GHz single-photon detector - Gisiphod

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ABSTRACT

In this ATTRACT project, we have investigated how to design and manufacture high-count rate single-photon detectors based on superconducting nanowire technology reaching a 1 GHz count rate. The company Single Quantum has partnered up with the Quantum Nano Photonics group at KTH. Together, we have investigated the requirements to achieve our high-count rate goal with different approaches. At Single Quantum we have leveraged and improved on our core technology, while at KTH the growth of superconducting films has been optimized and a new approach to directly fabricate detectors onto optical fibers has been developed.

Keywords: Detectors; Single-photons; Superconductors.

1. INTRODUCTION

The detection of light is quintessential for our daily lives from cameras, fiber-optical telecom networks, to analytical detectors in process control and medical appliances. Making these technologies more energy efficient and faster results in a reduced photon budget. Hence, there is a strong need for fast and ultra-sensitive single-photon detectors.
In this project, we leverage on the detection technology based on superconducting nanowire single-photon detector (SNSPDs) which has already shown its supremacy over more conventional detection technologies with respect to sensitivity, high time resolution, and broad wavelength response. However, high count-rate capabilities represent a major challenge. A standard SNSPD can only detect photons with strongly reduced efficiency at a rate above 100 MHz.

Our aim within the project Gisiphod and beyond is to improve this detector technology to be able to detect photons up to a rate of 1 GHz and make them available to the market. We predict that such a detector technology will significantly boost development and scientific insights in a wide field of applications from medical diagnostics and imaging, to quantum information processing, and space communication. All these applications have in common that fast, ultra-sensitive, and efficient detectors will have a profound impact on data quality and hence increase reliability, throughput, and processing time.

One of the main results of this project is the detailed understanding we have gained of how to design high-count rate SNSPDs. With this new design knowledge, we show that we can resolve two photon pulses at only 1 ns separation, which is an order of magnitude better than the best single-photon detectors commercially available.
Furthermore, we have shown that up to 100 MHz photon repetition rate, observing no drop in efficiency at telecom wavelength. We also developed new low noise amplifiers to cope with the electrical requirements of high-count rates.
All these breakthrough results were only possible with a strong collaboration with our partner at KTH which developed recipes for superconducting thin film sputtering especially suited for high count rate detectors. At KTH on the other hand, new means of superconducting film deposition and nanopatterning by e-beam induced platinum deposition (EBID) have been developed. We could show the successful coating of optical fibers with superconducting thin films. In addition, our novel nanofabrication technology allows the patterning of superconducting films on very demanding and extremely fragile optical structures, for example on tapered fibers.

2. STATE OF THE ART

Single-photon detection based on superconducting nanowire technology is regarded as the best technology combining ultra-sensitive photon detection, high efficiency with time resolution in the picosecond range, and wavelength range from the visible to the mid-infrared [1].

The detection principle works as such that a superconducting thin-film (typically on the order of 10 nm) is nanofabricated into a meander of about 1 mm length, but with a very narrow width of ~100 nm. If the nanowire is biased with a current close to the critical current of the superconductor, the devices become sensitive to single-photons. The energy of a single-photon is enough to break the superconductivity and render a small section of the nanowire to a resistive state where the photon has been absorbed. The huge effect of this quantum-phase change makes it easy to detect an electrical pulse from such an event by means of electrical amplification.

It has been shown that SNSPDs can achieve very high efficiencies up to 98 % at telecom wavelength [2], are ultra-sensitive with only one dark-count every 5 min [3], and has a time resolution of 7.7 ps full-width-half-maximum [1].

However, SNSPDs usually suffer from strong efficiency losses in high-count rate applications and can thus hardly be used above 100 MHz. One reason for this effect is that superconducting materials have a huge kinetic inductance which for SNSPDs can be three orders of magnitude larger than what would be classically expected from a non-superconducting wire, hence the limited high-count rate capabilities.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

In this ATTRACT project, we aimed at solving the count-rate problem of SNSPDs by fabricating small detectors either by conventional butt-coupling to small core fibers, or as a second pillar directly on a tapered fiber to keep the optical coupling efficiency high - but the kinetic inductance small.

