Large active area superconducting single photon detector

M Moshkova\textsuperscript{1,2}, P Morozov\textsuperscript{2}, A Divochiy\textsuperscript{2}, Yu Vakhtomin\textsuperscript{2,3}, K Smirnov\textsuperscript{1,2,3}

\textsuperscript{1}National Research University Higher School of Economics, Moscow, 101000, Russia
\textsuperscript{2}LLC “Superconducting Nanotechnology” (SCONTEL), Moscow, 119021, Russia
\textsuperscript{3}Moscow State Pedagogical University, 119991, Russia

Abstract. We present development of large active area superconducting single-photon detectors well coupled with standard 50 µm-core multi-mode fiber. The sensitive area of the SSPD is patterned using the photon-number-resolving design and occupies an area of 40×40 µm\textsuperscript{2}. Using this approach, we have obtained excellent specifications: system detection efficiency of 47% measured using a 900 nm laser and low dark count rate of 100 cps. The main advantages of the approach presented are a very short dead time of the detector of 22 ns and FWHM jitter value of about 130 ps.

1. Introduction
Superconducting single photon detectors (SSPD) [1] are the best solution for many applications [2] as they positively outperform other types of single-photon detectors. At the same time, up to now all the SSPD-based receivers demonstrated were equipped with an SSPD the sensitive area of which was rather small and well suited to be coupled to a single-mode (SM) optical fiber through which the radiation was delivered to the receiver. Large active area detectors with ultimate specifications are required for many applications, such as aerospace and defense technologies, LIDAR and quantum communications, biomedical sciences, etc. Unfortunately, attempts to create SSPDs with an enlarged detection area did not prove to demonstrate all the advantages of the SSPDs [2]. According to the SSPD detection mechanism [1], an SSPD with a large active area would require creation of a very long (several tens of millimeters) and narrow (about 100 nm) superconducting strip with an extremely small width deviation (less than 5 nm). This is a very complicated technological task. Also, there are additional drawbacks of this approach. First of all, such increase in the length of the strip leads to a significant increase in its kinetic inductance $L_k$ [3,4] which determines the recovery time (dead time) growth and consequently limits the maximal counting rate of such detectors drastically [5,6]. A significant increase in $L_k$ of the detector would inevitably lead to a degradation of its jitter, too. Several groups have developed large active area SSPDs with high system detection efficiency (SDE), but all of them have demonstrated a very large dead time and therefore low response counting rate [2,7]. Another common problem of the large-area SSPDs is a significant increase of the dark counting rate (DCR) which is determined by the background radiation [4] and is roughly proportional to the detection area. Compared to 9/125 SM fiber, 50/125 multimode (MM) fiber passes approximately 50 times more background-generated photons at room temperature onto the detector. Thereby, during development of a large-area SSPD, all the mentioned drawbacks should be addressed in order to preserve all the advantages of the SSPDs. In this work, we present results of development and research of the SSPD detectors coupled to a MM fiber with the core diameter of 50 µm. The topology of the photon number resolving (PNR) detectors [8] was implemented for creation of the detector with a large sensitive area. PNR SSPD contains several parallel meander-shaped sections connected to a single contact pad via additional in-series resistors for preventing...
the cascade switching of these strips when a resistive domain (or “hot spot”) is formed across any of the strips due to the photon detection event. Implementing this topology is beneficial for a number of reasons. First of all, the detection efficiency of each section does not depend on that of the other sections. Secondly, usage of such a topology leads to a decrease in the $L_k$ of the structure by a factor of $N^2$, where $N$ is the number of sections, and to a corresponding reduction of the detector's dead time. Also, as the jitter of the SSPD is partially determined by the superconducting strip length, significant decreasing in length of the strip due to the use of the PNR topology allows for reduction in the jitter, too.

