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Terahertz Spectroscopy with a Josephson Oscillator and a SINIS Bolometer

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The voltage response of a thin-film normal-metal hot-electron bolometer based on a SINIS (superconductor–insulator–normal metal–insulator–superconductor) structure to the radiation of a high-temperature Josephson junction in the terahertz frequency region was measured. Bolometers were integrated with planar log-periodic and double-dipole antennas, and Josephson junctions were integrated with log-periodic antennas. Measurements showed that the Josephson junction at a temperature of 260 mK was overheated by the transport current, so that its electron temperature exceeded 3 K at a bias voltage of 1 mV. The maximum response of a bolometer with a double-dipole antenna was observed at a frequency of 300 GHz, which agreed well with the calculated value. The Josephson radiation was observed at frequencies up to 1.7 THz. The voltage response of a bolometer reached 4×10^8 V/W, and the total noise-equivalent power reached 1.5×10^{-17} W/Hz$^{1/2}$. © *2004 MAIK "Nauka/Interperiodica".*

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1. SINIS bolometers. Normal-metal hot-electron bolometers with a capacitive decoupling of the superconductor–insulator–normal metal–insulator–superconductor (SINIS) structure were proposed in [1] and experimentally tested in [2]. The response to an external microwave signal and the noise-equivalent power of such a bolometer are determined by its electron temperature. To improve the noise and signal characteristics, a direct electron cooling of a normal-metal absorber by a superconductor–insulator–normal metal (SIN) tunnel junction was proposed in [3]. The electron cooling effect was demonstrated in [4] and further developed in [5].

A general view of a substrate with bolometers is presented in Fig. 1a. A broadband log-periodic antenna with a frequency range of 0.2–2 THz is positioned at the center of the substrate; two double-dipole antennas with a central frequency of 300 GHz are on the right, and one double-dipole antenna with a central frequency of 600 GHz is on the left. At the top and bottom, test structures are positioned with two pairs of SIN junctions for studying the electron cooling effect. The latter is described for such a structure in [6]. An atomic-force microscopic image of the central part of the bolometer is shown in Fig. 1b.

The first step in fabricating the samples was the formation of gold contact pads and traps for hot quasiparticles. The pattern was made by standard photolithography. Gold 60 nm in thickness was deposited by thermal evaporation. The next step consisted in the formation of the tunnel junctions and the absorber. The pattern was made by direct electron lithography. The films were deposited by thermal evaporation at different angles through a suspended double-photoresist mask. This method made it possible to deposit films of different metals in a single process in vacuum and provide their overlap in the tunnel junction regions. A 65-nm-thick aluminum film was deposited at an angle of 60° to the substrate and oxidized for 2 min in oxygen at a pressure of 0.1 mbar to obtain a tunnel barrier. A double-layer absorber film consisting of chromium and copper with a total thickness of 75 nm was deposited perpendicular to the substrate. The absorber volume was 0.18 μm^3. The outer cooling SIN junctions of the test structures had a resistance of 0.86 kΩ each, and the inner junctions had 5.3 kΩ each. The inner junctions had a simple crosslike geometry, where a segment of a normal-metal strip crossed the oxidized aluminum electrode. Their overlap area was 0.2×0.3 μm. The structure of the outer junctions was such that the ends of the normal-metal absorber covered the corner of each of the outer oxidized aluminum electrodes, and the junction area was 0.55×0.82 μm. An increase in the size of aluminum electrodes made it possible to improve the diffusion of hot quasiparticles carried away from the absorber by the tunneling current and to avoid a reabsorption in the normal metal for the phonons emitted upon quasiparticle recombination. Additionally, for the same purpose, one of the test structures had hot-particle traps in the form of normal-metal films located in the junction region under the aluminum film. In the experiments with electron cooling, the application of a bias voltage close to the energy gap of the outer SIN junctions caused a decrease in the electron temperature measured by the inner SIN thermometers from 260 to 100 mK.

