

# Superconducting Terahertz Receivers for Space and Ground-based Radio Astronomy

Jacques Lepine  
*Instituto da Astronomia  
University of São Paulo*

São Paulo, Brazil  
[jacques.lepine@iag.usp.br](mailto:jacques.lepine@iag.usp.br)

Sheng-Cai Shi  
*Millimeter and Sub-Millimeter Lab  
Purple Mountain Observatory CAS  
Nanjing, China*  
[scshi@pmo.ac.cn](mailto:scshi@pmo.ac.cn)

Lyudmila Filippenko  
*Laboratory of superconducting devices  
for signal detection and processing  
Kotel'nikov Institute of Radio  
Engineering and Electronics RAS  
Moscow, Russia,*  
[valery@hitech.cplire.ru](mailto:valery@hitech.cplire.ru)

Huabing Wang  
*Research Institute of Superconductor  
Electronics  
Nanjing University  
Nanjing, China*  
[hbwang@nju.edu.cn](mailto:hbwang@nju.edu.cn)

Andrey Baryshev  
*Kapteyn Astronomical Institute  
University of Groningen  
Groningen, The Netherlands,*  
[A.Baryshev@astro.rug.nl](mailto:A.Baryshev@astro.rug.nl)

Michael Fominsky  
*Laboratory of superconducting devices  
for signal detection and processing  
Kotel'nikov Institute of Radio  
Engineering and Electronics RAS  
Moscow, Russia,*  
[valery@hitech.cplire.ru](mailto:valery@hitech.cplire.ru)

Coenrad Fourie  
*Department of Electrical and  
Electronic Engineering  
Stellenbosch University,  
Stellenbosch, South Africa*  
[coenrad@sun.ac.za](mailto:coenrad@sun.ac.za)

Kirill Rudakov  
*Kapteyn Astronomical Institute  
University of Groningen  
Groningen, The Netherlands,*  
[A.Baryshev@astro.rug.nl](mailto:A.Baryshev@astro.rug.nl)

Valery Koshelets  
*Laboratory of superconducting devices  
for signal detection and processing  
Kotel'nikov Institute of Radio  
Engineering and Electronics RAS  
Moscow, Russia,*  
[valery@hitech.cplire.ru](mailto:valery@hitech.cplire.ru)

**Abstract**— The main task of the RFBR\_BRICS project "Superconducting terahertz receivers for space and ground radio astronomy" is the development of terahertz technologies and the creation of superconductor-insulator-superconductor (SIS) receivers with quantum sensitivity for novel radio telescopes, including ultra-long baseline radio interferometers. This research program brings together scientific groups from four BRICS countries (Brazil, Russia, China and South Africa), which have a high international reputation and successful experience in the development of ultrasensitive receivers. The report discusses the working plan and the first results of the project; in particular development of the SIS-receivers for Russian space program "Millimetron"

**Keywords**— radio astronomy, super-VLBI, SIS receivers, quantum-limited mixers.

## I. INTRODUCTION

A major goal of the BRICS project "Superconducting terahertz receivers for space and ground radio astronomy" is to advance sub-THz technology and develop quantum-limited SIS receivers and THz sources for applications in terrestrial and space radio astronomy, including super-VLBI. The BRICS member countries have strong traditions of excellence in radio-astronomy, which has the potential to answer fundamental questions on the origins of the universe. The "Millimetron" observatory with a 10-meter space telescope, which is a successor of the Russian ground-space interferometer "Radioastron", is designed to study various objects in the Universe including black holes at millimeter and infrared wavelengths. Black holes are extremely compact, so very high angular resolution is required to observe their immediate vicinity. Such resolution is provided by the "Millimetron" orbit configuration; the observatory will be located near the Lagrange point L2, at 1.5 million kilometers from Earth. Currently, research is being conducted in the framework of ground project Event Horizon Telescope (EHT); new interferometry points for VLBA are

being created, including the Large Latin American Millimeter Array (LLAMA) and the Russian-Uzbek radio telescope Suffa. The relevance of this direction was confirmed recently, when all the media published the first ever "image" of a supermassive black hole in the center of the galaxy M 87.

The BRICS program brings together Brazil, Russian, Chinese and South African groups who all have an international reputation and recognized track record in their field. Their complementary scientific and technical strengths, expertise in instrumentation development and experience in international collaborations results in highly successful prior collaborations. However, until now, these groups have been working together in bi-lateral project-driven partnerships with little structural character. The BRICS grant will help the participating groups to collaborate in a more structural way than in the past. The goal of the project is to advance THz technology and develop improved THz detectors/sources suitable for scientific and potentially industrial impact and technological spin-offs. It should be mentioned that the Kapteyn Astronomical Institute at University of Groningen is also involved in the consortium. The Kapteyn Institute is developing submm Terahertz receivers for cutting edge astronomical facilities such as ALMA, APEX, Event Horizon Telescope on the ground and future space missions. In particular the Kapteyn Institute is already in collaboration with University of São Paulo and is involved in the LLAMA project, which is the construction of a 12 m radio telescope in the Andes at 4800 m. This should be an ideal instrument to test receivers at sub-terahertz frequencies.

