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Active superconducting terahertz detector

© S.V. Shitov[1,2]

[1] Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences,
125009 Moscow, Russia
[2] National University of Science and Technology (NUST)„MISiS“,
119049 Moscow, Russia
e-mail: sergey3e@gmail.com

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The concept of an active superconducting terahertz detector for array applications is based on the combination of an RFTES bolometer and a microwave preamplifier based on a DC SQUID within the common integrated circuit providing the maximum, theoretically possible, signal transmission from the sensor to the amplifier. The problems associated with the design and positioning of the amplifier, that restrict the functionality and sensitivity of the ultra-low temperature detector, are considered. For the first time, a method for connecting a SQUID amplifier to an RFTES bolometer using the principle of partial loads of a resonator has been proposed and analyzed. The presented electromagnetic model of the active detector is suitable for optimization of RFTES, MKID and other detectors using high-Q superconducting planar resonators.

Keywords: RFTES, DC SQUID, low-noise amplifier, parametric amplifier, planar resonator, high-Q resonator, partial load of resonator, electromagnetic modelling.

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Introduction

Terahertz radiation due to its properties occupies an intermediate position between radio waves and visible light. In this region of the spectrum information about the most remote regions of the universe comes from space. This is attributable to the fact that the Planck spectrum of thermodynamic noise [1] rapidly reduces its intensity at frequencies above 0.5 THz, and relatively weak signals can remain distinguishable against the background of ambient noise. Cooled detectors with the use of superconductivity effects are designed to catch such signals, the sensitivity of which, under ultra-deep cooling, makes it possible to study the anisotropy of the polarization of the radiation of the Universe [2], the thermodynamic temperature of which is about 2.7 K. The relatively short wavelength and the possibility of creating synthesized apertures tens of kilometers in size make it possible to search for exoplanets and, in the future, remotely investigate the composition of their atmosphere [3]. All this contributes to the rapid development of theoretical astronomy, which in turn stimulates the development of ultra-sensitive THz-band radiometric devices.

From a practical point of view, it is of interest to further develop the technology of imaging arrays that allow obtaining maps of celestial objects, speeding up the research process and drastically reducing their cost. From a theoretical point of view, the best signal-to-noise ratio can be achieved by combining the cooling of the detector with the maximum possible noise averaging time at its output, which depends on the long-term stability of all elements of the receiving system. This means that a large array should either have a built-in multiplexer that allows the accumulated signal to be read from each pixel in turn, or a large number of parallel signal output channels, which can critically increase the heat flow to the cooled parts of the receiver. In the case of superconducting arrays, the optimal solution was found on the path of frequency separation of pixels, when one physical information transmission channel is used, for example, a superconducting coaxial cable, and signals from individual pixels arrive at the terminal recorder at different individual frequencies, which is similar to the well-known principle of radio reception of different stations with one antenna. Historically, this approach was first applied with TES (Transition Edge Sensor) [4], in which the heating of the absorber was recorded using extremely high temperature nonlinearity in a superconducting film acting as a thermometer; the FDM (Frequency Division Multiplexing) method [5] gained traction. Almost simultaneously, MKID (Microwave Kinetic Induction Detectors) [6] was suggested, using the nonlinear complex impedance of a superconducting microresonator, which is ideal for FDM technology.

