Applied Superconductivity Conference (ASC'98), Palm Desert, California, USA, September 14-18, 1998, report EMA-09
This work has been submitted to the IEEE for possible publication.

Superconducting Chip Receivers for Imaging Application

Sergey V. Shitov, Valery P. Koshelets, Andrey B. Ermakov, Lyudmila V. Filippenko
Institute of Radio Engineering and Electronics RAS, Moscow, Russia
Andrey B. Baryshev, Willem Luinge
Groningen Space Research Laboratory, Groningen, the Netherlands
Jian-Rong Gao
Groningen Space Research Laboratory and Department of Applied Physics and Materials Science Center, University of Groningen
the Netherlands

***Abstract*—Experimental details of the study on a unique superconducting imaging array receiver are discussed. Each pixel contains an *internally pumped* receiving chip of size 4 mm x 4 mm x 0.5 mm which is mounted on the back of the elliptical microwave lens made from silicon. Each chip comprises a quasi-optical SIS mixer and LO based on a superconducting flux-flow oscillator, all fabricated from the same niobium trilayer, Nb/AlO$_x$/Nb. A new design of the receiving chip has been developed to fit the silicon optics. Properties of the integrated lens antenna were studied using an externally pumped reference SIS mixer which showed antenna sidelobes below -17 dB and a receiver DSB noise temperature, T_{RX}, below 100 K within the frequency range 460 - 500 GHz that is close to the quantum noise. For the imaging array T_{RX} = 150 K has been measured at 500 GHz using internal LO. The concept of the balanced SIS mixer was tested preliminary showing T_{RX} < 100 K within range of 480 - 510 GHz using internal LO. A computer system is routinely used for the Integrated Receiver that includes control of the SIS mixer, frequency tuning of the LO and automatic optimization of the receiver regime for lowest noise temperature.**

I. Introduction

Recent progress on the low-noise Superconducting Integrated Receiver (SIR) made on quartz [1], [2] did encourage the development of a Superconducting Imaging Array Receiver (SIAR). Such an imaging receiver is of general interest for radio astronomy or monitoring of atmosphere pollution since it may save observation time and most of related technical and financial resources. The basic element (pixel) of the array is a chip receiver, SIR, which contains a quasi-optical SIS mixer and a flux-flow oscillator (FFO) as a local oscillator (LO). Low power operation and small size of the chip receiver are attractive features for dense packaging. The independent adjustment of the LO power and multi-frequency operation of such imaging array receiver are also possible. The use of an aspherical lens (which assumed to be silicon one) allows each pixel to be independent and equally good. For this reason devices used successfully with quartz optics [2] have been re-designed completely to fit silicon one. We present here results of the experimental study of SIR devices made on silicon substrates and intended for a nine-pixel SIAR at 500 GHz. Features of the new design are discussed as well. Recent progress on a phase-lock loop for the integrated LO is reported elsewhere [3], [4] being the last problem towards the practicable receiver.

Manuscript received September 14, 1998
The work was supported in parts by the Russian Program for Basic Research, the Russian SSP "Superconductivity" and ESA TRP contract No. 11653/95/NL/PB/SC.
E-mail: sergey@hitech.cplire.ru

II. Pixel Design

A. Optics

The optical combination called "fly's eye" is used for the Imaging Array to reduce inequality of pixels. The microwave lenses (truncated ellipse R_1 = 5 mm, R_2 = 5.228 mm) are made from single-crystal silicon by diamond turning. Such a lens has to be the *only* optical element providing a Gaussian beam ≈ f/10 in the frequency range of 450 - 550 GHz [5], [6]. The antireflection coating for the lenses [7] was made from Stycast 1264 epoxy (ε ≈ 2.9, thickness 87 μm) which does not contain carbon. Films made from this material passed a rigorous test at Fourier Transform Spectrometer (FTS) showing good performance at 500 GHz.

Fig. 1 is a microphotograph of the central part of the receiving chip; all main elements and interconnecting circuits are presented. The chip and the lens are mounted back-to-back using paraffin wax in a way that antenna is aligned with an accuracy better than 10 μm in respect to the axis of the lens. Aluminum wire bonds provide all electrical contacts to the chip.