Many applications will profit from these new high-count rate devices; it now becomes possible to detect and analyse much more photons, resulting in a much larger dynamic range for photon counting. This enlarged dynamic range makes it possible to use single-photon detectors where previously only linear detectors such as photodiodes could be employed, for example, in scanning microscopes and for high-speed telecommunication applications at a low photon number per bit.

At Single Quantum, SNSPDs were fabricated with 4 times smaller area than our conventional telecom devices which resulted in a 16-fold decrease of their kinetic inductance. We used single-mode fibers with core diameters in the sub 2-micron range to couple the light efficiently to our devices.

However, just making the detectors shorter is not good enough to aim at count rates of 1 GHz. To achieve this goal the detectors needed to be completely redesigned from ground up, involving material science, nano-fabrication, optics-, and electronic-design.

Within Gisiphod, we have partnered between Single Quantum and the Quantum Nano Photonics Group at KTH in Sweden. This two-pillar approach allowed us at Single Quantum to leverage on our proven detector technology and fabrication processes, while KTH followed a high-risk high-gain goal of fabricating a superconducting single photon detector directly on a tapered-optical fiber. Such an approach has the advantage to detect light in the evanescent field of the tapered-fiber which has been predicted to allow for near unit absorption efficiency over a wide spectral range.

Tab. 1. Comparison of key characteristics of conventional- and Gisiphod SNSPDs.

Parameter	Conventional SNSPD	Gisiphod SNSPD
Wavelength range	Telecom band	Telecom band
Count Rate	<100 MHZ	1000 MHz
Kin. Inductance	~500 nH	3 nH

4. PROJECT RESULTS

High-count rate detectors, 1st pillar

To achieve high-count rate SNSPDs four key points needed to be optimized simultaneously:

1) Small detectors (low kinetic inductance),
2) Long saturation,
3) Low operational current to prevent Joule heating,
4) Tailored readout electronics.

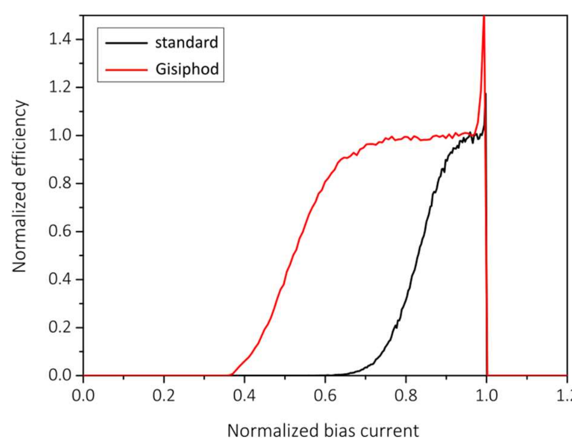

Fig. 1. Saturation behaviour of two SNSPD devices at 1550 nm. *Black curve:* standard telecom detector. *Red curve:* Gisiphod optimized detector, exhibiting more than five-fold longer saturation plateau at 1550 nm. Efficiency values above unity result from dark counts not being subtracted.

The most challenging parts of the list were to deposit a suitable superconducting thin film and fabricate a nanowire which shows a long saturation behaviour. This can be commonly achieved for wavelengths below 1000 nm. However, to maximize impact for practical applications, we wanted to also achieve such high performances for the telecom bands at 1310 and 1550 nm.

Figure 1 depicts the result of our optimization efforts. We compare the saturation curve of a standard telecom SNSPD at 1550 nm and a device optimized within the Gisiphod project. Once the curve reaches a plateau upon increasing bias current, the internal efficiency saturates. Hence, the longer the plateau the better the device. In Gisiphod, we managed to extend this plateau over five-fold! This was only possible with the close collaboration with KTH where the sputtering of NbTiN superconducting films have been carefully optimized.
In addition, the nanofabrication team at Single Quantum precisely designed the nanowire geometry so that low critical currents could be achieved. The lower the operational current of an SNSPD, the better for high count rate applications; reducing the operational current by half reduces the generated Joule heating in the nanowire four-fold. This is an important optimization step for thermal management of the device. We have been able to reduce the critical current as low as 8.5 µA. In Figure 2 we show results of our optimization work, we could generate detectors which have a flat efficiency response till 100 MHz (limited by our equipment) at 1310 nm at the single-photon limit.