Since modern terahertz receivers consist of a front-end sensor, which is usually integrated with an antenna and converts the input signal to a lower frequency, the quality of further processing (reading) of the received information critically depends on the quality of the subsequent amplifier. Sensor conversion efficiency, as a rule, does not exceed unity, and any signal loss between the detector and the amplifier can lead to significant degradation of sensitivity, increasing the contribution of amplifier noise. In the case of a low-resistance TES thermometer, it was possible to obtain a small contribution to the noise of the device using a SQUID amplifier of direct (low-frequency) current. The arrays created using this principle had a hybrid design of the FDM system with numerous rather bulky filters and several SQUID amplifiers [7]. Array developers have been inclined to use MKID technology since mid-2000s [6]. An array of such detectors ($\sim$1000) can be placed on a single chip so that all detectors are connected in series to a common transmission line of standard $50\,\Omega$, which is well combined with semiconductor amplifiers, provided that their noise temperature T_n is a few degrees Kelvin. It turned out that in the frequency selection range of $1-10$ GHz, the noise of the amplifier referred to the input of the MKID detector imposes a limit on the threshold sensitivity of $\sim 10^{-19} - 10^{-18}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, which is comparable to the intrinsic noise of the MKID sensor at a temperature of $T \approx 100$ mK, which approach TES noises. It was soon shown that the intrinsic noise of another resistive bolometric sensor based on a superconducting film with an electron gas near its critical temperature $T_c \approx 100$ mK (HEDD — Hot Electron Direct Detector) can be reduced to record values of NEP$< 10^{-20}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ and even lower [8] if a low-frequency SQUID amplifier is used, that is similar to TES. It can be assumed that the need for a SQUID amplifier hinders the development of the HEDD concept in its original form.

Recently, we managed to conduct a series of studies [9–11] and demonstrate that the new RFTES (Radio Frequency Transition Edge Sensor) technology, using microwave heating and reading the impedance of the electronic subsystem of a superconducting film near T_c, is similar to MKID in terms of simplicity and convenience and has approximately the same sensitivity potential as HEDD. These results, according to the authors, can be considered a serious step towards the serious improvement of the sensor for the imaging array. However, the problem of the optimal microwave amplifier that could replace the low-frequency SQUID, and whose NEP in terms of sensor input would be $\sim 10^{-21}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, remains unresolved. This paper is intended to demonstrate a new approach to such optimization, which implies the integration of a parametric microwave amplifier based on SQUID (SPA$-$SQUID Parametric Amplifier) directly into the sensor circuit.

1. Optimal SQUID amplifier

It is known that SPA noise at GHz frequencies can be limited by quantum fluctuations, which is about two orders of magnitude lower than for semiconductor amplifiers [12], and the SPA control circuit is simpler than that of a low-frequency SQUID amplifier, since SPA can operate without a feedback circuit. The known SPAs can be divided into 3 groups: 1) lumped amplifiers with one or more RF-SQUIDs and external pumping, which is close to the classic PA (Parametric Amplifier); 2) traveling wave amplifiers based on chains of RF SQUIDs with external pumping [13]; 3) lumped amplifiers comprising one or more DC-SQUIDs, which can be characterized as a self-pumping PA, the role of which is performed by the Josephson generation [12]. The problem of efficient signal transmission to the SQUID lies in the small active impedance of the superconducting loop, therefore, matching with standard circuits $50\,\Omega$ is implemented either using a resonant circuit or in a traveling wave mode using an array of SQUIDs distributed along a planar waveguide. Despite the fact that the resonant SQUID amplifier loses in bandwidth ($< 10\%$) and saturation power (< 1 pW), the use of a type 3 SQUID amplifier attracts with its simplicity and compact size. The application of the concept of an active superconducting detector (hereinafter ASD) makes it extremely easy to integrate a „personal“ SQUID amplifier into each pixel of a large array, while providing the maximum possible signal$-$to$-$noise ratio.

2. RFTES-detector prototype

According to the Mattis–Bardeen theory (MBT) [14], the surface impedance of a massive superconductor for all frequencies other than zero has an active component that decreases as the temperature decreases downwards from T_c and grows with increasing frequency. For a micro bridge made of thin film, this effect applies to the entire cross-section of the bridge. The effect can be considered weak and the frequency low if the photon energy is significantly less than the pairing energy Δ in a superconductor, $hf \leq 0.01\Delta$, which is true for most applications if $T \ll T_c$. If the temperature of the film in the superconducting state approaches T_c, then $\Delta \to 0$, and MBT predicts a smooth change in its impedance within the transition between the superconducting and normal states. In other words, a superconducting transition measured at a high-frequency current loses its abrupt character and turns out to be stretched along the temperature scale. The smearing „of the superconducting jump“ of the impedance increases at moderate frequencies at $hf \leq 0.2\Delta$, but a significant temperature nonlinearity persists near the critical temperature of the film. Thus, the hafnium film bridge ($T_c \approx 400$ mK), studied in [11], can be considered as a thermistor, which for a microwave current with a frequency of 1.5GHz at temperatures < 400 mK is in a state with a small but not zero active impedance component $\sim 0.1\,\Omega$, and at temperatures of > 400 mK it becomes a normal metal with resistance of $\sim 30\,\Omega$. Such a change in the active component of the impedance against the background of a relatively weak change in the reactive component (kinetic inductance) is the basis of the RFTES technology. A bridge made of a film of superconducting material is included in the microwave resonator circuit, the Q-factor of which is measured by the transmission coefficient S21 of the chip. If the bridge is heated by a terahertz current, then its resistance increases, and the Q-factor of the resonator decreases. It is convenient to call such a process a resonator response. A brief overview of experimental data for a prototype detector tested with a semiconductor microwave amplifier is provided in Fig. 1.