2. High-temperature Josephson oscillators. According to [7, 8], the maximal Josephson-oscillation frequency and power are determined by the critical current I_c, the normal resistance R_n, and their product $V_c = I_cR_n$. The characteristic frequency of a Josephson junction is $f_c = (2e/h)V_c$, where e is the electron charge and h is the Planck's constant. The characteristic voltage of a Josephson junction does not exceed the energy gap, which corresponds to frequencies on the order of 700 GHz for niobium junctions, while, for high-T_c superconductors (HTSCs) with a critical temperature above 77 K, the corresponding frequency may reach 10 THz and higher. However, high characteristic voltages and oscillation frequencies are realized only at temperatures much lower than the critical temperature. In particular, values of V_c above 5 mV are observed for the HTSC junctions at liquid-helium temperatures and lower. For the HTSC junctions on bicrystal substrates, the choice of the substrate material is highly important. The best dc characteristics are obtained for junctions on the strontium titanate substrates, but the high dielectric constant and the substantial losses at high frequencies render them unsuitable for use in the submillimeter wave range. Sapphire substrates proved to possess the most suitable characteristics, and they were used to fabricate the Josephson oscillators. Unlike standard bicrystal substrates with a misorientation in the substrate plane, we used substrates with a crystallographic axis inclined to the substrate plane. Epitaxial YBaCuO films were grown by laser ablation on the substrates whose c axis in the $\langle 100 \rangle$ direction was inclined at an angle of $14° + 14°$. Films 250 nm thick were deposited on a CeO_2 buffer layer. The critical temperature of the films was $T_c = 89$ K, and the transition width was $\Delta T_c = 1.5$ K. The bicrystal Josephson junctions were from 1.5 to 6 μm wide and, at a temperature of 4.2 K, had the characteristic voltage $V_c \geq 4$ mV. Under an external submillimeter radiation, their I–V characteristics exhibited Shapiro steps at voltages up to 4 mV, which corresponds to frequencies above 2 THz.

3. Bolometer response to changes in temperature and absorbed power. The main bolometer characteristics were measured at a temperature of 260 mK in a cryostat with a closed-cycle He-3 absorption refrigerator. The maximal voltage response to the temperature variations was 1.6 mV/K for a 10-kΩ SIN junction, and the maximal current response was equal to 55 nA/K for a 6-kΩ junction.

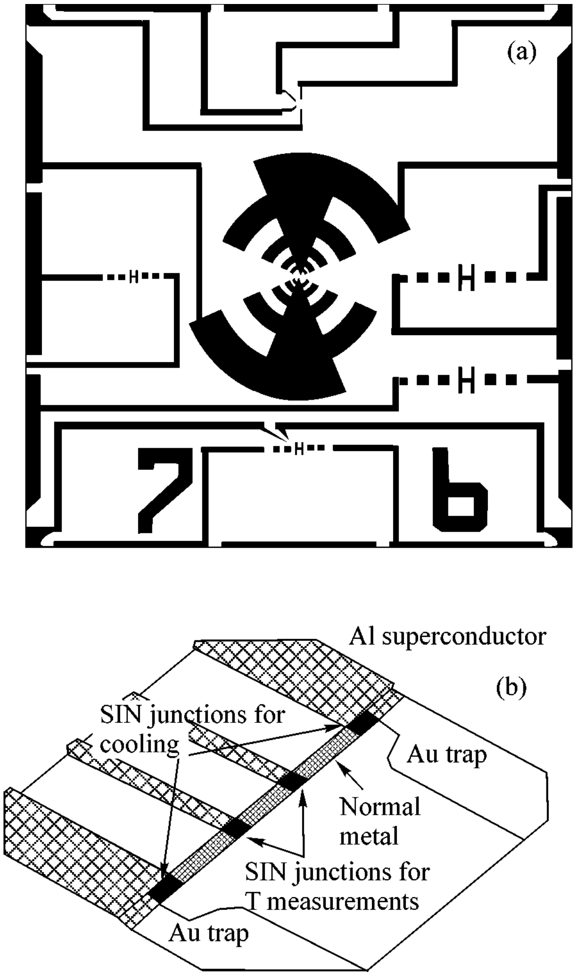

Fig. 1. (a) General view of a substrate with bolometer and (b) atomic-force microscopic image of the bolometer central part.

