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Prospects of Sensors Using RFTES Technology for Superconducting Quantum Circuits

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The article discusses the prospects for advancing the detector RFTES technology, which uses the principle of high-frequency heating of a superconducting absorber in a microwave resonator for dispersive reading of the state of superconducting qubits in the frequency range of 1–8 GHz. The compatibility analysis of the technology and circuitry of the qubit and RFTES detector required for the integration of such detectors on a single chip, as well as the required levels of sensitivity and suppression of the detector's backaction on the qubit, is carried out. The study showed that the existing level of RFTES technology already allows for the implementation of dispersive reading of a superconducting resonator with $Q = 1000$, which contains 10 photons at frequency 7 GHz, with a measurement rate of about $10\,\mu$s. The research shows that it is possible to suppress the feedback of the detector by approximately ~ 140 dB at the detector pumping frequency and by approximately ~ 90 dB at the qubit excitation frequency that might satisfy the conditions of their compatibility within a single microchip.

Keywords: direct detector, RFTES, superconducting qubit, dispersive reading, superconducting resonator, superconducting transition, superconducting microbridge, hafnium film, hot electron gas, RF superconductivity.

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Introduction

New technology of superconducting detectors, RFTES (Radio Frequency Transition Edge Sensor) was first proposed in 2011 and is being developed primarily for use in submillimeter astronomy [1]. Based on theoretical estimates and experimental data obtained, it can be concluded today that such thermal detectors can have record-breaking characteristics at physical temperatures in the range of 300–500 mK [2], achievable using modern closed-cycle sorption refrigerators. The Russian astronomical community, as far as the authors know, is interested in such sensors, but currently does not have the infrastructure to use detectors at such low temperatures, and it takes time for a serious technological transition, which objectively delays the implementation process. However, the rapidly developing field of quantum computing based on a superconducting platform has long been using deep cooling technologies based on dilution refrigerators He^3/He^4, allowing experiments to be carried out in the temperature range from about 1 K down to 10–30 mK, which depends on the specific heat load, which, as a rule, does not exceed $100\,\mu$W. Promising designs of RFTES detectors were tested on this equipment [3].

Experimental studies of superconducting quantum bits conducted in the world's leading laboratories have led to the idea of using ultra-sensitive microwave detectors to determine a change in the state of a qubit by recording the pulse energy generated by a frequency shift of a superconducting resonator weakly coupled to the qubit [4,5]. A change in the state of a qubit during the transition to a complementary state is recorded typically at frequencies of 5–8 GHz as a variation in the amplitude of the current in an resonant circuit, part of which is a two-level system (for example, a SQUID). Detailed studies of RFTES detectors with thin films of hafnium (Hf) near their critical temperature have shown that this material is also suitable for detecting signals at relatively low (communication) frequencies, for example, 1–10 GHz, which does not work for the nearest competing detectors — MKID detectors [6]. Several circuit design solutions have been developed and patented for the use of RFTES detectors at communication frequencies, including blackbody gigahertz and terahertz calibrators [7–9], as well as a number of laboratory experiments using solutions shown schematically in Fig. 1, *a*, *b*. The properties of the structures shown in Fig. 1, *c*, *d* will be considered in this paper.

1. Methods and approaches

Let us consider a simplified model of a superconducting qubit, which we represent as a nonlinear inductor, L_q, as shown in Fig. 1, *d*, connected to a resonator so that the resonator noticeably changes its frequency when the state of the qubit changes. The pulse occurring during this shift should be detected by the RFTES detector. In the study