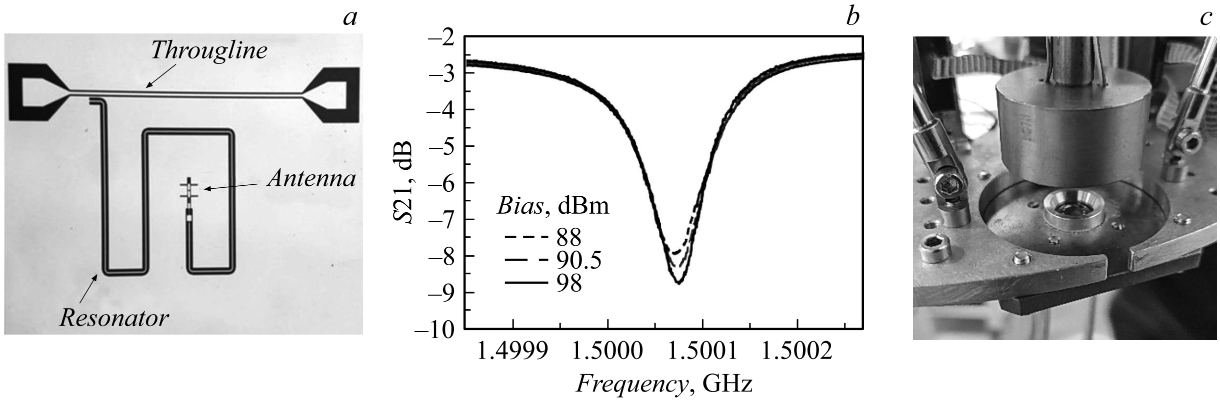

Figure 1. The prototype of terahertz detector is built using RFTES technology and designed to operate with a cooled semiconductor amplifier in a similar way to MKID. *a* — photo of the chip [9]. A quarter-wave resonator with a bridge and a terahertz antenna changes the S21 of the transmission line (throughline); *b* — the response S21 of the transmission line to the heating of the micro-bridge, confirming the active nature of the nonlinear impedance [11]; *c* — RFTES detector with a lens antenna and a Planck radiator directed from top to bottom in a dilution refrigerator; based on a rough estimate of the emissivity of the black body used, the sensitivity of the detector was $\sim 3 \cdot 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$, which is only three times worse than the theoretical limit calculated using the method [8] for the parameters of a specific experimental sample [11].