China is working on development of a terahertz telescope at Dome A in the Antarctic; this place offers the best possible access for ground-based astronomical observations in the terahertz and far-infrared band. It is planning to make observations mainly through the 0.9 THz and 1.4 THz atmospheric windows; the receiver for the first window will be developed in collaboration with Kotel'nikov IREE.

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Russian Foundation for Basic Research (grant No. 19-52-80023).

## II. BRICS PROJECT GOALS

The fundamental scientific problem addressed by the project is the development of basic principles for design of new types of terahertz generators and detectors based on superconducting nanostructures and the development of practical devices with a unique set of parameters. Currently, there are a number of major tasks in radio astronomy, astrophysics, and gas spectroscopy, which require implementation of novel receivers for operation in the terahertz frequency range (100 GHz – 10 THz). This range is relatively little explored; here lies the boundary between radio engineering and optical (quantum) methods of generating and receiving signals. As a result of the project, a number of receiving elements and devices for space and ground-based radio astronomy will be created and investigated, including the following:

1) The 211-275 GHz SIS receivers for Russian space project "Millimetron", ground-based Event Horizon Telescope (EHT) project and the Large Latin American Millimeter Array (LLAMA).

2) The SIS mixers based on Nb/AlN/NbN twin tunnel junctions incorporated in an NbTiN/Al microstrip line for waveguide receiver operating in frequency range of 790 – 950 GHz for Chinese radio observatory at Dome A in Antarctic, for Champ II+ at APEX in Chile, and for Brazilian LLAMA.

## III. DEVELOPMENT AND TESTING OF THE 211-275 GHz RECEIVER FOR MILLIMETRON

Low-noise mixers based on superconductor - insulator - superconductor (SIS) tunnel junctions are the best input devices for coherent receivers at frequencies from 0.1 to 1.2 THz; their noise temperature is limited only by quantum effects. The operation of SIS mixers in the quantum mode was theoretically analyzed in [1-3], in which all the basic relations for the mixer were derived based on the effect of photon-assisted quasiparticle tunneling and the possibility of such a mixer to operate with amplification was predicted. The noise temperature of an SIS mixer in double sideband regime (DSB) is theoretically limited only by the quantum value  $hf/2k_B$  (here  $h$  is the Planck constant,  $f$  is the frequency of the received radiation, and  $k_B$  is the Boltzmann constant). That is why heterodyne SIS receivers are used on the majority of both ground-based and space radio telescopes [4–11]; they employed in all high-frequency bands of the largest radio astronomy interferometer - the Atacama Large Millimeter/submillimeter Array (ALMA) [4–8]. The noise temperature of the 211-275 GHz SIS receiver is 40-60 K (in single-sideband mode at IF bandwidth of 4-12 GHz) [4]. It should be noted that the further development of the SIS technology of receiving systems is running in several main directions: the creation of matrix receivers [12], a significant expansion of both the input receiver range [13] and the intermediate frequency band [14], as well as the development of receivers with band separation [15, 16].

To realize the program of the Russian Space Agency "Millimetron" [10, 11] the receivers with a noise temperature of less than 50 K in the frequency range 211 - 275 GHz are required for Earth-Space interferometer. To realize such receivers we have implemented the technology for fabrication of tunnel junctions Nb-AlO<sub>x</sub>-Nb (area of about  $1 \mu\text{m}^2$ ) with low leakage currents (the ratio of resistances below the energy gap to the normal one is more than 30,

which is necessary to obtain extremely low noise temperatures); this technology was developed at the Kotel'nikov IREE [17].

To achieve a low noise temperature, it is necessary to compensate for the significant capacitance of the SIS junction ( $C_p \approx 0.085 \text{ pF}/\mu\text{m}^2$ ); for this purpose, the topology of the mixing element was developed and its operation was modeled [18]. To match the impedance of the SIS junction at a high frequency with a waveguide impedance of about 400 Ohm, a planar structure was used, consisting of sections of coplanar and microstrip Nb/SiO<sub>2</sub>/Nb lines (Fig. 1). To prevent RF signal leakage the RF rejection filters were used in the design of the mixing element [18]. The receiving element was fabricated on a quartz substrate with a thickness of  $125 \mu\text{m}$ , located perpendicular to the plane of wave propagation in a rectangular waveguide  $500 \times 1000 \mu\text{m}$ , it was located at a distance of  $230 \mu\text{m}$  from the end of the waveguide. The mixing waveguide block comprises the central part with the waveguide, the short-circuiting unit, the system to supply the magnetic field, and the input horn. Note that the adjusting microstrip lines make a considerable capacitive contribution to the sample impedance at the intermediate frequency. In future experiments an additional circuit will be installed to provide proper matching over the intermediate-frequency band.

