ISSN 1068-3356, Bulletin of the Lebedev Physics Institute, 2021, Vol. 48, No. 9, pp. 262–267. © Allerton Press, Inc., 2021.
Russian Text © The Author(s), 2021, published in Kratkie Soobshcheniya po Fizike, 2021, Vol. 48, No. 9, pp. 10–18.

Matrices of SINIS Detectors for Terahertz Radioastronomy

M. A. Tarasov[a,*], A. A. Gunbina[a,b], S. A. Lemzyakov[c], M. Yu. Fominsky[a], A. M. Chekushkin[a], G. V. Yakopov[c,d], V. F. Vdovin[b], and V. S. Edelman[c]

[a] *Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, 125009 Russia*
[b] *Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603950 Russia*
[c] *Kapitza Institute for Physical Problems, Russian Academy of Sciences, Moscow, 119334 Russia*
[d] *Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, 369167 Russia*
**e-mail: tarasov@hitech.cplire.ru*

Received April 20, 2021; revised July 7, 2021; accepted July 8, 2021

Abstract—Superconductor–insulator–normal metal–insulator–superconductor (SINIS) detectors are developed with promising applications in two scheduled instruments of the space project of the Millimetron radio telescope, as well as ground-based high-altitude BTA (Big Telescope Alt-Azimuthal) and Suffa telescopes. For the multipixel imaging array, two matrix versions are developed: half-wave and electrically small antennas with series and parallel connection of elements in each pixel. In the former case, readout is performed using field-effect transistors; in the latter case, readout is performed using superconducting quantum interferometers (SQUIDs). For multipixel applications, a structure with frequency multiplexing of channels, in which each pixel represents a coplanar resonator connected to a common coplanar line and read using a cryogenic microwave amplifier is developed and fabricated for the first time. As such an amplifier, a prototype of the Josephson traveling-wave parametric amplifier (JTWPA) based on aluminum SIS junctions is developed and fabricated for the first time. Such a design provides fast readout of hundreds of channels over one coaxial line, noise removal with spectrum $1/f$ in the readout channel due to an increase in the readout frequency to several gigahertz, as well as reduction of the heat load on a sorption refrigerator due to a decrease in the number of lead wires from several hundred to one coaxial cable.

Keywords: terahertz detectors, submillimeter astronomy, multipixel imaging arrays, SINIS detectors, SQUIDs, Josephson traveling-wave parametric amplifier (JTWPA), Millimetron project, Big Telescope Alt-Azimuthal (BTA), Special Astrophysical Observatory (SAO), noise equivalent power

DOI: 10.3103/S1068335621090086

In the Millimetron project, very ambitious problems are posed, in particular, for a photometer-polarimeter, it is planned to develop a matrix of 100 × 100 pixels with a noise-equivalent power of 10^{-18}–10^{-19} W/Hz$^{1/2}$ at a temperature of 0.1 K, with spectral resolution $R = f/\Delta f = 3$ in the range of 0.1–15 THz and with a polarization resolution no worse than 0.1%. For a low-frequency receiver, four sub ranges of 100–200, 200–350, 350–700, and 700–1000 GHz with a noise equivalent power (NEP) lower than 10–16 W/Hz$^{1/2}$ are provided. The broadband receiver should have a uniform spectral response, a high sensitivity, and a wide dynamic range. Such a device can be considered to be a distributed absorber shaped as a large matrix of electrically small antennas [1], matched with radiation using a horn or an immersion lens. An increase in the number of elements in each pixel makes it possible to increase the saturation power and dynamic range of the device.

We have developed, fabricated, and studied various versions of matrices of ring antennas, both half-wave and electrically small ones with various diameters from half the wavelength to 1/10 and with various ring widths. Matrices of half-wave rings contained 5 × 5 elements, and matrices of small rings contained 10 × 10 elements. The best results were obtained in the case of superconducting aluminum ring antennas with decreased electrical loss and improved heat sink from the region of tunnel junctions due to larger volumes of electrodes and antennas (Fig. 1). The measured ratio of maximum and asymptotic resistances (see Fig. 1) at an operating temperature of 100 mK has reached the record value of 10000. The responsivity of the signal characteristic of such a detector at a frequency of 350 GHz reaches 10^9 V/W.

