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Effect of an External Alternating Electric Field on the Efficiency of a Superconducting Single-Photon Detector

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In this paper, model of a surface ion trap for a scalable quantum computer with an RF electrode and a superconducting single-photon detector was studied with an operating temperature of 4 K. The amplitude range of the radio frequency signal varied from 10 to 800 mV at frequencies from 5 to 20 MHz. The effect of the induced external RF field of the trap on the dark and bright count rate of a single-photon detector is studied. The results of this work are important in the design of surface ion traps with planar single-photon detectors.

Keywords: surface ion trap, superconducting single-photon detector, niobium nitride, scalable ion quantum computer.

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Introduction

A large-scale quantum computer demonstrates efficient execution of specific tasks that pose computational challenges for classical computers [1]. Quantum information processing requires the coordinated manipulation of elementary objects called qubits. Qubits can be implemented on the basis of various physical quantum systems. Common implementations include superconducting circuits, photons, neutral atoms and trapped ions [2]. A promising strategy involves the use of ion qubits[3], wherein information is encoded within the electronic energy levels of individual ions trapped in ultrahigh vacuum system operating either at room temperature or temperatures around 4 K.

Three-dimensional radio frequency Paul traps were used for the first experiments on manipulating ion qubits. However, the use of two-dimensional (surface) ion traps (ST, surface trap) holds promising potential for the transition to large-scale quantum computing. Over the past few years, scientific groups have been developing the traps aiming for a scalable architecture [4]. Ion ST represents a microcircuit with a set of DC and radio frequency (RF) electrodes on its surface, creating a potential well for ion trapping at distance from the microcircuit surface.

For large ion arrays, efficient methods and technologies are needed to collect and detect photons emitted by individual ions. The accuracy of ion state measurement depends on the number of photons collected and detected. Superconducting single-photon detectors (SSPD) integrated into surface ion traps can be used to achieve this goal. SSPDs [5] boast low dark count rates (< 10 Hz) and high efficiency ($> 85\%$), enabling precise quantum state measurements for trapped ions on a chip without the radiation outputting from the cryostat.

Despite a successful demonstration of the operation principle, integrating ion ST with SSPDs faces challenges. The trap field can negatively affect detector characteristics, including critical current suppression, reduced detection efficiency, and increased dark count rate, potentially impacting the speed and accuracy of trapped ion state readout.

The authors in the paper [6] used an amorphous superconductor based on MoSi compound with a low critical current density ~ 1 MA/cm^2 as the SSPD nanowire material, which limited the critical current of the detector to 9 μA. A well-proven superconducting material niobium nitride (NbN) was selected to study the influence of an external alternating electric field. NbN has a critical current density ~ 5 MA/cm^2 which will increase the critical current to 30 μA.

1. Fabrication route of surface trap with SSPD model

The ST model studied in this work represents an SSPD with a titanium-gold (Ti/Au) electrode positioned

