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Study of a thermodynamic microwave-heated noise-source for calibration of RFTES detector

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A concept and experimental data are presented for testing a miniature thermodynamic noise-source based on heating a niobium film bridge in a superconducting resonator at a frequency of about 1.4 GHz. The thermodynamic noise signal was emitted by a double-slot superconducting integrated lens antenna in the range 550−750 GHz in the form of a collimated beam with a length of about 15 mm onto the aperture of the RFTES detector; both devices are installed on the same stage of a dilution cryostat at a physical temperature of the emitting chip and detector of about 60 mK. For the first time, the optical effect of a microminiature thermodynamic noise-source in the terahertz range on an ultra-low temperature bolometer has been observed. The thermal load of the experimental noise-source on the dilution cryostat was analyzed.

Keywords: thermodynamic noise, superconducting transition, superconducting microbridge, superconducting resonator, planar lens-antenna, direct detector, RFTES detector.

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Introduction

The recently tested RFTES detector has proved its high performance in the terahertz frequency range by demonstrating the noise equivalent power (NEP) $\approx 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ at about 400 mK [1]. The detector was tested with thermodynamic source in the form of heated resistive film covering the detector aperture [2], which is a variety of the traditional black (grey) body method used to measure the sensitivity of most types of broadband cooled sensors [3–4]. The advantage of the black body (BB) method is the simple calibration of spectral density through known physical temperature and absorption coefficient of the media. Sensors used at extra-low temperatures of about 100 mK are usually qualified using black-body sources placed in cryo-refrigerators to avoid the effect of thermal background entering the cryostat from a laboratory room through optical paths. This is done also because the thermal power capacity of such cryostats is not large (about 100 μW). Beside this problem, the BB-based sources of classical configuration in the form of a temperature-controlled cavity does not make it possible to perform quick measurements due to significant heat capacity of such device. The modern literature lacks the data concerning the use of classical BB in the form of a spherical cavity with a small opening that provides multiple internal rereflection resulting in full radiation thermalization with the wall temperature of such cavity. This is associated with the requirement to use a significant (about 1 cm) aperture of such emitter. In the overwhelming majority of applications, the cavity shape is transformed geometrically to satisfy the condition of large number of incident radiation rereflections, for example, in the form of a course-pored sponge or an internal surface of a metallic cone coated with an absorber layer. A heavy emitter usually exhibits thermal inertia at times of about 1 s and is not suitable for measuring the detector response time, which is directly associated with the heat sinking rate limit of the refrigerator. This drives the search for ways to create microminiature calibrated noise source with low heating power and low thermal inertia. Analysis of the miniature film absorber [2] has shown that the resistive film is always a grey body and, therefore, unlike BB, calibration accuracy is limited by the absorption coefficient (greyness) accuracy. The literature reports at least two approaches to creating miniature sources with properties close to that of BB: by means of back engineering of an pad-type microbolometer [5] and using a resistive radiating antenna [6]. Such sources may replace traditional black-body absorbers made of porous materials and/or cone-shaped cavities [3,7,8] and, thus, reduce heat production and improve the response rate. However, heat production of such calibrators in continuous modulation mode does not differ fundamentally from the film absorber [2] because it includes substrate heating. Another solution with using the microabsorber was proposed in [9–11]. The study develops these new approaches towards using local microwave (MW) heating of the microabsorber designed for qualification of experimental RFTES detectors and other sensors with quasi-optical input in the physical temperature range from 30 mK to 5−6 K. Temperature limits of microabsorbers may vary depending on the absorber material because it is dependent on the critical temperature T_c of the film microresistor that is the broadband thermodynamic noise source, and by the operating temperature range of other superconducting components of the circuit.

