National Research University Higher School of Economics

as a manuscript

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Quantum detector tomography of SNSPD

Dissertation summary
for the purpose of obtaining academic degree
Doctor of Philosophy in Engineering

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Moscow – 2023

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Introduction

The current development of quantum technology has generated a demand for photon detectors that have a single-photon sensitivity, but also capable of measuring the number of photons in an optical pulse with high accuracy. Although for most applications it is sufficient to distinguish between zero, one, two, and more than two photons, such a requirement is not trivial in itself. One of the best candidates for telecom wavelength applications is the superconducting single photon detector (SSPD), which exhibits near unity detection efficiency (DE) in this wavelength range, along with an extremely low false (dark) count rate. In addition, they potentially have very high operating speed (on the order of several GHz) and low jitter (sub -picosecond). The operation of a superconducting single-photon detector capable of measuring the number of photons in a pulse is based on the absorption of several photons that create hot spots, while the number of hot spots created in the superconductor can be measured by observing the characteristics of the measured pulses.

The relevance of research

- Continuous improvement of detector performance based on research results
- Deepening the understanding of the detection mechanism
- There are theoretical papers predicting the size of a hot spot and the distance at which two hot spots produced by the absorption of two photons will interact with each other. But at present, no experimental studies have been presented to confirm or refute this.
- Increasing the quantum key generation rate by increasing the counting rate of the superconducting single-photon detector.

- superconducting single-photon detectors are the only Russian devices of quantum technologies that determine the world level.

The degree of development of the problem

The most direct method for measuring the size of a hot spot, or rather the length of interaction between two hot spots, is quantum tomography of a superconducting single-photon detector [1].

Quantum detector tomography makes it possible to fully characterize the response of a superconducting single-photon detector, regardless of the input state, using a minimal set of operators.

In 2011 [2], a model was introduced in which a long nanowire was divided into sections and detection occurred only when two photons were absorbed in one section of the detector. As a result, it is possible to calculate the probability of detection in the multiphoton detection mode based on the single-photon mode of operation of the single-photon detector.

The application of quantum tomography methods to a superconducting single-photon detector was proposed by the Renem group [3]. The method was based on finding the probability that the detector will operate in response to *N* photons falling on it. These probabilities were determined by illuminating the detector with a known set of coherent states and measuring the detector's response probability as a function of input power. A pulsed laser source is usually used to generate coherent states.

Later, the method was applied to a detector made of a thin NbN film and a value of 23 ± 2 nm was obtained , however, due to the inhomogeneous geometry of the device and the need to take into account the linear losses of the device separately, the interpretation of the results is very ambiguous. In this work, the experiment was based on a comparison of two-photon and single-photon detection modes, so the method can only be applied to pure *N*-photon events. In most cases, it is not possible to determine what event was observed when the detector was triggered - one-photon or two-photon, one can only mark "click" or "no click".

In 2013, Elezov *et al*. [4] studied the detection modes and proposed a method for determining the regions of “pure” modes. For the same bias current, depending on the incident power, the detection efficiency is higher than the mode corresponding to a larger number of photons. Mixed detection modes have been considered and it has been shown how the intrinsic quantum efficiency of n-photon SSPD detection modes can be determined as a function of the bias current.

Goal of the work

Experimental study of the dimensions of a nonequilibrium region in a current-carrying strip formed as a result of photon absorption.

Investigation of the details of the mechanism of operation of a superconducting single-photon detector in terms of the size of the "hot" spot and the interaction of two hot spots.

Creation of superconducting single-photon detectors capable of distinguishing the number of photons using a single detecting element.

Research objectives

1. To develop a configuration of a superconducting single-photon detector that allows implementing the quantum detector tomography method.
2. Make a sample consisting of a narrow strip inscribed in a meander. This configuration was chosen to better match the radiation with a single-mode optical fiber.
3. Fabricate a detector that meets the requirements of the detector's quantum tomography method to determine the interaction length of two hot spots.
4. Experimentally implement the detector quantum tomography method.
5. Reveal the parasitic contribution of the bias scheme to the true values of the interaction length of two hot spots formed by the absorption of photons.