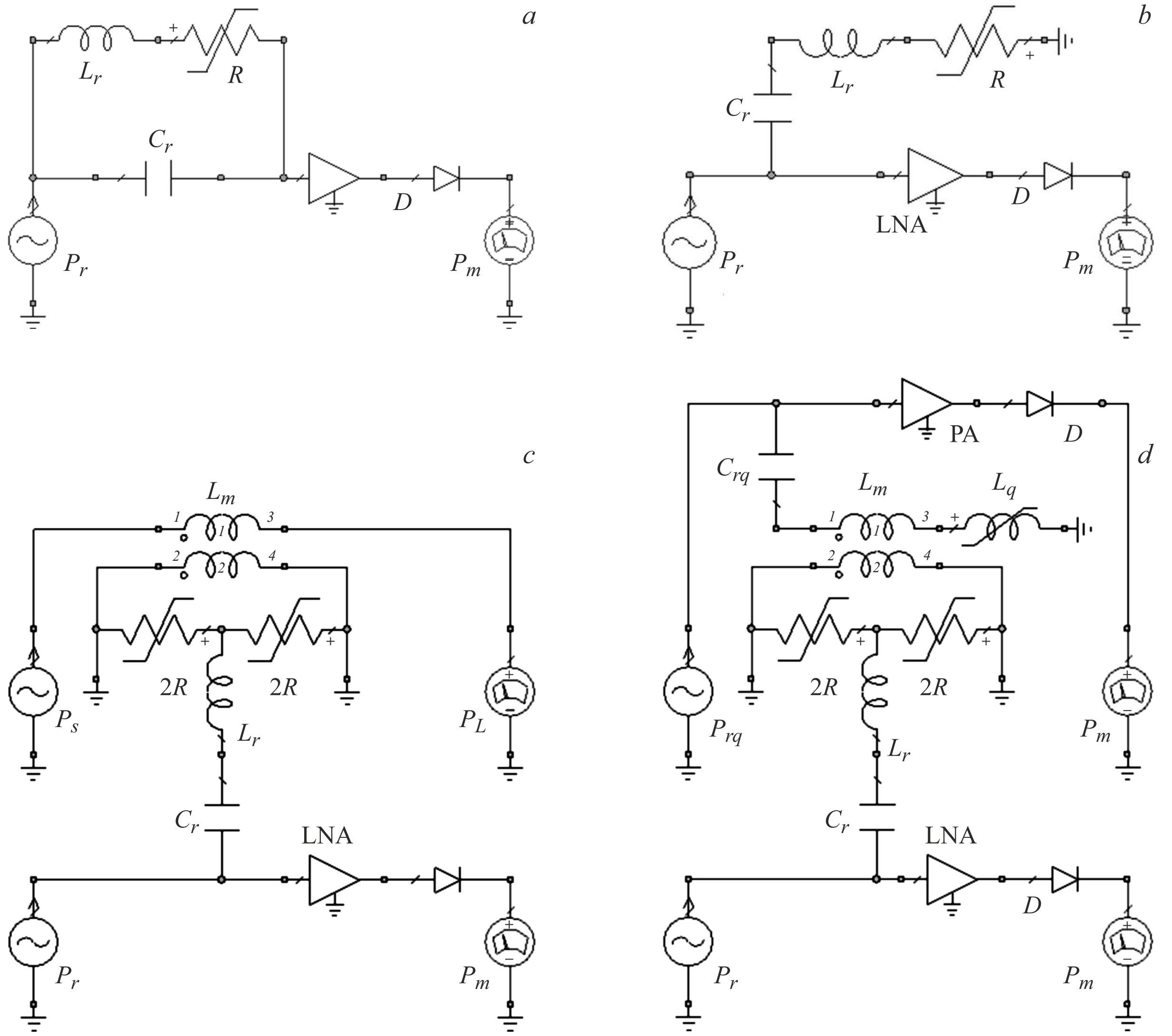

Figure 1. Equivalent (conceptual) circuits of various types of RFTES detectors, which include a carrier source P_r, an LNA buffer amplifier, and a recording system consisting of a direct detector D and a power/voltage meter P_m: a — RFTES detector C-type in which an absorber with an active nonlinear impedance R (bridge) changes the Q-factor of the resonator (L_r, C_r) and forms a band-stop filter with controlled transmission [1-3]; b — absorber R controls the Q-factor of the resonator shunting the line, which is similar to MKID; c — passing microwave power detector with balanced coupling of two bridges in the shunt resonator [10]: P_s — source of the measured signal, P_L — load power meter, L_m — inductor of mutual coupling of the signal line and the detector; d — a microwave transmission power detector integrated into a qubit resonator (this study): P_{rq} — qubit excitation source, L_q and C_{rq} — nonlinear inductance and capacitance of a resonator with a quantum object (qualitative model), PA — parametric amplifier.

below, most of the details of the design of a real qubit and its resonator are assumed to be of no significant importance for the overall conclusion. However, a number of important parameters essential for the detection process using the schemes shown in Fig. $1, c, d$ will be analyzed to the level of numerical estimates.