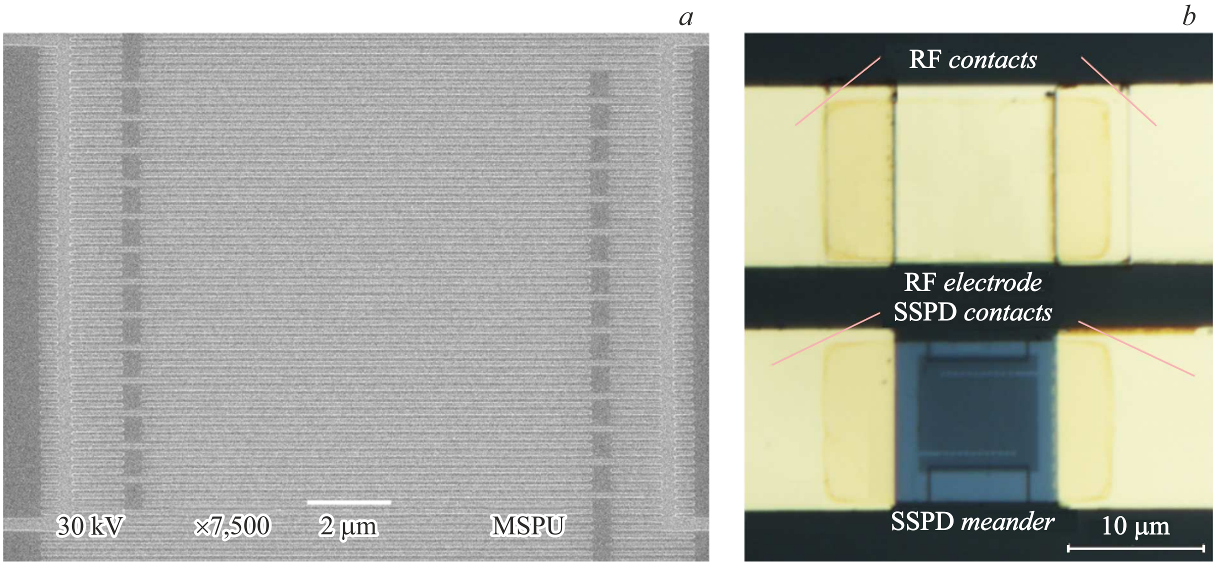

Figure 1. Model of a surface ion trap with SSPD; *a* — photo of the SSPD nanowires in a scanning electron microscope, *b* — photo of a model of an ion surface trap with SSPD, including SSPD contacts and meander, RF contacts and a Ti/Au RF electrode, to which simulating ion trapping field is applied.

next to it (Fig. 1). Fabrication included the following processes: deposition of ultrathin superconducting NbN film, photolithography of alignment marks, SSPD and gold RF electrode electron-beam (e-beam) lithography, contact pad and lids photolithography, NbN etching.

At the first stage of fabrication, we evaporate a thin film of niobium nitride (~ 7 nm) onto the sample, apply alignment marks using photolithography, and then conduct e-beam lithography of the active region of SSPD [7].

The golden bridge of a RF electrode of the surface trap was formed at the second stage using lift-off lithography. A two-layer MMA A6/PMMA A3 resist was used as a mask. Each layer was applied by spin-on (6000 rpm, 60 s) and baked on a hot plate (130°C, 60 s). The resist was developed in a solution of water (H_2O) and alcohol (2-propanol) in the ratio 8 : 1 for 20 s, the reaction was arrested in 2-propanol. The Ti/Au layer and contact pads were evaporated similarly to the process of evaporation the alignment marks.

Photolithography of lids and field etching of NbN was carried out at the third stage. Any unnecessary parts of niobium nitride were removed so that the final sample of the ST with SSPD model included only superconducting nanowires of the detector in meander form. Special lids were made for this purpose, i. e. places covering the active area of the detector for subsequent etching. The lids were formed by photolithography. The superconductor without lids was removed in SF_6 atmosphere by plasma chemical etching after illumination and development of the resist in a 7% KOH solution.

The main stages of fabrication of a surface trap with SSPD are schematically shown in Fig. 2.

2. Description of the experimental setup and measurement method

The scheme of an experimental setup for studying the influence of an external electric field (simulating the ST field) on the efficiency of a superconducting single-photon detector at a temperature of about 3 K is shown in Fig. 3. The setup consists of a closed-cycle cryostat, bias unit, pulse counter, RF field signal generator, thermometer and an oscilloscope.

The SSPD sample is placed on a cold cryostat plate with a minimum temperature of 3 K. The current was supplied to the detector using a bias unit, which includes a tunable current source, bias tee, amplifiers and the number of counts corresponding to each current value was recorded using a pulse counter. An external electric field with different values of amplitudes and frequencies was applied to the RF contact using signal generator. The study examined how SSPD detection efficiency and dark count rate are affected when illuminated by a 600 nm wavelength laser with a closed optical input.

3. The influence of an external alternating electric field on SSPD

Fig. 4, *a* shows the waveform of the signal from SSPD in ST which includes two components: the pulse from the detector (indicated in purple (in the online version)) and the induced external field (indicated by blue color (in the online version) and dashed lines). At first, the optimal trigger level was determined using the pulse counter at the first stage of the study. The current corresponding to 100 dark

