240 GHz DSB receiver performance

Kirill Rudakov, Andrey Baryshev, Ronald Hesper, Andrey Khudchenko, Daniel Montofre, Rob de Haan Stijkel, Pavel Dmitriev, and Valery Koshelets

***Abstract*— We have designed, simulated, manufactured and evaluated a double side band (DSB) receiver for the 211-275 GHz frequency range; in this design 4 – 8 GHz intermediate frequency (IF) band was realized. In order to achieve quantum limited sensitivity high quality Nb/AlOx/Nb superconductor-insulator-superconductor (SIS) tunnel junctions are employed; both a single-side and a double-side designs of the mixers elements installed in the waveguide RF hybrid block are tested. The uncorrected DSB mixer noise temperature as low as 9 K has been measured at 241 GHz in a narrow intermediate frequency (IF) band; the noise temperature is rising up to 22 K at the edges of the input frequency range. The DSB noise temperature measured at integration of the IF signal in the band 4-8 GHz do not exceed 30 K for all frequencies from 227 to 275 GHz.**

***Index Terms*— superconductor-insulator-superconductor (SIS) receivers, quantum limited sensitivity, intermediate frequency bandwidth, submillimeter waves, heterodyne terahertz receivers.**

I. Introduction

The mixers based on superconductor – insulator – superconductor (SIS) tunnel junctions are most sensitive devices at frequencies *f* from 0.1 to about 1.2 THz. Their noise temperature is limited only by the quantum value $hf/2k_B$, where h and k_B are the Plank and Boltzmann constants, respectively. The SIS mixers were successfully used both for the space missions like Hershel HIFI [1] and for the ground-based telescopes like the largest multi-element interferometer ALMA [2]).

The Russian" space observatory "Millimetron [3] with a 10-meter space telescope is presently under development. The observatory has two operational modes – the single-dish and Space-Earth interferometer modes. The second mode is aimed to observe the extremely compact objects, e.g. the immediate vicinity of black holes that require ultra-high resolution, up to tens of billionths of a second of arc. High angular resolution is provided by the orbit configuration (location near the Lagrange point L2 at 1.5 million kilometers from the Earth). For the Space-Earth interferometer the 2SB 211 - 275 GHz receivers with a noise temperature below 50 K are required.

This paper presents the results of the development and measurement of a test prototype of the DSB SIS heterodyne waveguide receiver for 211 - 275 GHz frequency band. The developed receivers can be used also for many other future ground-based radio astronomy projects.

II. Mixer Design, Technology and Results

To follow a successful Hybrid construction methodology of the ALMA Band 9 receiver [4] we place the mixer chip into a waveguide orthogonally to the propagation direction; the designs were developed using a Microwave Studio (CST). The Nb/AlOx/Nb SIS junction is placed into a planar $Nb/SiO_2/Nb$ tuning structure made on a 125 µm thick quartz substrate. The receiving chip (width 150 µm) is located in a rectangular 1000 x 500 µm waveguide at a distance of 230 µm from the backshort in the waveguide. The mixer block consists of a few separates elements: a central part with the waveguide, a magnet block unit with two magnet pins to suppress Josephson critical current, a back piece (BP) unit where the mixer chip is installed, and an input horn. The quartz chip placed in the waveguide channel is itself a dielectric waveguide with an excitation frequency of the first mode of about 320 GHz; to prevent leakage of the RF signal through this dielectric waveguide the blocking low-pass RF filters were used. A combination of the Coplanar (CPW) and Microstrip (MSL) lines were used to tune out the intrinsic SIS capacitance and to provide the matching of the resulted SIS impedance to the waveguide at RF.

To realize a quantum-limited performance, the SIS tunnel junctions with extremely small leakage current under the gap voltage and minimal energy gap spreading δVg are required. This is especially important for relatively low-frequency devices (f ~ 200– 300 GHz), since the δVg has to be much smaller than the size of the quasiparticle step hf/e, while the leakage current at a bias voltage of about $Vg - hf/2e$ determines the noise of the mixer. The fabrication technology of the Nb–AlOx–Nb tunnel junctions is based on the fact that a very thin Al layer can completely cover the base Nb electrode [5, 6], somehow "planarizing" the column-like structure of the Nb film. This Al layer is subsequently oxidized and the top Nb electrode is deposited on the oxidized layer to form a so-called tri-layer structure.