It is known that the resonator of a qubit is connected to the excitation line of the qubit, into which a signal P_r is applied at a certain fixed frequency F (Fig. 1). Let's assume that the electrodynamic circuits including the excitation/readout line are the external load of the resonator and, thus, determine its loaded Q-factor. The equivalent circuit of this system is presented in Fig. $1, b$. It is valid upon replacing the nonlinear resistor with a nonlinear inductor (e.g., a SQUID), a modification that lends circuit similarity to the qubit and the detector. Near the resonator frequency, a significant part of the wave traveling along the excitation line is partially reflected, which leads to a decrease in the transmission coefficient of the line from the excitation source P_r to the LNA amplifier and makes it possible to measure the Q-factor of such a system. A change in the state of the qubit leads to a change in the reactive impedance component of the „SQUID resonator“ system. The consequence of this is a change in the amplitude and phase of the current in the resonator, since the frequency of the resonator changes relative to a fixed excitation frequency. The evolution of the system can be described qualitatively in the form of movement along the slope of a resonant dip (according to the frequency dependence of the transmission coefficient S21 of the excitation line). Changing the frequency of the resonator at a fixed pumping frequency leads to a change in the energy stored in the resonator. The resonator either gives energy to the excitation line or receives it, depending on whether the oscillation amplitude decreases or increases. In „classic“ case, the excitation line is connected to a sensitive LNA buffer amplifier, which constantly absorbs the flow of pumping/excitation energy and amplifies variations in this flow. A change in the state of the qubit is recorded as a change in the pump flow due to absorption and reflection of such a flow by the resonator. It should be noted that due to the equivalence of both matched ports of the excitation line, half of the „signal“ transmitted by the resonator into the line is absorbed in the direction of the excitation source, and the other half is absorbed towards the LNA buffer amplifier connected to the output of the excitation line. Thus, for a pass-through excitation line, the efficiency of the qubit signal output to the amplifier cannot exceed 50 %. There are solutions based on a pump line with a single port operating on reflection, which avoids the above losses, but in such a system, just like in Ref. [5], it is required to use a non-reciprocal device (microwave circulator), which eliminates the integrated implementation of the entire device.

In a quantum processor, as a rule, several qubits with resonators at different frequencies are connected to one excitation line at once. At the same time, a hypothetical parametric amplifier (PA, Fig. 1, d) serving such an array over a common line should be sufficiently broadband. It is known that existing PA have a low saturation power, which carries a number of risks: the risk of nonlinear conversion of pumping of a large number of qubits in combination with broadband noise to the excitation frequencies of neighboring qubits, as well as the risk of exposure qubits to a parasitic pumping signal of PA close to or higher than the excitation frequency of the qubit. The arguments outlined above lead to several conclusions. The first is that PA is not an ideal solution for a large quantum processor. The second conclusion is that there is no limit for the existence of one or more signal lines for the qubit-resonator system, which in total take the same energy from the resonator as the only „classical“ excitation line loaded with a matched amplifier.

Let's try to smoothly transform the „classical“ system: imagine that we make the coupling of the excitation line with the resonator negligible, but sufficient to ensure proper excitation of the qubit, having at our disposal a „sufficiently powerful“ excitation generator. Under this condition, the excitation line does not affect the qubit, and a properly constructed „additional “ communication line with the resonator will take over the power absorption equivalent to the „classical“ case described above. That is how, based on the passing power detector [10], shown in Fig. 1, c, a qubit reading circuit is formed, shown in Fig. 1, d. Such a detector is designed to register a change in the amplitude of the current in the resonator. In this case, the „50 %“ limitation on the transfer of power from the resonator to the detector disappears in the case of a pass-through excitation line. This is not the main thing, but still a noticeable advantage of the new circuit, which allows you to get a signal-to-noise gain of two times compared to the same detector installed at the output of the „classic“ reading line, as, for example, in Ref. [2]. It can be shown that the dynamic range of the current in a high-Q resonator is several orders of magnitude wider than in the excitation line, which also improves the signal-to-noise ratio for the detector included in the resonator current circuit.

Phase-sensing assumes that the two states of the qubit differ so much in the frequency of the resonator that they lie on different sides (above and below) a fixed excitation frequency. This results in a phase change of the current to the maximum possible value close to 180°, which can be measured with a linear phase-sensitive amplifier (e.g. PA). In practice, the interference effect of a phase-stable reference signal and the measured signal is used to measure the phase. In this case, the amplitude noise of the measured signal inevitably turns into phase noise, i.e., the thresholds for detecting the signal during phase and amplitude measurements are not independent. It is clear that a limitation arises for a thermal detector that is not sensitive to the phase of the received signal. Such a detector cannot distinguish between two resonator states that are equidistant up and down from the excitation frequency, since the resonator currents for such states may differ little from each other. Thus, the qubit mode with a thermal detector should be chosen so that the current amplitudes in the resonator for the two states of the qubit differ significantly: both states should lie on the same slope $S21(F)$; ideally, one of the states should lie on the „bottom“ (in the local minimum) characteristics of $S21(F)$.