To study the response and improve the evaluation accuracy of spectral characteristics of receiving structures, the measuring testbed (Fig. 2, [3]) was modified. Radiation from a backward wave oscillator (BWO)

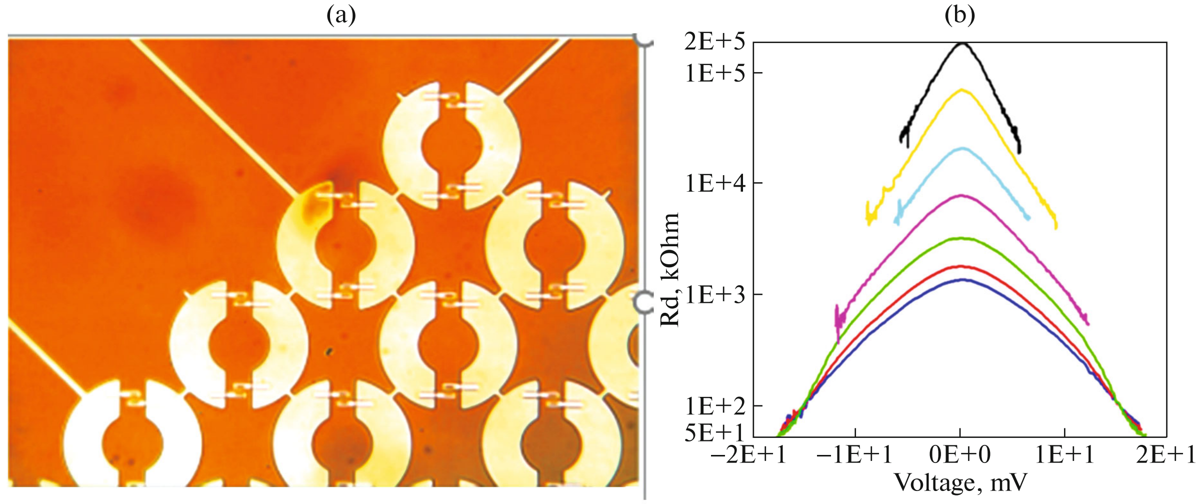

Fig. 1. Superconducting electrically small antennas: (a) micrograph of the fragment of the matrix of 10 × 10 elements and (b) measured differential resistance of the matrix at an operating temperature of 100–300 mK (from the upper to bottom curve) [2].

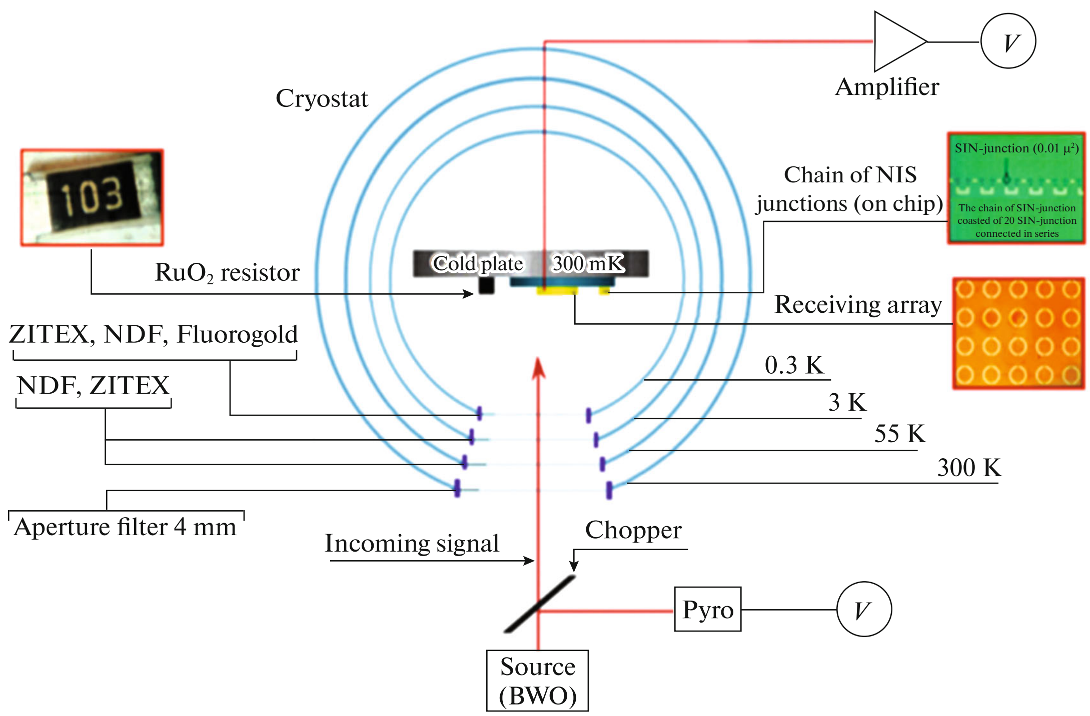

Fig. 2. Block diagram of the modified experimental setup for measuring spectral characteristics of cooled receiving elements [3].

