiplexing[10]. Recent demonstrations of multi-level integration [9, 11, 12] show the possibility to reduce the detection pulses group velocity on-chip, but the complexity of 3D integration places limits on device design and footprint, especially when integrating detectors with planar photonic circuits.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

INSPECT can simultaneously perform single photon detection, spectral analysis, time-stamping of detection events, and finally statistical analysis of photon sources. There are currently no available devices that simultaneously deliver these features, but for the purpose of surveying the field, we will mention competing devices that can only partially provide less competitive alternatives. Currently, two competing technologies are available to detect single photons at optical wavelengths based on two different material classes, semiconductors and superconductors. The detectors based on semiconductors are of the avalanche photo diode (APD) type, and for superconductors the detectors are made by etching a nanowire meander. Our team will use NbTiN superconducting detectors which surpass the specifications of APDs in detection efficiency, time jitter, dark-counts, rise time, dead time, detection rate, and after pulsing. Detection efficiencies of 95% with a time resolution approaching sub-20 ps, saturation count rates in the order of 100 MHz, and dark counts far below 1 Hz at a wavelength of 900 nm have been achieved at Single Quantum. It's worth mentioning that there is another class of superconducting detectors, transition edge detectors, despite their high detection efficiency and potential for number resolving detection, they offer orders of magnitude inferior timing resolution and operation speeds compared to NbTiN based superconducting detectors.

4. PROJECT RESULTS

The fabricated spectrometer is shown in Figure.2, it consists of a silicon nitride waveguide with forward and backward waves interfering at the centre of the device to form a standing wave pattern. 128 pixels are connected to 4 coaxial lines, so in total each coaxial line is used to read the signal form 32 pixels. This device is currently being tested due to a delay in the schedule due to covid-19. For multiplexing the pixels in time-domain, we utilize a powerful technique of waveguide dispersion engineering that is widely used for dielectric photonic circuits, which we applied here to superconducting transmission-lines[13]. By operating in the slow RF regime, group velocities much smaller than the group velocity of light in vacuum can be achieved, all using planar circuit geometry requiring only one lithographic step. A transmission line circuit diagram of the proposed device is shown in Figure.3a, it consists of series inductor, L_{SC}, representing the kinetic and geometric inductance of the superconducting wire, and parallel capacitance, C_{Finger}, which is introduced to create an LC low-pass filter circuit. By engineering the capacitance value, the rejection band can be tuned into the operational frequency of the SNSPD. In the proximity of the rejection band this yields vanishingly small group velocity, that goes to zero at the transition-edge. A schematic of the device is shown in Figure 3b, consisting of the main transmissionline with fingers of superconducting wires capacitively-coupled to ground.

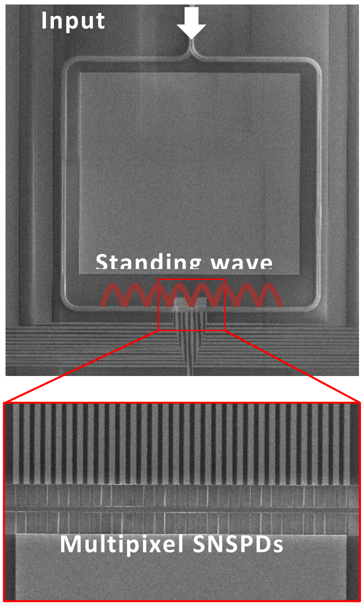

Figure.2. Fabricated spectrometer, consisting of a SiN interferometer with multi pixel single photon detectors.

The circuits were fabricated based on the simulation design parameters. Two pixels were connected with a transmission line consisting of N side capacitors, as shown in Figure 3 A closer look at the capacitively coupled transmission line is shown in Figure.3g, with dimensions chosen to directly match the simulated structure. The experimental setup for testing the devices is shown schematically in Figure.3d. The sample is illuminated with a 780 nm 3-picosecond laser, with 80 MHz repetition rate. The SNSPDs are cooled to a temperature of 2.5 K in a closed-cycle cryostat, considerably lower than their critical temperature. A room temperature bias-T and an amplifier with a bandwidth of 1.2 GHz are used for cur-rent biasing of the detector and amplification of the detection pulses, respectively.