Almost any high-frequency technology based on microchips benefits from combining several chips into one whole. A number of papers in the field of superconductivity confirm that this is also true in the case of superconducting microcircuits. The above-mentioned implementations of qubit reading by thermal detectors were performed on separate qubit and detector chips. The signal was read out according to the „classical“ scheme — from the excitation line [5]. It is clear that a detector built according to such a scheme cannot distinguish the signal of the desired qubit from several qubits excited along a common line at different frequencies, and the mentioned studies are nothing more than a demonstration of the fundamental possibility of reading a qubit by a thermal detector. Limitations on the parameters in Ref. [5] demonstrator were caused, among other things, by the need to suppress the back-action on the qubit from pumping the detector, for which ferrite valves/circulators and narrow-band filters were used. Obviously, such a system is unsuitable for integration in the form of a compact microcircuit.

2. Integration of qubit and detector: the back-action effect

Studying the literature, it is possible to conclude that the RFTES technology is fully compatible with the manufacturing process of superconducting qubits, which is favorable for their integration on a single chip. However, it is necessary to analyze some important factors: the back-action effect of pumping the RFTES detector per qubit and the possibility of aggregating several qubits into a single system. The description of the device „Superconducting microwave passing power detector “ [10] (hereinafter SPPD), based on RFTES technology, illustrates the principle of current measurement in a coplanar waveguide with low insertion loss $\sim 10^{-3}$. The conceptual scheme of the SPPD is shown in Fig. 1, *c*. It is clear that such a detector can be used to measure current in a coplanar resonator as a load, providing a Q-factor of $Q = 10^3$, and this resonator can be connected to a qubit, as shown in Fig. 1, *d*.

The design of the microcircuit combining the SPPD and the qubit is presented conceptually in Fig. 2: SPPD is located on the right, the qubit is located in the center *1* and is included in the resonator *2*, which is excited by the line *3* through the coupling section *4* at a frequency of $\sim$ 7 GHz (see example below). The SPPD resonator *5* is excited by the line *6* through the coupling section *7* and warms the bridges *8* to the operating temperature at a frequency of $\sim$ 1.5 GHz (in our example below). The auxiliary resonator *9*, which can act as a „switch“/damper of the qubit resonator, which is achieved by threshold switching of bridges 10 to a resistive state, can operate at a frequency not multiple of 7 and 1.5 GHz, for example, at a frequency of 1.8 GHz. The principle of operation of such a circuit is based on the negligibly weak interaction of two ideally orthogonal modes of a coplanar waveguide: the basic symmetric mode, represented in Fig. 2 by currents i_1 and i_2 in the resonator of the qubit *2*, and the slot mode, in which the resonator *2* acts on the bridges *8* and *10* in the resonators *5* and *9*, respectively. The interference from the SPPD (back-action effect) obviously is the leakage of the heating power of the RFTES absorber into the resonator circuit of the qubit. Such an effect on the qubit is suppressed in SPPD by the balanced coupling of two RFTES bridges *8*. In this case, the currents of the resonator of the qubit i_d and i_m can heat up the bridges *8* and *10*, as shown in Fig. 2, which allows detecting the state of the resonator of the qubit.

Such a suppression system is not ideal for several reasons. The current passing to the resonator of the qubit depends on:

1) the similarity of geometric and electrical parameters of circuits represented by two bridges and inductors shunting them;

2) the spatial phase shift of these circuits along the direction of wave propagation in the qubit resonator; for the same reason, the heating of the bridges by the qubit current is not exactly the same: the amplitude of the current in

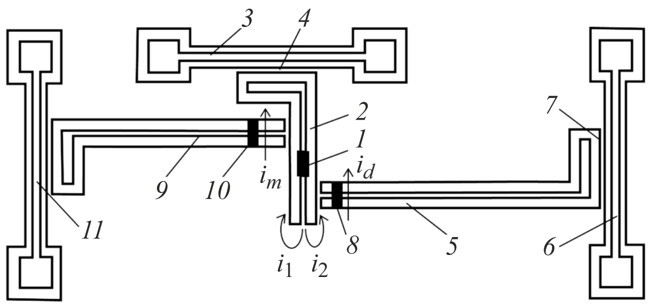

Figure 2. Illustration of a device for reading and modulating the resonator state with the effect of suppressing detector pumping (concept). Explanations for numerical designations are provided in the text.

the distributed (quarter-wave) resonator of the qubit varies along the resonator, and any physical distance between the circuits leads to amplitude corrections.

All of the above factors can be automatically taken into account using electromagnetic modeling based on the assumed geometry of the device.

