Waveguide integrated superconducting single-photon detector for on-chip quantum and spectral photonic application

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Abstract. With use of the travelling-wave geometry approach, integrated superconductor-nanophotonic devices based on silicon nitride nanophotonic waveguide with a superconducting NbN-nanowire suited on top of the waveguide were fabricated. NbN-nanowire was operated as a single-photon counting detector with up to 92\% on-chip detection efficiency in the coherent mode, serving as a highly sensitive IR heterodyne mixer with spectral resolution ($f/df$) greater than $10^6$ in C-band at 1550 nm wavelength.

1. Introduction
Hybrid superconductor-nanophotonic devices (SND) have been proven to be one of the most promising approaches for development of complex quantum photonic integrated circuits (QPICs) [1]. One of the main components of SND is a superconducting nanowire single-photon detector (SSPD or SNSPD), which combines high detection efficiency, low dark count rate, high temporal resolution and a compact design [2]. Since SSPD is a threshold detector, it detects the presence or absence of photons, but misses information about its energy or frequency. However, for some applications knowledge about the wavelength of photons is desirable, and optical heterodyne technique was recently implemented to overcome this imperfection of SSPDs [3]. Here we adopt this approach for QPICs and demonstrate both single-photon counting as well as coherent detection with high resolution. Unlike previous studies, here we investigated the coherent detection in the vicinity of the superconducting transition, heating up the electron subsystem with a high power optical local oscillator (LO).

2. Device design and fabrication
Fabricated device includes two focusing grating couplers (FGCs) for 1550-nm light coupling, 50:50 Y-splitter for calibration of optical power as well as U-shaped superconducting NbN nanowire (4 nm thickness and 80 nm width) as a single-photon detector (Figure 1a,b). For fabrication of devices we used three steps of electron beam (e-beam) lithography. In the first step, Au-contact pads and alignment marks are formed using PMMA resist and standard lift-off technique. In the second step, U-shaped NbN nanowires are made with use of HSQ resist by reactive ion etching (RIE) in CF$_4$. Finally, negative electron resist maN-2403 and etching in atmosphere of CHF$_3$ are employed for nanophotonic waveguides formation.

3. Experimental results

3.1. Measurement of critical temperature and critical current density
After fabrication process, the critical temperature ($T_c$) and the critical current density ($j_c$) of the NbN nanowires were measured. Our devices were installed on to a cold plate of a closed-cycle refrigerator operating with the minimum reachable temperature of $T_b=1.78$ K. Measurements of the $T_c$ were carried out at a current of less than 100 nA, so as to exclude the Joule heating. As the width of the nanowire...
decreased, the critical temperature of the film decreased from 9.5 K for wire 120 nm wide and 8.5 K for wire width 60 nm, which we associate with the effect of the proximity effect at the edges of the nanowire (Figure 2a). For the same the nanowires we measured the critical current also. In Figure 2b shown measured critical current (black dots) and their linear approximation (red line) is made. Using a nominal value of 4 nm as the nanowire thickness, we found the critical current density \( j_c = 1.7 \text{ MA/cm}^2 \), which is comparable with the values obtained on other substrates.

3.2. Single-photon counting

Tunable fibre-coupled laser (LS) (New Focus TLB-6600) was used as a light source, which was routed to the device through attenuator (AT1), polarization controller (PC1) and beam splitter (BS), with real-time measurement of power \( (P_{in}) \) by the first channel of optical power meter (PM1). The light, coupled by the first FGC into the optical waveguide, was divided by the on-chip Y-splitter into two parts. One half was directed through the calibration arm (1) for the measurement of output power \( (P_{out}) \) by the second channel of the optical power meter (PM2), the other half routed to the nanowire (2). We determined the coupling efficiency \( (C_{eff}) \) from the input and output powers as: \( C_{eff} = \sqrt{P_{out}/(P_{in} \times S \times WT_1)} \), where \( WT_1 \) refers to the waveguide transmission for the calibration arm and \( S \) is the splitting ratio of the on-chip Y-splitter \( (S = 0.5) \). The photon flux reaching the detector can be estimated as \( \Phi_{ph} = (P_{in}/h \cdot f) \times S \times C_{eff} \times WT_2 \). Absorption of single photons by the NbN nanowire leads to electrical pulses, which are amplified (A) and registered by a counter (C) (Figure 1c). The on-chip detection efficiency of the integrated SSPD \( (\eta_{dc}^{counter}) \) can be determined as ratio of the count rate of the detector \( (CR) \), with the exception of dark count rate \( (DCR) \), to the photon flux reaching the SSPD:

\[
\eta_{dc}^{counter} \equiv \frac{CR-DCR}{\Phi_{ph}}.
\]

The dependence of the on-chip detection efficiency on the normalized bias current, measured at a telecommunication wavelength \( \lambda = 1.55 \text{ µm} \) is shown in the Figure 2e. We found saturated efficiency at the level of 92 % in a linear scale close to the critical current as well as DCR not exceeded of \( 10^4 \text{ (s}^{-1}) \).

Figure 1 (a-c). (a) Optical image of a nanophotonic circuit in false colors; (b) SEM image of NbN nanowire atop the nanophotonic waveguide in false colors; (c) Schematic view of the experimental setup for measurement both single photon counting and coherent mixing in travelling wave geometry approach. Equipment marked blue and gray colors correspond to single photon counting regime, blue and red equipment correspond to heterodyne mixing regime. Abbreviation of the equipment: SL – signal laser; LO – local oscillator; AT1, AT2 – tunable attenuators; PM1, PM2 – optical power meter for input/output power; CS – current source; A – amplifiers; C – counter; SA – spectrum analyzer.

3.3. Coherent detection

In order to demonstrate on-chip coherent detection, we have introduced an additional tunable and stable laser, which is referred to as the LO, and whose radiation of almost same wavelength also passes a power attenuator and polarization controller, and a beam-splitter is used to combine power of both the lasers
into a single-mode optical fiber (Figure 1c). We used rather large LO power in order to heat the electron temperature of the nanowire from the bath temperature ($T_B = 1.78$ K) to the superconducting transition temperature. In this case, the detector begins to operate not in a single-photon mode, but in a bolometric mode.

For the dependence of the total electric field $E(t)$ of the heterodyne ($E_{LO}$) operated at the frequency $f_{LO}$ and the signal laser ($E_s$) at frequency $f_s$, one can write:

$$E(t) = E_{LO} \cos(2\pi f_{LO} t) + E_s \cos(2\pi f_s t).$$

(2)

The total field power is proportional to the $E^2(t)$ and defined as

$$P(t) = E^2(t) = E_{LO}^2 \cos^2(2\pi f_{LO} t) + E_s^2 \cos^2(2\pi f_s t) + 2E_{LO}E_s \cos(2\pi f_{LO} t) \cos(2\pi f_s t).$$

(3)

The bolometer is not fast enough to follow the RF, so the dissipated power at these frequencies is the time averaged values ($P_{LO}, P_s$) However, if the intermediate frequency (IF) $f_{IF} = |f_s - f_{LO}|$ is low enough, the bolometer can follow this variation, so the time dependent term presents in this frequency.

$$P(t) = P_{LO} + P_s + 2\sqrt{P_{LO}P_s} \cos(2\pi f_{IF} t).$$

(4)