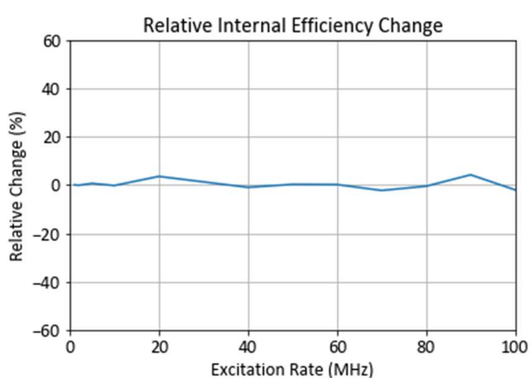

Fig. 2. Relative internal efficiency change. Response is flat till 100 MHz, limit of our measurement equipment.

In addition, we have achieved 840 MHz count rate under CW excitation at 1310 nm with an average photon flux of 100 photons per detected pulse. Furthermore, we were able to resolve two pulses of a picosecond laser at 1064 nm spaced by only 1 ns, showing that we could fulfil the goal of the Gisiphod project reaching 1 GHz count rate.
To achieve these results, we have carefully optimized our readout electronics. We used cryogenic amplifiers together with an optimized low noise room temperature amplifier.

Detector directly on an optical fiber, 2nd pillar

KTH developed NbTiN thin film deposition directly on an optical fiber and proceeded with the development of new fabrication techniques as standard electron beam lithography-based methods are not suitable for this non-planar structure.
A functional SNSPD device was realized by EBID and subsequent reactive ion etching. A Pt-based precursor gas was introduced in the scanning electron microscope system and a focused electron beam was used to decompose the precursor molecules. With this method, a Pt nanowire meander was written on a silicon substrate on top of a NbTiN thin film and used as an etch mask. To compare our new fabrication process with standard SNSPD fabrication, the room temperature resistance of the device was 240 kOhm, comparable to detectors fabricated by electron beam lithography with similar geometry. Figure 3 presents the normalized count rates versus bias current for four different wavelengths from visible light at 650 nm to telecom at 1550 nm.

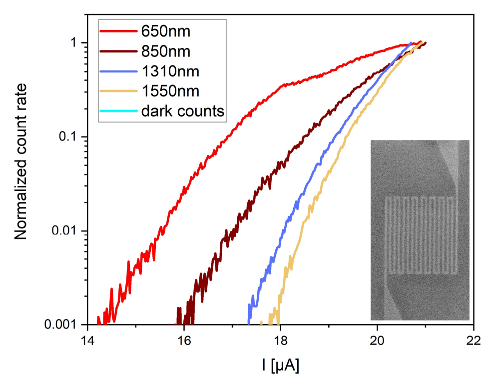

Fig. 3. Normalized count rates for SNSPD fabricated on silicon substrate by the newly developed EBID method for four different photon wavelengths. The bottom right inset shows a representative SEM image after Pt deposition (nanowire width 100 nm, detector area 5x5 µm). Note that no significant dark count rates were observed when operating the detector close to the critical current.

Our optimized magnetron sputtering-based deposition procedure resulted in NbTiN thin films with good adhesion to the optical fibers (no delamination was observed upon bending) and superconductivity was confirmed for a continuous NbTiN layer. Figure 4 shows a prototype Pt structure realized by EBID directly on an optical fiber coated with NbTiN, similar to the SNSPD realized on a silicon substrate. The main challenges for fabricating a functional device are non-planar topography, high surface roughness of the optical fiber and sample charging occurring during EBID processing. In this regard, our EBID-based approach has several advantages compared to patterning with electron beam lithography.

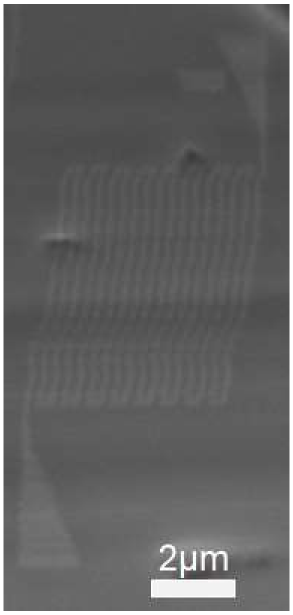

Fig. 4. Prototype structure fabricated on a tapered optical fiber coated with NbTiN using the EBID method. Surface topography and sample charging complicate detector fabrication.