In recent years, high quality-factor superconducting resonators made on the basis of quarter-wave segments of coplanar lines made of niobium ($T_c \approx 9\,\mathrm{K}$) have become widespread. It is known that the current in a quarter-wave resonator is distributed unevenly along the length, reaching its maximum in the region of the shorted end of the resonator and reducing down to zero in the region of the open end of the resonator. Detectors built using MKID and RFTES technology, at first glance, have a topological similarity. However, the fundamental difference is that the MKID antenna and the superconducting sensor film are placed in the short-circuited region of the resonator, where the current is maximum, while the antenna and the RFTES absorber are placed on the opposite side, near the open end of the resonator. This is attributable to the fundamentally different value of the active part of the impedance R_{B} for MKID and RFTES sensors. It is possible to determine the embedding impedance for the longitudinal coordinate of the resonator L, as it is done in [15]. When the incertion point is moved from the short-circuit area towards the open end of the resonator, the active part of the embedding impedance is $\mathrm{Re}(Z_{\mathrm{S}}(L))$. It varies from a very small value $\sim 10^{-4}\,\Omega$, which is optimal for MKID, to large values near the open end of the resonator, where the optimal load is $\sim 10\,\Omega$. For RFTES, the point of incertion of the sensor in the resonator should simultaneously satisfy the relation $Z_{\mathrm{S}}(L) = R_{\mathrm{B}}$ and the optimum thermal sensitivity $\mathrm{d}R_{\mathrm{B}}/\mathrm{d}T$ inside the superconducting transition. A terahertz signal in the form of a current coming from the antenna breaks Cooper pairs and increases the number of quasi-particles, which additionally reduces the quality factor of the resonator. This is how the main features and principle of operation of the prototype RFTES detector can be briefly described [9–11]. The above consideration is important for further understanding the role of the resonator in the proposed integrated device.

3. The principle of resonant matching

It follows from the above consideration of currents in a distributed superconducting resonator used for MKID and RFTES detectors that the nonlinear load controlling the Q-factor of the resonator can be divided into two or more parts spaced along the resonator. The principle of design an active detector is based on this very approach. It will be demonstrated below that one of these loads can be a parametric SQUID amplifier, and the other is a bridge sensor, and these devices can be almost perfectly matched with each other in terms of signal transmission.

An equivalent transformation of a high-quality resonator with a Q-factor of Q is shown in Fig. 2 for two loss sources (for two loads) in the resonator. This figure illustrates that a superconducting (ideal) resonator built using a special circuit can have the same Q-factor (frequency band) as a classical circuit consisting of a capacitor with leakage $R_{\mathrm{C}} \sim 10^5\,\Omega$ and an inductor with ohmic losses $R_{\mathrm{L}} \sim 10^{-4}\,\Omega$. At the same time, arbitrary active loads can be included in the superconducting resonator, including those with equal values, for example, $\sim 1\,\Omega$. It is important to note here that a high-quality resonator based on distributed microwave circuits ($Q \sim 10^4$) can be described with sufficient accuracy near its resonant frequency using lumped circuit elements — inductors, capacitances and resistors. This is intuitively clear, since in a narrow frequency band ($\Delta f / f_0 \sim 10^{-4}$), the effective inductance and capacitance of a quarter-wave resonator changes negligibly (linearly with frequency), which is confirmed by our electrodynamic modeling in the AWRDE Microwave