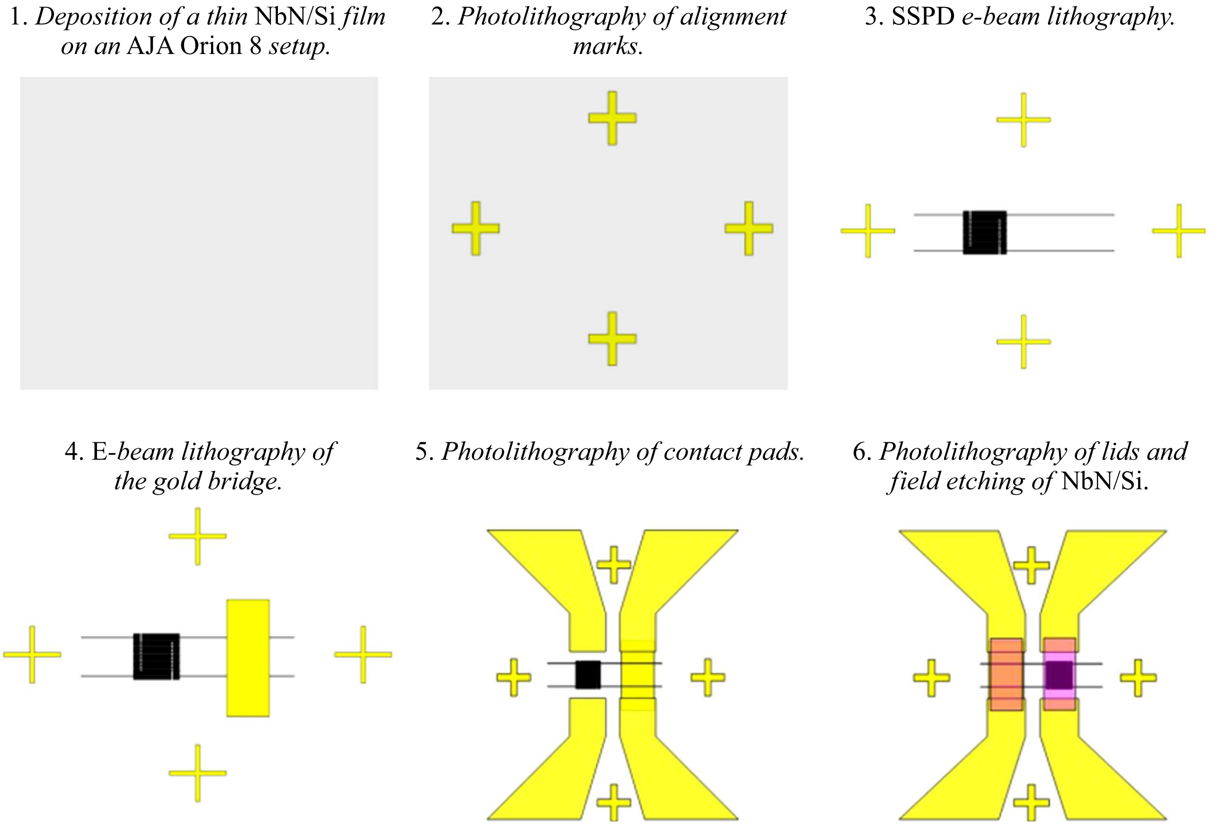

Figure 2. Illustration of the fabrication route of a surface trap with SSPD: *1* — deposition of NbN/Si thin film using AJA Orion 8 system, *2* — photolithography of alignment marks, *3* — e-beam lithography of SSPD, *4* — e-beam lithography of the golden bridge, *5* — photolithography of contact pads, *6* — photolithography of lids and field etching of NbN/Si.

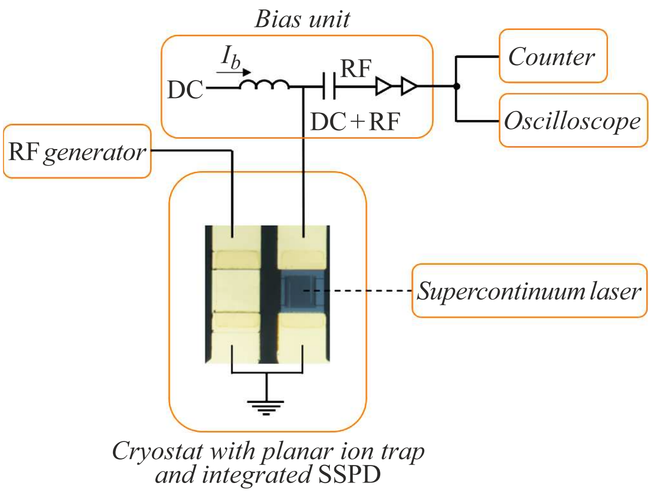

Figure 3. Scheme of the experimental setup. Black lines — electrical coaxial cables, dashed lines —optical fiber. Supercontinuum laser, RF generator, bias unit, pulse counter, oscilloscope, experimental sample, cryostat with planar ion trap and SSPD model.

counts per second was applied to the sample and the trigger value on the pulse counter changed from 0 to 300 mV (Fig. 4, *b*). Three ranges were identified on the graph of the dependence of counts per second on the trigger level: the 1st range (up to 12 mV), in which the counts sharply changed with the level of trigger, the 2nd range (from 16 to 280 mV) with virtually unchanged value of the counts and the 3rd range (> 280 mV) with decreasing to zero number of detector counts.