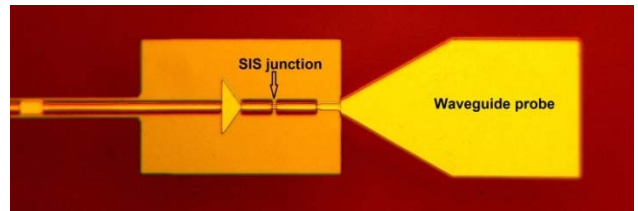
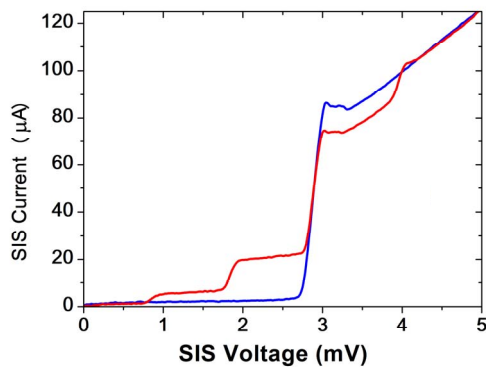
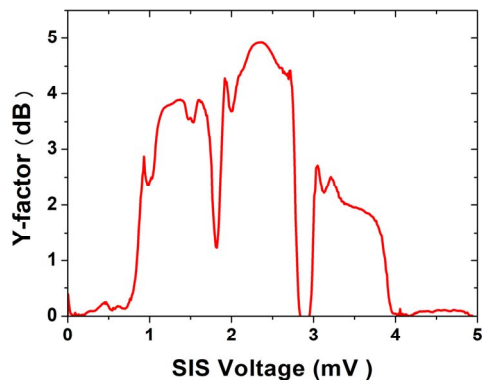


Fig. 1. Photo of the SIS mixer structure for frequency range 211-275 GHz. The SIS element is inserted in the planar structure formed by segments of coplanar and microstrip Nb-SiO<sub>2</sub>-Nb lines. Waveguide probe is shown on the right.

The current-voltage characteristic (IVC) of the Nb-AlO<sub>x</sub>-Nb SIS mixing element with an area  $1 \mu\text{m}^2$ , measured in the voltage biasing mode, is shown in Fig. 2 with a blue line; the critical current of the SIS junction is suppressed by the magnetic field. The red curve shows the IVC of the SIS mixer pumped by a local oscillator with a frequency of 240 GHz at a power that is optimal for the operation of the SIS mixer. Quasiparticle current steps are clearly visible, the voltage size of which is determined by the local oscillator frequency (about 1 mV at a frequency of 250 GHz). The DSB mixer noise temperature was determined by the standard Y-factor measurement method; an absorber at 295 K was used as a "hot" load, and an absorber cooled to 78 K with liquid nitrogen was used as a "cold" load. Fig. 3 shows the dependence of the Y-factor of the SIS bias voltage, measured at a local oscillator frequency of 240 GHz. The Y-factor was determined by subtracting the responses measured for hot and cold loads. It can be seen that the value of the Y-factor at the best point reaches 5 dB, which corresponds to a receiver noise temperature of 24 K. The noise temperature values were obtained without corrections for losses in the beam splitter and the cryostat window; they are only twice the value of  $hf/k_B$  in the range from 240 to 265 GHz. The dependence of the DSB noise temperature of the SIS receiver on the local oscillator frequency was measured [18]; it was shown that the obtained values meet the technical requirements to the 211-275 GHz receiver for the Millimetron space radio-telescope.



**Fig. 2.** IVCs of the Nb-AlO<sub>x</sub>-Nb SIS mixer (area 1 µm<sup>2</sup>) measured in the voltage biasing mode; the critical current of the SIS junction is suppressed by the magnetic field. Autonomous IVC is shown by a blue line; the red curve shows the IVC of the SIS mixer pumped by a local oscillator with a frequency of 240 GHz at a power optimal for operation of the SIS mixer.



**Fig. 3.** Y-factor of the SIS receiver measured at intermediate frequency (IF) 6.5 GHz on the SIS bias voltage, measured for the local-oscillator frequency 240 GHz (see text).

#### IV. SIS MIXER BASED ON Nb/ALN/NbN TUNNEL JUNCTIONS

The SIS mixers based on Nb/AlN/NbN junctions offer a higher gap voltage (up to 3.2 mV, that provides wide dc-bias rang), even being incorporated in a NbTiN/Al microstrip line. Moreover, the Nb/AlN/NbN junctions are also able to achieve high quality at high critical current densities, which are important for superconducting SIS mixers operation at high frequencies. 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. The SIS mixers developed for upgrade of the CHAMP+ high-band array on the APEX telescope (frequency range of 790 – 950 GHz) are based on twin Nb/AlN/NbN junctions incorporated in a NbTiN/Al microstrip line; waveguide receivers have DSB noise temperatures from 210 to 400 K [7].

#### ACKNOWLEDGMENT

The work was supported by the RFBR (grant No. 19-52-80023). Development of the 211-275 GHz mixer was carried out under RSF project 19-19-00618. The fabrication of the SIS mixer elements was carried out at the Kotelnikov IREE within the framework of the state task (by USU # 352529).

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