Research methods

- Quantum Detector Tomography: Excitation of two hot spots in a superconducting detector strip by absorbing photons and changing the width of the strip to values close to the interaction length of two hot spots formed by absorbing photons.
- The distance between hot spots arising from the absorption of photons depends on the average number of photons in the laser pulse
- It is necessary to exclude from detection the process of detection of one photon. With a decrease in current and an increase in light intensity (the number of photons per unit area increases), the probability of the detector triggering when absorbing 2 or more photons increases.

Scientific novelty

1. A new detector configuration has been developed, which is necessary for the correct study of the interaction of two hot spots formed by the absorption of photons: "a narrow strip in a meander"
2. A parasitic systematic contribution to the true values of the interaction length of two hot spots formed by the absorption of photons is revealed.
3. Improved measurement method for finding the interaction length of two hot spots in a superconducting single-photon detector
4. In detectors made of NbN and MoSi superconducting films , the maximum interaction length of two hot spots was determined, which corresponds to the width of the SC strip.
5. The Limit of the stripe width is determined, at which two hot spots formed by the absorption of two photons will cease to influence each other.

Basic provisions for defense

1. The maximum distance at which two hot spots interact, formed by the absorption of two photons in the detector at a wavelength of 1550 nm, is close to the width of the current-carrying strip of the detector.
2. An additional spurious contribution to quadratic readings is associated with the bias circuitry and is detected according to its dependence on the laser pulse repetition rate
3. The maximum interaction distance of hot spots arising from the absorption of photons in a single-mode detector optical waveguide, the same as in a fiber single-mode detector - about 100nm

Author's personal contribution

- Participation in task setting
- Development of the design of a superconducting single-photon detector, which makes it possible to implement the quantum tomography technique.
- Participation in the technological stages of manufacturing superconducting single-photon detectors - the process of photolithography, electron beam lithography, plasma-chemical etching and thermal deposition.
- Characterization of the resulting superconducting single-photon detectors using scanning electron microscopy.
- Development of an experimental setup for the implementation of the quantum tomography technique with fabricated superconducting single-photon detectors.
- Carrying out the processing of the obtained experimental data to find the length of interaction of two hot spots.
- Presentation at a number of conferences
- Preparation of the text of publications

Main results of the work

Chapter 1 of the dissertation presents a review of the literature showing the main directions in the development of a superconducting single-photon detector. This chapter consists of five parts - detection mechanisms, metrics, superconducting materials, optical matching techniques, and a superconducting single-photon detector quantum tomography techniqu.

This chapter of the dissertation presents the basic mechanisms for detecting single photons, generating false positives, and the influence of various factors (photon energy, nanostrip quality) on the spectral range of a superconducting single-photon detector. The main metrics used to assess the quality of SSPD performance are introduced - quantum efficiency, dark counts, jitter and spectral range. For each of the characteristics of the SSPD, cutting-edge results from various international groups are presented. Further in chapter 1 of the dissertation, an overview of the various superconducting materials used to create SSPDs is presented. Various techniques for depositing superconductors on a substrate are shown, as well as the main properties of materials that affect the characteristics of SSPD. Also in chapter 1 of the dissertation, the main methods of optical matching of SSPD with external radiation are given. In the final part, the main results obtained on the subject of the dissertation research are demonstrated.

To apply the method of quantum tomography of a superconducting single-photon detector, a special configuration of the detector has been developed. Thus, to reliably extract the length of interaction between two hot spots, narrow and relatively short detectors are needed, but such a configuration will lead to problems in the transition of the detector back to the superconducting state. To avoid this problem, an additional inductance implemented in the form of a meander is added to the sensitive element of the detector. A schematic representation of a typical sample used in the framework of the dissertation research is shown in Figure 1.