The numerical simulations and experimental study of the receivers were supported by the Russian Science Foundation (Project No. 19-19-00618). The fabrication of the tunnel circuits was carried out at the Kotel'nikov IREE RAS within the framework of the state task.

The research leading to these results has received funding from the European Commission Seventh Framework Programme (FP/2007-2013) under grant agreement No 283393 (RadioNet3)

K. Rudakov, A. Baryshev, R. Hesper, A. Khudchenko, D. Montofre, and R. de Haan Stijkel are with the Kapteyn Astronomical Institute, University of Groningen, 9712 CP Groningen, the Netherlands (e-mail: k.rudakov@astro.rug.nl)

K. Rudakov and A. Khudchenko are also with the Kotel'nikov Institute of Radio Engineering and Electronics RAS, Moscow 125009, Russia; K. Rudakov is also with the Moscow Institute of Physics and Technology, Institutskii per., 9, 141700 Dolgoprudny, Moscow Region, Russia

P. Dmitriev and V. Koshelets are with the Kotel'nikov Institute of Radio Engineering and Electronics RAS, Moscow 125009, Russia. (e-mail: valery@hitech.cplire.ru).

The SNEAP technology was used in this work for fabrication of the SIS receiving structures based on Nb/Al-AlOx/Nb circuits, details are presented in [7–9]. To prevent etching of the quartz substrate in the process of plasma etching during the junction definition process a "monitor" layer of Nb with a thickness of about 100 nm was deposited in the substrate by DC magnetron sputtering. The SIS junctions are formed by plasma-chemical etching in CF4 by removing the top Nb layer of the tri-layer Nb/Al-AlOx/Nb structure according to the mask from the photoresist determining the junction geometry. After plasma-chemical etching, anodizing is performed up to 10 V using the same photoresist mask; then an insulating SiO_2 layer, typical thickness of which is 250 nm, is deposited by RF magnetron sputtering; opening of contacts to the junctions is carried out by lift-off.

The current-voltage characteristic (IVC) of a Nb/Al-AlO_x/Nb SIS-mixing element with an area of about 1 μm^2 is shown in Fig. 1, the IVC is measured in the voltage-bias mode, the critical current of the SIS junction is suppressed by a magnetic field. The normal resistance of the SIS junction is Rn ~ 34 Ω, the quality parameter characterized by the ratio of the resistances under and above the gap Rsg/Rn ~ 36, the gap voltage Vg ~ 2.75 mV, the energy gap spreading δV ~ 0.1 mV. It should be mentioned that the well-pronounced knee-like feature arising on the IVC at voltages slightly higher than Vg. This feature is due to the presence of a normal aluminum layer near the tunnel barrier; its presence substantially modifies the density of electron states in the superconducting electrode. A theoretical model of such a structure [10] is built on solving the quasi-classical Usadel equations with the realization of the conditions of the so-called dirty limit. Experimentally, the dependence of the effect on the parameters of the tunnel structure was investigated in [7].

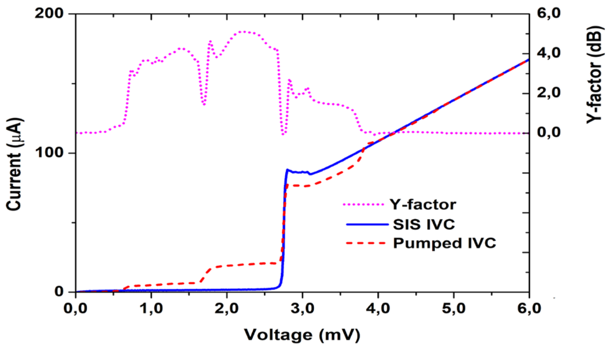

Fig. 1. The SIS IVCs (autonomous and pumped by LO at 241 GHz at was optimal LO power level); the corresponding Y-factor is presented

In order to evaluate a wideband radiation matching of the SIS mixer at RF the Michelson Fourier transform spectrometer (FTS) technique was used. A wideband GHz-THz source – glow bar - was matched with the FTS which was loaded to the SIS mixer as a detector. The mixer was voltage biased at 3mV, then a direct current response was measured versus a mirror position; these data were Fourier transformed into a mixer response on the frequency.