An electromagnetic model of a block performing functions similar to those schematically shown in Fig. 2 was developed and optimized to verify the proposed approaches. The circuit parameters were calculated in the Cadence AWRDE electromagnetic simulation environment. In this model, the coefficients of transmission along the qubit excitation and detector pumping lines, as well as the coefficient of signal transmission from the detector pumping line to the qubit excitation line, were measured.

Fig. 3 shows the calculated characteristics of the electromagnetic model described above, consisting of a qubit and a detector, confirming the feasibility of a reading device with low crosstalk. A resonant dip in the transmission of the excitation or pumping line means the frequency range of the excitation of the corresponding resonator. The resonator of the qubit was tuned to a frequency of about 7 MHz, and the equivalent impedance of the qubit inserted into the resonator was set to $10^{-5}\,\Omega$, which means a weak coupling of the excitation line with the qubit, about 30 dB, and practically does not affect the calculation results. The data obtained confirm that the interference suppression coefficient from the detector excitation line exceeds 90 dB near the frequency of the resonator of the qubit of $\sim$ 7 GHz, and 120 dB at the detector frequency. In addition, it should be noted that all three lines feeding the qubit, detector, and modulator, shown in Figs. 2, *3*, *6*, *11*, can be connected in series, and the degree of signal isolation shows virtually no degradation if they are detuned from each other by more than 30 MHz.

The balance condition, which prevents interference in the resonator circuit of the qubit, may be violated due to the inaccuracy of the structure. It should be borne in mind here that the voltage balance on the bridges and the counter-directional currents injected into the resonator of the qubit are determined mainly by the impedance balance

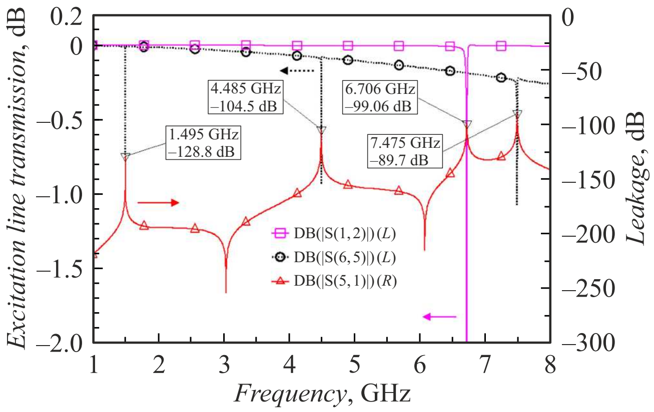

Figure 3. Calculated characteristics of transmission coefficients for dispersive reading of a superconducting qubit using an integrated RFTES detector shown in Fig. 2 (modulator, elements *9–11* not used). Legend: S(1,2) — transmission coefficient between ports *1* and *2* of the line *3* qubit excitation, S(6,5) — for the pump line ports of the detector *6*, S(5,1) — between the ports of the qubit and the detector (between the lines *3* and *6*). The curve marked with squares — characteristic of the excitation/reading line of the qubit, in the vicinity of the resonance of 6.706 GHz, it has a dip width of ~ 7 MHz ($Q \approx 1000$). Dashed line curve (circles) — characteristic of the excitation line of an RFTES detector with a quarter-wave resonance at 1.495 GHz and high-order resonances at 4.485 GHz (three-quarters of a wave) and 7.475 GHz (five-quarters of a wave). The markers are linked to the extremes of the S(5,1) curve (triangles). It can be seen that the isolation of the parasitic pump leakage from the excitation line of the detector resonator into the qubit excitation circuit at a frequency of 1.495 GHz is almost -130 dB, and at a frequency of the qubit resonator 6.706 GHz, the isolation of the detector circuit is almost -100 dB.

of the shunt inductors, that follows from the diagrams in Fig. 1, *c*, *d*. The impedance of the inductors is small, it differs by more than an order of magnitude from the impedance of the bridges, and the inductors themselves are geometrically larger in size, and their accuracy is also an order of magnitude better than the accuracy of the bridges. A calculation performed using a lumped-elemen equivalent circuit in which there are no spatial effects showed that for two bridges with an impedance differing by 10%, the power leakage into the qubit resonator at a frequency of 1.5 GHz lies at the level of -99 dB. The same suppression occurs when the inductance of the shunts differs by 1 %, which indicates the dominant role of the symmetry of the inductors, the possibility of which is beyond doubt. Thus, the deviation from the nominal resistance of the bridges plays an order of magnitude smaller role than the unavoidable spatial separation of the absorbers, typically at a distance of $10\,\mu$m, with a characteristic leakage of -40 dB.

