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Superconducting Sub-THz Receivers for Space and Ground-Based Radio Astronomy

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Abstract—The developments in the field of low-noise receiving systems in the sub-THz range, performed at the Kotelnikov Institute of Radio Engineering of the Russian Academy of Sciences in recent years and aimed at the creation of receivers with quantum sensitivity for space and ground-based radio telescopes are presented. Superconductor–insulator–superconductor (SIS) mixers based on high-quality tunnel junctions are key elements of the most sensitive sub-THz heterodyne receivers. The article presents the results of the development of SIS receivers in the 211–275 GHz and 800–950 GHz ranges with a noise temperature in the double-sideband (DSB) mode of about 20 K and 220 K, respectively. These achievements will be used to develop receiving systems for APEX and LLMA ground-based telescopes, as well as for the Millimetron space mission.

Keywords: radio astronomy, niobium based high quality tunnel junctions, low-noise SIS receivers, terahertz range quantum-limited mixers

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1. INTRODUCTION

Tunnel structures superconductor—insulator—superconductor (SIS) are the best input elements for coherent receivers at frequencies from 0.1 to 1.2 THz [1–10]. They are used in most modern receivers for radio astronomy. This is explained by the extraordinarily high nonlinearity of superconductor tunnel elements and the possibility of achieving extremely low-noise temperatures bounded only by the quantum limit; this is caused by low leakage currents in high-quality tunnel structures and cryogenic operating temperatures. Heterodyne SIS receivers continuously function in most ground-based radio telescopes; they are used in all high-frequency ranges of the largest multielement interferometer Atacama Large Millimeter/submillimeter Array (ALMA) [7–9]. SIS receivers efficiently operated onboard of the Hershel space observatory incorporated a HIFI (Heterodyne Instrument for the Far Infrared) [5, 6, 11]. Currently, several space missions are under development, including the Millimetron project of the Russian Space Agency [12, 13]. The Millimetron project is aimed at the study of astronomical objects in the Universe in far infrared, submillimeter, and millimeter spectral ranges with ultrahigh sensitivity. It is planned to conduct measurements both in the mode of a single telescope and in the mode of the Space–Earth interferometer with a record high angular resolution.

To solve scientific problems of the Millimetron project, a number of heterodyne receiving systems with a sensitivity close to the quantum limit should be developed. Receivers of the range of 211–275 GHz with noise temperatures lower than 45 K in the single-sideband (SSB) mode are required for operation in both the Space–Earth interferometer mode and for the high-resolution spectrometer ($R > 10^6$) in the single telescope mode. We note that receivers of this range were used to obtain the first-ever "image" of the supermassive black hole at the Galaxy M 87 center within the Event Horizon Telescope (EHT) project. To improve noise characteristics of the 7-pixel matrix receiver for the APEX (Atacama Pathfinder Experiment) telescope [14], SIS receiving structures with an operating frequency to 950 GHz were developed and studied. In this paper, the results of the development of the SIS receiver of ranges of 211–275 and

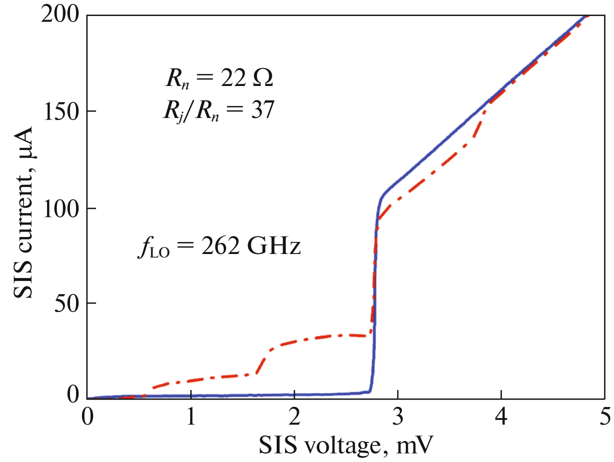

Fig. 1. I–V characteristic of a mixer element based on the Nb/Al/Nb–AlO_x–Nb structure 1 μm^2 in area: the solid curve is the autonomous I–V characteristic; the dash-dotted curve is the I–V characteristic upon exposure to an optimum-power heterodyne at a frequency of 262 GHz.

790–950 GHz at the Kotelnikov Institute of Radio Engineering and Electronics with colleagues from the Astronomical Institute of the University of Groningen are presented.

2. SIS MIXER OF THE RANGE OF 211–275 GHz

As a receiving element for the waveguide mixer of the range of 211–275 GHz, a tunnel Nb–AlO_x–Nb SIS junction fabricated on a quartz substrate 125 μm thick was used. The SIS junction 1 μm^2 in area was incorporated in a planar structure based on coplanar and microstrip Nb/SiO_2/Nb lines, which made it possible to compensate for the SIS junction capacitance in the operating frequency range and to match the SIS junction interface at a high frequency (of the order of 20–40 Ω) with the waveguide impedance. To prevent the HF signal leakage through the sample structure, HF blocking filters were fabricated on its surface. The waveguide receiving element is placed in a rectangular waveguide 500 × 1000 μm^2 orthogonally to the wave propagation plane at a distance of 230 μm from the waveguide end [15].