2. Device fabrication and characterization

2.1. Device fabrication

Large area detectors were made using 7 nm thick NbN film by implementing a standard technology routine which is described in details elsewhere [9]. An optical cavity formed by 12 bilayers of Bragg reflector was optimized in order to maximize photon absorption by NbN structure at wavelength range of about 900±50 nm. The large area detector consists of four independent sections, where each of the sections is a meandering superconducting NbN strip of ~120 nm width (filling factor is 0.6) and is connected to a 4 Ohm series resistor made from a thin film of gold. The sensitive area of the detector is 40×40 μm² and each section is evenly distributed over this area, as shown in Fig. 1a. Detector was coupled to a standard MM fiber with 50 μm core diameter and installed onto the cold plate of a GM closed-cycle refrigerator (Sumitomo RDK-101D) with minimally reached temperature of 2.1 K. Equivalent circuit of the four-section PNR SSPD detector is presented in Fig. 1b. The operation principle of such a detector resolving the number of photons during a short optical pulse is given in [8,10,11]. Briefly, the absorption of a photon by one of the sections leads to generation of a voltage signal along the strip. At the same time, the current redistribution between the sections is hampered by the $L_k$ of the section and the series resistance $R_s$. Therefore, when a photon is absorbed by any of the sections, the others still remain in the superconducting state and are capable to detect another photon. When two photons are simultaneously absorbed by two different sections, the resulting voltage pulse becomes roughly two times larger, and so on. In our case, it is not the ability to resolve the number of photons that is important but a possibility to decrease the large area detector’s kinetic induction to a value comparable to that of a “standard” small area detector (i.e., detector with the sensitive element area coupled to SM fiber).

![Figure 1(a, b). (a) Schematic view of the 4-section SSPD topology; (b) Equivalent circuit of the 4-section topology SSPD detector [Ref. 8, Fig. 2a.].](image_url)

2.2. System detection efficiency and dark count rate

System detection efficiency (SDE, i.e. efficiency referred to the input of the MM fiber) and DCR were measured using a standard technique described in Ref. [9]. As the light source, an IR-spectrophotometer
was used where a wideband light from a halogen lamp was transformed into a narrowband (~1nm) radiation with help of a diffraction grating with 600 lines/mm and a set of cut-off filters. The output power was collected by a coupler (collimating lens) and fed to a multi-mode 50/125 fiber. We used SPAD (Excelitas SPCM-NIR) and a universal frequency counter (Agilent, A53131) to measure the in-fiber power. The power was adjusted by the voltage applied to the halogen lamp and by changing the spectrometer output gap. The SDE was calculated by measuring the number of electrical pulses generated by the SSPD. The results of the experiment are presented in Fig. 2a. The maximal value of the SDE is about 50% at DCR of 300 cps and about 47 % at DCR of 100 cps. It can be seen that dependence of SDE \((I_D)\) demonstrates a tendency to saturating at a current which is close to the critical current of the SSPD. It means that internal quantum efficiency, i.e. probability of the voltage pulse generation due to the photon absorption event by the superconducting structure is close to unity. Difference between the measured system detection efficiency and calculated absorption of \(~0.65\) is associated primarily with the insufficiently effective optical coupling between the SSPD with the active area of \(40 \times 40 \mu m^2\) and MM fiber with core diameter of 50 \(\mu m\).

For measurement of the dependence \(DCR (I_D)\) the optical input to the SSPD was covered by a black cap. It has to be noticed that in order to reach a low DCR level, it is required to filter out the background radiation, which is irradiated by the room temperature (300 K) load and inevitably arrives to the detector through the fiber. Compared to the single-mode fiber, the number of the background photons incident onto the detector through the multimode fiber, is extremely increased. Unfortunately, an effective method of filtering out the background radiation, which was applied to receivers based on the single-mode fiber [12], cannot be used for receivers based on the multi-mode fiber. In such situation, we decided to decrease the quantum efficiency of the detector beyond the target wavelength range around 900 nm by two methods simultaneously. The first one diminishes absorption efficiency at wavelength above 1500 nm. For this, we used a substrate with the Bragg-reflector which has good reflection in the range 800-1000 nm (>95%) and is well transparent at wavelengths above 1500 nm. In addition, we intentionally reduced internal quantum efficiency of the detector at wavelengths greater than 1500 nm. As known, the internal quantum efficiency of the SSPD depends on the superconducting strip cross-section and for detectors, which operate well at longer wavelengths a smaller cross-section strip is required [13]. At the same time, the detectors with wider strip and the unchanged thickness can operate at short wavelengths sufficiently well. So, we fabricated detectors with different width of the superconducting strip using 7 nm thick NbN film and found out that detectors with width of 120 nm

![Figure 2(a, b).](image-url)
demonstrated an $SDE(I_b)$ dependence close to saturation at 900 nm and at the same time a very low internal detection efficiency (less than 5%) at wavelengths longer than 1500 nm. Thanks to these two techniques, we managed to achieve a level of dark counting rate of less than 100 cps. The dependence of DCR vs. bias current is shown in Fig. 2a. Dark counts are completely due to the room temperature background but the DCR is still within a few hundred of counts per second, which is a reasonable value for a practical receiver. The region of the exponential growth of DCR vs. bias current of the detector’s intrinsic dark counts corresponds to a bias current of more than 42 $\mu$A and is not represented in the figure.

