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SOLID STATE

# Analysys of the Concept of a Superconducing Bolometer with RF Readout

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**Abstract**—The concept of a superconducting transition-edge bolometer with rf readout, which was proposed in a number of earlier publications, is analyzed. It is shown that such a device cannot in fact operate at the edge of the superconducting transition, and nonequilibrium effects in the superconductor play the major role in its response to the electromagnetic action. A mathematical model is developed, which explains qualitatively the experimental results reported earlier and indicating an unstable response to the action of a readout (pump) signal. The possibility of obtaining a stable response with an optimal choice of parameters of the device is also demonstrated.

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## INTRODUCTION

Superconducting bolometers operating at the transition edge (transition edge sensors, TESs) are widely used in radio astronomy as submillimeter radiation sensors [1–3]. With the application of SQUID amplifiers for readout, the noise equivalent power (NEP) of such detectors can be lower than $10^{-19}$ W Hz$^{-1/2}$ [4]. A linear response and the dynamic range required for applications in radio astronomy can be obtained due to a strong electrothermal negative feedback (NF) [5, 6].

Hot electron bolometers (HEBs) are a version of TESs. These devices are based on the effect of heating of the electron gas in an absorber [7] at the transition edge. The record value of NEP at the working temperature of about 0.4 K for a HEB used as a direct sensor was demonstrated experimentally by the Karasik group (the NEP of the device was $3 \times 10^{-19}$ W Hz$^{-1/2}$ at a frequency of 620 GHz) [8–10]. Such values could be attained using a submicrometer-size absorber in which hot electrons are confined with the help of Andreev's mirrors. In spite of high parameters attained in these experiments, superconducting HEBs are not used as of yet as direct sensors in view of the nonlinearity of the response and the narrow dynamic range.

The designing of superconducting microwave kinetic inductance detectors (MKIDs) [11] for submillimeter waves is a rapidly developing trend at present. These detectors operate in the superconducting state at $T \ll T_c$. Under the action of radiation with energy $\hbar\omega \geqslant 2\Delta$, nonequilibrium quasiparticles appear in the superconducting absorber, which changes its kinetic inductance. The change in the inductance is detected from the frequency shift of the resonator in which the absorber is embedded. The Q-factor of such resonators can attain values of $10^6$ so that even a very small frequency shift can be detected. A set of such resonators can be coupled with a single transmission line for readout, thus implementing frequency multiplexing. This makes it possible to construct large matrices with a small number of conducting wires, thus reducing the required cooling power, which is especially important for autonomous astronomical systems. The MKID voltage–power response is so large that makes it possible to use cooled HEMT amplifiers instead of SQUID amplifiers for the output signal; in this case, a single amplifier can operate with hundreds of detectors [11].

In line with the demonstration of high-sensitivity superconducting HEBs and rapid development of MKIDs, Shitov et al. [12–14], proposed a new type of direct detector referred to by these authors as radio frequency transition edge sensor (RFTES). This device combines, according to its authors, two technologies. The main idea is readout of superconducting HEB at frequencies of a few gigahertz using compact integrated resonators in a similar way as MKID works. The design of the RFTES resembles in many respects the design of the HEB developed by the Karasik group [8–10]. RFTES is a superconducting bridge coupled with an integrating antenna and connected at a certain point of a coplanar $\lambda/4$ resonator tuned at a frequency of a few gigahertz [13, 14]. The resonator is in turn inductively coupled with a readout line. According to the authors, the bridge can be installed in such a system at the operating point at the superconducting transition edge, heating it by a readout microwave signal. The authors of [12–14] believe that a change in the Ohmic resistance of the bridge due to heating of the electron gas by radiation must change the Q factor of the resonator, which can be used for obtaining a response. In their opinion, such an approach can be used in constructing large superconducting HEB matrices with frequency multiplexing, thus taking advantage of one of the merits of MKIDs.

In this study, the RFTES concept is analyzed in detail. We will show that RFTES cannot operate at the superconducting transition edge and is neither a TES nor an HEB, as erroneously assumed in [12–14]. We will describe the model of a device, which can be used for explaining the effects experimentally observed in [13, 14].