in it is alternately incident on the pyroreceiver and sample through a quasioptical switch; then, through four optical windows, radiation arrives at the cryostat chamber which contains a receiving matrix, a calibration bolometer based on a RuO_2 resistor on a cold plate of the cryostat, and a thermometer shaped as a long chain of SIN junctions on the chip under study for calibrating arriving radiation. Such a technique makes it possible to reduce errors in the determination of spectral characteristics.

Two fundamentally different approaches are possible to numerical simulation of antenna matrices. One approach considers a single matrix cell and its periodic repetition in infinite limits with periodic

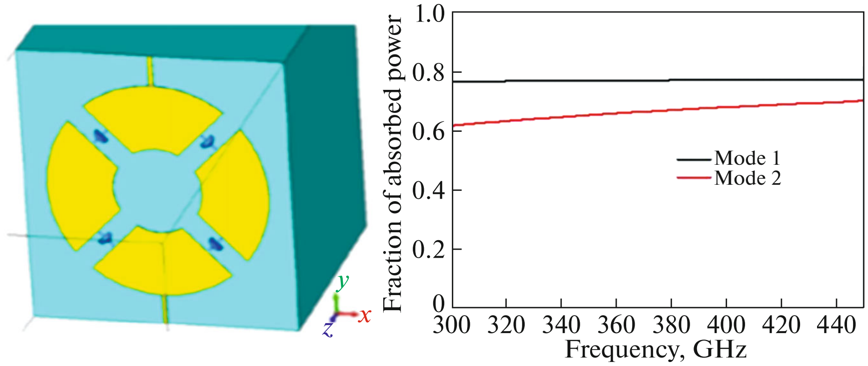

Fig. 3. Simplified numerical simulation of a single cell with infinite periodic repetition and periodic boundary conditions [1, 5]. Modes 1 and 2 correspond to vertical and horizontal polarization, respectively.

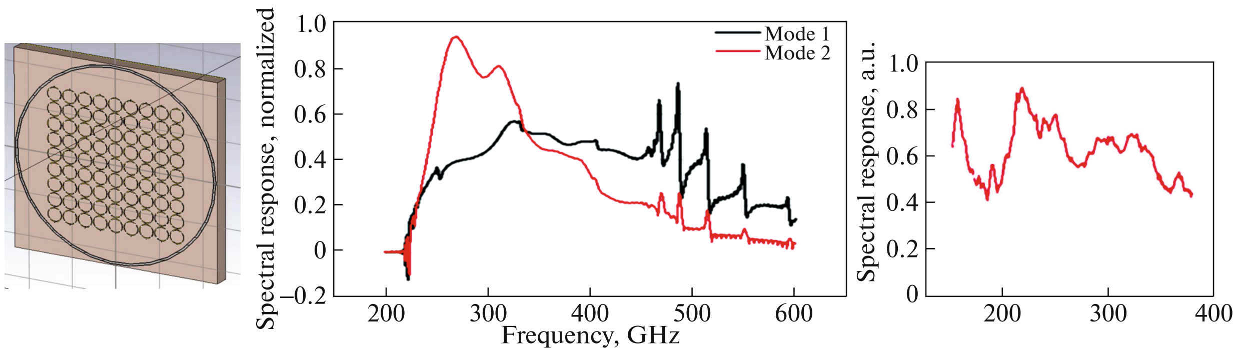

Fig. 4. Central panel shows numerical simulation of the full finite matrix of ring antennas with SINIS detectors [3, 2] with modes 1 and 2 for different excitation polarizations. The right panel shows experimental data.

boundary conditions as in our early works [1, 4, 5]. In this case, we simulate in essence a phased array, which does not reflect reality in the case of dissipation in matrix elements, see Figs. 3 and 4. Such an approach is applicable to the calculation of quasioptical filters with pure reactive parameters and makes it possible to determine the transmission spectrum with sufficient accuracy in a narrow band near the resonant frequency, but does not properly operate with dissipative elements. Simulation of the entire matrix with a large number of absorbing and re-emitting ports is a more complex problem and requires a hundred times longer computation time reaching 10 days for a complex structure. However, this approach yields a more realistic spectral dependence, as shown in Fig. 4.