Since near the superconductor transition, the bolometer has a strong resistance-temperature dependence, in general, it can be shown that the absorbed power leads to a change in temperature, a change in temperature to a change in the resistance, which in turn leads to a voltage dependence at IF on the bolometer on the radiation power:

$$V_{IF} = 2S\sqrt{P_{LO}P_s},$$

(5)

where $S$ is the voltage responsivity:

$$S = \frac{I (dR/dT)}{G \sqrt{1 + (2\pi f_{IF})^2 \tau_{th}^2}}$$

(6)

where $I$ is the bias current, $G$ is the thermal conductance to the bath temperature, $dR/dT$ is the derivative of film resistance vs temperature and $\tau_{th}$ is the thermal response time. For low enough $(2\pi f_{IF})^2 \tau_{th}^2 < 1$, the bolometer can follow the IF power modulation, but for $(2\pi f_{IF})^2 \tau_{th}^2 > 1$, the IF voltage will decrease as well as conversion efficiency

$$\eta_{loc, bolometer} \equiv \frac{P_{IF}}{P_{RF}}$$

(7)

will decrease.

With use of an RF spectrum analyzer (SA) placed instead of the counter, we have observed a beat signal which is generated due to superposition of the two waves of the signal ($f_s$) and local oscillator laser sources ($f_{LO}$) at the difference (“intermediate”) frequency $f_{IF} = |f_s - f_{LO}|$. In Figure 2d is shown the electrical signal generated by the nanowire and measured by the (SA). The signal full width half maximum (FWHM) equal to 4 MHz, which is limited by the frequency stability of the laser sources. Nevertheless, even with such stability, the spectral resolution of our setup is $193.5 \times 10^{-2} / 4 \times 10^6 \approx 5 \times 10^7$, which can be used for high-resolution spectroscopy on a chip.

To choose the operating point with maximum on-chip conversion efficiency, we measured the IV characteristics at various $P_{LO}$. Three of them (dash lines), as well as $P_{IF}$ for the 80 nm nanowire width and 140 $\mu$m total length are shown in Figure 3a.
The measured dependence of the resistance on temperature for nanowires 60 nm and 120 nm wide; (b) The measured dependence of the critical current for nanowires with the different widths; (c) Electrical output of NbN nanowire after amplification in a single-photon regime; (d) Electrical output of NbN nanowire in a coherent regime; (e) On-chip detection efficiency (blue dots) and dark count rate (black squares) measured for the fabricated integrated detector.

The $f_0$ were fixed at 200 MHz, far from cut-off frequency. The maximum value of signal occurs at the first IV curve without critical current. Above that curve the negative differential resistance causes unstable operation of the mixer. At fixed $P_{LO}$ corresponding the negative differential maximum $P_{IF}$, we also measured the dependence of the bandwidth of the mixer. In Figure 3b the dependence of $P_{IF}$ versus IF is shown (color points). The experimental data are fitted by formula $P_{IF} = -10\log_{10}(1 + (f_{IF}/f_{3dB})^2)$. The dotted line indicates the cut-off frequencies $f_{3dB}$ corresponding to 3 dB decrease of the $P_{IF}$. The bandwidth drastically changes with applying dc power and rises up to 3.5 GHz at 2.5 µA, but at the cost of significantly reduced signal power.

4. Discussion
For further analysis we used a numerical calculation of the temperature profile. One of the main features of travelling wave geometry approach is that the absorption along the nanowire decreases exponentially with the nanowire length. For this reason the front parts of the nanowire have higher electron
temperature \( T_c \) than subsequent. To model the \( T_c \) distribution along the nanowire, we have adapted the heat balance equation by introducing the dependence on coordinates.

The simulated electron temperature profiles along NbN nanowire for IV curves from Figure 3a are shown in Figure 3c. Black line corresponds to the maximum observed \( P_{fr} \). Such temperature profile of 70 \( \mu \text{m} \) nanowire (140 \( \mu \text{m} \) the total length) can be divided into three distinct parts. The first part of the nanowire, starting from the device input point, is equal about 1 \( \mu \text{m} \) long and is heated close to the middle of the superconducting transition \( (dR/dT)_{max} \) without bias current (dash-dot line). DC bias (solid line) corresponding to the maximum signal, leads to a substantial increase in the electron temperature in this nanowire section, as well as to the increase in its length. The second part of the nanowire in the range from 2 to 30 \( \mu \text{m} \) has lower temperature. The temperature in this section is substantially below the transition temperature and the current does not affect the \( T_c \). The last and the longest nanowire part with 40 \( \mu \text{m} \) length is not heated with radiation and remains at the bath temperature equal to 1.78 K.