B. Quasi-Optical SIS Mixer

The concept of a quasi-optical double-dipole antenna SIS mixer is used [1], [2], [5]. The micron-size junction (R_N = 15 – 25 Ω) placed in the center of the mixer is a shared load of two dipole antennas. To achieve a beam of high efficiency and good symmetry, a back reflector is installed at the quarter-wave distance from the antenna. The back reflector is a silicon chip (800 μm × 800 μm, thickness 44 μm) covered from one side with a film of Nb/Au. The coupling (tuning) circuit was optimized for the frequency about 500 GHz. The length of the tuning lines, if calculated straightforward for SiO_2 insulation, is much longer than the

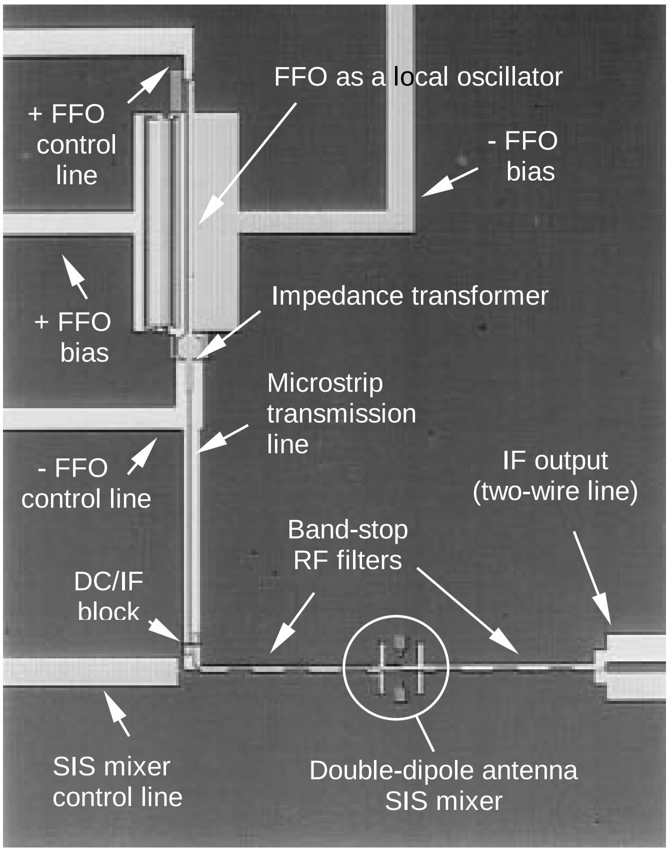

Fig. 1. Photograph of the chip receiver. The field of view is 1 mm x 1.5 mm.

optimum distance between the antennas. Since it is not possible to bend the lines in the space available between antennas like it was done for double-slot antennas [8], [9], each dipole antenna is tuned with a special open-ended stub [10].

C. Coupling of LO Power from FFO

To couple the LO power from FFO with output impedance of about 0.4 Ω [1], [2], the two-stage transformer has been synthesized empirically on a base of the stair-type microstrip connection (Fig. 1). A 900 μm long microstrip line (Z_0 = 14 Ω) is used for supply LO power from FFO to the mixing junction. A *dc*/IF break in both leads [11] is inserted at about halfway between the FFO and the mixer. Impedance of the LO path is transformed up to $\approx 60\,\Omega$ at the point of connection to the SIS junction that mean about 20-30 % of the signal loss towards LO. The SIS mixer may consume about one-half of power delivered from the LO path. The second half is emitted by antennas towards the signal source. This effect was assumed as a possibility of *rf* cross-talk between pixels. To minimize loss of the signal and prevent emission of LO power toward the source, the concept of a balanced SIS mixer has been proposed [2]. This device can in principle use 100 % of both signal and LO power. The details on design and study of balanced SIR will be published elsewhere. To obtain reference data on the best possible performance of the SIR, a special chip device containing SIS mixer without LO has been designed.