## 1. ELECTRIC IMPEDANCE OF A SUPERCONDUCTING BRIDGE IN THE VICINITY OF $T_c$ AT HIGH FREQUENCIES

Analysis in [12–14] was based on the statement that the impedance of the superconducting bridge at frequencies of about a few gigahertz can be described by the dc dependence $R(T)$. This statement is erroneous since, in accordance with the BKS theory, the ac conductivity of a superconductor is a complex quantity ($\sigma = \sigma_1 - i\sigma_2$), while the dc dependence $R(T)$ reflects only the fluctuation contribution [15]. In accordance with the Mattis–Bardeen theory of the anomalous skin effect [16], we have

$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta(T)}^{\infty}(f(E) - f(E+\hbar\omega))g(E)dE - \frac{1}{\hbar\omega}\int_{\Delta(T)-\hbar\omega}^{-\Delta(T)}(1 - f(E+\hbar\omega))g(E)dE,$$

$$\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar\omega} \tag{1}$$

$$\times\int_{\Delta(T)-\hbar\omega,-\Delta(T)}^{\Delta(T)}\frac{(1-2f(E+\hbar\omega))(E^2+\Delta(T)^2+\hbar\omega E)}{\sqrt{(\Delta(T)^2 - E^2)((E+\hbar\omega)^2 - \Delta(T)^2)}}dE,$$

$$g(E) = \frac{(E^2+\Delta(T)^2+\hbar\omega E)}{(E^2-\Delta(T)^2)((E+\hbar\omega)^2-\Delta(T)^2)},$$

where $f(E)$ is the quasiparticle distribution function (Fermi function in the equilibrium case), $\Delta$ is the energy bandgap, and $\omega$ is the frequency. The second term in the expression for $\sigma_1$ can be evaluated only if $\hbar\omega > 2\Delta$; in addition, in this case, $-\Delta$ is taken as the lower integration limit for $\sigma_2$. The temperature dependence $\Delta(T)$ of the energy bandgap can be determined from the equation [15]

$$\int_0^{\hbar\omega_D}\frac{1-2f(\sqrt{E^2+\Delta(T)^2})}{\sqrt{E^2+\Delta(T)^2}}dE = \int_0^{\hbar\omega_D}\frac{1}{E}\tanh\left(\frac{E}{2kT_c}\right)dE, \tag{2}$$

where $\omega_D$ is the Debye frequency.

For thin films with $d \ll \xi$, the fluctuation corrections to the ac conductivity are given in [17–19]. For $T > T_c$, we have

$$\sigma_1^H(\omega, T) = \frac{e^2}{16\hbar\tau d}\left[\frac{\pi}{\tilde{\omega}} - \frac{2}{\tilde{\omega}}\arctan\left(\frac{1}{\tilde{\omega}}\right) - \frac{1}{\tilde{\omega}}\ln(1+\tilde{\omega}^2)\right], \tag{3}$$

where $\tau = (T - T_c)/T_c$, $\tilde{\omega} = |\pi\hbar\omega/(16k_b\tau T_c)|$, $d$ is the film thickness, and $\sigma_2 = 0$ above $T_c$. If, however, $T < T_c$, the corrections have the form

$$\begin{aligned}\sigma_1^L(\omega, T) &= \frac{e^2}{16\hbar\tau d}\left(\frac{\tilde{\omega}}{1+\tilde{\omega}^2}\right)\times\left[\pi - 2\arctan\left(\frac{1}{\tilde{\omega}}\right) - \frac{1}{\tilde{\omega}}\ln\left(\frac{1+\tilde{\omega}^2}{4}\right)\right],\\ \sigma_2^L(\omega, T) &= \frac{-e^2}{16\hbar\tau d}\left(\frac{1}{1+\tilde{\omega}^2}\right)\times\left[\pi - 2\arctan\left(\frac{1}{\tilde{\omega}}\right) + \frac{1}{\tilde{\omega}}\ln\left(\frac{1+\tilde{\omega}^2}{4}\right)\right].\end{aligned} \tag{4}$$

As a result, the conductivity in the vicinity of $T_c$ with fluctuation corrections can be written in the form

$$\sigma = \begin{cases}\sigma_1 + \sigma_1^L + i(\sigma_1 + \sigma_2^L), & T < T_c\\ \sigma_1 + \sigma_1^H, & T \geq T_c.\end{cases} \tag{5}$$

Here, we consider bridges with a thickness of about 20 nm and a width smaller than 1 μm at temperatures close to $T_c$, at which the penetration depth can be assumed to be much larger than the bridge size, and the current density in the bridge can be treated as uniform. The impedance in this case can be calculated using the simple expression $Z/R_n = (R + iX)/R_n = \sigma^{-1}$, where $R_n$ is the normal resistance.