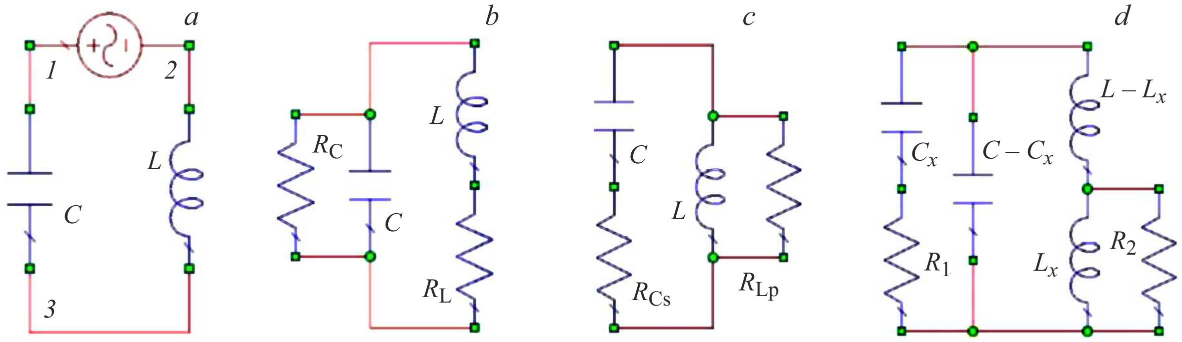

Figure 2. Equivalent transformations of a standard resonant LC circuit into a resonator circuit comprising two active elements with an almost arbitrary (incommensurable) active impedance R_1 and R_2. *a* — an ideal (superconducting) resonator with a voltage source connected to points *1–2*. The current tends to infinity (voltage resonance) near the resonant frequency. In this case, the voltage between the pairs of points *1–3* and *2–3* tends to infinity (current resonance). In circuits *b–d* voltage source, having zero impedance is excluded from the circuit for ease of consideration. *b* — imperfect resonant circuit with losses. For the experimental resonator [11], $Q \sim 10^4$ was obtained, which can be represented theoretically in the form of capacitor leakage resistance $R_C \sim 10^5\,\Omega$ and inductor resistance $R_L \sim 10^{-4}\,\Omega$. At the same time, the active resistance of the experimental RFTES bridge is $\sim 1\,\Omega$, but it provides the same effect, which is explained by partial inclusion, as described below. *c* — the small resistance of the inductor R_L is converted into a large parallel resistance R_{L_p}, providing equivalent losses, and a large parallel resistance R_C — into a small series resistance R_{C_s}. *d* — partial inclusion of losses. By dividing the physical capacitor C into two parallel (two portions), and the inductor L — into two series (also two portions), it is possible to build a circuit where an arbitrary value of the bridge R_1 (RFTES detector) can be matched to an arbitrary R_2 (amplifier).

Office [16] environment. Thus, equivalent transformations of the oscillating circuit (Fig. 2) can be accurately applied to the transformations of a distributed quarter-wave resonator, where a small (partial) capacitor C_x characterizes the small electrical capacitance of the resonator segment near the open end, and a small (partial) inductor L_x — the resonator segment from the shorted-end side.

It follows from the analysis of the circuit of Fig. 2, *b, c* that the condition of maximum power transfer between two active elements in the resonator circuit — is the equality of $R_L = R_{C_s}$, which is true only at the resonant frequency ω. Let's find the condition of such equality for the desired circuit Fig. 2, *d*. If the following conditions are met in the inductive part of this circuit: $L_x \ll L$ and $R_2 \gg \omega L_x$ (the voltage at R_2 is small, or the resistance R_2 is large), then the effective series resistance in the inductive part of Fig. 2, *b* will be small: $R_L \approx (\omega L_x)^2/R_2$, and it can be made much lower R_2. Similarly, the ratio $R_{C_s} \approx R_1 (C_x/C)^2$ is obtained for the capacitive part of the resonator, under the condition $C_x \ll C$ (the capacitive section is small, the current is small), which also means small losses, $R_{C_s} \ll R_1$. Let's write the equality of the inserted losses: $R_1 (C_x/C)^2 = (\omega L_x)^2/R_2$. This is the condition for full matching of the bolometric bridge R_1 and the amplifier R_2 within a high-quality resonator. The matching condition can be represented using the partial division of capacitance and inductance as $R_1 (C_x/C)^2 = Z_0^2 (L_x/L)^2/R_2$, where $Z_0 = \sqrt{L/C}$ — the characteristic impedance of the resonator. The above consideration allows concluding that it is possible to include very different impedance values in the resonant circuit and match them with each other, without sacrificing Q-factor of a high quality resonator via using, partial current division (C_x/C) and voltage division (L_x/L). This approach was successfully tested in experiments with a prototype detector, where a capacitive divider $C_x/C \approx 100$ [10,11] was used.

4. Integration of a microwave amplifier based on DC-SQUID

The classic DC-SQUID is a superconducting magnetic sensor comprising two Josephson junction connected into a loop with a low inductance (about 60 pH) and a typical size of $50 \times 50\,\mu$m [17]. In operating mode, a bias is applied to the DC-SQUID in the form of a combination of direct current and a constant magnetic field. It is known that the current response of the SQUID to the magnetic field is periodic, the sensitivity to small increments of the magnetic field or to the increment of the amplitude of the resonator current in our case is of practical interest.