1. Concept of a black body with antenna

Functioning of the device is based on a well-known conclusion of Lorentz's reciprocal theorem stating that a receiving antenna may be transformed into a radiating antenna in the same frequency range with the same efficiency and the same electromagnetic field distribution with accuracy to the coefficient of dissipation and reflection loss in waveguiding circuits and optical components. This means that a bolometric microbridge well-matched with the antenna may be transformed into a black-body emitter if the microbridge is heated with direct current or fast alternating current. In terms of MW electrodynamics, such terahertz frequency solution is the equivalent of the classical method of matched load terminating the coaxial cable or waveguide that is widely used at signal frequencies f_s of about 100 GHz. In our case, a quasi-optical beam in free space formed by an integrated lens antenna serves as the power transfer channel. In other words, thermodynamic fluctuations in the resistive microbridge heated locally to T are transmitted to the planar antenna equipped with the collimating lens, emits a noise signal in the form of a quasi-optical beam in the direction of a detector, and if the detector is matched with such beam, then the received signal is equal to the first approximation with the signal from BB having the same temperature T as the locally heated resistive bridge. It is intuitively apparent that local heating of the microbridge and its thermal insulation from the substrate play a fundamental role in heat flow reduction and response rate increase of such calibrator.

For a practical perspective, the temperature of the locally heated microresistor shall be preferably determined without any thermometer attached to the absorber. This would make the structure as compact as possible. Note that traditional thermometry is inherently impossible for the inverted electron gas bolometer because the electronic subsystem and lattice temperatures do not coincide essentially. The critical film temperature T_c is the evident reference point: the superconductor changes its resistance dramatically in the narrow temperature range near T_c, which can be easily recorded. Note that the Planck radiation spectrum of BB in the terahertz frequency range, unlike the gigahertz frequencies at temperatures below 1 K, have a negligibly low density, therefore, the test signal with a reasonable power, e.g. about 10^{-16} W, may be obtained only when BB is heated above 2 K. This means that the heat flow from the source at T_c shall be isolated from the refrigerator operating stage $T_r \approx 100$ mK or the thermal power of such sink shall be negligible. In the first case, if the sink is used for a more powerful refrigerator stage, a problem may arise with an increase in the radiation load on the dilution stage, because in this case the cryostat cooling stage $3-4$ K is generally used. The second approach may be implemented using electron gas microbridges. Summing up, an advanced calibrator with super low heat production may be created using the electron gas microbridge integrated into the planar antenna and having the critical temperature $T_c > 2$ K.

Let's consider the maintenance of an arbitrary temperature of the radiating bridge. Our study [9] has shown that to determine the temperature of the superconducting bridge heated by current to the temperature above T_c, thermal hysteresis of its current-voltage curve (CVC) namely $I(V)$ may be used. This method allows to evaluate the absorber thermal conductivity near T_c and to extrapolate $T(I)$ for $T > T_c$. However, for accurate measurement of the CVC hysteresis loop, a DC source with quite low noise is required, which is a separate experimental problem requiring special techniques to be used, including multistage noise rejection filter.

Comparing several microresistor temperature measuring and maintenance methods, it is suggested that the method of Q factor measurements of the microwave cavity like in the RFTES detector may be used similar to the thermal hysteresis method because it makes possible to calculate the thermal conductivity of the absorber. Let's use a virtual experiment. For the RFTES detector [1] one can measure the Q factor of its resonant cavity by monitoring the normalized chip transmission S_{21}. It is known that by increasing the carrier power, the absorber can be heated to T_c of the bridge and it will change from the superconducting into the normal state, and the resonant cavity Q factor will decrease as an abrupt jump. Thus, by heating the microbridge with the resonator current to the Q factor jump, we generate BB radiation with T_c and radiation beam whose geometry is defined by the combination of chip-integrated antenna and collimating immersion lens. Quick response of such hypothetical emitter is defined by the heating rate of the microabsorber film, rather than of the whole chip.

Summing up the aforesaid, the microminiature emitter can constitute a modified RFTES detector version that includes the same lens antenna and differs only in a higher T_c of the bridge. The RFTES detector under test at 200–400 mK and RFTES noise source shown in Figure 1, *a* heated to 5–6 K (depends on the emitter film material) may be placed opposite to each other as shown in Figure 1, *b* and, therefore, the thermodynamic radiation transfer efficiency close to 100% may be achieved. Disadvantages of this method may include measurement errors of the microbridge temperature other than the known value of T_c. Basically, the extrapolation method may be used: absorber temperature increase with respect to the substrate temperature will take place proportionally to the MW power dissipated in the bridge. However, such extrapolation is based on constant thermal conductivity and the absence of the effect of such heating on the resonant cavity electrodes in the area of the contact with the bridge. The thermal conductivity that defines the