III. Experimental Set-Up

The *rf* tests of the array receiver are performed in a vacuum cryostat with liquid helium at temperature 2 - 4.2 K. The signal has been introduced through a Mylar window (180 μm thick, diameter 110 mm) followed with infrared filter (Teflon plate 5 mm thick at 80 K shield and Zitex film 40 μm at 4.2 K shield). The 9 pixels of SIAR are arranged in two vertical rows (4+5) using the maximum packaging density of a honey comb with a period of 13 mm [2]. The undersampling factor of 4 is a design estimate for this configuration. Output signal was measured at intermediate frequency in the range of 1.1 - 1.7 GHz. To test each pixel separately, a smaller dewar was used [10].

Since FFO is a highly magnetic sensitive device [3], [4], a carefully designed shield is necessary. We use two coaxial cans: external one made from μ-metal and internal one made from led-on-copper (superconducting). Pixels are mounted far enough from the opening of the shield. The shield was tested qualitatively by placing a magnet of $\approx$ 1000 at the distance of 5 cm from the opening; a suppression factor of 10^3 - 10^4 was estimated.

The data acquisition system IRTECON was developed for the ***I***ntegrated ***R***eceiver ***Te***st and ***Con***trol. It collects *dc* and *rf* data automatically. The program is written under LabWindows to control two computer cards from National Instruments: 16-bit card for FFO and 12-bit card for the SIS mixer. The GPIB interface for the lock-in amplifier, 4 DAC and 10 ADC are used in the system to hook-up the analogue bias supply and IF power meter. One of the routines of IRTECON finds the best pump level and the optimum bias point for the SIS mixer minimizing the receiver noise temperature, T_{RX}, at particular frequency. The pump of the SIS mixer is varied via the FFO bias current while the frequency (i.e. FFO bias voltage) is kept constant by adjustment of magnetic field (via FFO control line). The Y-factor was measured with a fast *rf* detector, lock-in amplifier and running hot/cold chopper.

IV. Experimental Data and Discussion

A. Antenna Beam Test

The antenna beam pattern of the *reference* double-dipole SIS mixer is shown in Fig. 2. The beam of the antenna has a profile quite close to Gaussian one with the first-order sidelobes at the level of about - 17 dB and second-order at - 25 dB that is close to the theoretical prediction [6]. Fig. 3 presents data obtained for two neighboring pixels at 490 GHz. The level of the first – order sidelobe is about - 16 dB, the beam width is 3.7 degrees and 6.7 degrees at -3 dB and -10 dB levels correspondingly. The first minimum in the radiation pattern occurs at approximately at

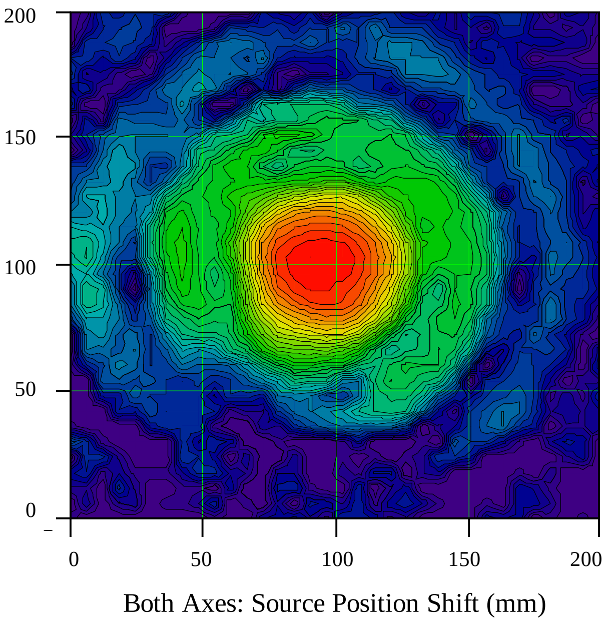

Fig. 2. Antenna beam pattern of reference SIS mixer; contour step is 1 dB.