The current–voltage (I–V) characteristic of the Nb–AlO_x–Nb junction fabricated by the conventional technology contains a knee-shaped feature slightly above the gap voltage V_g. This feature is caused by the normal aluminum layer near the tunnel barrier; its presence significantly modifies the electron density of states in the superconducting electrode. The knee-shaped feature results in the sloping portion with quasiparticle steps under the action of the heterodyne power, causing SIS mixer operation instability and significantly reducing the operating range.

To solve this problem, the fabrication technology of tunnel structures was modernized; an additional aluminum layer 5 nm thick was introduced into the lower electrode at a distance of 50 nm from the tunnel barrier. This layer not only improved the niobium film morphology near to the barrier to, but also significantly changed the electron distribution function in the electrode near the barrier. All these factors resulted in total suppression of the knee-shaped feature, the I–V characteristic of the Nb/Al/Nb–AlO_x–Nb tunnel structure is shown in Fig. 1. The new fabrication technology made it possible to produce not only tunnel junctions without sloping portions and features, but also to realize an extraordinarily low leakage current at voltages below the gap one (the ratio of resistivities under and over the gap is $R_j/R_n = 37$). It is close to ultimate value for niobium-based junctions and allows the implementation of noise temperatures bounded only by the quantum limit. Under the action of the heterodyne signal with frequency f_{LO} on the tunnel junction, quasiparticle steps appear in the I–V characteristic, whose size in voltage is controlled by the heterodyne frequency $\Delta V_{qp} = hf_{\mathrm{LO}}/e$ (h is the Planck constant and e is the electron charge).

Experimental I–V characteristic upon exposure to the heterodyne with a frequency of 262 GHz and a power optimal for the SIS mixer operation is shown in Fig. 1 by the dash-dotted curve. The receiving element response was measured using a Michelson Fourier-transform spectrometer (FTS). As a broadband source of subTHz radiation, a resistive heater was used. To measure the receiving element response at the

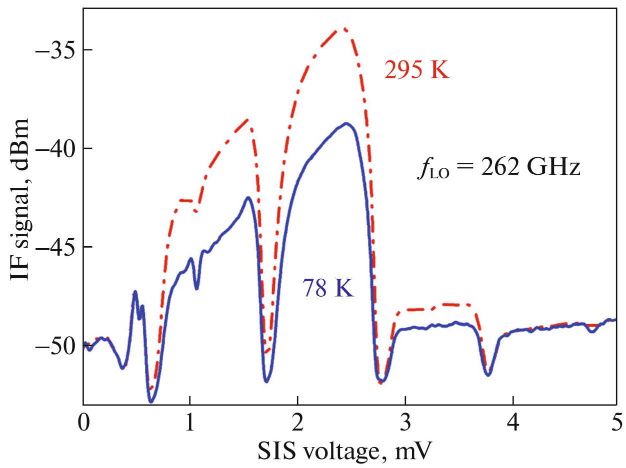

Fig. 2. Dependences of the output signal of the SIS receiver for Nb/Al/Nb–AlO_x–Nb structures without knee, measured at the intermediate frequency of 6.5 GHz at cold and hot loads at the input (solid and dash-dotted curves, respectively).

SIS junction, a working point was set at a voltage level of 2.5 mV (slightly lower than the gap voltage); the FTS results showed good agreement with the required frequency range.

The noise temperature was measured by the standard Y-factor method using absorbers at 295 K and 78 K as hot and cold loads, respectively. The absorber temperature was measured and continuously inspected using calibrated thermometers with an accuracy of 0.2 K. Figure 2 shows the dependences of the output signal of the SIS receiver on the bias voltage, measured at a heterodyne frequency of 262 GHz at an intermediate frequency (IF) of 6.5 GHz (the IF filter band is 40 MHz); the responses for the cold and hot loads at the input are shown by solid and dash-dotted curves, respectively. The difference of these curves gives the Y-factor which reaches 5 dB at the best points, which corresponds to the receiver noise temperature below 20 K. The measured dependences of the double-sideband (DSB) temperature of the SIS receiver were obtained without any corrections for losses in the receiver channel (losses in the beam divider, cryostat entrance, and filters at steps of 78 and 4.2 K were not subtracted). The double-sideband noise temperatures measured in the IF band of 4–8 GHz only slightly exceed the quantum limit hf/k_B and are 19 ± 2 K at a frequency of 251 GHz. The presented accuracies of the final noise temperature (±2 K) account for not only errors in absorber temperature measurements, but also other possible measurement errors. The obtained noise temperatures satisfy technical requirements for the receiver of the range of 211–275 GHz for the receiving system of the Millimetron space radio telescope.

