Superconducting Integrated Receivers for Radio Astronomy and Atmospheric Monitoring

Valery P. Koshelets, Pavel N. Dmitriev, Andrey B. Ermakov, Lyudmila V. Filippenko, Andrey V. Khudchenko, Nickolay V. Kinev, Oleg S. Kiselev, Irina L. Lapitskaya, Alexander S. Sobolev, Mikhail Yu. Torgashin, Pavel A. Yagoubov, Ruud W.M. Hoogeveen, Gert de Lange, and Wolfgang Wild

***Abstract*—The Superconducting Integrated Receiver (SIR) comprises in one chip a planar antenna integrated with a superconductor-insulator-superconductor (SIS) mixer, a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and a second SIS harmonic mixer (HM) for the FFO phase locking. A new generation of the SIR devices with improved FFO performance and optimized interface between FFO and SIS/HM has been developed and comprehensively tested. To overcome temperature constraints and extend operation frequency of the all-Nb SIR we have developed and studied Nb-AlN-NbN circuits with a gap voltage Vg up to 3.7 mV and extremely low leakage currents (Rj/Rn > 30). A possibility to phase lock the Nb-AlN-NbN FFO at any frequency in the frequency range 350-720 GHz has been experimentally demonstrated. Phase–locked SIR operation over frequency range 450 – 700 GHz has been realized, spectral resolution below 1 MHz has been confirmed by gas cell and CW signal measurements. An uncorrected double side band (DSB) noise temperature about 150 K has been measured for the SIR with phase-locked FFO. The intermediate frequency bandwidth 4-8 GHz has been realized. To ensure remote operation of the phase-locked SIR several procedures for its automatic computer control have been developed and tested. Latest results on development of a single-chip SIR for the Terahertz Limb Sounder (TELIS) balloon project intended to measure a variety of stratosphere trace gases will be presented and discussed; the first flight is foreseen in November 2007. To overcome the limitations imposed by a regular room-temperature phase locking loop (PLL) system we propose cryogenic phase detector (CPD) based on a well-developed tunnel SIS junction. First results of the CPD development and study will be presented; main parameters of this novel device are estimated.**

***Index Terms*— Submillimeter wave integrated receivers, phase-locked oscillators, superconducting integrated circuits.**

Manuscript received May 01, 2007.

The work was supported in parts by the RFBR projects 06-02-17206, ISTC project # 3174, NATO SfP Grant 981415, and the President Grant for Leading Scientific School 7812.2006.2

V.P. Koshelets, P.N. Dmitriev, A.B. Ermakov, L.V. Filippenko, A.V. Khudchenko, N.V. Kinev, O.S. Kiselev, I.L. Lapitskaya, A.S. Sobolev, and M.Yu. Torgashin are with the Institute of Radio Engineering and Electronics, Russian Academy of Science, Mokhovaya 11, 125009, Moscow, Russia, (telephone: 7-095-2032784, e-mail: valery@hitech.cplire.ru)

P.A. Yagoubov, R.W.M. Hoogeveen G. de Lange W. Wild are with the SRON Netherlands Institute for Space Research, P.O. 9700 AV Groningen, the Netherlands, (tel.: 31-50-3634074, e-mail: P.A.Yagoubov@sron.rug.nl)

I. Superconducting Integrated Receiver Design

The Superconducting Integrated Receiver (SIR) comprising in one chip a superconductor-insulator-superconductor (SIS) mixer and a phase-locked superconducting Flux Flow Oscillator (FFO) is under development for the atmosphere monitoring (project TELIS - TErahertz and submm LImb Sounder [1]), as well as for the future space missions like Millimetron [2] and ESPRIT [3]. The concept of the SIR [4], looks very attractive for spaceborne applications not only because of the light weight, small volume and low power consumption but also due to a wide tuning range of the FFO [5], [6], [7]. Presently, the frequency range of the most practical heterodyne receivers is limited by the tunability of the local oscillator (LO). For a solid-state multiplier chain the fractional input bandwidth typically does not exceed 10-15 %. In the SIR the bandwidth is basically determined by the SIS mixer tuning structure and matching circuitry between the SIS and FFO; bandwidth up to 30 - 40 % may be achieved with a twin-junction SIS mixer design.