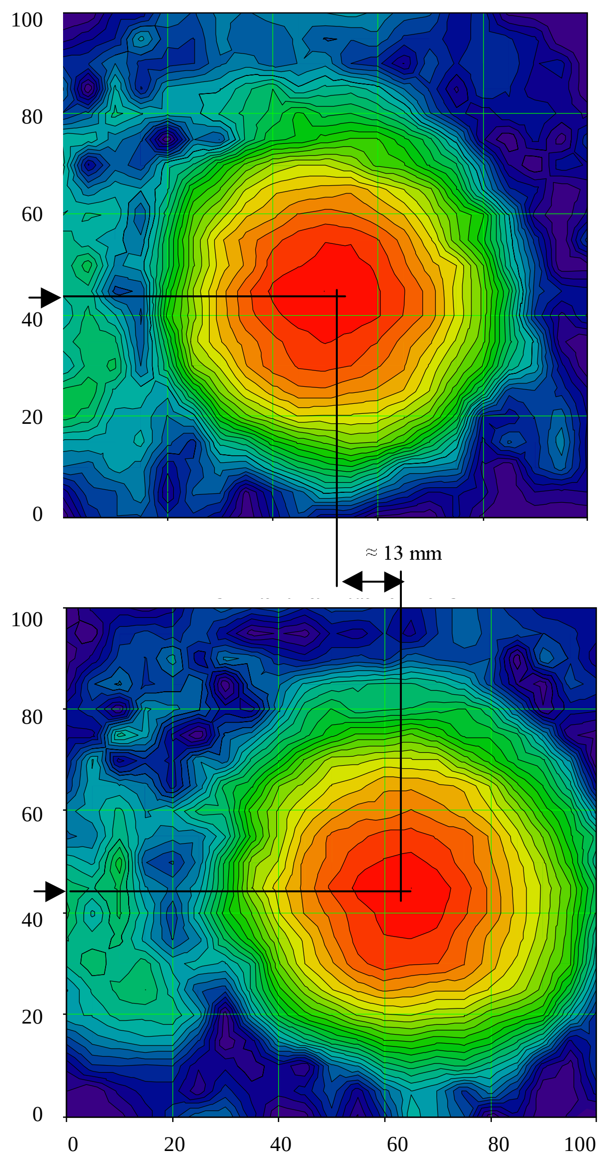

Fig. 3. Antenna beam patterns for two adjacent pixels; contour step is 1 dB. Both axes: source position shift (mm).

4.5 degrees. This corresponds roughly to a f/9.4 beam with a waist size $w_0 \approx 3.6$ mm. The beam separation indicated in Fig.3 well corresponds to the geometrical position of the pixels. The antenna beam patterns are, within the accuracy of the measurement, similar to ones measured preliminary in the single-pixel cryostat. They are also quite similar to the beam of the reference mixer. This indicates that LO circuitry located in the antenna-mixer has a minor effect on the antenna. The *rf* cross-talk from pixel to pixel has been found for a highly reflective source placed in front of the cryostat window (i. g. mirror). No cross-talk originated within the array mount or cryostat has been found.

B. SIS Mixer Test

The low-noise performance of the SIR is *not* possible without suppression of the Josephson effect in the SIS mixer. For this purpose the tuning strip is narrowed down to 3 μm in the vicinity of the SIS junction and used as a superconducting control line. This narrow line can provide magnetic field strong enough for second or even third minimum of critical current for a 1 - 2 μm^2 area junction.

To learn about the instantaneous bandwidth of the SIS mixer, FTS test is performed. The central frequency within range of 490 - 520 GHz and instantaneous bandwidth of 70 GHz and 90 GHz were found for the single and balanced mixers respectively that agrees well with design values. The typical receiver DSB noise temperature, T_{RX}, for the Imaging Array configuration is presented in Fig. 4. The noise temperature of the *reference* receiver was measured in the modified single-unit (test) cryostat and was found as low as 40 K at 470 GHz that is, to our knowledge, *the lowest reported* for this frequency range [12]. The balanced SIS mixer has demonstrated T_{RX} = 85 – 90 K at 485 –500 GHz (Fig.5).

The data presented in Fig. 4 and Fig. 5 are taken by use of IRTECON system. IV-curves of both SIS junction and FFO are initially swept. The complete *dc*-test takes approximately 30 - 45 minutes per chip. The pump current of SIS junction obtained with IRTECON can be also used to estimate frequency response of the SIS mixer (see top-left window in Fig. 6).