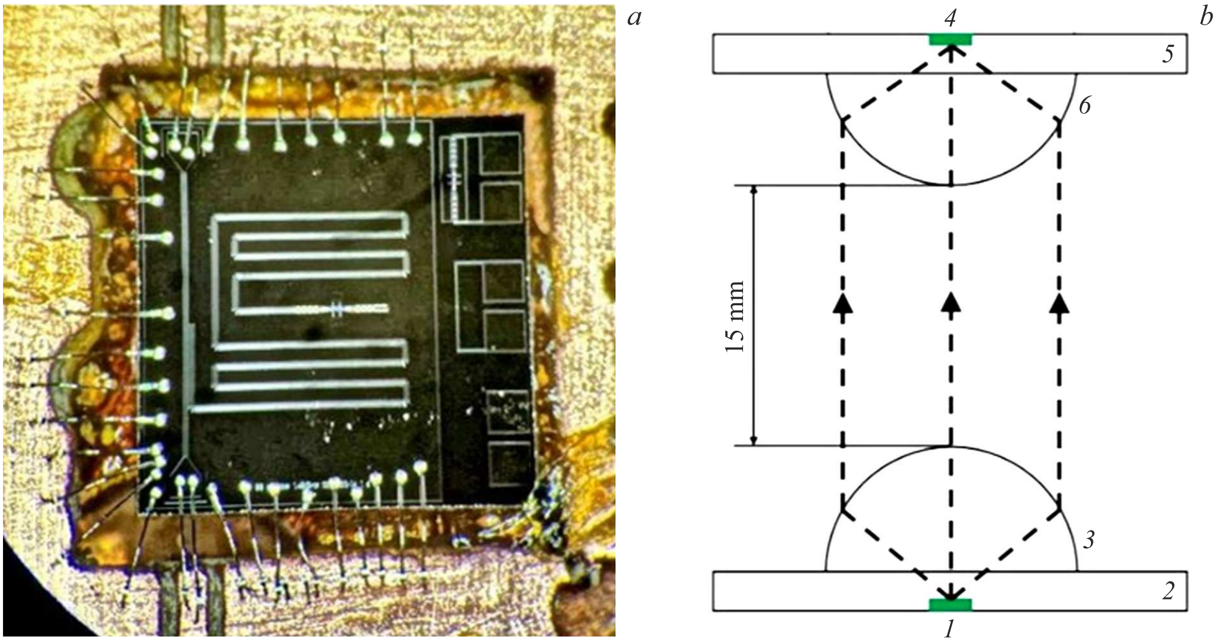

Figure 1. *a* — photograph of the miniature source chip mounted on a flat surface of the immersion sapphire lens. *b* — diagram for signal transmission from the emitter microbridge (*1*) through the chip substrate (*2*) and immersion lens (*3*) to the detector absorber (*4*) through the similar immersion lens (*6*) and detector chip substrate (*5*). The detector and emitter have independent circuits of bias by microwave current and an independent heat sink to the common dilution cryostat stage.

electronic temperature relaxation rate grows quickly with the electronic temperature for the electron gas model and with the physical temperature. For most superconductors, thermal conductivity has a wide peak in the temperature range of $1-10$ K [12].

Let's discuss the factors influencing the absorber microbridge absorption (blackness). Near T_c, the pairing energy in the bridge becomes very low, and even for currents with f_s of about 10 GHz, unlike for MKID, the film impedance becomes almost independent on the temperature and close to the normal resistance R_n. In other words, if condition $2\Delta(T) \ll hf_s$ is satisfied, then the superconductor film becomes an absorber. As follows from the fluctuation-dissipative theorem, such film shall become a radiating BB within the antenna matching range independently on its DC conductance. Therefore, recording on the superconducting transition in the resonant cavity using a relatively low bias frequency $hf_b < 2\Delta(T)$ is only the indication of the electronic subsystem temperature T_c, but not the condition for film transition from an ideal (noiseless) conductor into a black-body terahertz photon source. In other words, if $2\Delta(T) \ll hf_s$ is valid for the experiment temperatures and signal frequencies, then the smooth variation of BB radiation intensity may be obtained within the range from the cryostatting temperature of the chip to T_c of the microbridge. Thus, the chip temperature (cryostatting temperature) also reflects adequately the thermodynamic radiation temperature. This means that the existing RFTES bolometer with the hafnium bridge (unpairing frequency of about 30 GHz) may be also used as an noise source, if the temperature of its chip is known. The chip temperature operating range will be limited by the antenna's Q factor, rather by the critical temperature of the resonant cavity (it is not necessary and not used in case of external heating), which certainly will take place up to $T_{cNb}/2 = 4-4.5$ K for niobium films. For higher temperatures and/or frequencies, such system will behave similar to [6], and the radiation modulation rate will be limited by the heating time defined by the thermal mass of the chip and collimating lens integrated with the chip.

