PAPER • **OPEN ACCESS**

Extracting hot-spot correlation length from SNSPD tomography data

To cite this article: M I Polyakova *et al* 2019 *J. Phys.: Conf. Ser.* **1410** 012166

Extracting hot-spot correlation length from SNSPD tomography data

M I Polyakova[1], I N Florya[2], A V Semenov[2,3] A A Korneev[1,2], G N Goltsman[1,2]
[1] National Research University Higher School of Economics, Moscow 101000 Russia
[2] Moscow State Pedagogical University, Moscow 119991
[3] Moscow Institute of Physics and Technology, Moscow region, Dolgoprudny, 141700, Russia

Abstract. We present data of quantum detector tomography for the samples specifically optimized for this problem. Using this method, we take results of hot-spot correlation length of 17 ± 2 nm.

1. Introduction

Since the first realization of the superconducting nanowire single-photon detector (SNSPD) in 2001, they have substantially evolved and now they demonstrate high detection efficiency, high count rate low timing jitter. During the time passed several theoretical models of SSPD operation have been proposed**.** There is a model according to which a local suppression of superconductivity is limited to a small area of the strip, called 'hot spot', and the transition of the film to the normal state occurs due to current crowding around it. The absorption of photons reduces the entrance barrier for vortices and contributes to the nucleation of a vortex-antivortex pair inside the film in the presence of a weak superconducting region. If the bias current is high enough the Lorenz force starts driving a vortex. The resistive area is formed and grows due to Joule heating, thus switching the superconducting strip in a resistive state [1]. However, this model does not answer the question about the size of the hot spot. For better use of such devices it is necessary to understand where and when the absorption event occurred, but the hot spot is too small and has a too short lifetime to be measured in a direct way. The closest to the direct measurement will be the quantum detector tomography (QDT). Here, we apply the QDT method to samples that were specially made in order to conveniently implement the protocol.

2. The method

The QDT method, which we use in our work, is described in detail in our previous publication [2].
In brief, if a photon is absorbed in the detector's strip, a hot spot is formed. The appearance of the hot spot can result in a voltage pulse, which we will call a "click", but can also result in nothing observable, depending on whether the bias current is large enough. The production of the click by the hot spot is a probabilistic process, with probability dependent on the bias current *I*. the probability to have a click when exactly one photon is absorbed is $\eta_1(I)$, we shall call it "single-spot efficiency". We consider the situation when the bias current is low and one hot spot is not enough to produce a click **(Fig.1a).** But two spots formed close to each other, say, in the same cross-section of the strip, are able to do it. We call click of this kind "double-spot count" and denote the double-spot efficiency by η_2.

To find $\eta_2(I)$, we proceeded as follows. First, we calculated mean number of absorbed photons *M*, just multiplying known mean number of incident photons by on-chip detection efficiency (OCDE) at saturation, assuming, that each absorbed photon produces a click. Then, we fitted the dependencies *P(M)* by the 2-nd order polynomial

$$P(M) \approx \eta_0 + \eta_1 M + \frac{1}{2}(a_2 M^2) \quad (1)$$

Here, the term η_0 represents the probability of a dark count.

Repeating this fit for data at different bias currents, one can obtain $\eta_1(I)$, which is of course trivial, and $\eta_2(I)$ – which is the quantity of our interest. Our ultimate goal is to find *s-hot-spot correlation length* . To do it, we have to observe saturation of $\eta_2(I)$ with the increase of *I*, at some level $\eta_2{}^{max}$, which can then be interpreted as *s/L*.

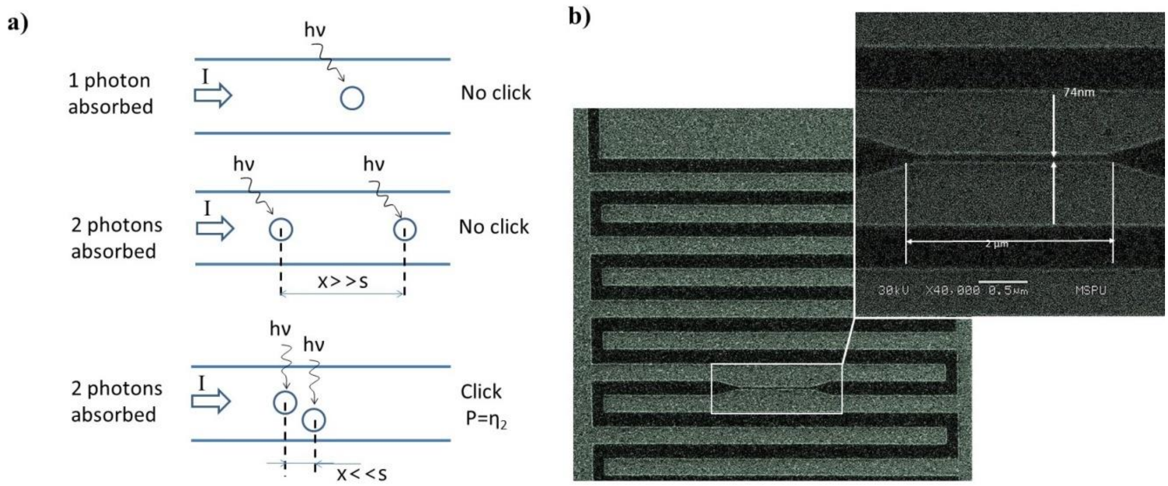

Figure 1. **a)** small current- two photons produce the click if they can be absorbed at the distance less then value called hot-spot correlation length. **b)** SEM-image of superconducting strip that is enclosed in a meander.