Conclusion

The Superconducting Integrated Receiver, SIR, based on silicon has demonstrated a superior low-noise performance at about 500 GHz being pumped by its internal FFO. The receiver DSB noise temperatures as low as 85 - 100 K and 150 K have been measured for various samples at their

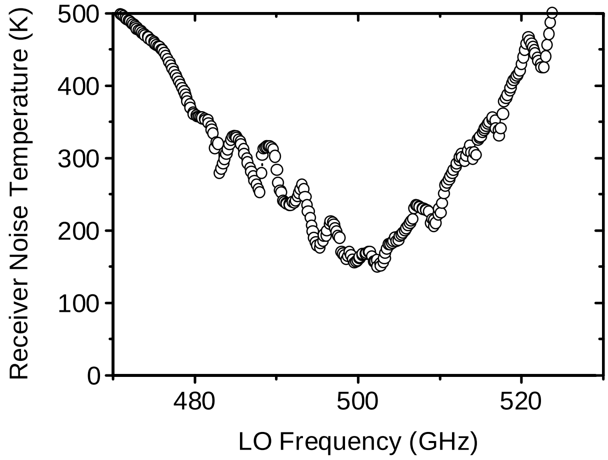

Fig. 4. Experimental data on a pixel with single-junction SIS mixer in the *array* dewar (pumped by internal FFO).

single and array (SIAR) configurations correspondingly. The instantaneous bandwidth of 15 – 20 % has been estimated via heterodyne measurements that fit requirements for practical application. The antenna beam ≈ f/10 with sidelobes below - 16 dB is provided by the double-dipole lens-antenna SIS mixer that makes SIAR suitable for coupling to a real radio telescope. The computer system IRTECON is proven to be a suitable instrument for both the chip qualification and for operating of a Superconducting Integrated Receiver.

Authors thank M. J. M. van der Vorst who suggested the optimal parameters for our double-dipole antenna, J. Evers for testing the Stycast coatings, D. van Nguyen for mounting samples, Th. de Graauw and N. Whyborn for fruitful discussions.

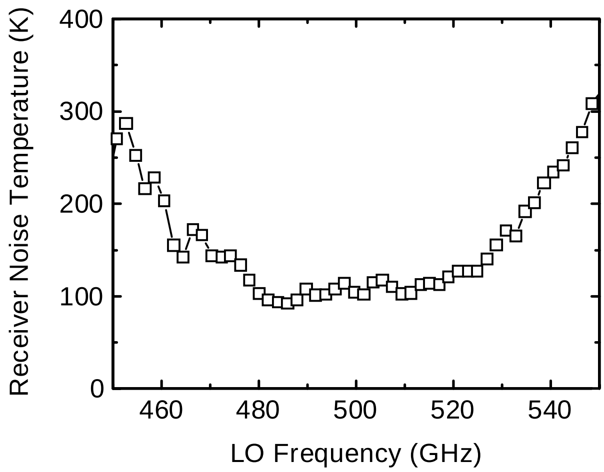

Fig. 5. Data on a pixel with *balanced* SIS mixer pumped by FFO in *test* cryostat.

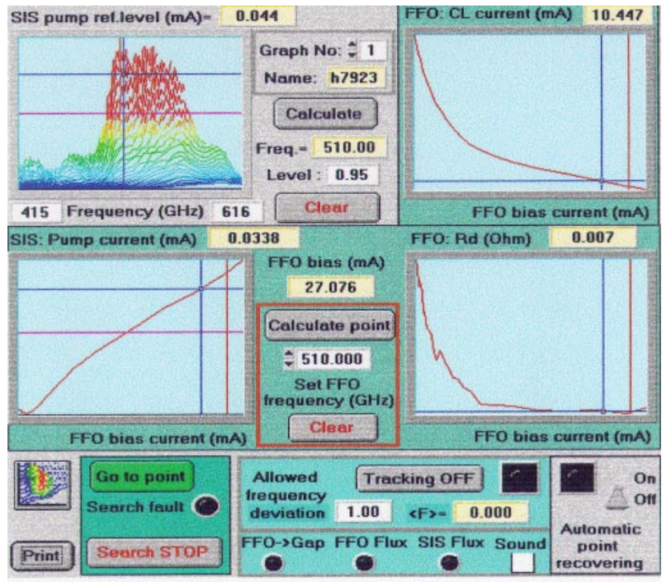

Fig.6. Panel of IRTECON showing data on pump efficiency of SIS mixer.