As indicated in the project requirements of the high-frequency receiver of the Millimetron project, it should contain 10000 channels. Assuming that the mass of one semiconductor amplifier is 10 g, an amplifier unit mass will be 100 kg and will be connected to the matrix by 20000 wires, which is impossible even for ground-based receivers. The solution of this problem consists in the use of frequency multiplexing and microwave readout via a single coaxial cable. We have developed a prototype of an element of such a matrix with a quarter-wave resonator at a readout frequency and a double slot antenna tuned to the signal frequency [6, 7], see Fig. 5. For the readout system with frequency multiplexing, a commercial cooled semiconductor amplifier with a noise temperature of ~5 K can be used. To achieve limiting characteristics, a Josephson traveling-wave parametric amplifier (JTWPA) with a noise temperature at the level of the quantum temperature, i.e., lower than 0.5 K in the range of 4–8 GHz, can be developed. A tenfold improvement of the amplifier noise temperature means a decrease in the noise-equivalent (NEP) power also by an order of magnitude, since so far noise characteristics of SINIS detectors were limited by readout noises [1–7]. To solve this problem, we develop two JTWPA versions using the conventional limited by technology of shadow evaporation (Fig. 6 [8]) and using the new technology of magnetron sputtering and direct electron lithography, Fig. 7 [2, 9].