For structures with four SIN junctions, it was possible to apply power to the inner pair of junctions and measure the response of the outer pair. The measured dependences of the response on the bias voltage are shown in Fig. 2. The maximal voltage response was 4×10^8 V/W for a pair of 70-kΩ junctions, and the maximal current response was 550 A/W for a pair of 10-kΩ junctions. These values correspond to the noise-equivalent power (NEP)

$$\mathrm{NEP} = I_n/S_i \quad \text{or} \quad \mathrm{NEP} = V_n/S_V, \tag{1}$$

where I_n is the current noise, V_n is the voltage noise, $S_i = dI/dP$ is the current response, and $S_V = dV/dP$ is the bolometer voltage response. Setting the noise voltage of our preamplifier equal to 3 nV/Hz$^{1/2}$, we obtain the technical noise-equivalent power:

$$\mathrm{TNEP} = 1.25 \times 10^{-17}\ \mathrm{W/Hz^{1/2}}. \tag{2}$$

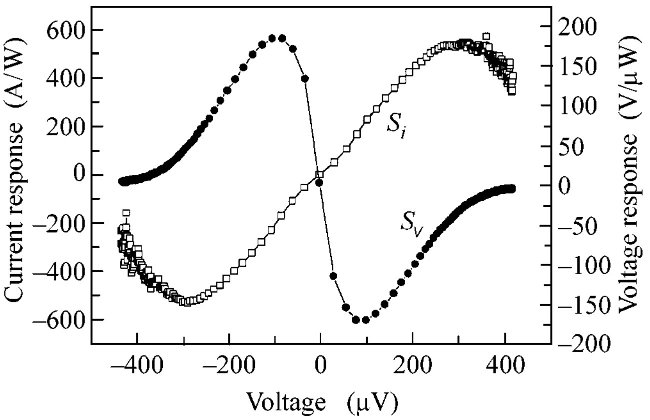

Fig. 2. Current and voltage responses of bolometer with a tunnel junction resistance of 10 kΩ vs. the bias voltage at a temperature of 260 mK.

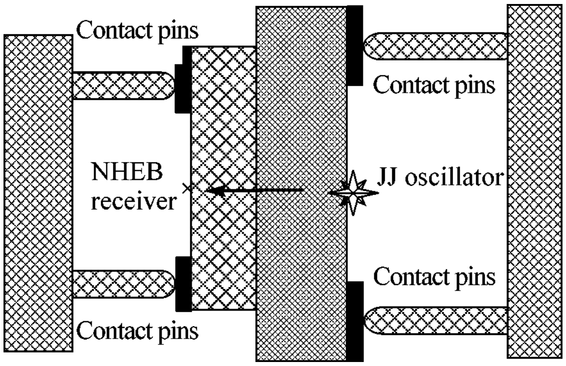

Fig. 3. Schematic diagram of the experiment at 260 mK with the backside of the Josephson oscillator substrate pressed to the backside of the bolometer substrate.

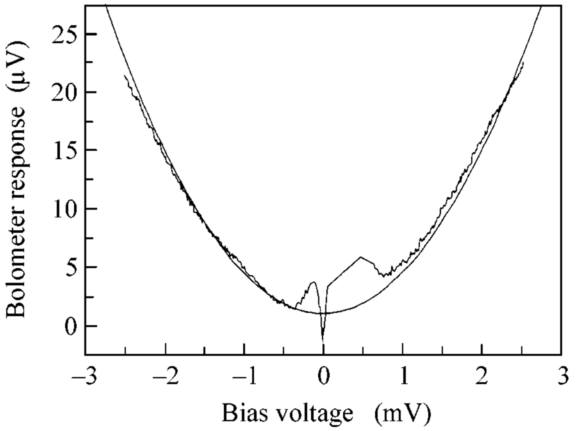

Fig. 4. Bolometer response to the radiation of a Josephson source. The solid parabola corresponds to Joule heating.

Substituting the measured values of the response to changes in temperature and power, we obtain the bolometer heat conductivity

$$G_V = \frac{\partial P}{\partial T} = \frac{\partial V/\partial T}{\partial V/\partial P} = 0.8\times 10^{-11}\ \mathrm{W/K}. \qquad (3)$$

The thermodynamic noise-equivalent power is determined by the expression

$$\mathrm{NEP}^2_{\mathrm{TD}} = 4kT^2G. \qquad (4)$$

Taking into account that $G = 5\Sigma\nu T^4 = 10^{-11}$ W/K, we obtain $\mathrm{NEP}_{\mathrm{TD}} = 1.4\times10^{-18}$ W/Hz$^{1/2}$ and, substituting the heat conductivity in a voltage-bias mode, we obtain

$$\mathrm{NEP}_{\mathrm{V}} = 1.3\times 10^{-18}\ \mathrm{W/Hz}^{1/2}. \qquad (5)$$

The use of a SQUID-based low-noise reading device with a current resolution of 50 fA/Hz$^{1/2}$ will allow the noise-equivalent power to be improved by an order of magnitude as compared to the technical noise-equivalent power determined by the noise of a warm transistor amplifier.