In our models we expect that $a_2 = \eta_2 - (\eta_1)^2 \equiv \eta_2 + a_2{}^{stat}$. With the increase of the bias current, single-spot efficiency increases too, the linear contribution becomes larger than quadratic and make it difficult to extract the coefficient a_2. There is also a parasitic effect of AC-biasing [2]. In order to check the contribution of this parasitic effect, we can write: $a_2{}^{bias} = 2I\eta_1\, d\eta_1 / dI\ \varphi$ hence

$$a_2{}^{stat} + a_2{}^{bias} = -(\eta_1)^2 + 2I\eta_1 \frac{d\eta_1}{dI}\varphi \quad (2)$$

Here $\varphi = f\tau$, where f is pulse repetition rate, and τ is the SSPD pulse duration. The φ parameter depends on length of device: the shorter the sample, the shorter the time $\tau = \varphi / f$.

The expected value of $\eta_2{}^{max}$ is inversely proportional to the length of the sample, so for the most accurate measurement it is preferable to have a short sample. At the same time, the length should not be too short, so that the detection event at the transition points from the wide NbN film to the detector strip can be neglected, detection in the contact areas and non-uniform current distribution in the sample strip can be excluded.

Based on these considerations, we fabricated samples 74 nm wide and 2 µm long. The contribution from areas of non-uniform current distribution was minimized and amounted to no more than 10%.

3. Sample (or experiment)

Superconducting strip was made out of 6 nm- thick niobium nitride (NbN) film by means of electron-beam lithography using negative resist MAN 24-01. Figure 1(a) shows superconducting strip having width of ~70 nm and length 2 µm. For better alignment with single-mode fiber (diameter of the light-bearing core is 9 µm) and preventing latching, the superconducting strip is enclosed in a meander (area of 10x10µm^2, width of 350 nm). For our protocol, we used a pulsed lasers, one at wavelength 1064 nm with 5ps pulse width, and the second at 1550 nm wavelength with ~50ps pulse width. The photons should be absorbed simultaneously. The measurements were carried out at a temperature of 1.7 K and critical current of the sample *Ic* was 16.4 uA.