References

[1] V. P. Koshelets, S. V. Shitov, L. V. Filippenko and A. M. Baryshev, H. Golstein, T. de Graauw, W. Luinge, H. Schaeffer, H. van de Stadt, "First Implementation of a Superconducting Integrated Receiver at 450 GHz," *Appl. Phys. Lett.*, vol. 68 (9), pp. 1273-1275, 1996.

[2] S. V. Shitov, V. P. Koshelets, A. M. Baryshev, L. V. Filippenko, J.-R. Gao, H. Golstein, Th. de Graauw, W. Luinge, H. van de Stadt, N. D. Whyborn, P. Lehikoinen, "Study of a quasioptical superconducting integrated receivers for imaging applications at 400-700 GHz," *Proc. of 8th Int. Symp. on Space Terahertz Technology*, pp. 281-290, 1997.

[3] V. P. Koshelets, S. V. Shitov, A. V. Shchukin, L. V. Filippenko, J. Mygind, A. V. Ustinov, "Self-pumping effects and radiation linewidth of Josephson flux-flow oscillators," *Phys. Rev. B*, vol. 56, pp. 5572-5577, 1997.

[4] V. P. Koshelets, S. V. Shitov, A. V. Shchukin, L. V. Filippenko, P. N. Dmitriev, V. L. Vaks, J. Mygind, A. B. Baryshev, W. Luinge, H. Golstein, "Flux-flow oscillators for sub-mm wave integrated receivers," this Conference, report EQB-04.

[5] A. Skalare, Th. De Graauw and H. van de Stadt, "A planar dipole array antenna with an elliptical lens," *Microwave and Optical Technology Letters*, vol. 4., pp. 9-12, 1991.

[6] M. J. M. van der Vorst, *Design and Analysis of integrated lens antennas*, Graduation report, Fac. of Electrical Engineering, Eindhoven Univ. of Technology, 1995.

[7] M. J. M. van der Vorst, P. J. I. de Maagt and M. H. A. J. Herben, "Matching layers for integrated lens antennas," *Proc. of the Int. Symp. on Antennas*, (JINA '96), pp. 511-515, 1996.

[8] J. Zmuidzinas, and H. G. LeDuc, "Quasi-optical slot antenna SIS mixers," *IEEE Trans. on Microwave Theory and Tech.*, vol. 40, pp. 1797-1804, 1992.

[9] J. Zmuidzinas, N. G. Ugras, D. Miller, M. Gaidis, H. G. LeDuc, J. A. Stern. "Low-noise slot antenna SIS mixers," *IEEE Trans. on Appl. Superconductivity*, vol. 5, No. 2, p. 3053, 1995.

[10] S. V. Shitov, A. B. Ermakov, L. V. Filippenko, V. P. Koshelets, W. Luinge, A. M. Baryshev, J.-R. Gao, P. Lehikoinen, "Recent progress on the superconducting imaging receiver at 500 GHz," *Proc. of 9th Int. Symp. on Space Terahertz Technology*, pp. 263-272, 1998.

[11] S. V. Shitov, V. P. Koshelets, A. V. Shchukin, A. M. Baryshev, I. L. Lapitskaya, L. V. Filippenko, Th. de Graauw, J. Mees, H. Schaeffer, H. van de Stadt, "Experimental study of a superconducting integrated receiver at submillimeter wavelengths," *Digest of 19th Int. Conf. on Infrared and Millimeter Waves*, pp. 122-123, 1994.

[12] A. B. Baryshev, W. Luinge, V. Koshelets, S. Shitov, T. M. Klapwijk, "Zero-point fluctuation limited SIS receiver at 500 GHz," unpublished.