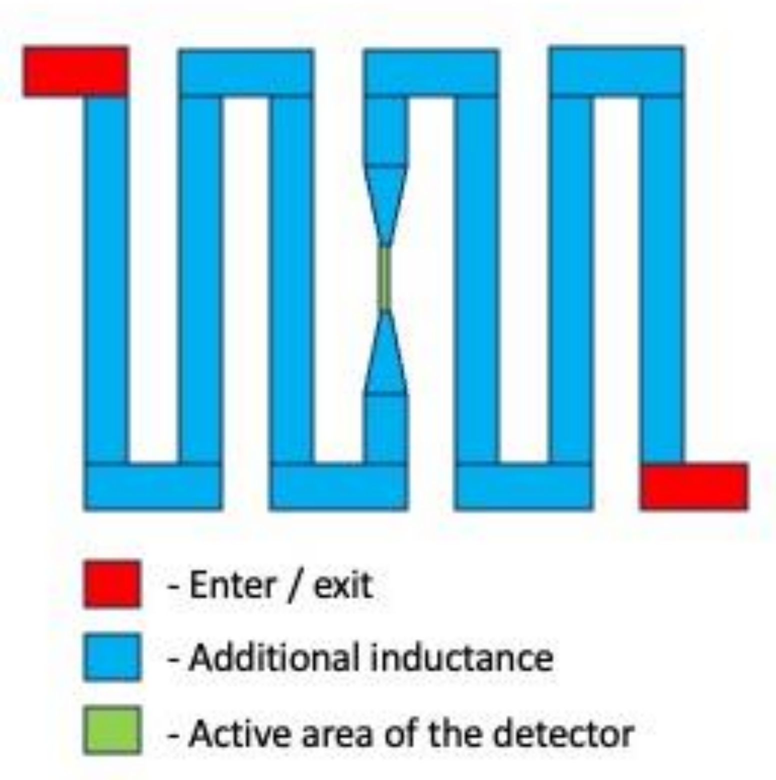

Figure 1 - is a schematic representation of a superconducting single-photon detector used in the dissertation research.

Chapter 2 of the dissertation consists of five parts, each of which describes the technological processes in which the author of the dissertation research participated. A brief diagram of the technological process of manufacturing superconducting single-photon detectors is shown in Figure 2. This diagram shows the following stages: a) cleaning of substrates before deposition of superconducting niobium nitride by reactive magnetron sputtering. b) reactive magnetron sputtering of niobium nitride; A typical micrograph taken with a scanning electron microscope (SEM) is shown in Figure.

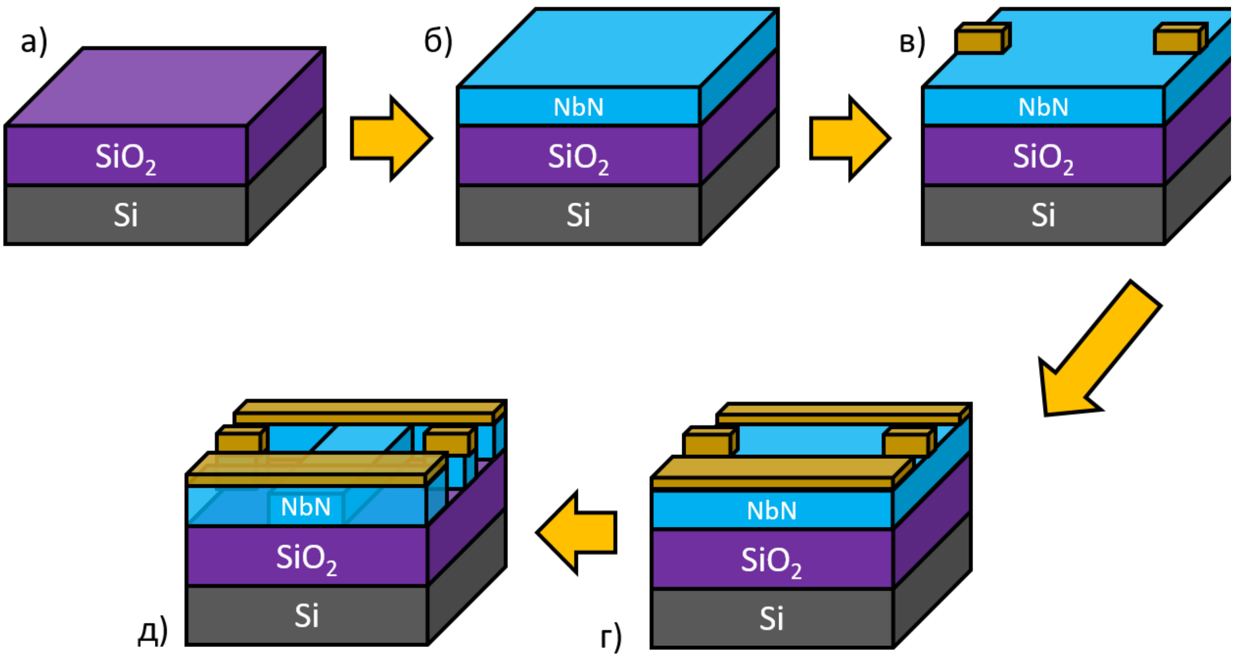

Figure 2 - Technological process of manufacturing a superconducting single-photon detector.