Normal conductivity $\sigma_n$ of Ti, Hf, and Nb superconducting films conventionally used for fabricating HEBs is on the order of $10^6$–$10^7$ S [8, 20–22]. Figure 1 shows the temperature dependence of the impedance calculated using formulas (1)–(5) for a bridge with $\sigma_n = 5 \times 10^6$ S and $d = 15$ nm for various values of $\hbar\omega/2\Delta$. For $\omega = 0$, we obtain the dc dependence $R(T)$ described by the Aslamazov–Larkin formula [15]; upon an increase in frequency, the dependence is blurred and acquires imaginary part $X$. It can be seen that even for $\hbar\omega/2\Delta_0 = 0.01$, the impedance of the bridge can in no way be presented by the dc dependence $R(T)$ (curve *3* in Fig. 1). In accordance with the relation $2\Delta_0 = 3.52kT_c$, this corresponds to a frequency of only 733.4 MHz for a superconductor with $T_c = 1$ K.

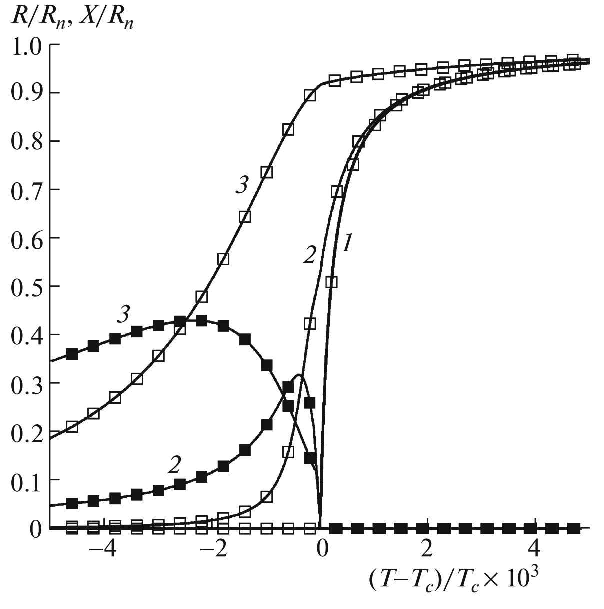


**Fig. 1.** Temperature dependence of the impedance of a thin superconducting bridge near $T_c$: (light squares) real part $R$ of the impedance; (dark squares) imaginary part $X$; digits mark the curves corresponding to different values of $\hbar\omega/2\Delta_0$: (*1*) 0 (DC); (*2*) 0.001; (*3*) 0.01.

Thus, the fundamental statement of Shitov [12] that the dc dependence $R(T)$ can be used for describing the operation of RFTES for a readout signal frequency of a few gigahertz is erroneous. The more so that films with values of $T_c$ much lower than 1 K are used for fabricating low-noise superconducting detectors [8].

Let us now consider the statement forming the basis of [12–14] according to which the superconducting bridge in RFTES can be biased at the edge of the transition by heating with a readout signal of frequency ~ 1 GHz. Let us determine the frequencies of the readout signal, at which the superconducting TES stops operating in the fluctuation region. For this, we take a specific working point (e.g., $R/R_n = 0.5$). In accordance with relation (3), the Ginzburg parameter determining the width of the fluctuation region can be written as $Gi = e^2/(16\hbar d\sigma_n)$. For $\sigma_n = 5 \times 10^6$ S and $d =$ 15 nm, this parameter is $2.03 \times 10^{-4}$. Solving numerically the equation obtained from (5),

$$\frac{R}{R_n} = \frac{\sigma_1(\omega,\tau) + \sigma_1^L(\omega,\tau)}{(\sigma_1(\omega,\tau) + \sigma_1^L(\omega,\tau))^2 + (\sigma_1(\omega,\tau) + \sigma_1^L(\omega,\tau))^2} \quad (6)$$