Trigger level allows separating signal measurements from various noises and leads, and isolating the external RF field of the ST, was selected at the level of 200 mV for the entire series of measurements (Fig. 4, *b*).

Figure 5 shows the dependences of the bright and dark count rate of SSPD on the bias current at external trap fields with amplitudes 10–800 mV at frequencies from 5 to 20 MHz. The figure shows that the external RF field significantly affects the dark count rate due to parasitic currents in the detector arising in the background of the radio frequency signal. The value of the resulting RF currents increases with increasing amplitude of the external field at a fixed frequency. This facilitates the transition of the detector from the superconducting state at currents below the critical value in the case of the external field being turned off. However, the amplitude of the RF currents in the detector increases as the frequency increases (comparing graphs *a*–*d* in Fig. 5) according to the behaviour of the curves of the number of dark counts per second at a fixed

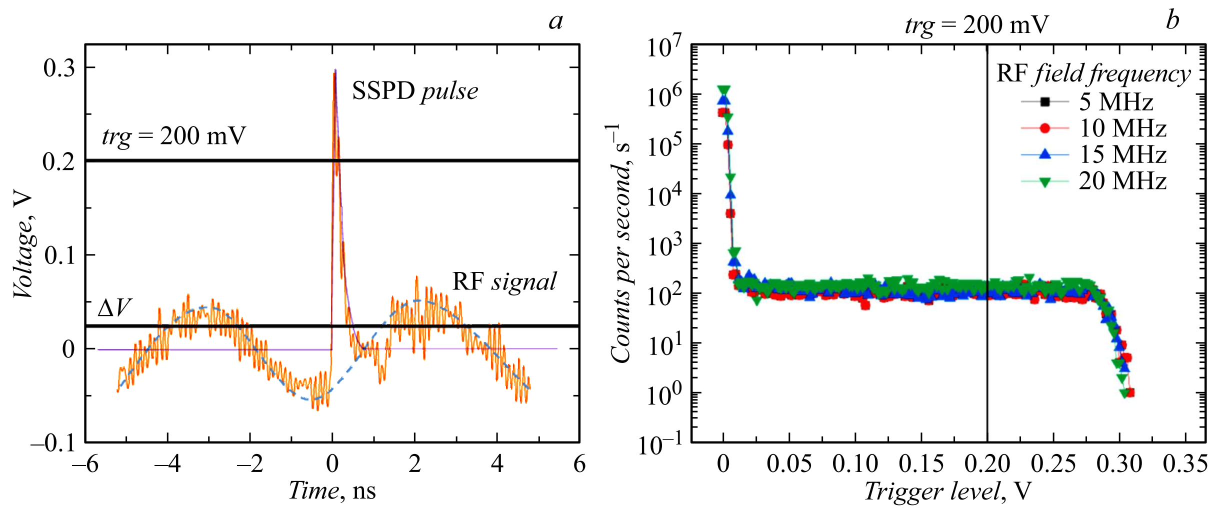

Figure 4. Trigger level for measuring the ST model *a* — pulse waveform of the SSPD detector (SSPD pulse) with induced field (sine, RF signal), *b* — measurement of the trigger level for measuring the ST model for different frequencies of the external field (5, 10, 15 and 20 MHz) with an amplitude of 10 mV.