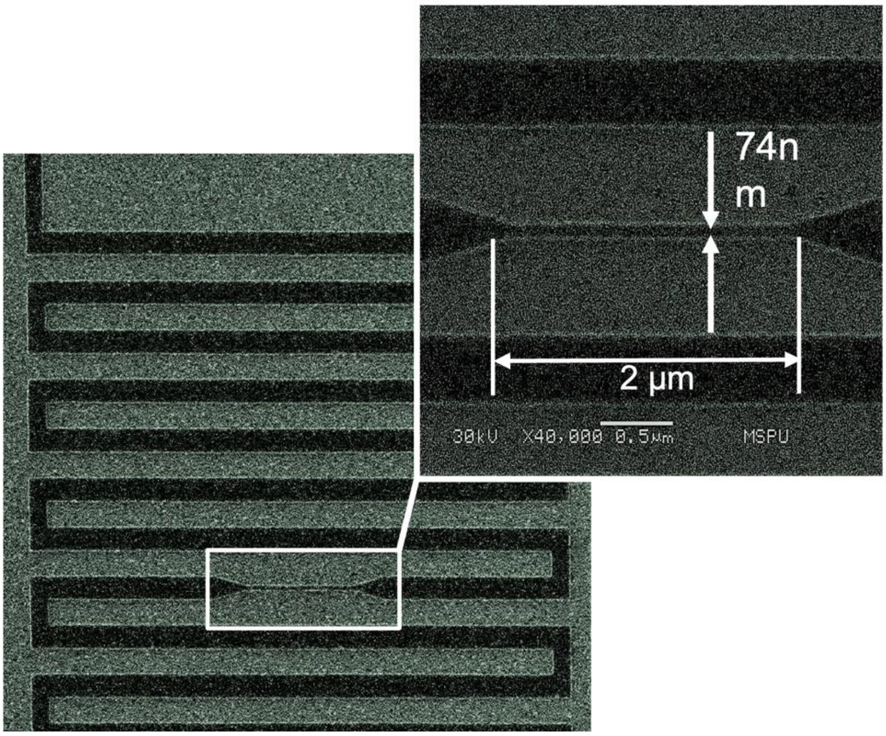

Figure 3 — SEM image of the detector used in the dissertation research

Chapter 3 of the dissertation presents a quantum tomography method for a superconducting single-photon detector, which allows one to determine the two-spot detection efficiency and extract the interaction length of two hot spots (s) formed from the absorption of photons at one hundred percent internal detection efficiency. The chapter also presents a method that allows one to determine the spurious contribution associated with the bias scheme and shows a way to eliminate this contribution in the subsequent processing of experimental data. From the analysis of data for a superconducting single-photon detector integrated with a waveguide, the interaction length of two hot spots is found to be equal to the width of the superconducting band.

The interaction length of two hot spots is related to the two-spot efficiency as $s = L\,\eta_2(I)$. In order to find $\eta_2(I)$it is necessary to first calculate the average number of absorbed photons M by multiplying the average number of incident photons by the detection efficiency in the saturation region, assuming that each absorbed photon in this region produces a trigger. Then the obtained dependencies $P(M)$ are approximated by a second-order polynomial

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

In this expression, η_0 is the probability of a dark count.

$$a_2 = \eta_2 + a_2^{stat} + a_2^{bias}$$

$$a_2^{stat} = -(\eta_1)^2, a_2^{bias} = 2I\Phi\eta_1(\frac{d\eta_1}{dI})$$

$\Phi = f\tau$is the product of the laser pulse repetition frequency f and the duration of the response pulse of the superconducting single-photon detector τ, $\eta_1$is the one-spot detection efficiency, $\eta_2$is the two-spot detection efficiency

Then this approximation procedure is repeated for different values of the current, until the contribution η_1 does not prevail over the quadratic contribution. In this case, the extraction of the coefficient a_2 becomes impossible due to the statistical dispersion of the measurement results. An example of experimental data approximation is shown in Figure 4.