The same picture is held higher levels of \( P_{lo} \). Regarding the superconducting transition temperature, in all these cases, there are "overheated" parts in the beginning of the nanowires, "unheated" parts in the middle and "cold side" at the back end. Due to differences in the electron temperature in different parts of a nanowire, each part contributes to the measured conversion efficiency and the \( \eta_{oc}^{\text{bolometer}} \) can be generally found only numerically. For simplicity we did not put into our numerical model several effects like electro-thermal feedback, which play important role in gain bandwidth. However even with such rough estimation we can qualitatively identify the factors influencing the \( \eta_{oc}^{\text{bolometer}} \).

One can expect higher contribution to \( \eta_{oc}^{\text{bolometer}} \) in those parts of a nanowire, where the electron temperature is close to the middle of the superconducting transition and \( dR/dT \) has the maximum value. But in the case of U-shaped nanowire its normal resistance vary from about 0.5 MOhm for 120 nm to 1 MOhm for 60 nm nanowire width at the same total length of 140 \( \mu \text{m} \). This leads to the fact that the maximum signal is not observed when all nanowire parts are uniformly heated to the middle of the superconducting transition, but rather a small portion at the beginning of nanowire, so that the resistance of the nanowire is close to the 50 \( \Omega \) impedance of the amplifier.

Figure 3d shows the measured dependence of \( \eta_{oc}^{\text{bolometer}} \) (black circles) and required \( P_{LO} \) (blue squares) versus nanowire width. As with conventional NbN HEB can be noted in the ultra-low \( P_{LO} \) at operating point. The figure also shows that an increase in the width of the nanowire increases both \( \eta_{oc}^{\text{bolometer}} \) and optimal \( P_{LO} \). Qualitatively, such dependence can be explained by the following main reasons using the formula for

\[
\eta(\omega) = 2\beta S^2(\omega)P_{LO}^2P_L^{-1},
\]

where \( \beta \) is the coupling factor of radiation to the nanowire and \( R_L \) is the load resistance (50 \( \Omega \)).

Firstly, by increasing the width of the nanowire the area of overlap between evanescent waveguide modes and a nanowire also increases, which leads to an increase in absorption. When the width of the nanowire changes from 60 nm to 120 nm, absorbance per micron length ranges from 0.058 dB/\( \mu \text{m} \) to 0.266 dB/\( \mu \text{m} \). This leads to the increasing the length of nanowire with temperature close to critical temperature. And a greater part of nanowire starts to work in the mixing mode, contributing to heterodyne signal conversion.

Secondly, when the width of a nanowire increases, its critical current also increases, and consequently increases the required \( P_{LO} \) (Figure 3d) to heat to the first IV curve without negative differential resistance slope.

The third reason is connected to the decrease in resistance of the nanowire when width increases. This allows the point with maximum \( dR/dT \) going closer to point with 50 \( \Omega \), leading reducing mismatch with the amplifier.

These three reasons contribute to the increase the conversion efficiency. But on the other hand an increase of the nanowire width leads to a decrease in \( S(\omega) \) due to increase volume that reduces \( \eta_{oc}^{\text{bolometer}} \).
5. Conclusion
Dividing the power of the signal at the intermediate frequency by the incident optical power, we found on-chip conversion efficiency in the best operating point to be equal to \(-17\) dB. We found a conversion bandwidth of up to 3.5 GHz by tuning frequency of the LO laser. Direct comparison with the data presented in [3] shows significant increase of the conversion bandwidth under hard illumination of the LO power, but at the expense of the sensitivity. Therefore choice of the detection regime depends on both available optical power, and desired sensitivity.

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