To demonstrate advantages of the SIR concept an integrated receiver for TELIS project has been developed [6]. TELIS is designed to be a compact, lightweight instrument capable of providing broad spectral coverage, high spectral resolution and long flight duration. To achieve the required instantaneous bandwidth of 500-650 GHz with emphasis on 500-550 and 600-650 GHz frequency ranges, a twin-SIS mixer with 0.8 μm^2 junctions and new design of the FFO/SIS matching circuitry were implemented. Microphotograph of the central part of the SIR chip with double slot antenna is presented in Fig. 1. The receiver chip is placed on the flat back surface of the elliptical silicon lens (integrated lens-antenna).

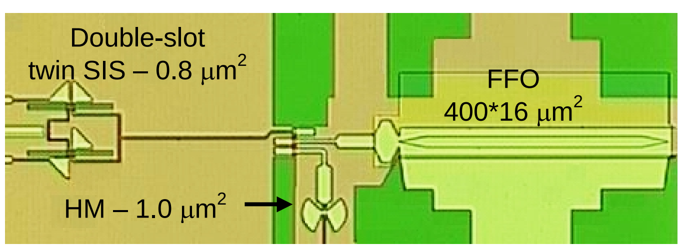

Fig. 1. Photo of the central part of the SIR chip with double slot antenna.

II. Nb-AlN-NbN Tunnel Junctions

The implementation of an AlN tunnel barrier in combination with a NbN top superconducting electrode provides a significant improvement in SIS junction quality [7] compared to traditional Nb-AlN-Nb circuits. The gap voltage of the junction Vg = 3.7 mV that potentially allows operation of the SIS mixer up to 1.5 THz. In Fig. 2 typical current-voltage dependencies of a Nb-AlN-NbN SIS mixer, pumped by a Nb-AlN-NbN FFO. One can see that the FFO provides more than enough power for mixer pumping. Although the Nb-AlN-NbN FFOs behave very similar to all-Nb ones there is a number of very important features related to energy gap structure and losses in the FFO (Josephson transmission line) due to NbN top electrode that differ their properties from regular all-Nb FFOs. It was demonstrated [7] that Nb-AlN-NbN FFOs provide continuous frequency tuning from 300 to 700 GHz with linewidth well below 10 MHz that make possible the FFO phase-locking in very wide frequency range.

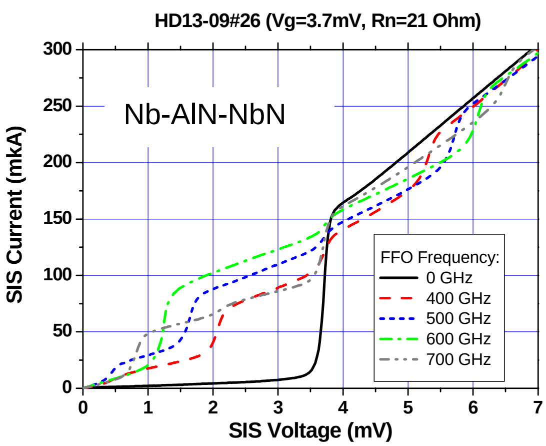

Fig. 2. The IVC of an SIS mixer pumped by an integrated FFO. Solid curve – unpumped mixer, dashed and dotted lines - pumped at different frequencies..

III. SIR Performance

The SIR microcircuits have been tested as a receiver showing a possibility to realize the PL SIR concept. SIR chip is mounted in a flight configuration mixer block surrounded by a magnetic shield in a liquid helium cooled cryostat. Noise temperature measurements are done using Y-factor technique by chopping between hot (295 K) and cold (80 K) loads in the signal path of the receiver (see Fig. 3). IF response of the mixer is amplified by a cryogenic InP based 4-8 GHz low-noise amplifier (LNA) amplifier followed by a 60 dB gain GaAs room temperature amplifier. The signal is detected by a fast power meter. We have also used the flight configuration of the PLL system and could phase-lock the FFO practically at any frequency in the 450-650 GHz range.