The problem of matching the SQUID with an external magnetic signal is the small geometric size of the DC-SQUID loop, which makes it difficult to capture the magnetic flux. For static and slowly changing fields, this problem is solved by using a superconducting transformer which is a multi-turn inductor that concentrates the flux in the area of the SQUID loop. Such an inductor in an integrated circuit is manufactured using planar technology in the form of a flat spiral with extremely narrow conductors and minimal gaps between the turns. The inductor becomes one of the most critical elements of the entire chip if such a coil is placed in the upper layer of the chip. The proposed structure does not have such problem: the inductor is represented by a short

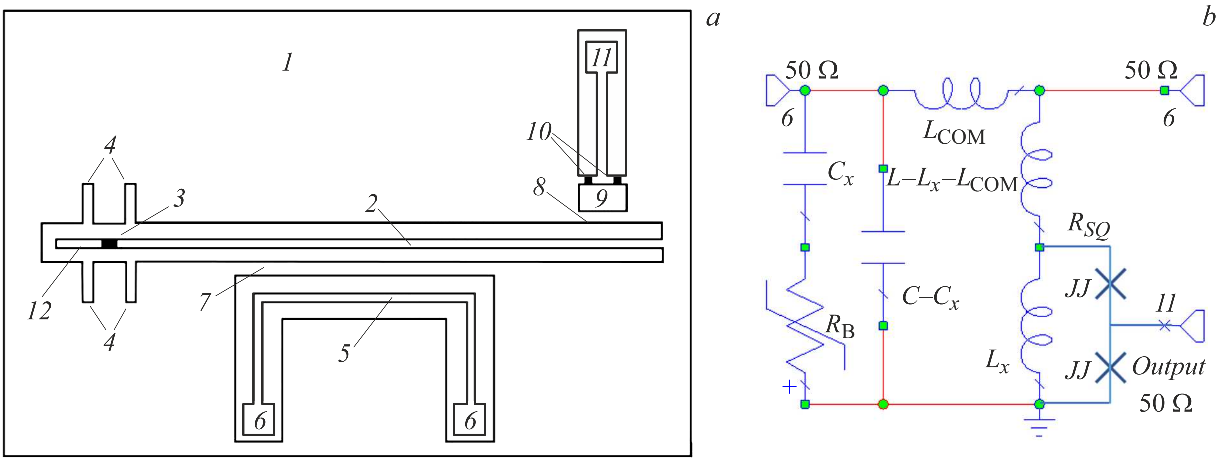

Figure 3. Simplified structure (a) and equivalent circuit (b) of a superconducting active detector: *1* — dielectric substrate coated with a superconducting film; solid lines show the film boundaries; *2* — central strip of a quarter-wave coplanar resonator; *3* — thermoresistive bridge with impedance R_B; *4* — planar double-slot antenna; *5* — coplanar resonator excitation line; *6* — terminals of exitation line loaded with coaxial waveguides 50 Ω (not shown); *7* — resonator magnetic coupling element L_{COM}; *8* — SQUID magnetic coupling element (L_x, Fig. 3, b); *9*, *10* — SQUID magnetic loop and two Josephson junctions JJ (shown with crosses); R_{SQ} — microwave current impedance in SQUID loop; *11* — SQUID output terminal; *12* — the end capacitance of the resonator (C_x, Fig. 3, b), the ratio C_x/C determines the coefficient of inclusion of the bridge impedance *3* in the resonator.

resonator segment galvanically connected to a SQUID loop, as will be described below.

The signal current is converted into a magnetic field in the SQUID loop to amplify the microwave signals. The flux transformers mentioned above are poorly suited for microwave applications, since the length of the coil conductor is several wavelengths, which leads to inavoidable parasitic effects. The solution to this problem was found by using the antinode of the magnetic field of a microstrip resonator placed on top of a SQUID loop [12,17]. The intrinsic noise of such a SQUID amplifier in the frequency range 1–10 GHz at temperatures of $\sim 50 - 100$ mK, is close to the fundamental limitation — to quantum noise [12]. The use of resonators in the input circuits of microwave SQUID amplifiers leads to a narrowing of the band, and this is considered a disadvantage or an inavoidable cost of matching. The resonator also sets a narrow frequency band of the amplifier for the case of the proposed active detector, but it coincides with the sensor band, which is the optimal condition for signal transmission. According to the diagram of Fig. 2, d, an inductor L_x presents a segment of the resonator circuit, which is a part of the input loop of the SQUID corresponding to the condition of matching the resistance of the bridge R_1 with the active impedance of the SQUID R_2.