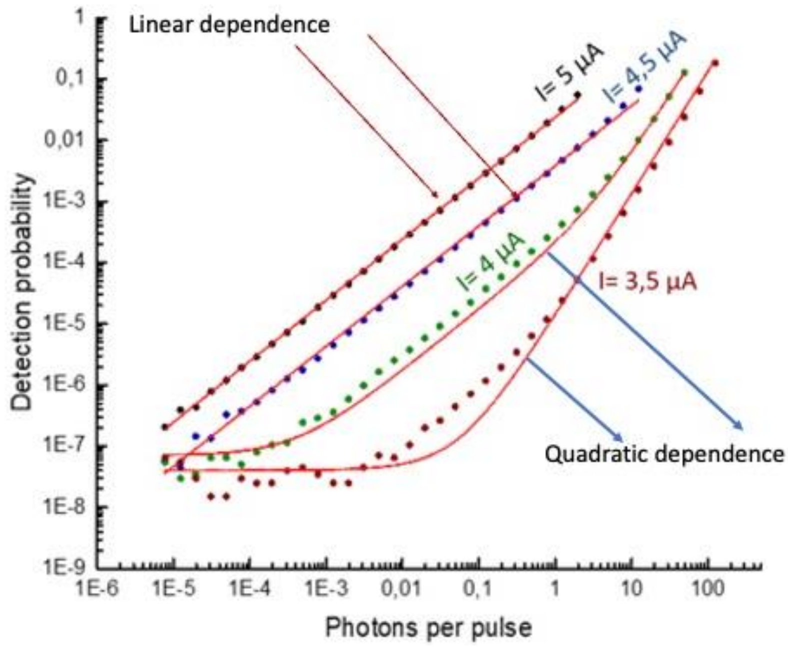

Figure 4 — Approximation of experimental data by a second-order polynomial to extract the two-spot detection efficiency

In order to obtain the dependence of the two-spot efficiency on the current, it is necessary to use the approximation of the data by formula (1) to extract the coefficient a_2 and subtract the systematic errors a_2^{stat} and a_2^{bias}. If the value of the product of the laser pulse repetition frequency and the duration of the response pulse of a superconducting single-photon detector is precisely determined, then to find the parasitic contribution arising from the bias current and determined by the coefficient, a_2^{bias} it is necessary to vary the laser repetition frequency f . An example of separating spurious data from the true value of $\eta_2(I)$ is shown in Figure 5.

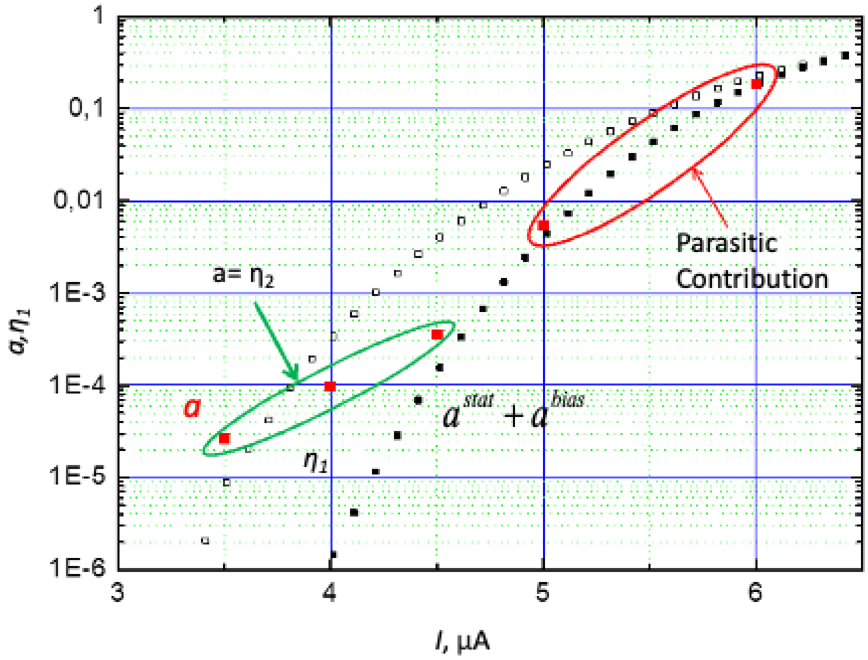

Figure 5 - Illustration of the parasitic contribution from the bias circuit

In this chapter, the method is applied to a superconducting single-photon detector integrated with a waveguide. The results are presented in Figure 6.