A new approach to tune out the mixer's parasitic and filter's capacitances suggested by Jacob Kooi was implemented in a recently developed and tested IF-network for the SIR [8]. A section of the coplanar line was grounded at RF by the integrated on-chip capacitors and worked as a shunt tuning inductance. As a result variation of the receiver noise temperature of about 50K was realized over IF band 4–8 GHz.

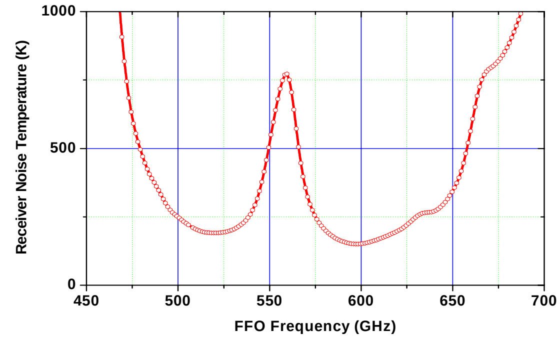

Fig. 3. Uncorrected DSB noise temperature of the SIR as a function of the FFO frequency measured over IF band = 4 - 8 GHz. A dip at 560 GHz is partially due to water vapor absorption line

Far-field amplitude beam pattern of the integrated antenna measured at 625 GHz in a heterodyne mode with phase-locked FFO is symmetric with the first sidelobe level below -17 dB. It is close to the theoretically predicted diffraction pattern calculations; the full width half maximum (FWHM) is 3 deg. To prove capability of the SIR for high-resolution spectroscopy we have successfully measured line profiles of OCS gas around 625 GHz. As a back-end spectrometer we used Digital Auto Correlator (DAC). SIR was operated in a phase-locked mode. The spectrum recorded by the DAC is a convolution product of the signal (gas emission lines) with the FFO line spectrum, resolution is limited by DAC back-end. To recover the signal, we apply a simple direct deconvolution process using the measured FFO line shape.

New superconducting element, a cryogenic phase detector (CPD) has been proposed and preliminary tested. The CPD is based on a SIS junction and intended for phase locking of a FFO in a SIR. First results of the CPD development and study are very encouraging [8]; a sinusoidal response of the CPD has been measured; phase locking of an FFO by the CPD with the spectral ratio as high as 80 % has been demonstrated.

References

[1] R.W.M. Hoogeveen, *et al.*, "New cryogenic heterodyne techniques applied in TELIS: the balloon borne THz and submm limb sounder for atmospheric research", Proc. of SPIE, Infrared Spaceborne Remote Sensing XI, 5152, p. 347-355, 2004.

[2] http://www.asc.rssi.ru/millimetron/eng/millim_eng.htm

[3] W. Wild, et al, "Terahertz Technology for ESPRIT – Far-Infrared Space Interferometer", *The 16th International Symposium on Space Terahertz Technology*, Sweden, May 2005, Proceedings ISSTT 2005, p. 68 - 73.

[4] V. P. Koshelets and S. V. Shitov, "Integrated Superconducting Receivers," *Superconductor Science and Technology*, vol. 13, pp. R53-R69, 2000.

[5] T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida, "Flux-flow type Josephson oscillator for mm and submm wave region," *J. Appl. Phys.*, vol. 54, p. 3302, 1983, see also Pt. II: *J. Appl. Phys.* vol. 56, p. 3284, 1984; Pt. III, *J. Appl. Phys., vol.* 58, p. 441, 1985; Pt. IV, *J. Appl. Phys.*, vol. 63, p. 1130, 1988.

[6] V.P. Koshelets, *et al.*, "Superconducting Integrated Submillimeter Receiver for TELIS", *IEEE Trans. on Appl. Supercond.*, vol. 17, June 2007.

[7] M.Yu. Torgashin, *et al.*, "Superconducting Integrated Receiver based on Nb-AlN-NbN-Nb Circuits", *IEEE Trans. on Appl. Supercond.*, vol. 17, June 2007.

[8] A.V. Khudchenko, *et al.*, "Cryogenic Phase Detector for Superconducting Integrated Receiver", *IEEE Trans. on Appl. Supercond.*, vol. 17, June 2007.