Figure 3 shows a simplified structure and equivalent circuit of an active superconducting terahertz detector. Unlike the experimental detector in Fig. 1, a, the resonator is depicted in Fig. 3, a simplistically and not on a scale — not in a folded, but in a linear configuration, which is done for ease of understanding. The change here is the position of the resonator excitation region *7*, which is slightly offset from the resonator short circuit region, which is necessary to accommodate a SQUID amplifier; such a change within 1 mm is not important in respect to a total resonator length of about 20 mm. The thermosensitive sensor is heated by terahertz photons, which changes its resistance (the active part of the impedance) R_B, and the amplitude of the resonator current through the inductor L_x changes. At the same time, the amplitude of the magnetic field applied to the SQUID with the active impedance of the input loop R_{SQ} changes; the signal energy is redistributed from the sensor into the SQUID; the SQUID gain can be $\sim 10 - 20$ dB [12,17].

The two-junction DC-SQUID (elements *8–11* in Fig. 3, a) operates as a narrow-band parametric amplifier with an input impedance of the order $\sim 1\,\Omega$. It should be noted that the signal can be read from the pixel (Fig. 3) both from the DC-SQUID output (*11* — this is the DC bias electrode of the SQUID), and traditionally, from the resonator excitation line (contacts *6*). The parameters of the integrated SQUID amplifier, built using the principles of the study [17], at a physical temperature T_{ph} at the operating frequency of the resonator f [GHz] at the Q-factor of the resonator Q_{sq} can be as follows: gain G [a.u.]$\approx 40/f$, $T_n \approx 0.2T_{ph}$, $\Delta f \approx f/Q_{sq}$. The presence of an individual parametric amplifier with $G \approx 10 - 40$ in each pixel makes it possible to combine signals from a large number of pixels at the input of a broadband semiconductor amplifier without sacrificing sensitivity. Such pixels are well protected from interference, and in case of a defect in individual DC-SQUIDs, the possibility of traditional reading along the resonator excitation line (contacts *6*) remains. At the same time, the effect of the defective SQUID on the resonator can be eliminated by its transition to a superconducting state.

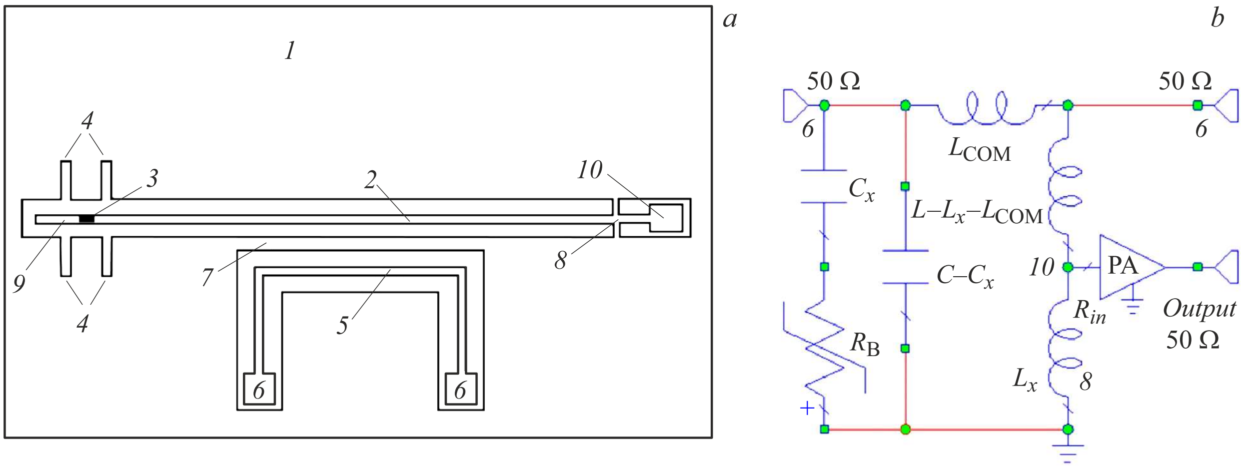

Figure 4. Simplified structure and equivalent circuit of a superconducting active detector for the case of connection (integration) of an alternative parametric amplifier (parametric amplifier — PA) to the contact *10* of the coplanar line (*a*). The equivalent circuit (*b*) uses the same notation as in Fig. 3. The differences are in the configuration of element *8* and the contact *10*, which are loaded with the input impedance of the parametric amplifier R_{in}. The terminal capacity C_{x} is marked as *9*. The numbers *6* and *10* indicate the physical terminals for the equivalent circuit.