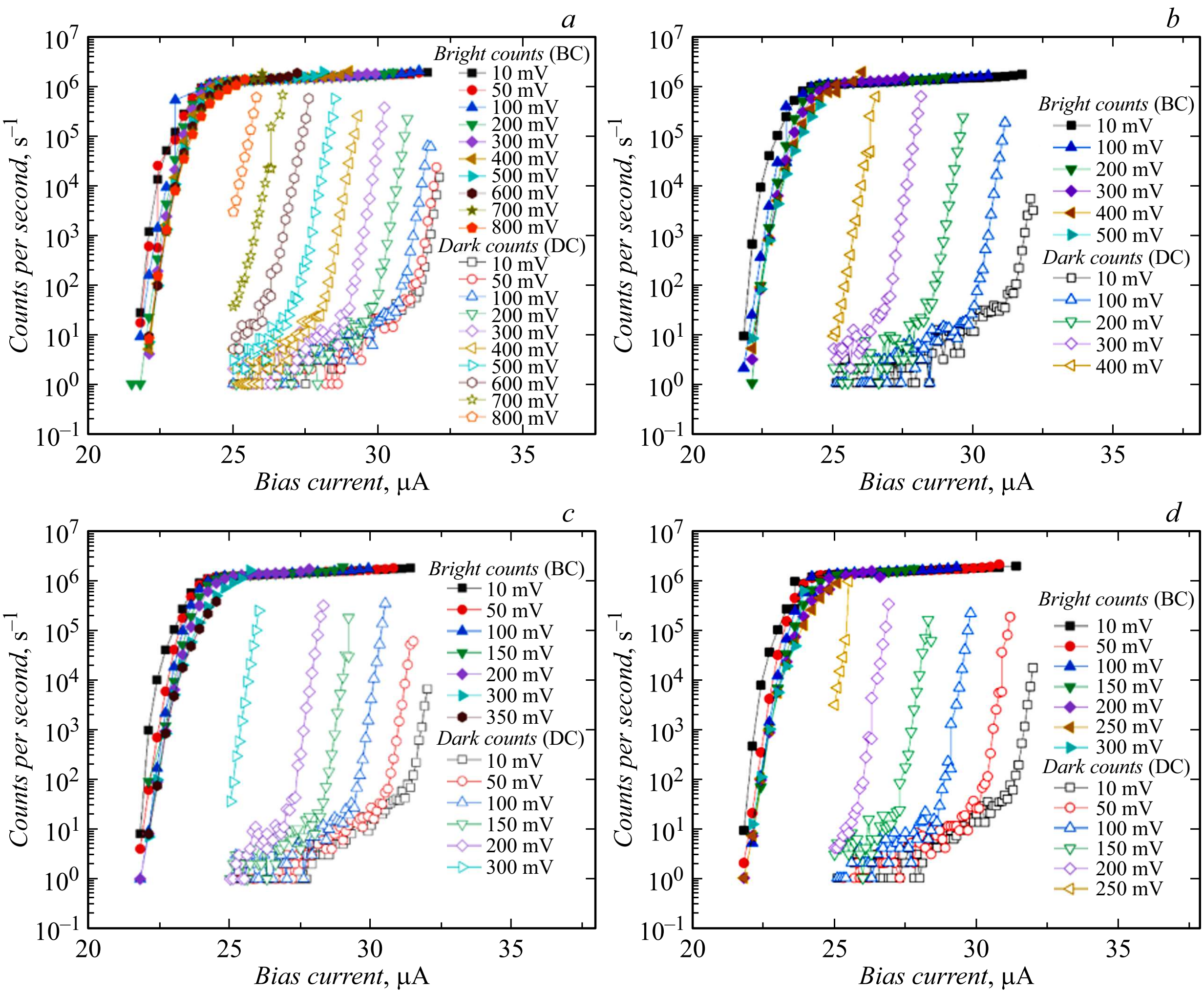

Figure 5. Dependence of the bright counts per second (BC) and dark count rate (DC) of SSPD on the bias current for different amplitudes of the external field of surface trap at different frequencies: *a* — 5, *b* — 10, *c* — 15, *d* — 20 MHz.