for $\omega$ at $\tau = Gi$, we obtain $\hbar\omega/2\Delta_0 = 1.38 \times 10^{-3}$, for which working point $R/R_n = 0.5$ is out of the fluctuation region. This corresponds to a frequency of only 101.3 MHz for $T_c = 1$ K. It follows hence that the TES will reliably operate in the fluctuation region at readout signal frequencies up to tens of megahertz. Therefore, an RFTES operating at frequencies exceeding 1 GHz cannot operate in any way at the superconducting transition edge. This means that abbreviation RFTES itself is simply incorrect. Naturally, RFTES cannot operate like an HEB as stated by the authors of [12–14] because the effect of electron heating is manifested only in the fluctuation region [7].

This result shows that for constructing matrices of superconducting TESs with frequency multiplexing, the sensing signal frequencies up to tens of megahertz should be used. Such a system was successfully implemented in suspended bolometers [23] and can probably be used for HEBs.

## 2. ROLE OF RF PUMPING OF RFTES

As established in the previous section, RFTES in fact cannot operate at the transition edge. Therefore, the RFTES response to the action of a readout signal (microwave pumping) observed in [13, 14] experimentally is obviously associated with nonequilibrium phenomena in the superconducting bridge.

It can be seen from the Mattis–Bardeen formulas (1) that the ac conductivity of a superconductor depends on quasiparticle distribution function $f(E, T)$, which is a Fermi function in the equilibrium state. Under the action of radiation of various frequencies, nonequilibrium distributions that cannot be described by a Fermi function appear, leading to a change in the conductivity in accordance with Eq. (1). Such nonequilibrium distributions of quasiparticles and phonons were considered in detail by Chang and Scalapino [24].

In the case of microwave pumping of RFTES, radiation with $\hbar\omega < 2\Delta$ is acting on the superconducting bridge. This energy is insufficient for breaking Cooper pairs, and radiation absorption leads to a redistribution of thermal quasiparticles. The quasiparticles at the edges of the bandgap, where the states are populated most strongly, are transferred upwards by $\hbar\omega$, producing a distribution peak near $\hbar\omega + \Delta$; in this case, the population of states at the bandgap edge can be reduced to below the equilibrium value (see Fig. 4 in [24]). The outflow of quasiparticles from the bandgap edge caused its expansion. The effects of anomalous increase in $I_c$ and $T_c$ associated with this phenomenon [25, 26], as well as "cooling" of superconducting resonators [27] by the pump signal leading to an increase in the Q factor and resonance frequency, are well known. However, such effects are actually observed only in aluminum characterized by anomalously long relaxation times for quasiparticles [28]. In "traditional" superconductors such as Nb, rapid recombination of quasiparticles leads to intense generation of nonequilibrium phonons with energy $\Omega > 2\Delta$, which are usually accumulated in the superconductor due to insufficient transparency of the film–substrate interface [29]. The excess of such phonons causing indirect breaking of pairs and generation of quasiparticles at the bandgap edge compensates the outflow of

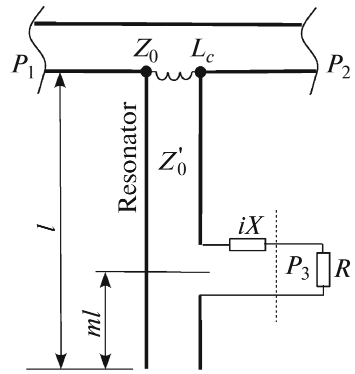


**Fig. 2.** Equivalent circuit of RFTES.

quasiparticles. In such a case, the change in the properties can be described by an equivalent increase in the temperature [29].

In experiments carried out by Shitov's group [13, 14], no anomalous "cooling" of the niobium resonator of the RFTES by the pump signal was observed. Therefore, it is expedient to use the effective heating model for describing the RFTES qualitatively. The question arises: which law should be used for describing the energy flow in the superconducting bridge? To answer this question, we can employ a qualitative approach analogous to that used in [30] for analyzing the behavior of superconducting resonators. It involves the application of the following simple power dependence of the heat flow:

$$P_t = K(T_e^5 - T_a^5), \tag{7}$$

where $T_e$ is the effective temperature of the superconducting bridge and $T_a$ is the temperature of the ambient (substrate). Naturally, effective heating due to the phonon accumulation effect cannot be described by such a dependence according to [29]; nevertheless, it was shown in [25] that the exact form of the $P_t(T_e)$ dependence is immaterial for a qualitative description and can vary over wide ranges, leading to qualitatively similar results.