The linearity of the built-in SQUID amplifier is an important issue. Studies [11] showed that the oscillation power in the RFTES resonator changes when the bridge is heated by no more than 10 dB, therefore, the same power variations occur at the input of a matched amplifier. The following estimates can be obtained for a SQUID based on Josephson junctions $Al/AlO_x/Al$. The operating bias voltage of the SQUID should be at least $V_{\text{bias}} = 30 - 40\,\mu$V, which is realized at the characteristic SQUID voltage $V_{\text{c}} = 100 - 120\,\mu$V, and corresponds to the frequency of Josephson oscillator (internal parametric pumping) 15–20 GHz, which at a frequency of 1.5 GHz provides gain $\sim 10 - 11$ dB. In this case, the power transmitted by the SQUID to the load 50 Ω is determined by the voltage amplitude, which cannot exceed $P_{\max} = \left(V_{\text{bias}}/\sqrt{2}\right)^2/50 \approx 1 \cdot 10^{-11}$ W, which corresponds to the SQUID input signal (bridge heating) $\sim 10^{-12}$ W. The obtained estimates fit satisfactorily with the experimental data, where the heating capacity of the RFTES bridge with the size $6 \times 2 \times 0.08\,\mu$m [11] (Fig. 1, *b*) was $\sim 0.3 \cdot 10^{-12}$ W, as well as with the parameters of the previously studied microwave SQUID amplifier at a frequency of 4 GHz [17]. It should be noted here that the sensitivity of the bridge with the electron gas increases with a decrease of its size (volume), which requires less heating power and removes the problem of saturation of the SQUID amplifier.

The proposed concept can in principle be used with other types of amplifiers and sensors that allow integral or hybrid connection to the inductor L_{x}, as shown in Fig. 4. The connection to the resonator between the point *10* and the ground shield *1* can be used in this case (Fig. 4, *a*). The exact configuration of the SQUID loop and the external connection contacts should be calculated using modern methods of electromagnetic analysis, for example, a package [16], used to design a detector prototype. It should be noted that shorted half-wave segments of coplanar lines can also be used as microresonators. In this case, the described approaches to SPA integration are applicable for MKID. In this case, the absorption region of terahertz photons and the amplifier should be located near two opposite ends of the half-wave resonator.

Conclusion

The developed approach to the design of an active superconducting detector allows concluding that a single DC-SQUID can be used as an individual amplifier for a sensor integrated into a high-quality superconducting resonator using FDM technology, for example, for a pixel of a array RFTES or MKID detector. Quantitative estimates confirm the technological possibility of creating such a pixel and the feasibility of setting this task in the plan for further experimental research of RFTES technology.

This study has methodological, scientific and practical value. A method based on the principle of partial loads of the resonator for connecting a microwave amplifier with an arbitrary input impedance to an RFTES, MKID or other detector using a high-quality superconducting resonator is proposed and theoretically justified for the first time. An electromagnetic model of the practical structure of an active detector which provides the maximum, theoretically possible, signal transmission from the sensor to the amplifier is presented also for the first time. The method of connecting the resonator to a parametric amplifier of an arbitrary type is also justified, including in the standard 50 Ω. In this case, problem of a broadband parametric or any other amplifier is actually removed, since the matching band will be determined by the resonator, and the bandwidth of the amplifier used does not play any significant role. The issue of combining active detectors into a array remains outside the scope of this study and requires special consideration, the relevance of which depends on the results of the planned experiment on the implementation of an active RFTES detector.

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Conflict of interest

The authors declare that they have no conflict of interest.

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