First, the surface morphology of the optical fiber can be inspected with scanning electron microscopy imaging immediately before the patterning process, which allows to pre-select the area where the detector device will be written. Second, our EBID approach does not require the use of resists for the patterning step. Hence, issues related to uneven resist coverage on non-planar geometries are avoided and sample charging can be mitigated. Future steps include the development of contacting and packaging schemes for the nanowire devices realized on the optical fiber including their performance validation and benchmarking.

5. TECHNOLOGY SCALING

At Single Quantum we have extensive experience in developing technology from low TRL levels. In the ATTRACT project Gisiphod we have achieved a working prototype level of our high-count rate detector technology of TRL 4. ATTRACT phase 2 would be a key funding source to push this development up into the TRL 5-7 range.

To scale the technology, we will need to validate our working prototype in a relevant environment. The next step would be to involve partners who need high-count rate detectors at the single-photon level. This would help us to bundle the necessary synergies and learn from user experience to improve our technology. This feedback would allow us to build a final prototype that can be used as a start for bringing high count rate single-photon detectors to the market.

5.1. Project Synergies and Outreach

Several ATTRACT projects could leverage on our high-count rate detector technology. We have been in contact with a few of them, especially in the field of imaging and electronics to discuss the possibility to form a larger consortium.
In ATTRACT Phase 2 we would facilitate the visibility of the consortium through different channels: First, social media and our website are an ideal platform to target and address a broad range of interested individuals. In addition, we would again seek to work with interested students promoting the spirit of the ATTRACT program to young researchers.

5.2. Technology application and demonstration cases

Sensitive photodetectors can be used in a plethora of applications. We envision that the most useful of these applications for Europe and the world might lie in secure telecommunication, medical diagnostics, and remote sensing.

However, it would be unfeasible to tackle all these topics in ATTRACT Phase 2. We foresee, that once the technology has been established in one field, cross-fertilization will happen naturally. We predict that the largest impact on society given with the resources provided in ATTRACT Phase 2 would be the field of secure telecommunication. Fast single-photon detector can be part of the key enabling technology, for example to mitigate blinding attacks. Blinding attacks are a major issue that hampers secure communication and can be prevented by high-count rate single-photon detectors.

Naturally, partner organizations would involve a fair share of universities. This has the advantage of first educating young researchers in the field. Second, we can leverage on the very good research infrastructure available and maintain Europe's technology independence.

5.3. Technology commercialization

Single Quantum is already manufacturing and selling SNSPD technology. Hence, we have all the necessary structure in place for commercialization. However, one of the main issues preventing a larger market adaptation is the limited count rate. Once we have developed a Minimum Viable Product of this high-count rate detector technology, we will use our current sales and customer channels to start the commercialization. We already have a lot of requests from potential customers who could evaluate and ultimately purchase our devices. If it is needed to scale up our production, we have a lot of interest from private investment stakeholders, who are eager to invest in emerging quantum technologies.

5.4. Envisioned risks

From what we have learned so far in this project we do not expect major risks in terms of technology development.

5.5. Liaison with Student Teams and Socio-Economic Study

We are proud that our project Gisiphod was selected by a student team ("The fantastic 5") under the umbrella of the CERN IdeaSquare Summer School, a project established between TU Delft and CERN. The goal of the Summer School was to select an emerging technology, analyse it, and eventually find an alternative and unexplored application, with high social impact.

The team consisted of four MSc students with a diverse background: Innovation Management, Electrical Engineering, Physics & Astronomy and Architecture.

The team decided to analyse Gisiphod mainly because of its broad set of potential applications, and its breakthrough innovation potential. Working with Gisiphod, the team ideated and validated the concept of GisiHOT, a new potential application for Gisiphod, in which laser ranging is used to help authorities to prevent and detect bushfires before becoming megafires.

Both principal investigators of the project at KTH and Single Quantum were very happy to facilitate the work of the students by answering their questions and providing additional background information. We foresee that a similar working way would be very suitable for the upcoming ATTRACT Phase 2 socio-economic study.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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