## 3. RFTES MODEL

Let us now try to explain the phenomena observed in experiments with the RFTES prototype [13, 14]. It was found in these experiments that the shape of the resonance curve for RFTES varies in a peculiar way depending on the power of the readout signal fed to the device (see Fig. 2 in [14] and Fig. 7 in [13]). When the power increases from a certain threshold value, a "crater" increasing with the power appears on the smooth curve near the resonance frequency. The authors of [13, 14] noted that the crater emerges abruptly in a narrow interval of intensities of the readout signal and apparently corresponds to the formation of a hot spot in the superconducting bridge.

To explain the above observations, we will use the model based on the equivalent circuit of the RFTES shown in Fig. 2. In the circuit, the $\lambda/4$ resonator formed by a segment of a transmission line of length $l$ with impedance $Z_0'$ is weakly coupled by inductance $L_c$ with the readout line having impedance $Z_0$. The superconducting bridge with impedance $Z = R + iX$ is connected to the resonator at distance $ml$ from its open end. The circuit has three ports $P_1$–$P_3$, where port $P_3$ is a virtual point of connection of resistance $R$ of the bridge.

The $Y$ parameters of the circuit under investigation can be written in the form

$$\begin{aligned} Y_{11} &= Y_{22} = Y_{12} = Y_{21} \\ &= \left(\frac{1 + (\coth(m\gamma l) + ix)\tanh(1-m)\gamma l}{\coth(m\gamma l + \tanh(1-m)\gamma l) + ix_b} - \frac{i}{\beta_c}\right), \\ Y_{33} &= \frac{1}{\coth(m\gamma l) + \coth(1-m)\gamma l) + ix} - \frac{i}{\beta_c}, \\ Y_{13} &= Y_{31} = Y_{23} = Y_{32} = \frac{2\sinh(m\gamma l)}{2\cosh(\gamma l) + ix\sinh(m\gamma l)}, \\ \gamma &= \alpha + i\beta, \end{aligned} \tag{8}$$

where $\beta_c = \omega L_c/Z_0'$, $x = X/Z_0'$, $\beta = 2\pi/\lambda$ is the propagation constant, $\alpha$ are losses, and $l$ is the resonator length. Using the $Y$ parameters, we can easily calculate the $S$ parameters [31]:

$$S = (E - \sqrt{Z}Y\sqrt{Z})(E + \sqrt{Z}Y\sqrt{Z})^{-1}, \tag{9}$$

where $E$ is the unit matrix and $Z$ is the diagonal matrix of impedances containing the impedances of loads of all ports: $Z_{11} = Z_{12} = Z_0/Z_0'$ and $Z_{33} = R/Z_0'$.

Knowing the $S$ parameters, we can determine the electric power released in the bridge:

$$P_e = P_{\text{bias}}|S_{31}|^2, \tag{10}$$

where $P_{\text{bias}}$ is the power of the readout signal supplied to port $P_1$. The experimentally measured transmission of the signal via the sensing line is determined by quantity $|S_{21}|^2$.

We will describe the behavior of the superconducting bridge by a simple time-independent heat balance equation in effective temperature $T_e$ of the bridge:

$$P_e(Z(T_e)) - P_t(T_e) = 0, \tag{11}$$

where $P_t$ is the heat flow to the ambient, which is described by relation (7).

## 4. RESULTS OF SIMULATION

Numerical simulation of RFTES was carried out for parameters closest to the experimental conditions in [13, 14]: $T_c = 6.7$ K, operating temperature $T_a = 5$ K,