4. Measurement of the Josephson junction radiation at 260 mK. In the first series of experiments, the backside of a substrate with the Josephson oscillator was directly attached to the backside of a substrate with the bolometer (Fig. 3), and this assembly was cooled to 260 mK. Since the planar antennas were deposited on the substrates with a dielectric constant higher than 10, the main lobes of their directivity patterns were oriented toward the dielectric and, when the radiating antenna was positioned opposite the receiving antenna, an efficient power transfer occurred from the Josephson junction to the bolometer. The log-periodic antennas of the oscillator and the receiver were identical and rated for a frequency range from 200 GHz to 2 THz.

The dependence of the bolometer response on the voltage applied to the Josephson junction is shown in Fig. 4. By applying a magnetic field, the critical current of the Josephson junction can be suppressed to zero, and then the junction will be a simple current-heated resistor. In this case, depending on the bias on the radiating junction, the bolometer receives thermal radiation from a cold or heated load. The dependence of the response on the bias is found to be parabolic, which corresponds to the Joule heating proportional to the square of applied voltage. This experiment allows one to separate the Josephson radiation component, whose frequency corresponds to the bias voltage, from the broadband thermal component, whose power is proportional to the square of bias voltage. It is significant that, above 1 mV, the Josephson junction is strongly overheated both in the absence and in the presence of magnetic field and its effective electron temperature considerably exceeds the refrigerator equilibrium temperature.

The maximal Josephson radiation power can be estimated as $P_{\mathrm{osc}} = 0.1I_cV_c = 2\times10^{-9}$ W [7]. In the case of a log-periodic radiation antenna with a knife-edge pattern and double-dipole reception antenna with a pencil-beam pattern, the mismatch of the directivity patterns takes place and the losses increase by more than 10 dB. The oscillator substrate had five log-periodic antennas on its surface, and the bolometer substrate had two double-dipole antennas and one log-periodic antenna. The oscillator and receiver antennas were never directed toward each other, resulting in the losses of no less than 10 dB. No convergence lenses were placed between the oscillator and receiver, so that the received beams diverged, adding another 10-dB (or greater) loss. The mismatch with antenna, the mismatch between the radiating and receiving beams, the inaccurate alignment of the directions of different antennas, the reflections from the sapphire–silicon boundary, and the difference in polarizations—all this provides a total loss of no less than 30 dB at frequencies on the order of 1 THz. As a result, the power received by the bolometer is less than 10^{-12} W. Setting the response of the bolometer under consideration to $S = 1.1 \times 10^8$ V/W, we find that the maximal voltage response is equal to approximately 1.1×10^{-4} V. In our experiments, the response to the Josephson radiation reached a level of 10 μV. The difference of one order of magnitude may be caused by such factors as nonideal characteristics of the Josephson junction, excess current, and overheating, which reduce the output power. The response to the non-Josephson radiation on the parabolic portion of the response curve may be ascribed to the receipt of the submillimeter and infrared radiation from the matched load integrated in the broadband antenna circuit and radiating into the quasi-optical channel.

If we accept the overheating model for the Josephson junction as a bridge of variable thickness [4], we can estimate the temperature in the middle of the bridge as

$$T_m = \sqrt{T_b^2 + 3\left(\frac{eV}{2\pi k}\right)^2}. \tag{6}$$

From this relation, we obtain an equivalent electron temperature of about 3 K for a Josephson junction bias of 1 mV. Considering that the thermal radiation is scattered within a solid angle of 4π and that the bolometer is placed at a distance of about 1 mm in a dielectric, the value of 5 mK of the effective temperature measured by the bolometer becomes understandable. Since the power is first radiated and then received, it is also necessary to take into account the quantum character of radiation according to the Planck law:

$$P_r = \frac{hf}{e^{hf/kT} - 1} 0.3 f. \tag{7}$$

According to this relation, the maximal radiation occurs at a frequency corresponding to the temperature: $hf \approx kT$. Applying Eq. (7) to Eq. (1) and neglecting the phonon temperature, we arrive at the expression