There are several other factors potentially affecting the integration of RFTES detectors with superconducting qubits. These are heat generation, blackbody (thermodynamic) radiation from the detector's absorber in the sensitivity spectrum of the qubit, as well as the generation of relatively high-energy quasiparticles. Let's look at all these factors below.

In accordance with the law of conservation of energy, all signals absorbed on the chip, mainly the heating power of the detector, as well as the active pumping and control losses of the qubit, are converted into heat, which, in turn, is absorbed by the refrigerator through the thermal conductivity of the chip within the qubit circuit. This means that an active change of qubit states will lead to some kind of averaged heating of the chip, which can be considered as a kind of stable parameter. However, local heating can be orders of magnitude stronger than the average on the chip. The assessment of heat spread performed as described in Ref. [7] for a sapphire substrate, shows that a temperature increase only by $\sim 3 \cdot 10^{-6}$ K at a distance of $10\,\mu$m can be expected from a heat source in the form of RFTES bridges heated with a power of $\sim 10^{-12}$ W.

The heated electron gas in the bridges is an ultra-wide-band black (really gray) body and, naturally, creates thermodynamic noise, the intensity of which can be determined based on Planck's formula for a narrow band within the spectrum of a black body. It should be noted that the noise current in circuits external to the bridges can be excited only in the resonator band of the qubit and detector. Let's assume that the critical temperature of the RFTES absorber cannot be reduced from the experimentally obtained value of 400 mK. This temperature corresponds to the cutoff frequency of the Planck spectrum of 8.3 GHz, which means that all higher modes of the quarter-wave resonator (21.35 GHz . . ., etc.) do not significantly contribute to the Johnson noise in the bridge, which is -136 dBm, that is almost two orders of magnitude less than the power, dispersion pulse, and five orders of magnitude less than the power stored in the resonator of the qubit as will be shown below.

The detection using a physical model of an electron gas, implemented in the RFTES detector [2,3], is based on the fact that hot electrons (quasi-particles) cannot escape from the bridge into the connecting electrodes due to the presence of Andreev mirrors, which is especially effective at low frequencies. It was shown for experimental detectors that quasi-particles relax exclusively inside the volume of the bridge, transferring heat to the phonons of the bridge film. The difference between the phonon temperature and the substrate temperature is determined by the Kapitza resistance, which is two orders of magnitude less than the thermal relaxation resistance of the electron gas, which means that the difference between the phonon temperature and the substrate temperature is negligible, and the problem of wandering quasi-particles, at first glance, can also be eliminated.

Nevertheless, it is known that even single quasiparticles interacting with the Josephson junction of a qubit can be a problem for correct reading. It should be noted that the Andreev barrier is a pure galvanic contact between two metals, and it is not an insulator, which means it can have defects at the atomic level and still allow a countable number of quasi-particles to pass through. One of the advantages of the RFTES technology is that Andreev mirrors are not required for microwave currents, and instead dielectric layers between electrodes and bridges can be used, which eliminates the likelihood of leakage of quasi-particles into the electrodes and their associated Josephson contacts.

3. Sensitivity requirements of the RFTES reader detector

NEP (Noise Equivalent Power) is considered as the parameter for comparing direct detectors. The main component of the NEP bolometric detector is phonon noise, determined by the temperature of the absorber T and its thermal conductivity G: $\mathrm{NEP}_{phon} = (4kT^2G)^{0.5}$. In our experiments for detecting terahertz radiation, the detector heating power was about ~ -86 dBm (~ 2 pW) on the chip and about -90 dBm on the bridge absorber volume $2 \times 2 \times 0.05\,\mu$m at NEP $\approx 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ and at temperature of 200–390 mK [3]. From the point of view of the quantum system, the heating power is very high. When using electronic lithography, the size of the bridge can be easily reduced to $0.2 \times 0.2 \times 0.05\,\mu$m, i.e., the volume will decrease by 100 times and G will proportionally decrease. In this case, NEP will decrease to $\sim 10^{-18}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, and the bridge heating power G will decrease to -110 dBm. When the temperature drops from 200 mK to 10–30 mK, which corresponds to the operating temperature of the qubits, NEP will decrease $\propto T^{3.5-4}$ and drop to $< 10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$. Thermal conductivity will decrease faster — $\propto T^{4-5}$, and the required heating power, according to an experimentally tested model, will decrease to -150 dBm. The balanced circuit [10], according to our calculations, suppresses this power by at least 40 dB, i.e., an „undesirable“ signal at a frequency of 1.5 GHz is injected into the resonator at a frequency of 7 GHz with a power of the order of -190 to -200 dBm ($10^{-23} - 10^{-22}$ W), and this is $2-3$ orders of magnitude less than the NEP value of the already proposed improved RFTES detector. Considering that with fast reading, the signal detection threshold will increase (deteriorate) as the root of the reading frequency, according to the known ratio $P_{det} = NEP \cdot \sqrt{\Delta f} \cdot \mathrm{SNR}$, for the reading time $\tau = 1/(2\pi \cdot \Delta f) \approx 10\,\mu$s, the threshold detector power (SNR $= 1$) will be $\sim 10^{-17}$ W for an improved detector. We will proceed from this value and compare it with the time-averaged power of the pulse leaving the „qubit-resonator“ system with a dispersive frequency shift of the qubit.