2. Thermal and electrical models

To implement the inverted RFTES bolometer concept, detailed structural analysis of such emitter was performed with focus at the parameters of known materials and electromagnetic model of the RFTES detector. According to the foregoing, the bridge material shall have $T_c > 2$ K. With reference to the data from [12,13], ~ 10 nm Nb films having $T_{cNb1} \approx 6$ K were selected. This temperature is lower than the critical temperature of the resonant cavity made from bulk Nb film of about 200 nm in thickness ($T_{cNb2} \approx 9$ K). Using the literature data [11], thermal conductivity of a $2 \times 2\,\mu$m Nb bridge at a temperature of about 5 K may be estimated as $G \approx 10^{-7}$ W/K, and the MW carrier power necessary for heating may be estimated as 200 nW, which is much lower than the nominal thermal power of a standard dilution refrigerator at 100 mK (about $100\,\mu$W).

It is known that for electrodynamic performance analysis of RFTES a lumped circuit model may be used. It can be explained by the fact that variation of any distributed element may be neglected, if the frequency varies negligibly, and this is exactly the high-Q (narrow-band) resonant cavity case. In the equivalent lumped-element circuit, the absorber bridge is connected to the resonant circuit capacitor through a small coupling that limits the MW current through the bridge and, thus, supports the low dissipation level in the resonator. Such configuration is typical for bridge connection near the open end of the coplanar resonator where currents along the central conductor are low and vanish at the open end of the resonator which is shown in [1]. When the bridge connection point is moved closer to the short-circuited end of the coplanar resonator, current through the bridge increase and the system Q factor for the particular resistance of the bridge decreases. If the bridge is inherently in the superconducting state, then it does not influence the Q factor of the resonant cavity at any incertion point. However, depending on the connection point, closer or farther from the short-circuited resonator end, a lower or higher carrier power, respectively, will be necessary to achieve the critical current (or microwave heating of the electronic subsystem) and to get the bridge to the resistive state. Note that the shift towards the short-circuited resonant cavity end is equivalent to the current source impedance reduction at the feed electrodes of the bridge, i.e. we get a condition identical to the steady state operating of a classical TES (Transition Edge Sensor) [14]. This means that smooth transition of the bridge from the superconducting state to the normal state can be achieved easier by setting the bridge impedance from a negligibly low impedance to the normal-state resistance.

3. Experiment details

The experimental noise source is structurally and topologically similar to the RFTES detector, except for the fact that the microbridge is made from a material with a critical temperature about 6 K (20 nm thick Nb film) and is shifted closer to the shorted end of the resonator. The resonant frequency of the source is intentionally shifted with respect to the RFTES detector frequency to prevent spurious interaction of high-Q resonators through free space of about 15 mm between the devices. According to the wave optics, diffraction evolution of the collimated beam of 6 mm in diameter at 475 μm at a distance of 15 mm will result in growing up 6%, i.e. the source beam wavefront almost coincides with the wavefront of the receiving lens and the estimated signal transfer coefficient is 0.94. This coefficient may be degraded due to inaccurate alignment of the chip, radiating and/or receiving antennas on the optical axis of the immersion lens that result in deviation of the optical axis of signal reception/transmission and, therefore, to only patial overlapping of such beams. The calculations shows that, when the error of antenna installation on the optical axis of the lens is 10 μm, the receiving aperture and radiation beam coverage efficiency will be 0.96, but when the chip installation error achieves 100 μm, then the efficiency decreases to 0.39. Such geometrical deviations and the relevant coefficients shall be considered for each of the beams.