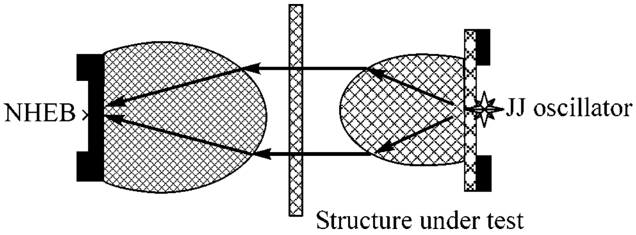

Fig. 5. Schematic diagram of the quasi-optical experiment, where the bolometer was positioned on the flat surface of a hyperhemispherical sapphire lens at 260 mK and the substrate with the Josephson oscillator was placed on a similar silicon lens at 1.8 K. The oscillator and receiver were 3 cm apart, so that the tested object could be placed between them.

$$P_{\rm rad} = \frac{0.6}{4\pi^2}\frac{e^2V^2}{h}, \tag{8}$$

which fits the quadratic dependence observed in the experiment.

5. Irradiation of bolometer by the Josephson junction at 1.8 K. To increase the output power of the Josephson source and the oscillation frequency, it is necessary to increase the characteristic voltage of the Josephson junction, i.e., its critical current. Placing the Josephson junction at the He-4 cooling step, we prevent the bolometer overheating by the dc bias-current power of the Josephson junction. For example, in a junction with a resistance of 10 Ω, a power of 0.2 μW is absorbed at an oscillation frequency of 300 GHz, and this power increases to 2.5 μW at a frequency of 1 THz.

In the quasi-optical configuration (Fig. 5), the bolometer was placed on the flat surface of a hyperhemispherical sapphire lens at a temperature of 260 mK, and the substrate with the Josephson oscillator was placed on a similar silicon lens at a temperature of 1.8 K. The oscillator and the receiver were spaced 3 cm apart.

The topology of the Josephson samples was the same as in the experiments at 260 mK, but the critical current exceeded 0.5–1 mA at 4 K. In the absence of an external magnetic field, the value of I_cR_n exceeded 5 mV. With increasing magnetic field, the critical current oscillated. Under the irradiation by a backward-wave oscillator, the Shapiro steps were observed up to 4 mV. The experimental curves are shown in Fig. 6. Figure 6a represents the response of a bolometer with a double-dipole antenna rated for a central frequency of 300 GHz and the response of a bolometer with a log-periodic broadband antenna in the range 0.2–2 THz. Figure 6b shows the response of a bolometer with a double-dipole antenna for two values of magnetic field, i.e., for the higher (upper curve) and lower (lower curve) values of critical current and characteristic voltage. The response corresponding to the highest frequency (1.7 THz) is shown in Fig. 6c. The same curve exhibits the third and fifth harmonics of the antenna fundamental mode.