Let us assume the following conditions: the first state corresponds to the maximum current in the resonator, which is determined by the number of photons and the Q factor of the resonator, in the second state the signal transmitted from the resonator to the detector almost equal to zero — the resonator „departed“ from the excitation frequency, and the amplitude of the current is negligible. Incomplete departure can be estimated by introducing a coefficient of the order 0.1–0.5. For the sake of certainty, we will assume that the operating frequency of the resonator $F = 7$ GHz, is selected for reading the qubit, and the effective Q-factor of such a resonator is $Q = 1000$, and there are few pump photons in the resonator at the same time $N = 1-10$. For the sake of simplicity, let's assume that when completely leaving the resonance, the oscillations in the resonator completely fade out, i.e. $\Delta N = 10$. The decay time of such oscillations is directly proportional to the Q factor of the resonator and is about $0.14\,\mu$s for $F = 7$ GHz and $Q = 1000$.

It is clear that under the condition of a negligibly weak coupling of the resonator of the qubit with the excitation line, the Q-factor of the qubit is not determined by the coupling with the excitation line, as in the „classical“ case, and by coupling the resonator of the qubit with the absorbers of the RFTES detector of transmitted power [10], which dampens the resonator in the same way as the excitation line loaded with LNA. Such a replacement of the damper (absorber) does not physically change the energy distribution process in the „qubit-resonator“ system, which was discussed above. We will use a lossy lumped oscillatory LC circuit model for a distributed resonator, which is valid for the high-Q case. Let us assume that the losses introduced into the resonator will be determined by the active coupled impedance of the detector $R = 0.01\,\Omega$. This value is close to the resistance introduced by the absorber of the experimental RFTES with an operating resistance $R_{det} = 3\,\Omega$, shunted by an inductor of 100 pH at a frequency of 1.5 GHz; in our model, the resistance R will be the sum of all active losses in the resonator. Under the given conditions, the characteristic impedance of the resonator will be $Z = 10\,\Omega$, and the values of the equivalent capacitance and inductance of the resonator will be $L = 0.23$ nH and $C = 2.3$ pF, respectively. The total energy stored in the resonator can be written as $E = Z \cdot I^2/(2\omega)$, and the reactive power, which is the transfer of energy from an electric field to a magnetic field per second, as $P = Z \cdot I^2/2$, where I is the amplitude of the current in the resonator, defined by the excitation line. It should be noted that, according to the lumped resonant circuit model, the entire current I flows through the detector resistance R. The average number of photons can be calculated as follows: $N = E/(F \cdot h)$, where h is the Planck's constant. The set value $N = 10$ corresponds to $E = 4.7 \cdot 10^{-23}$ J, and the stored (reactive) power in the resonator will be $P = 2$ pW with the resonator current of $I = 0.64\,\mu$A. According to the law of conservation of energy, the active current power $P_{det} = R \cdot I^2$ and the decrease in reactive power at a frequency of 7 GHz, calculated as $P_{out} = P/Q$, must coincide, i.e., it is converted into heat $P_{det} = 2 \cdot 10^{-15}\,\mathrm{W} = 2$ fW in the detector. Registration of fast jumps of this power, the source of which is the interaction of the excitation generator and the qubit, is the task of the integrated detector.

It follows from the above estimates of the detection threshold with $\tau \approx 10\,\mu$s that using already available samples of RFTES detectors with $NEP = 1 \cdot 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, it is possible in principle to register such a signal with a boundary SNR ≈ 1. By optimizing RFTES in size and temperature to NEP $\sim 10^{-19}\mathrm{W}/\sqrt{\mathrm{Hz}}$, we obtain the value SNR ≈ 100 for $N = 10$ and SNR ≈ 10 when only one photon leaves the resonator ($N = 1$).

