Low-noise THz-range Nb based SIS Receivers for Radio Astronomy

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Abstract—**This repost describes our results on development of low-noise heterodyne THz receivers for ground based and space radio astronomy. Superconductor-insulator-superconductor (SIS) mixers that employ high quality Nb-based tunnel junctions are the key element of the most sensitive heterodyne THz receivers. In particular we present here the SIS receivers for frequency range 211-275 GHz and 800-950 GHz with double sideband (DSB) noise temperature of about 25 K and 220 K, respectively. The latest results on development, fabrication techniques and experimental study of the SIS receivers will be discussed.**

I. INTRODUCTION

A major goal of this study is to advance sub-THz technology and develop quantum-limited SIS receivers for applications in ground-based and space radio astronomy, including super-VLBI. The "Millimetron" observatory with a 10-meter space telescope, which is a successor of Russian ground - space interferometer "Radioastron", is designed to study various objects in the Universe at millimeter and infrared wavelengths. The observatory will have two operational modes – the single-dish and Space-Earth interferometer modes. The second mode is aimed to solve scientific problems that require ultra-high resolution, up to tens of billionths of a second of arc. High angular resolution is provided by the orbit configuration. The observatory is located near the Lagrange point L2, located at 1.5 million kilometers from Earth.

Nb-based tunnel junctions are basic elements of most low-T_c superconducting electronic devices and circuits. In particular, the superconductor-insulator-superconductor (SIS) mixers that employ high quality Nb-based tunnel junctions have the noise temperature limited only by the fundamental quantum value. That is why the SIS receivers that employ high quality Nb-based tunnel junctions are currently used in both ground-based and space terahertz radio telescopes [1, 2]. To realize a quantum-limited performance, SIS tunnel junctions with a high current density and extremely small leakage currents are required; this forces one to decrease junction dimensions to sub-micron level to achieve matching between such high current density junctions and antenna. Implementation of the sub-micron Nb/AlN/NbN junctions that combine high gap voltage with low leakage current at extremely high tunnel current density allows us to realize a quantum-limited performance for frequencies up to 950 GHz.

II. TECHNOLOGY DEVELOPMENT

The technology for fabrication superconducting tunnel junctions Nb-AlOx-Nb and Nb-AlN-NbN with record parameters (current densities up to 100 kA/cm^2) [3], as well as electron-beam lithography techniques for reproducible fabrication of tunnel junctions of submicron sizes (area down to 0.1 μm^2) have been developed. This allows to increase the operating frequency of SIS mixers, expand their bandwidth, and create a number of ultra-sensitive receivers in the 200 - 1000 GHz range [4-6], as well as develop a number of superconducting quantum interference devices for various applications. Implementation of the sub-micron Nb/AlN/NbN junctions that combine high gap voltage with low leakage current at extremely high tunnel current density allows us to realize a quantum-limited performance for frequencies up to 950 GHz. For example, the corrected noise temperature of the receiver at a frequency of 725 GHz was 120 K, which is only 3 times higher than the quantum limit hf/k_B

III. 250 AND 850 GHZ SIS RECEIVERS

This part of the section describes the results of developing a SIS receiver for the 211-275 GHz frequency range for the Millimetron observatory. The Nb/AlO$_x$/Nb tunnel junction (area of about 1 μm^2) fabricated on a 125 μm-thick quartz substrate, was used as the receiving element [5]. To reach ultimately low noise temperature, large capacitance of the SIS junction should be compensated in the operation frequency range; in addition SIS impedance at a high frequency (about 20–40 Ω) should be matched to the waveguide impedance of about 400 Ω. This was realized by inserting the SIS junction in the planar tuning structure formed by segments of coplanar and microstrip Nb/SiO$_2$/Nb lines (see Fig. 1). The receiving probe of the SIS element (partially shown in left part of Fig. 1) was located in a rectangular waveguide with the dimensions 500 ×1000 μm orthogonally to the wave-propagation plane at a distance of 230 μm from the waveguide end.

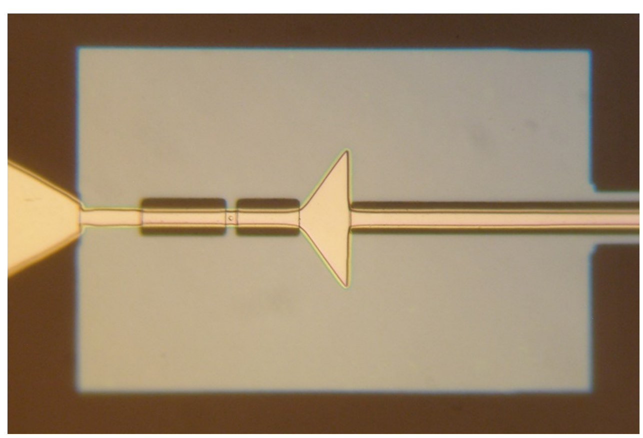

Fig. 1. Photo of the SIS mixer element inserted in the planar structure formed by segments of coplanar and microstrip Nb/SiO$_2$/Nb lines.