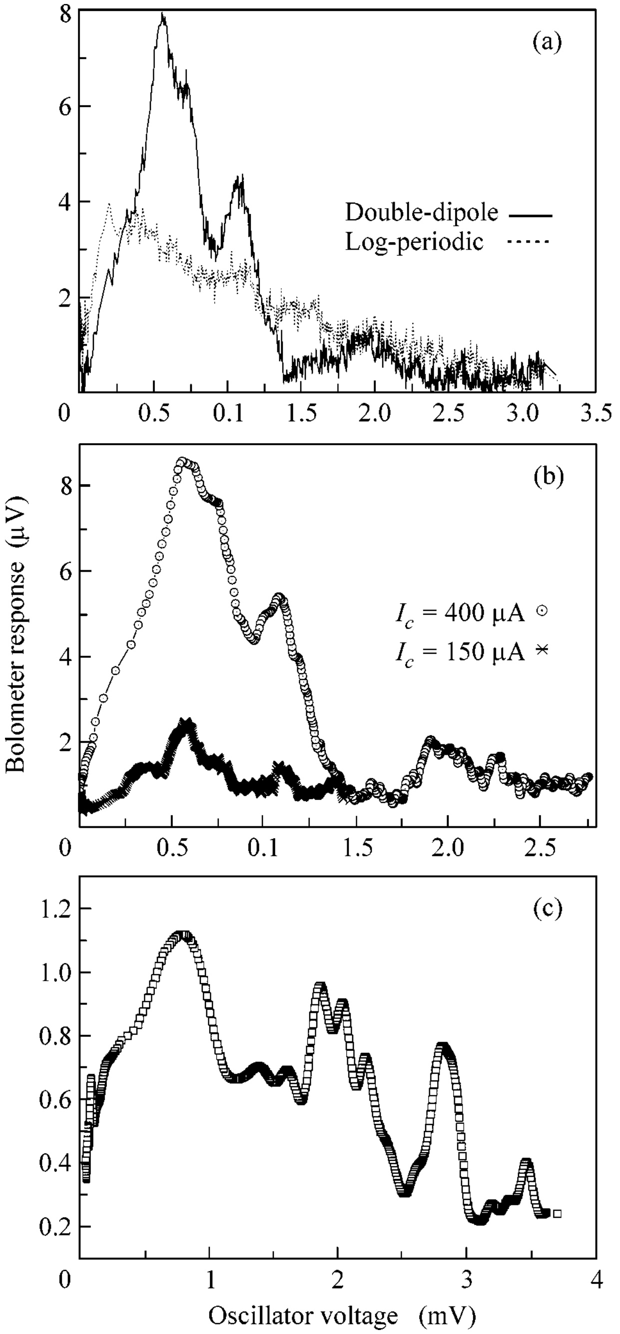

Fig. 6. (a) Responses measured by a bolometer with a double-dipole antenna (upper curve) and a bolometer with a log-periodic antenna (lower curve). (b) Response of a bolometer with a double-dipole antenna for two values of magnetic field and critical currents of 400 (upper curve) and 150 μA (lower curve). (c) Response measured at high bias voltages without magnetic field. The last maximum corresponds to a frequency of 1.7 THz.

6. Discussion. A simple analytic expression for the voltage response of bolometer [9] gives a rough estimate of the practically attainable power response at a temperature of 260 mK:

$$S_V^{\max} = \frac{2k_b}{e\Sigma\nu T_e^4} = 10^8 \text{ V/W}.$$

A more accurate calculation, according to [9], yields a value of 4×10^8 V/W, which coincides with the experimental data. With allowance made for the bolometer noise at the operating point and the amplifier noise V_N = 6 nV/Hz$^{1/2}$ in a current bias mode, the noise-equivalent power is

$$\mathrm{NEP_V} = V_N/S_V^{\max} = 1.5 \times 10^{-17} \text{ W/Hz}^{1/2}.$$

Let us also estimate the characteristic values for the voltage bias mode with electron cooling. The main heat flow occurs from hot phonons to electrons that are subjected to electron cooling:

$$P_{Ph-e} = \Sigma\nu T_{Ph}^5 = 0.5 \text{ pW}.$$

To remove this power from the electron system, it is necessary to apply cooling current

$$I_c = \frac{eP_{Ph-e}}{k_bT} = 2.2 \times 10^{-8} \text{ A}.$$

This current gives rise to a shot noise. Taking the theoretical value of the current response $S_I = e/2k_bT = 6 \times 10^3$ A/W, we obtain the noise-equivalent power

$$\mathrm{NEP_I} = \sqrt{4k_bT_e\Sigma\nu T_{Ph}^5} = 1.3 \times 10^{-17} \text{ W/Hz}^{1/2}. \quad (9)$$

This value is smaller than the measured value of 5×10^{-17}. This can be explained by the fact that the current response of high-resistance SIN junctions is weaker than the theoretical value obtained for an optimal resistance of 1 kΩ.

The voltage response has been measured for a SINIS bolometer at 260 mK to give 4×10^8 V/W. The noise-equivalent power limited by the bolometer and amplifier noise is 1.5×10^{-17} W/Hz$^{1/2}$. The measurements of the radiation from an HTSC Josephson junction have shown that, at bias voltages on the order of 1 mV, the junction is overheated, and its effective temperature exceeds 3 K for a substrate temperature of 260 mK. The use of HTSC junctions at low temperatures is advantageous, because these junctions allow one to obtain high values of characteristic voltage I_cR_n and increase the radiation frequency at least to 1.7 THz. A combination of a Josephson terahertz oscillator with a high-sensitivity SINIS bolometer makes it possible to realize a compact cryogenic terahertz network analyzer with a frequency resolution on the order of several gigahertz.

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