Several devices with different numbers of side capacitors were fabricated. We investigate the effect of increasing the length of the slow-RF transmission line on the arrival time of detection events from the two pixels, while keeping the physical distance between the two pixels fixed at 1.6 mm. Figure.4a shows the IV characteristic of a 60 side-capacitor device. This two-pixel detector has a critical current of 13μA, with signature of internal efficiency saturation under illumination from the laser. We clearly see an increase in the arrival time of detection events from pixel 2 as the number of side-capacitors is increased. We extracted the measured temporal delay between the two pixels versus number of capacitor fingers as shown in Figure.4c, with a linear fit of the data. The experimentally measured group delay between the two pixels is extracted from the fit to be 0.26±0.03 nanoseconds per 10 side capacitors. The maximum measured delay in the 100-finger capacitor device corresponds to a group velocity of 0.19% the speed of light in vacuum (1.7 picoseconds delay per 1μm of propagation).

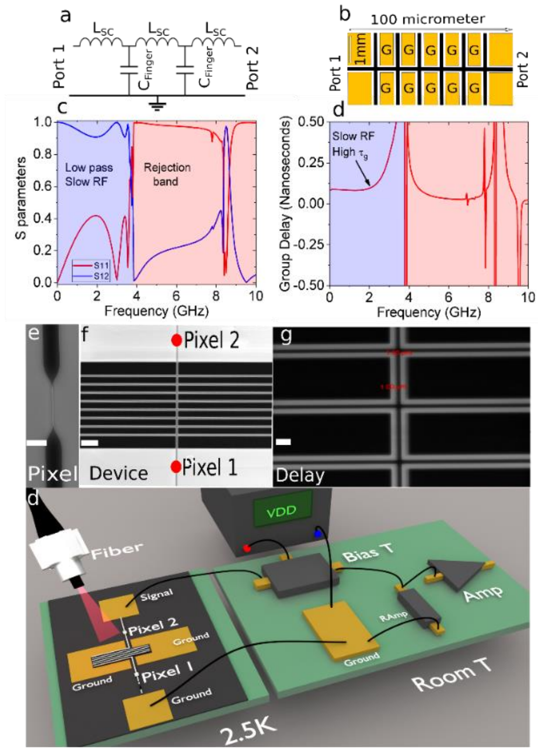

Figure 3 (a) and (b) circuit diagram and schematic of the simulated structure. (c) and (d) S parameter and group delay of the simulated transmission line. SEM of one pixel (e), fabricated device (f), and delay element (g). (d) Schematic of the experimental setup

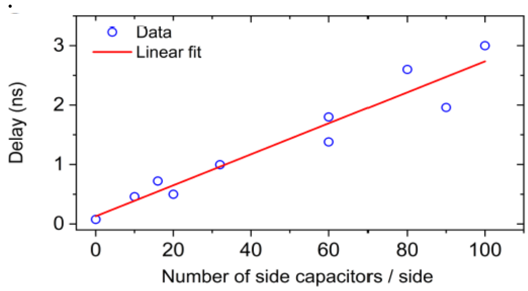

Figure.4 Extracted delay for devices with different number of side-capacitors on each side, linearly fitted to a straight line. The slope of the linear fit is 0.26±0.03 nanoseconds per 10 side-capacitors

5. FUTURE PROJECT VISION

5.1. Technology Scaling

INSPECT partner Single Quantum BV is an industry leader for single photon detectors, covering applications in quantum science, sensing, LIDAR, and biology. INSPECT will make use of the large customer base Single Quantum established, and further expand on it by opening up new applications based on the simultaneous spectral and temporal resolution our devices deliver. To achieve this, foundry-based fabrication of the photonic circuits is needed to maximize the yield and repeatability of the devices, going from prototyping to large scale integration and packaging.