Since the detector has a PNR structure, we investigated the cascade switching effect in order to analyze the crosstalk between the meander sections. For that, we used a CW laser source with power corresponding to a level at which the theoretical probability of simultaneous response of any two sections of the detector is four orders less than the probability of a single section response. We have measured the experimental probability of cascade switching by measuring the number of counts depending on the counter trigger level. These results are depicted in Fig. 2b where 5 dependencies corresponding to different bias currents are shown. The effect of cascade switching at bias current of 36 $\mu$A is big enough and is about 37%. However, the cascade switching effect is decreasing with decrease of the bias current and at operation current of 30 $\mu$A where $SDE \approx 47\%$ and DCR is $\sim$100 cps, probability of the cascade switching is less than 2%. It should be noted that effect of the cascade switching plays an important role when the SSPD is operated as the PNR detector because this effect leads to a distortion of the measured photon statistics. In our case, we did not use the detectors in the PNR mode and the cascade switching could only influence the timing characteristics of the emerging voltage pulses, namely, jitter and dead time of the SSPD.

2.3. Dead time and jitter

The dead time of the detector was deduced from the oscilloscope traces of the electrical pulses generated by the detector. Fig. 3a depicts an oscilloscope trace of the electrical pulse when only one section of the detector was triggered. According to this trace, the dead time, determined as the time corresponding to the falling edge voltage decrease by a factor of $e$, was 22 ns. Similarly, dead time in case when two sections of the detector are triggered is 28 ns, and in case when three sections of the detector are triggered is 37 ns. As it was shown above, the probability of cascade switching of a second section at 30 $\mu$A bias current is about 2%; the cascade switching of a third section is less than 0.01%. Therefore, this neither should make a significant contribution to the jitter and dead time, nor have a significant impact on the measurement results when using such a detector.

The jitter was determined by a standard method [9] using TCSPC SPC-150NX from Becker&Hickl GmbH and a pulsed laser (pulse duration $\sim$1 ps). The pulsed laser has a standard single-mode fiber (SMF-28e) as the output. So, pulsed radiation from the laser’s SMF-28e fiber was fed to the multi-mode fiber coupled to the large area SSPD. Such approach does not allow to illuminate all the active areas of the detector uniformly, but we that this did not have a significant impact on the data obtained. We set the laser power to a level corresponding to $\sim$0.1 photons per pulse and therefore the detector was operated at conditions where the probability of simultaneous triggering of several detector sections at simultaneous absorption of several photons was negligible. The jitter was measured at the counter trigger level of 50 mV, which is approximately a half of the voltage pulse amplitude when a single section of the detector is triggered. Of course, cascade switching pulses were also counted. The results of the jitter measurements are presented in Fig. 3b. The measured FWHM (full width at half maximum) jitter value was $\sim$130 ps. This value is larger than the jitter of the SSPD coupled to the single-mode fiber [14,15], due to the fact that the length of the superconducting strip of each section of the large area detector is approximately two times longer than that of a standard “small area detector” which leads to a proportional decrease in the steepness of the rising edge of the pulse, and the bias current flowing through each section is just $\sim$7.5 $\mu$A which inevitably ensures a significant contribution of the noise component to the measured jitter value [16]. Nevertheless, the measured jitter of the large-area SSPD was demonstrated to be smaller than that of an APD based single photon counters [17] and can
be further improved by optimizing the length of the superconducting strips constituting the SSPD sections and the bias current applied.

Figure 3(a, b). (a) Waveform of the pulse generated by the large active area SSPD; (b) Jitter of the detector with the large active area, measured at bias current $I_b = 32 \mu A$.

3. Summary
We have developed the SSPD detector with the large active area of $40 \times 40 \mu m^2$, which can be well-coupled to the standard 50-$\mu$m core multimode fiber. The overall performance of the devices (SDE, DCR, dead time, jitter, cascade switching) is only marginally inferior to that of conventional detectors coupled to SM fiber but explicitly exceeds previously obtained results for detectors with a large active area. In addition, the developed SSPD can be advantageously used in any application whenever the photon number resolving is required.

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