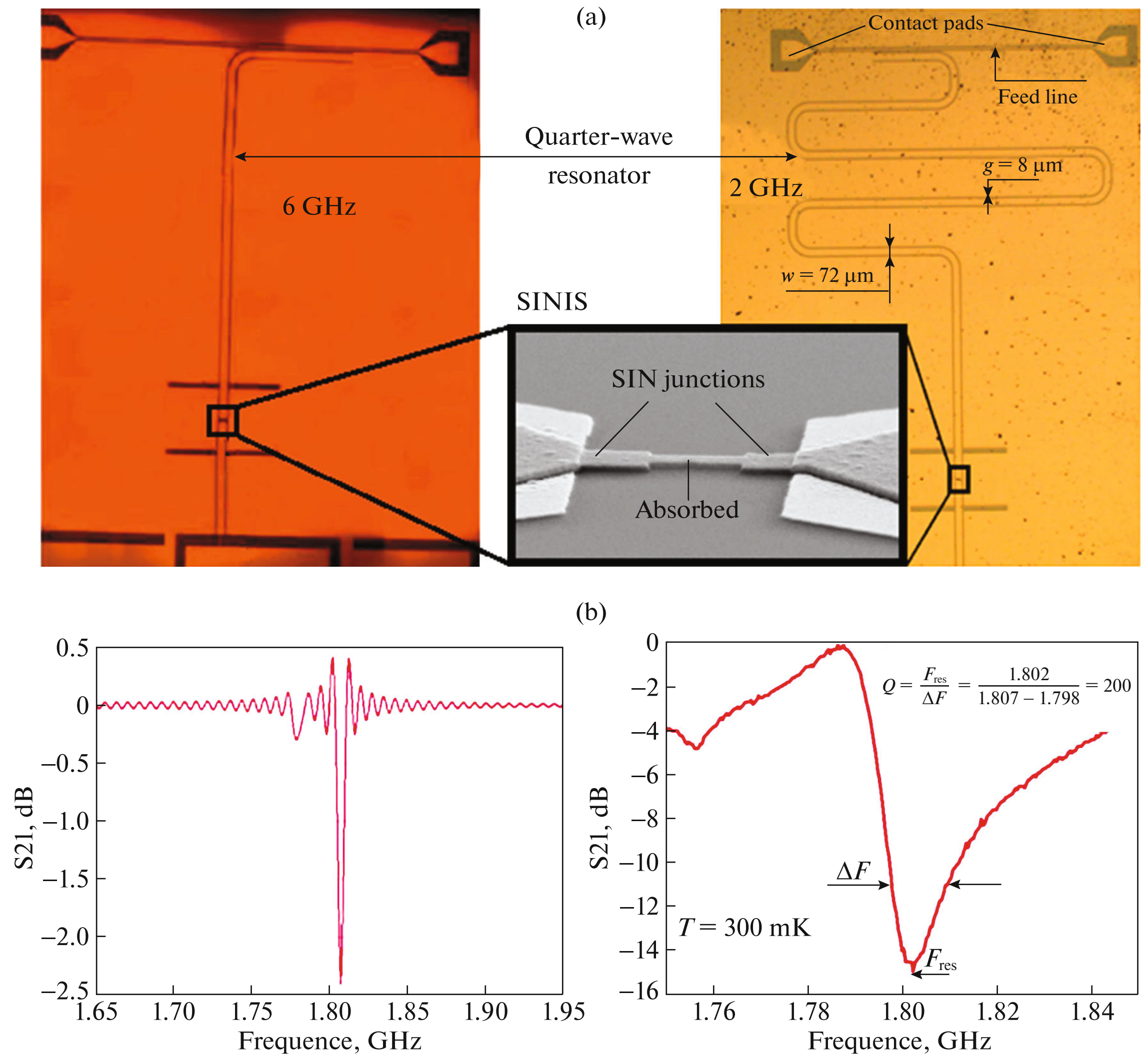

Fig. 5. Prototype of the receiving pixel for implementing frequency multiplexing: (a) micrographs of single pixels with a signal frequency of 90 GHz for frequency multiplexing at readout frequencies of 6 GHz (left) and 1.8 GHz (right); the central panel shows the micrograph of the SINIS detector; (b) simulated and measured S21 parameter.

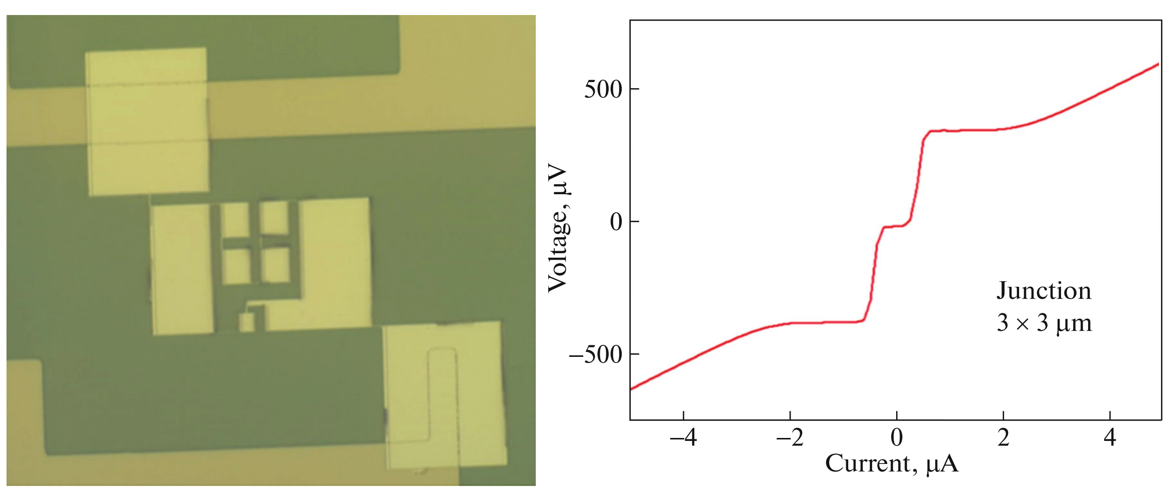

Fig. 6. Micrograph of the JTWPA squid element fabricated by the shadow technology, and its current–voltage characteristic [10].