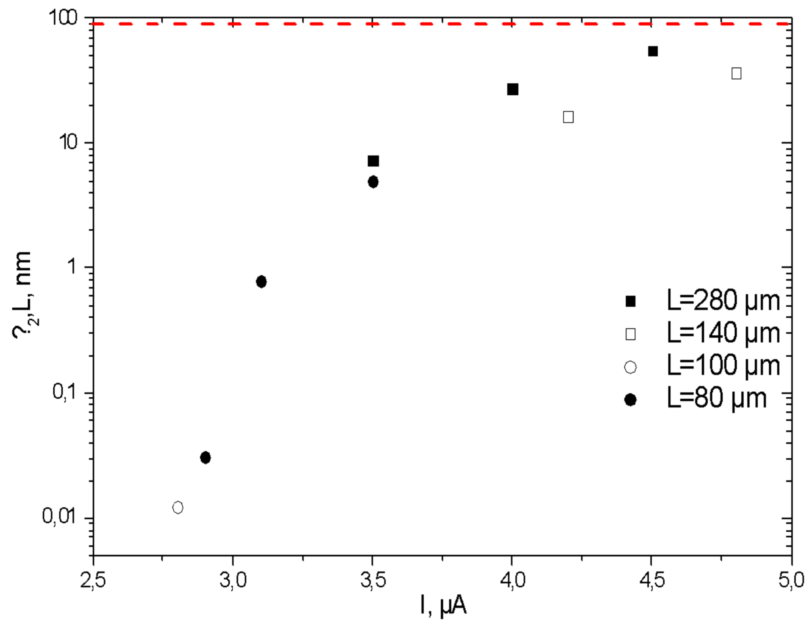

Figure 6 - Results of applying the method of quantum tomography of a superconducting single photon detector to a waveguide SSPD

Bias bias was checked for each measurement and spurious data was removed from consideration.

Chapter 4 of the dissertation presents the results of quantum tomography of a superconducting single-photon detector of micron length. The high internal quantum efficiency of the detectors under consideration makes it possible to extract one- and two-spot detection efficiencies from the dependence of the count rate on the power of radiation incident on the detector and to determine the interaction length of two hot spots. Detectors made from NbN films with different surface resistances and films made from MoSi were experimentally studied. Detectors with different widths of the superconducting strip were considered. The measurement results are shown in Figures 7 and 8.