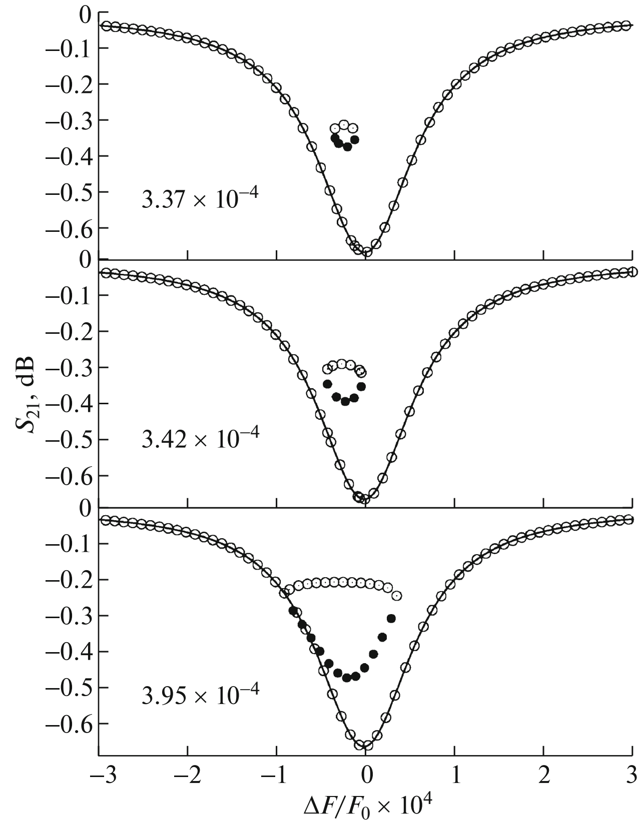


**Fig. 3.** Calculated resonance curves for RFTES with $\beta_c = 0.004$, $m = 0.015$, and $T_a = 5$ K. Light and dark symbols show stable and unstable solutions, respectively; the values of $P_{\text{bias}}$ are indicated; solid curves correspond to $P_{\text{bias}} = 10^{-6}$.

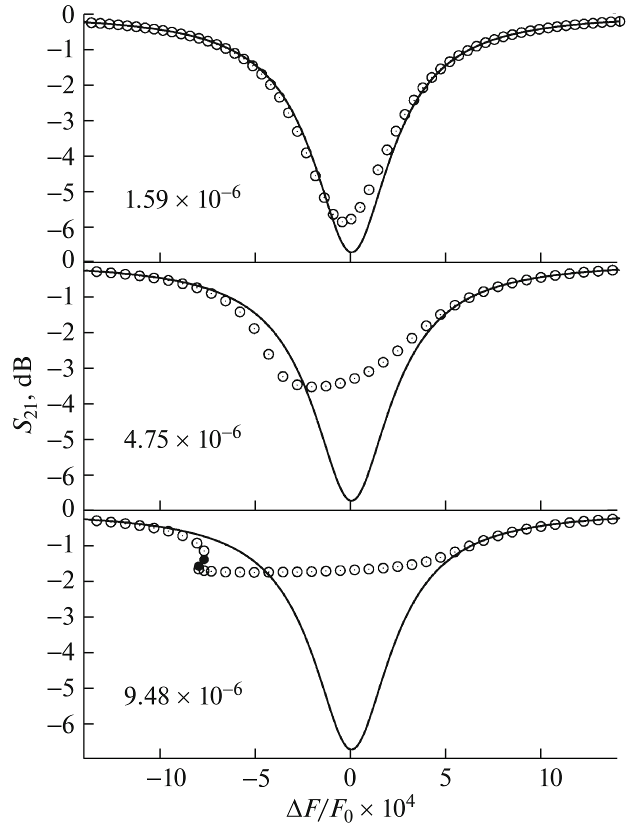


**Fig. 4.** Calculated resonance curves for RFTES with $\beta_c = 0.025$, $m = 0.08$, and $T_a = 6.3$ K. Light and dark symbols show stable and unstable solutions, respectively; the values of $P_{\text{bias}}$ are indicated; solid curves correspond to $P_{\text{bias}} = 10^{-8}$.

resonance frequency $F = 6$ GHz, superconducting bridge size $5 \times 2.5$ μm, and thickness $d = 15$ nm. The normal conductivity was taken equal to the average conductivity for similar films, which is approximately $5 \times 10^6$ S (see below) because no information on its value was given in [13, 14]. The equivalent circuit parameters $\beta_c$ and $\alpha$ were selected so that the depth of the resonant dip and the Q factor coincided with the experimental data, according to which the depth was 0.7 dB and Q = 7000. Close characteristics of the model were ensured for $\beta_c = 0.004$ and $\alpha = 10^4$. The position of point $m$ of connection of the bridge was chosen as 0.015.