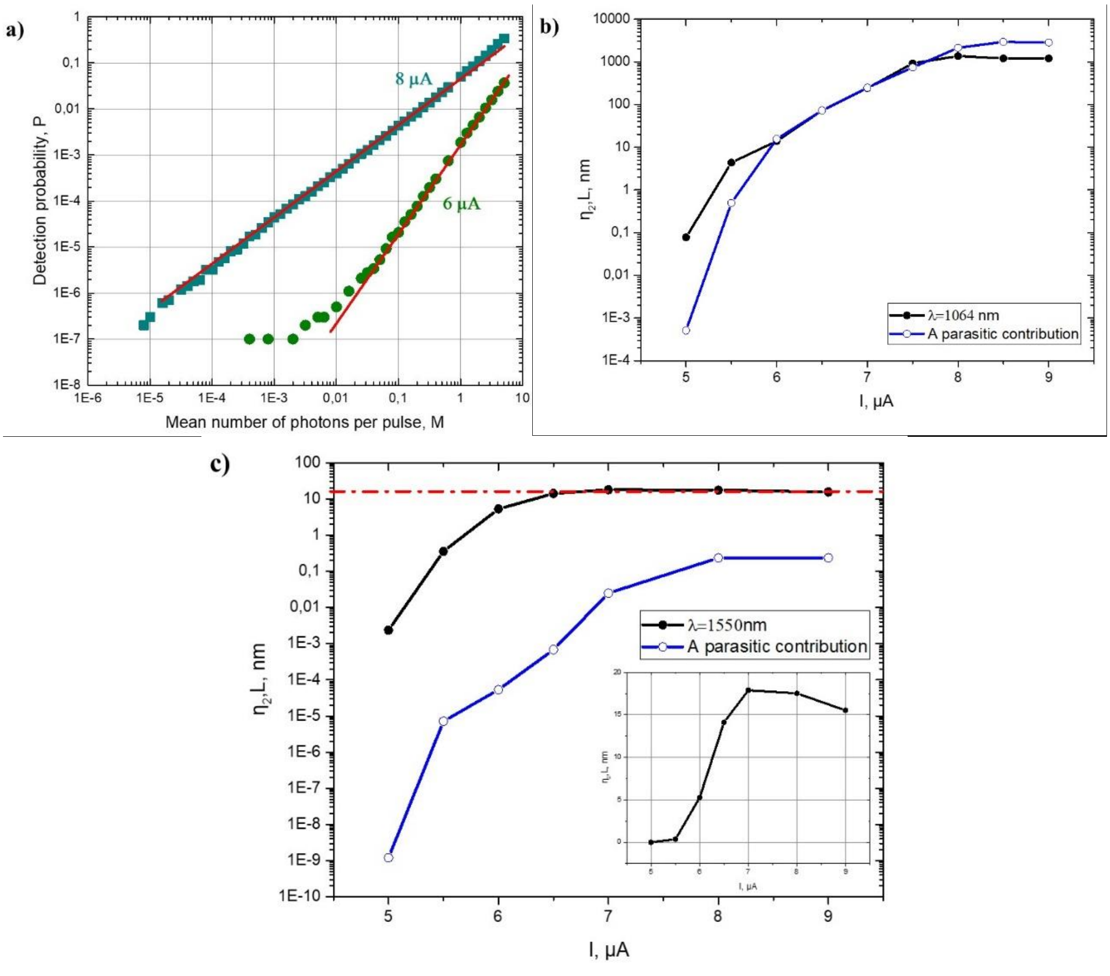

Figure 2 a) single-spot and double spot counts and how determine it. (b) hot-spot correlation length for wavelength of 1550 nm (black curve) and parasitic contribution (blue curve) of 1550 nm. The red line shows saturation which can be interpreted as the hot-spot correlation length **(c).** hot-spot correlation length for wavelength of 1550 nm (black curve) and parasitic contribution (blue curve) of 1550 nm

In order to determine the absorption coefficient, it is necessary to have one hundred percent internal quantum efficiency. In our experiment, a plateau was observed, which we interpret as one hundred percent internal quantum efficiency. We found an absorption coefficient of $4x10^{-7}$. Further, we measured the dependence of the count per second vs power for different currents. With the same bias current, but different powers, SSPD can operate in different detection modes, while two-photon events are usually observed with a small current and high power [3]. Fig.2a shows the count rate vs mean number of photons per pulse for the current, at which the single-photon mode prevails (squares) — the linear slope of the curve, and the second curve (circles) measured at a higher current, at which the two-photon mode is observed — the quadratic slope of the curve prevails. The coefficients η_1 and η_2 were found by applying a fit of the experimental data taken at various currents: from 5 to 9 μA. By applying our protocol to this data, the single- and double-spot efficiencies were extracted as a function of current. The results are presented in Fig. 2 b and 2c.

4. Results

Figures 2b) and 2c) show the dependences obtained at the wavelength of 1064 nm with a pulse repetition rate of 200 MHz and 1550 nm with a pulse repetition rate of 10 MHz. As we assumed, starting at some current value of η_2 start to saturate. To make sure that we see exactly the saturation of the coefficient η_2 (black solid circles in the fig. 2b) and 2c) we analyzed parasitic contribution (blue open circles in the fig. 2b and 2c). It is seen that for the wavelength of 1550 nm, this contribution is small everywhere. We find hot-spot correlation length of 17 ± 2 nm (fig 2c). For a wavelength of 1064 nm, the value of the two-spot efficiency, multiplied by L reaches saturation at about 100 nm, but unfortunately, due to the laser repetition rate being too high, most of the data obtained is a parasitic contribution (Fig. 2b). results are presented in Fig. 2 b and 2c.

5. Conclusions

Using our QDT protocol and applying it to specially designed sample, we were able to accurately measure the correlation length at the wavelength of absorbed photon of 1550 nm and find that it equals 17 ± 2 nm for the sample with the width of 74 nm.. Made of 6nm-thick NbN strip.

Let us discuss what is the relation of the obtained correlation length to the size of the hot spot. There are two alternative interpretations of the hot-spot correlation length. The first one, is that the distance between two spots is of the order of the width of the strip. We can divide the strip into squares [4], then a double-spot count is occurring when two spots fall into one square of the strip. In this case, the correlation length should be proportional to the width of the sample. The second scenario – the two-spot count appears when the two hot-spots touched each other. Then the hot spot correlation length can be interpreted as the hot-spot size.

Although our resulting value of the correlation length is less than the width of the strip, it is of the order of the width, and therefore we cannot consider it to be contradiction to the first interpretation. As a speculation, we note, however, that our result supports rather the second interpretation. Besides the small absolute value of the extracted correlation length, this value is close to what was obtained in the work of Renema *et.al.*[5], 23 ± 2 nm, with the use of wider samples and another protocol. This indicates that the correlation length does not grow with the strip width, which agrees with the second scenario. Of course, to come to a more valid conclusion, a systematic study of the dependence of the correlation length on the width of the strip is needed.

Acknowledgments
The work was supported by RSF grant # 17-72-30036.

References
[1] Zotova A.N. *et al*. 2014 *Supercond. Sci. Technol.* **27** 125001
[2] Polyakova M. *et al.* 2019 *IEEE Transactions on Applied Superconductivity* **29** 10518223
[3] Elezov M.S. *et al*. 2013 *Journal of Optical Technology* **80**
[4] Akhlaghi *et al*. 2009 *IEEE Transactions on Applied Superconductivity* 19 361-366
[5] Renema J.J. *et al.* 2012 *Optics express* **3** 2806-2813