The team at *INSPECT* already have successfully demonstrated transfer of research ideas into a well-established industrial products, Single Quantum, based on superconducting technology (TRL9). *INSPECT* will follow a similar path in exploring new markets such as health care and environmental sensing to develop user/friendly systems that can be either as a part of new spin/off or to expand the already solid portfolio of superconducting detectors systems that Single Quantum develops

5.2. Project Synergies and Outreach

In addition to KTH and Single Quantum, two more partners can potentially scale-up and speed the commercialization of the devices. The first is IMEC, a leader in microchip technology with in-depth expertise in software and integrated circuits. IMEC expertise and knowledge is highly valuable for hybrid integration of photonics and electronics, which complements KTH and Single Quantum expertise in superconducting technology and detection. The second partner is an industry leader in glass processing and fiber splicing, such as Nyfors AB, whome the PI has previously established collaborations with. Through Nyfors' patented beam shaping technology, optical fibers can be seamlessly packaged to our developed detectors with close to unity efficiency.

Our dissemination strategy targets four audiences to create immediate impact of the INSPECT project. (1) With a strong focus on excellent science, conference contributions and high-impact publications in peer-reviewed international scientific outlets are anticipated. A dedicated budget is reserved for prioritizing open access journals to achieve highest visibility of INSPECT results within the quantum optics community. Critical feedback from leading experts and additional visibility of the work on I-MAQ will further be sought through hosting an international workshop during the second year of the funding phase. (2) To gain recognition beyond fellow experts in the field, the consortium will engage with transdisciplinary audiences with a scientific interest through press releases, contributions in online science channels and multidisciplinary scientific forums. (3) Social media platforms as well as public events will enable us to approach the general public. The consortium will prepare visually appealing video material about the project. The consortium's public relations departments will support this effort and identify suitable event formats.

5.3. Technology application and demonstration cases

Globally, air pollution contributes to 6.1 million deaths – about 11% of the total global deaths in 2016. We will target atmospheric LiDAR for air quality monitoring, our ultra-high timing resolution detectors will provide mm accuracy mapping of the atmosphere. The novel spectral capabilities of our devices will enable independentand
simultaneous monitoring of common atmospheric pollutants, such as carbon monoxide, methane, hydrocarbons and nitrogen oxide. These gas species have specific absorption lines in the infrared range. The 3D mapping is realized through optical communication between drones and earth station containing our nano-spectrometer.

INSPECT can open opportunities for new imaging applications in medicine including optical biopsy for cancer, disease recognition and non-invasive imaging of sensitive human tissue such as an eye. The advanced techniques for non-invasive detection of tumours using optical techniques such as Raman spectroscopy, fluorescence spectroscopy, multispectral imaging technique, and thermography, will have orders of magnitude spatial resolution in localizing infected areas, coupled with spectral resolution of the detectors, all performed at the single photon level for ultra-high sensitivity.

5.4. Technology commercialization

Single Quantum already developed a commercial system, Iris-S19 targeted for single photon source characterization, time-resolved spectroscopy, and single molecule fluorescence spectroscopy. It is a turn-key system for single photon spectroscopy and photon correlation measurement with an unprecedented time resolution and high detection efficiency. Iris-S19 couples a high-throughput spectrograph via an optical fiber to superconducting single photon detectors (SNSPDs) and processes the detection events by a qutools time correlator. It is the ideal solution for a number of applications. The next step is to develop the next generation of minaturized spectrometers developed in INSPECT, with no moving parts combining both high spectral resolution delivered by the Fourier spectroscopy in addition to the high time resolution.

5.5. Envisioned risks

The increase of the timing jitter of the detection events can pose limitation on the pixel size in time domain, which in turn limits the number of addressable pixels by each coaxial lines. A mitigation strategy would be to employ cryogenic amplifiers to push the FWHM of the detection pulse to less than 10 picoseconds, coupled with dispersion engineering of the superconducting transmission line to achieve impedance matching. Another approach would be to combine, time multiplexing with either spatial or amplitude multiplexing, thus exploring different sub-spaces for pixel realizations.

5.6. Liaison with Student Teams and Socio-Economic Study

At Single Quantum we developed together with a master student in electrical engineering a new scalable electronic driver with no hard limit on the number of detectors it can read out. Such a system allows in the future for massive scaling of SNSPD systems to aggregate single pixel SNSPDs to multipixel systems.

6. ACKNOWLEDGEMENT

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