As shown theoretically in [9], the microminiature source concept makes it possible to localize the heat consumption and minimize the chip heating. For the experiment, the Nb microbridge was heated by MW current of the resonator excited by the vector network analyzer (VNA) and transmission AFR (amplitude frequency response) of the chip was recorded (parameter S_{21}). The VNA output power increased in small steps before the abrupt decrease in Q factor of the measured resonance that is recorded near its resonance frequency (S_{21} jump). Such Q factor variation corresponds to bridge's critical temperature of 6.2 K and considere as a reference point. The radiated power calculation accounts for the Planck distribution of the spectral density of BB radiation and frequency ranges of the radiating/receiving antennas that are the same in our case (550−750 GHz). Thus, the source temperature may be modulated by varying the carrier power at the resonant cavity frequency with the carrier frequency of about 1.4 GHz using, for example, the balanced mixer as described in [2] (was not used for this experiment). The electronic thermal conductivity of the bridge is much higher than that of the hafnium bridge in the RFTES detector indicating a potentially faster response rate of the noise source that may be used not only to define optical sensitivity, but also to define its response rate.

4. Discussion

The emitter and detector chips were mounted into similar units made of oxygen-free copper as described in [1] and placed above each other as shown schematically in Figure 1, on the same dilution cryostat stage at 60 mK. The detector unit had a good thermal contact with the cryostat and was simultaneously thermally insulated from the emitter that had a separate heat sink in the form of an oxygen-free copper harness to the same cryostat stage. The emitter was heated by MW power in the range from −20 dBm to +9 dBm at the vector network analyzer output at a resonance frequency of about 1.39 GHz. Transition from the superconducting state into the normal state was recorded for the noise source by the resonance disappearance that corresponded to the carrier power +9 dBm as shown in Figure 2. This power is reduced due to 2-m coaxial cable and a cold attenuator 20 dB resulting in total power from 13 to 14 dBm or 40−50 μW at the chip input. This is almost two orders of magnitude lower than for a film balck-body source from [2].

Response of the RFTES detector with the hafnium-based bridge was measured at the carrier power of −46 dBm that,

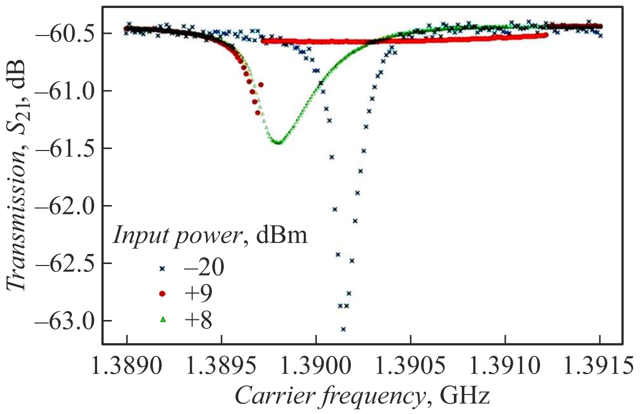

Figure 2. Resonance transmission curves of the noise source chip at a fixed temperature of 60 mK for three different MW heating powers. Transition of the Nb resonator into the low Q factor state is observed when the carrier power varies from +8 to +9 dBm (at the coaxial cable input towards the dilution cryostat). It can be seen that the resonator exhibits strong kinetic effect due to smooth MW heating of the electron subsystem and to reduction of superconducting carrier concentration in the vicinity of the film's critical temperature (about 6.2 K).