Noise temperature has been measured by using Y-factor method with an absorber placed in liquid nitrogen (78 K) as a cold load and a room temperature (296.4 K) absorber as a hot load (see Fig. 1) The measured DSB uncorrected noise temperature is presented in the Fig. 2 in comparison with quantum sensitivity level (Callen & Welton) [11]; the frequency range was limited to 227 – 275 GHz by parameters of the used LO source. The data were measure over the IF band 4 - 8 GHz; even lower DSB noise temperature was obtained at integration in narrow intermediate frequency (IF) band 40 MHz: the T_r as low as 9 K has been measured at 241 GHz; all details will be presented elsewhere [12].

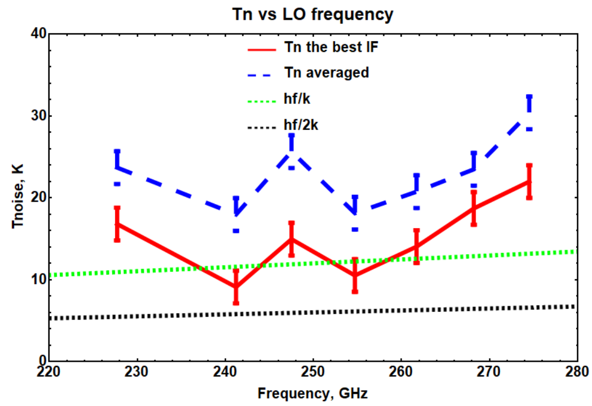

Fig. 2. Uncorrected noise temperature measured in the IF band 4-8 GHz is presented at the graph by symbols in comparison with the quantum sensitivity level hf/k_B (Callen & Welton) shown by lines. The measurements uncertainty is of about 2K

References

[1] Th. de Graauw, et al, "The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)", Astronomy & Astrophysics, 518, L6 (2010) DOI: https://doi.org/10.1051/0004-6361/201014698

[2] https://www.almaobservatory.org/en/about-alma-at-first-glance/how-alma-works/technologies/interferometry/

[3] http://millimetron.ru/index.php/en/

[4] A.M. Baryshev, et al, "The ALMA Band 9 receiver Design, construction, characterization, and first light", Astronomy &Astrophysics, 577, A129 (2015) DOI: 10.1051/0004-6361/201425529

[5] M. Gurvitch, W. A. Washington, and H. A. Huggins, "High quality refractory Josephson tunnel junctions utilizing thin aluminum layers", *Appl. Phys. Lett.*, vol. 42, pp. 472-474, 1983.

[6] S. Morohashi, and S. Hasuo, "Experimental investigations and analysis for high-quality Nb/Al-AlO_x/Nb Josephson junctions", *J. Appl. Phys.*, vol. 61, pp. 4835-4849, 1987.

[7] P. N. Dmitriev, et al, "Niobium Tunnel Junctions with Multi-Layered Electrodes", *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 3970-3973, 1999.

[8] L.V. Filippenko, et al, "Integrated Superconducting Receiver: fabrication and yield", *IEEE Trans. on Appl. Supercond.*, v.11, No 1, pp. 816-819, (2001).

[9] P.N. Dmitriev, et al, "High Quality Nb-based Integrated Circuits for High Frequency and Digital Applications", "*IEEE Trans. on Appl. Supercond.*", vol. 13, No 2, pp. 107-110, 2003.

[10] A.A.Golubov, E.P.Houwman, J.G.Gijsbertsen, V.M.Krasnov, J. FLokstra, H.Rogalla "Proximity effect in superconductor-insulator-superconductor Josephson tunnel junctions: theory and experiment", *Physical Review B*, vol. 51, 2 pp. 1073-1089, 1995.

[11] A.R. Kerr, M.J. Feldman and S.-K. Pan, "Receive Noise Temperature, the Quantum Noise Limit, and the Role of the Zero-Point Fluctuations", *Eighth International Symposium on space Terahertz Technology*, Harvard University, March 1997.

[12] K.I. Rudakov, et al, "240 GHz waveguide receiver with quantum limit performance", "*IEEE Trans. on THz Science and Technogy*", will be published, 2019.