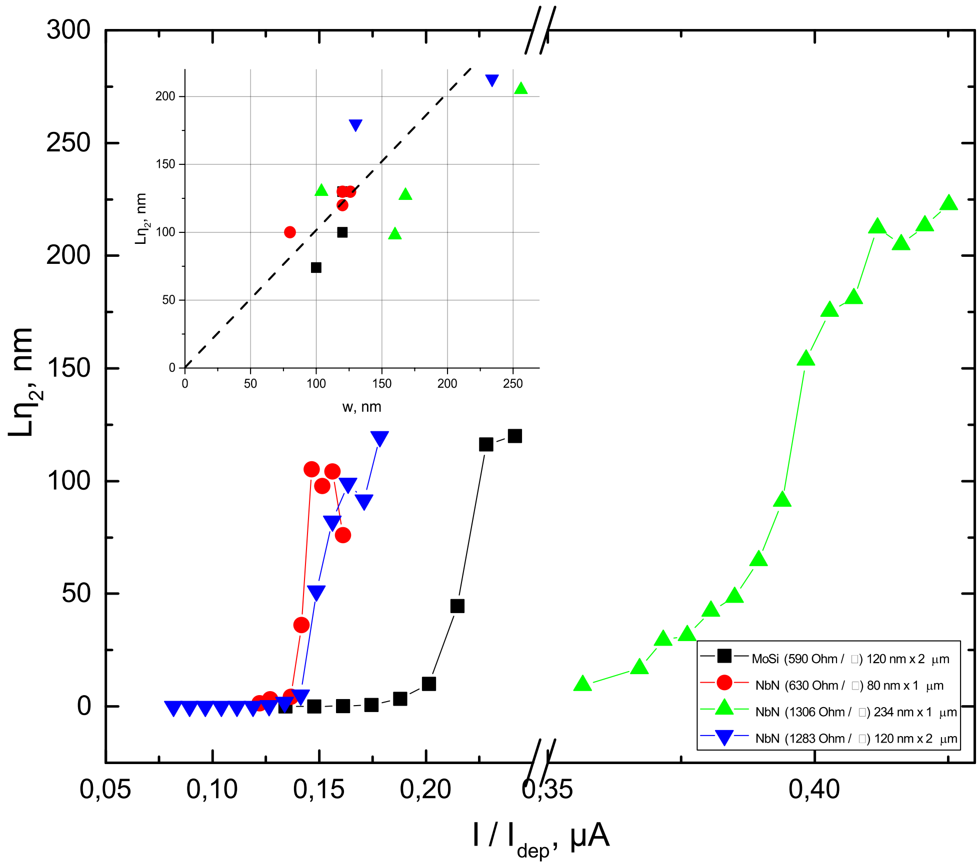

Figure 7 - Comparison of the interaction length of hot spots in detectors made of high-resistance NbN films , standard NbN and MoSi films

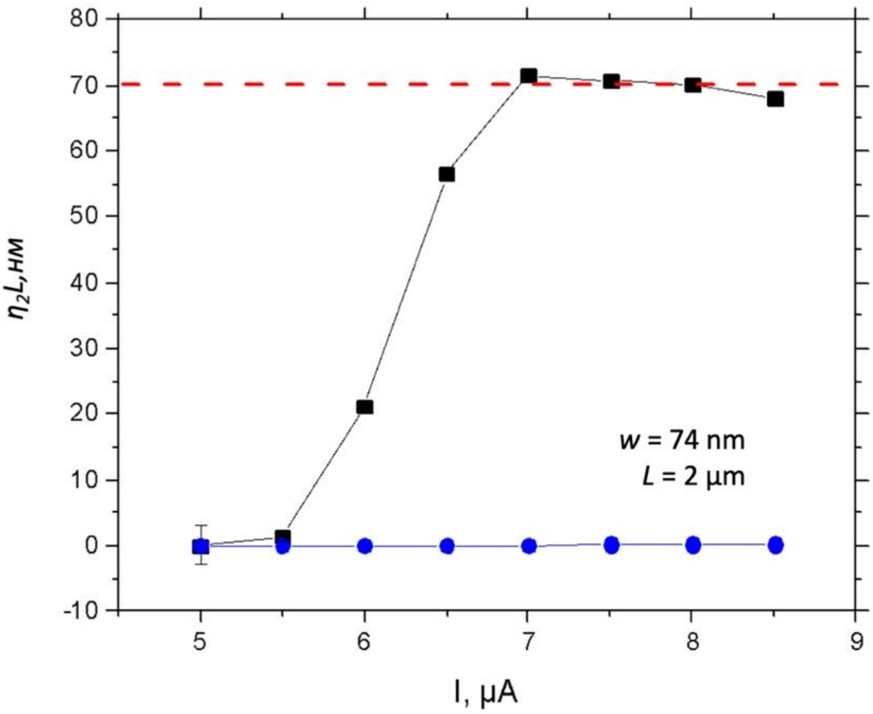

Figure 8 - Interaction length of two hot spots, for a detector made of NbN . Length 2 µm, width 70 nm.

In conclusion, the main results of the work are formulated:

- to the probability of detector operation upon absorption of a photon is found , even for the region in which the response to one photon prevails, which makes it possible to determine the level of saturation of the two-spot detection efficiency.
- An additional parasitic systematic contribution to the values of the hot spot interaction length is found. It is related to the detector bias circuit
- We demonstrate how to eliminate this contribution to obtain results relating only to the interaction length of two hot spots.
- For a superconducting single-photon detector based on an optical waveguide, a systematic monotonic dependence of the interaction length of two hot spots on current has been found. The saturation value of this quantity (i.e. s) is close to the width of the strip.