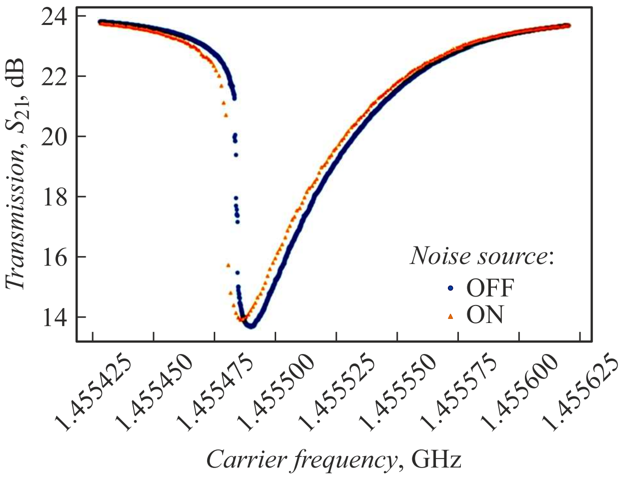

Figure 3. Response of the RFTES detector with the hafnium bridge to Nb miniature noise source heated by the microwave power of 40−50 μW at 1.39 GHz is exhibited as a resonance frequency offset due to the increase in the kinetic inductance of the hafnium microbridge exposed to terahertz photons arriving from the noise source. The miniature noise source and detector are installed on the same dilution cryostat stage at 60 mK, but are thermally isolated from each other.

including the cable loss and cold attenuation, corresponded to the on-chip power from 77 to 78 dBm or 16−20 pW. The temperature of 60 mK is not the best for the RFTES detector; such temperatures give rise to a nonlinear effect caused by the kinetic inductance and exhibited by the resonance dip asymmetry $S_{21}(f)$. The detector response has demonstrated mainly frequency offset, rather than amplitude behavior. Such mode was chosen to demonstrate the compatibility between the BB emitter and RFTES detector at a ultra-low temperature. As mentioned above, the detector and noise source respnators' frequencies were intentionally made different, 1.455 and 1.39 GHz, respectively, to enshure no interaction between resonators due to radiating antenna coupling. The noise source absorber heating to the normal state required the carrier power of +9 dBm and a clear response was received from the RFTES detector resonator as shown in Figure 3.

We have noticed that long-term heating of the microbridge above 6 K at the dilution stage at temperature of 60 mK with a power of 40−50 μW (+9 dBm at the cryostat input) resulted in gradual overheating of the cryostatting system, which may be explained by the insufficient refrigerating power of our cryostat (nominally $\sim 100\,\mu$W). This indicates that the existing noise source chip version does not meet the optimum parameters yet, and either a slightly higher refrigerating power or chip optimization in terms of microbridge heating current reduction is required to use long-term (rather than pulsed) modulation.

The observed dilution stage overload may be explained by the fact that thermal conductivity of the Nb microbridge near T_c is two orders of magnitude higher than that of the Hf microbridge, and it has turned to be insufficient to move the absorber connection point by 200 μm towards the short-circuited end of the resonator. Critical temperature ratio of the experimental resonator and absorber film was $T_{c\mathrm{Nb}2}/T_{c\mathrm{Nb}1} \approx 1.5$, which was not sufficiently high that could result in competition between the critical current of the quarter-wave resonator in its short-circuited area so the current needed to heat the bridge. The numerical estimates show that to heat the Nb bridge to 6 K in the experimental chip configuration (without the effect of electron gas with a thermal conductivity of $G \approx 10^{-7}$ W/K), a current of about 250 μA is required, i.e. the heating current is of the same order of magnitude as the critical current of the resonator film. This problem may be solved by reducing the bridge width and changing the bridge connection point in the resonator moving it along the resonant cavity towards the short-circuited end.

Conclusion

The experimental study of the bolometer-type RFTES detector exposed to the thermodynamic radiation transmitted optically from the Nb film microbridge has demonstrated that the concept of such noise source is a feasible solution. Thermal power of the radiating Nb bridge heated by the microwave resonator current was sink to the same dilution cryostat stage where the detector was mounted (about 60 mK) and this power turned to be comparable with the refrigerating power of the cryostat. However, the temperature behavior analysis has shown that the registered response is not likely attributed to detector chip heating, i.e. the response may be associated with the black-body radiation of the microbridge or the whole chip. For further optimization of the noise source, the resonant cavity shall be improved in such way that it retains high Q factor also at the temperature of bridge transition to the normal state. The obtained data suggest that the microwave power heating the emitter shall be reduced, which is possible by means of correction of the microbridge placement within the resonator as well as by reducing the bridge dimensions using, for example, the submicron electron-beam lithography.

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Conflict of interest

The authors declare that they have no conflict of interest.

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