3. MATRIX RECEIVER OF THE RANGE OF 790–950 GHz FOR THE APEX TELESCOPE

To modernize the 7-pixel matrix receiver of the APEX telescope [14] of the range of 790–950 GHz (see Fig. 3), SIS mixers were developed based on Nb–AlN–NbN tunnel junctions with high critical current density, incorporated into a microstripe line consisting of a NbTiN lower electrode 320 nm thick and an Al upper electrode 500 nm thick, separated by a SiO_2 insulator 250 nm thick. The critical temperature of the NbTiN film is 14.5 K; constructional details and fabrication technologies were presented in our paper [14]. An important advantage of new Nb–AlN–NbN mixers is a higher gap voltage in comparison with old mixers with Nb electrodes: 3.15 mV and 2.8 mV, respectively. This plays an important role for high-frequency applications, since the photon step for a frequency of 950 GHz is 3.9 mV and exceeds the gap voltage of the junction. For modernized mixers, the voltage range accessible for the SIS mixer operation is approximately 0.7 mV wider than that of existing mixers, which is a significant advantage.

Nb–AlN–NbN SIS junctions [10, 16] allow the implementation of tunnel current densities up to 30 kA/cm^2 while retaining a high quality (the ratio of the leakage resistance to the normal state resistance is 25–30). The use of the structure with double SIS junctions makes it possible to achieve a broadband response and to provide a good noise temperature in the required frequency range (see Fig. 4).

The corrected noise temperature of DSB mixers varies from 200 K at low frequencies to 400 K at a frequency of 950 GHz. A correction for the beam splitter loss (~10%) and the contribution of the heterodyne source, determined at a temperature of 300 K [17], was introduced to the noise temperature. The data of

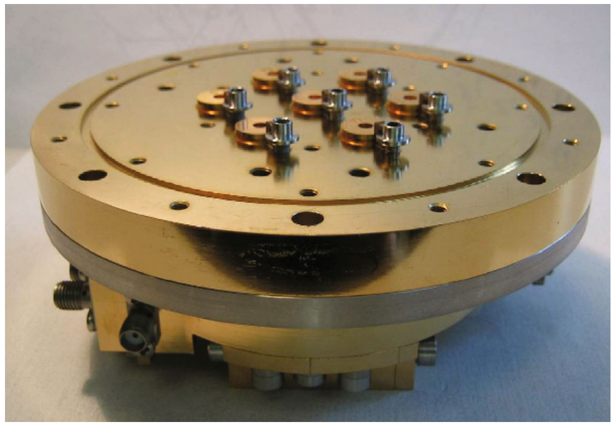

Fig. 3. Photograph of the 7-pixel matrix receiver of the range of 790–950 GHz for the APEX (Atacama Pathfinder Experiment) telescope; input horns of mixers are seen.

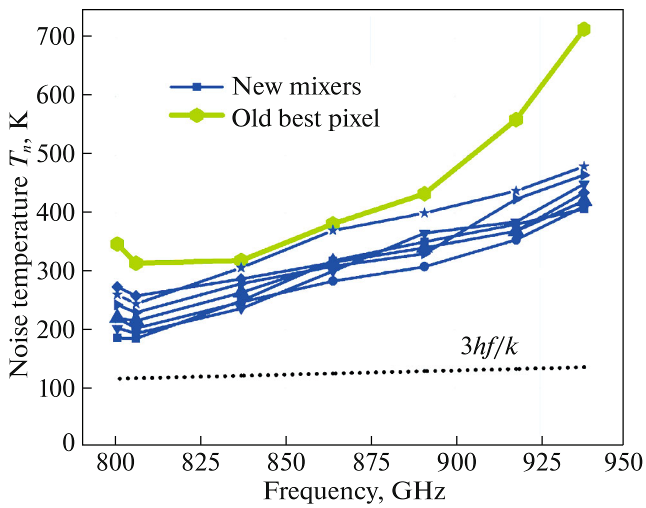

Fig. 4. Dependence of the noise temperature of matrix receiver pixels on the heterodyne frequency, measured in the IF range of 4–12 GHz. For comparison, the data for the central pixel of the previous receiver are given.

Fig. 4 allow the conclusion that the SIS mixer modernization makes it possible to significantly improve the CHAMP+ receiver sensitivity. For the modernized central pixel, the noise temperature of the mixer is 203, 283, and 407 K at frequencies of 800, 864, and 938 GHz, which is better by a factor of 1.7, 1.35, and 1.75 than for the previous version (345, 381, and 716 K, respectively). Such an improvement in the sensitivity allows an about twice increase in the rate of astronomical measurements, as well as offers opportunities for observing previously inaccessible sources.

Thus, SIS mixers of the range of 211–275 GHz with noise temperatures lower than 20 K were developed and studied. The obtained double-sideband noise temperatures only slightly exceed hf/k_B, which makes such receivers major candidates for new ground-based and space radio astronomical projects. The results of the modernization of the 7-pixel matrix receiver on the APEX telescope of the range of 790–950 GHz; the noise temperature of developed Nb–AlN–NbN mixers varies from 200 K to 400 K. The SIS mixer modernization allowed an improvement in the CHAMP+ sensitivity approximately by a factor of 1.5, which makes it possible to reduce measurement time by half.

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