Figure 3 shows the resonance curves calculated by solving Eq. (11) for various intensities of the readout signal. The intensity is given in arbitrary units because the model is only qualitative. The curves in Fig. 3 show that for a threshold intensity of $3.37 \times 10^{-4}$, a domain with several solutions, one of which does not satisfy the stability criterion $\partial P_t/\partial T_e > \partial P_e/\partial T_e$ [32], appears. Upon a further increase in the power, this domain expands, while at the remaining points, the curve almost does not deviate from its initial position at a low power.

The existence of a multivalued domain is associated with the specific form of dependence $P_e(Z(T_e))$ and indicates instability of the system, which is analogous to thermal instability of conducting filaments and narrow bridges. Detailed analysis of such phenomenon can be found in review [33]. In particular, hysteretic switching or relaxation oscillations of temperature $T_e$ can be observed in this domain. The experimentally measured $|S_{21}|$ curves, which reflect the time-averaged value, must pass somewhere between stable solutions in Fig. 3 or must exhibit jumpwise switching from one solution to another. In any case, such a domain most likely appears in the form of a crater observed in experiments near the bottom of the resonant dip in [13, 14].

At the next stage, the model parameters were optimized for correcting the $P_e(Z(T_e))$ dependence and for obtaining a smooth variation of the shape of the resonance curve on the pump power. Such a regime of the RFTES operation was initially mentioned in [12–14], but was not demonstrated experimentally. Figure 4 shows the results of calculations. It can be seen that the resonance curve in this case varies smoothly with increasing power, and the multivalued domain appears at a distance away from the resonance frequency only for a strong distortion of the resonance. The values of the power are reduced by two orders of magnitude as compared to the previous case, which can be explained by the fact that ambient temperature $T_a$ became closer to $T_c$.

## CONCLUSIONS

We have analyzed the new concept of a submillimeter wave detector with frequency multiplexing (RFTES) proposed in [12–14]. It is shown on the basis of the Mattis–Bardeen theory of the anomalous skin effect that the superconducting bridge connected to the resonator, which is the key element of the device, cannot operate in the fluctuation region at the edge of the superconducting transition because of the too high frequency of the readout signal on the order of a few gigahertz. Thus, the abbreviation RFTES itself is incorrect (i.e., the instrument is not a transition edge sensor (TES)).

The mechanism of the RFTES response to the microwave pumping is based on nonequilibrium effects and not the effect of electron gas heating at the edge of the superconducting transition, as was assumed by the authors of the concept in [12–14]. In the conditions of the dominating effect of accumulation of nonequilibrium phonons, it is possible to describe the operation of the device using the effective heating model. Such an approach formed the basis of a qualitative model of the RFTES using the equivalent circuit of a $\lambda/4$ resonator coupled with the readout line and containing a superconducting bridge and the time-independent heat balance equation for the bridge.

The results of simulation of the RFTES investigated experimentally in [13, 14] have shown that the observed sharp anomaly on the resonance curves of the model, which appears upon an increase in the pump power, is a "thermal" instability domain. For a certain choice of the model parameters, it is possible to attain smooth variation of the resonance shape with a power not leading to the formation of such a domain. Such a regime of the RFTES operation was initially presumed by the authors of RFTES [12–14], but has not been demonstrated experimentally as of yet.

In the effective heating model, the mechanism of RFTES response to electromagnetic radiation is based of the temperature dependence of the impedance $Z$ of the superconducting bridge near $T_c$. The steepness of this dependence at gigahertz frequencies of the readout signal is much smaller than the steepness of the $R(T)$ curve in the region of dc superconducting transition (see Fig. 1). This means that the electrothermal negative feedback of the RFTES is always weaker than in a bolometer operating at the transition edge [4, 6]. It follows hence that it is difficult to ensure a competitive dynamic range and linearity of the detector even when RFTES operates in a stable regime with an optical response.

It was established in [33] that nonequilibrium superconducting detectors are most effective at $T \ll T_c$, which stimulated the designing and rapid development of MKID [11]. Being in fact a nonequilibrium superconducting device, RFTES is designed to operate near $T_c$ [12–14]. In this context, RFTES is just an ineffective version of MKID; for this reason, the prospects of its application as a detector of submillimeter waves appear as dubious.

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