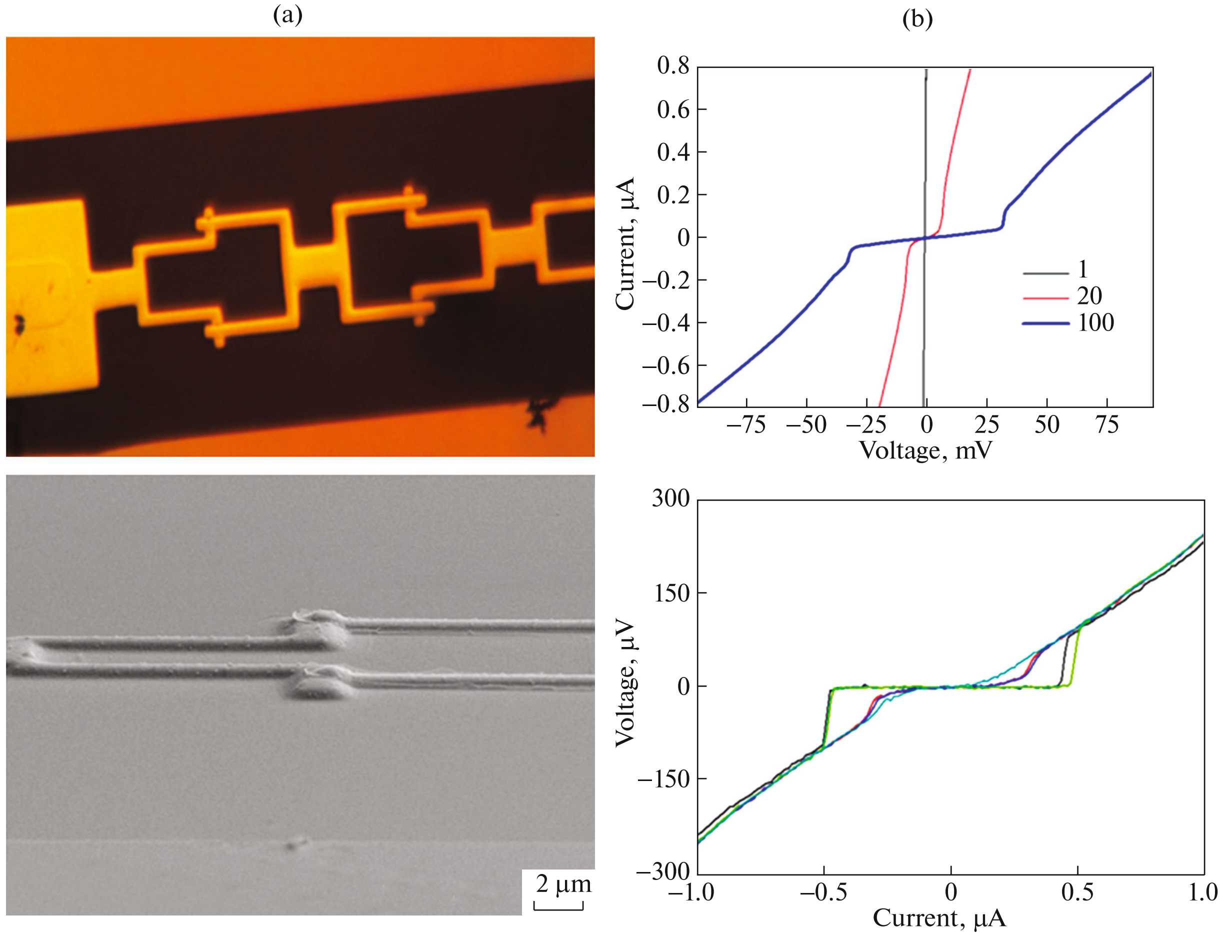

Fig. 7. Aluminum SQUIDs fabricated by the magnetron deposition technology with separate lithography: (a) an optical micrograph of several SQUIDs (top) and an electron microscope image of a single SQUID (bottom); (b) current–voltage (I–V) characteristics of SQUID chains with 1, 20, and 100 elements (top) and the I–V characteristic of one SQUID at various magnetic flux levels; the measurement temperature is 300 mK.

CONCLUSIONS

Receiving matrices with integrated SINIS detectors were developed, fabricated, and experimentally investigated for astrophysical studies with a characteristic responsivity to 10^9 V/W, which satisfies the requirements technical requirements of the Millimetron project. It was shown that it is most promising to use matrices of electrically small antennas made of a superconducting material (aluminum). SINIS prototypes of detectors with a microwave readout system for implementing frequency multiplexing were fabricated for the first time. As a readout system, the Josephson traveling-wave parametric amplifier (JTWPA) structure was developed. Test JTWPA samples based on SQUIDs were fabricated by the aluminum technology using the magnetron sputtering and direct electron lithography and studied for the first time.

FUNDING

This study was supported by the Russian Foundation for Basic Research–BRICS, project no. 19-52-80023, and within the State contract of the Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, project no. AAA-A19-119041990058-5.

The development and fabrication of experimental setup elements were supported by the Russian Science Foundation, project no. 19-19-00499, and within the State contract of the Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod. The experimental study of samples was supported within the State contract of the Kapitza Institute for Physical Problems, Russian Academy of Sciences, Moscow, and the Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz.

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Translated by A. Kazantsev