The first results on development, fabrication and testing of the Nb/AlN/NbN mixers circuits for 211- 275 GHz frequency range are quite encouraging. The noise temperature was measured by the standard Y-factor method (see Fig. 2); the absorber at a temperature of 295 K was used as a “hot” load, while the absorber cooled to 78 K was used as a “cold” load. The output signal of the SIS receiver on the bias voltage, measured for the local-oscillator frequency 240 GHz at the intermediate frequency (IF) 6.5 GHz (the bandwidth of the IF filter is 40 MHz). The uncorrected receiver noise temperature 25 K was measured at frequency 240 GHz, which is only 2 times higher than the quantum limit hf/k_B (see Fig. 3). Note that the experimental data in Fig. 3 [5] are presented without corrections for losses in the beam splitter and the input window of a cryostat. The receivers under development are intended for a number of terrestrial newly-built radio telescopes: e.g., ground-based Event Horizon Telescope (EHT) project and the Large Latin American Millimeter Array (LLAMA), as well as for the Millimetron space program [7].

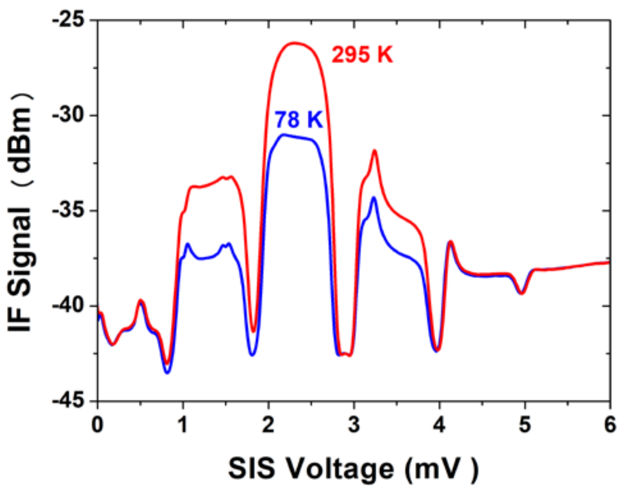

Fig. 2. Output signal of the SIS receiver at intermediate frequency (IF) 6.5 GHz on the SIS bias voltage, measured for the cold and hot input loads (78 K - blue curve and 295 K - red curve, correspondingly) at the local-oscillator frequency 240 GHz.

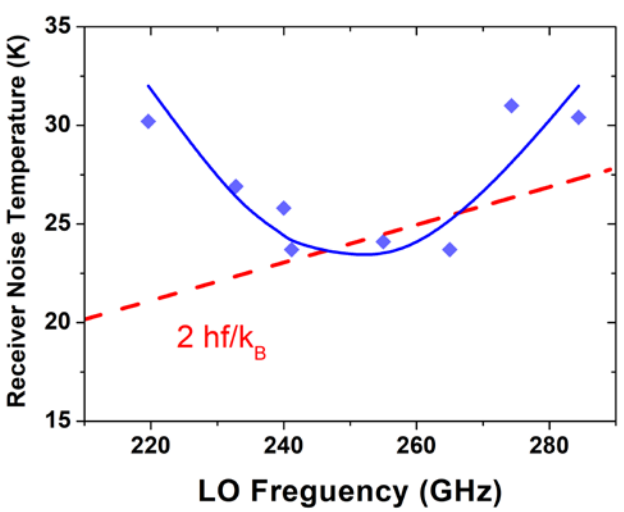

Fig. 3. Double sideband (DSB) receiver noise temperature of the SIS receiver on the local oscillator (LO) frequency; the experimental data are presented without any corrections for losses in the input optic elements.

The SIS mixers based on Nb/AlN/NbN twin tunnel junctions incorporated in a NbTiN/Al microstrip line for waveguide receiver operating in frequency range of 790 – 950 GHz intended for Chinese radio observatory at Dome A, Antarctic, for Champ II+ (APEX observatory at Atacama site in Chile) and for Brazilian LLAMA located in the Argentinean Andes has been developed and tested. The SIS mixers developed for upgrade of the CHAMP+ high-band array on the APEX telescope have double-sideband (DSB) noise temperatures from 210 to 400 K. Based on these results the design of sideband separating (2SB) mixer for 800–950 GHz, has been developed and characterized; this is the first waveguide 2SB SIS mixer demonstrated at such a high frequency. The design is based on classical quadrature hybrid architecture and aimed on the reduction of reflections in the RF structure to minimize the RF imbalance, in order to achieve a high image rejection ratio (IRR). The assembled 2SB mixer yields a SSB noise temperature from 450 to 900 K, with an IRR above 15 dB in 95% of the band. The obtained noise temperatures (450–900 K) are mainly determined by the SIS device noise temperatures (taking into account the theoretical losses in the waveguide structure due to anomalous skin-effect regime (about 0.6 dB or 15%). The gain in sensitivity for spectral-line observations is about 10% (20% in observation time). If state-of-the-art SIS devices are employed, the sensitivity gain should go up to about 20% (40% in observation time). It makes the presented waveguide solution an attractive option for potential ALMA upgrades.

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