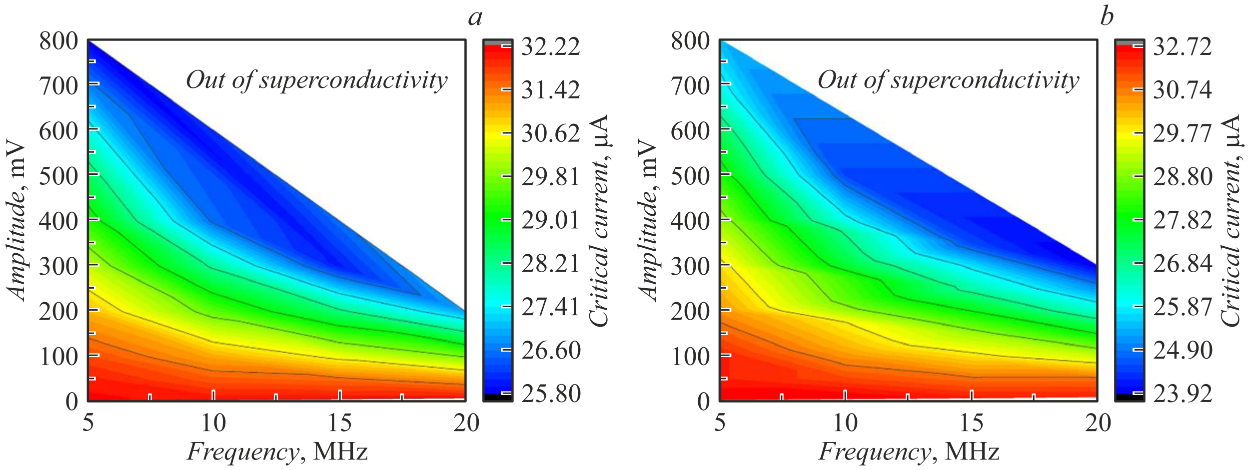

Figure 6. Three-dimensional maps of the dependence of the critical current on various amplitudes and frequencies of the trap's external field: *a* — dark count rate and *b* — bright count rate. White areas — out of superconductivity.

amplitude of the external field. This is also leads to a transition of the detector from the superconducting state to normal one at lower currents. Bright count rate (and therefore detection efficiency) remains virtually unchanged with increasing of dark count rate and restricting of critical current. This is due to the high internal efficiency of the NbN detector, when the efficiency practically does not depend on the bias current [7,8].

Qualitatively, the mechanism of influence of an external electric field can be described on the basis of two non-contradictory approaches. The first approach is related to the features of the detector bias [5]. The SSPD is biased by a current close to critical on the superconducting part of the current-voltage characteristic. The operating point moves along the load resistance from the superconducting branch to the metastable region and back: for dark counts per second proportionally to thermal and quantum fluctuations [9], for bright counts per second - to the photon flux. If the value of the bias current and induced current is greater than the critical one, then the detector does not fall into a metastable region from which it can return back, but into a resistive one and does not return to the superconducting state ceasing to operate. An increase in the amplitude and frequency of the field leads to an increase in the probability of transition to a normal state.

Another approach is related to the signal pickup scheme. An external RF field leads to the occurrence of an induced field and to the charging of capacitors in the signal pickup circuit (bias tee and amplifier in Fig. 3). The actual value of the alternating voltage ΔV (Fig. 4 *a*) in the line depends on shape and amplitudes of the external RF field. The additional current generated by discharging capacitors through the detector (ΔI) is added to the current source (I_b), increasing the detector bias current I_b^*, ($I_b^* = I_b + \Delta I$), which leads to suppression of superconductivity. The impact of the constant component of the RF field is small at low frequencies, but it increases with the increase of the amplitude and frequency of the RF field.

The second approach was used by the authors of the papers [10–12] to explain the decrease of the critical current of the detector and the occurrence of artifacts depending on the counts with the photon count of $> 10^7$ cps (counts per second). In this case, the pulses from the detector directly comprised the variable signal, the effective value of which charges the capacitors in the bias circuit. The use of a DC bias circuit without capacitors in the line made it possible to increase the count rate of the detector up to two times [10].

Figure 6 shows three-dimensional maps of the dependence of the critical current on different values of amplitudes and frequencies of the induced external field. These maps allow estimating at what values the detector can operate and finding the optimal ones. It will not be possible to measure the bright counts per second of the SSPD with the external field with a frequency of 15 MHz and an amplitude of 600 mV, since the detector is already exiting the superconductivity state in this region (the bright region). Similarly for dark count rate.

Experimental studies show that the use of a detector with a higher critical current density reduces the effect of the external electric field on the dark count rate and minimizes the influence of the field on the efficiency of the detector. But it is not sufficient for using such detectors at high field values with an amplitude of more than 800 mV. Further increase in the operating range of the detector can be associated both with filtering the output signal from the induced external RF field (Fig. 4, *a*) and with shielding the active area of the detector.

Conclusion

A study of the model of an ion surface trap with NbN SSPD was performed. The dependence of the bright and dark count rates of the detector was measured with an active radio frequency signal with different amplitudes at frequencies of 5, 10, 15 and 20 MHz at a wavelength of 600 nm at a temperature of about 4 K. Obtained data demonstrate a decrease in the critical current of a single-photon detector with an increase in the amplitude and frequency of the radio frequency signal. Three-dimensional maps are also presented that allow finding optimal frequencies and amplitudes of the external field to measure the influence of the RF field on the SSPD efficiency.

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Conflict of interest

The authors declare that they have no conflict of interest.

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