It is clear that increasing the integration time allows to change the detection threshold (improve it), but the integration time cannot be too long. It definitely cannot be longer than the lifetime of a qubit and should be as short as possible for fast calculations. On the other hand, the measurement time cannot be shorter than the relaxation time of the qubit resonator to a new state or the response time of the detector. For reliable reading of two quasi-static states, the qubit operation time (switching process $P_{out} \rightarrow 0 \rightarrow P_{out}$) should be longer than the detector response time, typically $10\,\mu$s. This means that our detector will be able to operate if the lifetime of the qubit is at least $100\,\mu$s.

Assuming that a reliable reading requires SNR $= 6$, then to register the step $P_x(F) = 2 \cdot 10^{-15}$ W in time $10\,\mu$s, it is necessary to use a detector with NEP $= 3 \cdot 10^{-18}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ with an integrator band at the detector output of 15 kHz. At the same time, approximately 50,000 counts per second can be implemented. The authors express confidence that experimental RFTES detectors can overcome this threshold with a decrease in temperature and a simultaneous decrease in the volume of the absorber, which has already been experimentally confirmed [3].

4. Aggregation of multiple qubits and detectors

The approach to creating a processor with a large number of qubits can be based on our proposal to integrate each qubit with its own separate RFTES detector, which is the load of the qubit resonator and operates at its own unique frequency, which does not match either the frequency of the qubit resonator or the frequencies of the resonators of other detectors. This approach allows reading an array of qubits, which is controlled via a common excitation line and is equipped with a set of RFTES detectors, which are also controlled via their own separate excitation/reading line. In this case, the dimension of the detector array coincides with the dimension of the array of qubits, and pumping none of the detectors does not interact with other detectors or with any of the qubits, as described above. Thus, a system of qubits with detector dispersion reading can look like two lines, with „qubits“ strung on one of which and detectors strung on the other. Taking into account the calculation results (Fig. 3), it can be concluded that the excitation lines of all detectors and all qubits can be combined into one sequential circuit, provided that all resonators in such a circuit are tuned to unique frequencies. It should be noted that RFTES detectors operating in the kinetic mode [3] have a significant gain, which may make a buffer amplifier unnecessary at the dissolution stage, and the signal from the quantum processor can be sent directly to the LNA located at stage 3 K.

In summary, we would like to note that, according to the developed concept, the temperatures of the detector and the qubit are the same, since they are integrated on the same chip. For currently available RFTES detectors with electron gas, one can expect a decrease in NEP to $\sim 10^{-19}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ only due to a decrease in temperature. However, it will not be possible to increase the counting speed, since the increase in sensitivity associated with a decrease in temperature is based on the effect of slowing down the electron-phonon interaction, which makes the relaxation of such a detector (dead time) also slower. It will be necessary to expand the range of excitation frequencies to accommodate a large number of qubits on a single line or use resonators with a narrower band (with a higher quality factor). As the Q-factor of the resonator increases, the same number of photons in the resonator means a lower power outflow, and this can make registration more difficult, as well as limit the response rate of the qubit resonator to a change in the state of the quantum system. If the small number of photons in the resonator is considered a priority factor, then lowering the temperature of the detectors when placed on the same chip, leading to improved sensitivity (increased SNR), is a positive trend, and RFTES detectors look like a fully functional sensor for dispersive reading of superconducting qubits.

Conclusion

The conducted study inspires optimism because the existing level of RFTES technology allows focusing efforts for the implementation of dispersion reading of a superconducting qubit. The characteristics of the RFTES technology demonstrated so far confirm the prospects of expanding the niche of detectors based on niobium and hafnium films with electron gas for applications in communications and quantum computing systems in the $1-1000$ GHz frequency range of received signals and possibly wider. The high sensitivity of experimental prototypes combined with a rate of about $10\,\mu$s and technologically sound approaches to increase sensitivity to NEP $= 10^{-20}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, as well as patented circuit solutions, allow us to start designing multichannel reading and control circuits with frequency selection over a common microwave line, including for the implementation of quantum processors based on superconductors. The achieved results allow asserting that RFTES detectors are fully compatible with superconducting qubits not only in terms of manufacturing technology, but also in terms of the principle of communication and control. The analysis showed that the comparatively high electronic temperature of the experimental bridges in the operating mode is far from having a critical effect on the qubit. Nevertheless, it seems rational to move towards lower values of the critical temperature of the absorbers, i.e. closer to the operating temperature of the qubit, as well as towards a decrease in the volume of the electron gas. To date, the first samples of compatible detectors have been manufactured and tested; tests with qubits are planned for the near future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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