- Tomography of a superconducting single photon detector requires short strips. So, for example, a strip with a length of 1 and 2 μm showed a confident saturation of the coefficient η_2, while detectors with a total length of 140–280 μm show signs of saturation.
- Saturation η_2 depending on the bias current for nanostrips made from ultrathin NbN and MoSi films , with a width varying from 56 to 300nm. This makes it possible to extract the maximum interaction length *s of hot spots* .

Work approbation

1. 6th International School-Conference on Optoelectronics, Photonics and Nanostructures "Saint Peterburg OPEN 2019", St. Petersburg, Russia, April 22-25, 2019, report "Extracting hot-spot correlation length from SNSPD tomography data";
2. XXIV International Symposium "Nanophysics and Nanoelectronics", Nizhny Novgorod, Russia, March 9 - 12, 2020, report "Quantum tomography of a superconducting single-photon detector integrated with a waveguide";
3. XXV Symposium "Nanophysics and Nanoelectronics", Nizhny Novgorod, March 9-12, 2021, report "The length of the interaction of hot spots for a superconducting single-photon detector with a quantum efficiency close to unity";
4. 7th International School-Conference "SPBOpen 2020", St. Petersburg, Russia, April 27-30, 2020, report "Quantum detector tomography of superconducting single photon detector based on MoSi film";
5. EUCAS 14th European Conference on Applied Superconductivity, Glasgow, Scotland, September 1-5, 2019, report "Disordered superconducting NbN thin film as a material of choice for single-photon detectors for linear optical quantum computing";
6. EUCAS 15th European Conference on Applied Superconductivity, Moscow, Russia, September 1-5, 2021, report "Quantum detector tomography on NbN single strip SNSPDs".

List of published articles on the topic of the dissertation

All published articles reflecting the main results of the dissertation are included in the international citation system Scopus:

1. Polyakova , M., Semenov, A.V., Kovalyuk , V., Ferrari, S., Pernice , W.H., & Gol'tsman , G. N . Protocol of measuring hot-spot correlation length for SNSPDs with near-unity detection efficiency //IEEE Transactions on Applied Superconductivity. - 2019. - T . 29. - no. 5. - S. 1-5.M .
2. Polyakova , M.I., Florya , I.N., Semenov, A.V., Korneev , A.A., & Goltsman , G.N. (2019, December). Extracting hot-spot correlation length from SNSPD tomography data. In *Journal of Physics: Conference Series* (Vol. 1410, No. 1, p. 012166). IOP Publishing.
3. Polyakova M.I., Korneev A.A., Semenov A.V. Comparison single-and double-spot detection efficiencies of SSPD based to MoSi and NbN films //Journal of Physics: Conference Series. - IOP Publishing, 2020. - T . 1695. - no. 1. - S. 012146.
4. Polyakova , M., Sheveleva , E., Semenov, A., & Goltsman , G. Measuring Hot-Spot Interaction Length in Single-Strip SNSPD //IEEE Transactions on Applied Superconductivity. - 2022. - T . 32. - no. 4. - S. 1-4.

The author's name has been changed. Supporting documents are attached

References

1. JS Lundeen, A. Feito , H. Coldenstrodt -Ronge, KL Pregnell , C. Silberhorn , TC Ralph, IA Walmsley, Tomography of quantum detectors //Nature Physics. - 2009. - T . 5. - no. 1. - S. 27-30.
2. Akhlaghi M. K., Majedi A. H., Lundeen J. S. Nonlinearity in single photon detection: modeling and quantum tomography //Optics express. – 2011. – T. 19. – №. 22. – C. 21305-21312.

3. Renema JJ et al. Modified detector tomography technique applied to a superconducting multiphoton nanodetector //Optics express. - 2012. - T . 20. - no. 3. - S. 2806-2813 .
4. Elezov MS et al. Investigating the detection regimes of a superconducting single-photon detector // Journal of Optical Technology. - 2013. - T . 80. - no. 7. - S. 435-438 .