MMA Memo # 279

A submm SIS receiver with an integrated superconducting LO

Valery P. Koshelets, Sergey V. Shitov

Institute of Radio Engineering and Electronics RAS, Moscow, Russia

ABSTRACT. Fully Superconducting Integrated Receiver has been developed in tight collaboration between Space Research Organization of the Netherlands (SRON-Groningen) and Institute of Radio Engineering and Electronics (IREE-Moscow). This single-chip submm receiver contains a planar double-dipole antenna, SIS mixer and a superconducting Josephson-type local oscillator (flux-flow oscillator, FFO). The receiver has demonstrated a DSB noise temperature below 100 K around 500 GHz being pumped by its internal LO. The instantaneous bandwidth of 15 – 20 % has been estimated via heterodyne measurements, that meets the requirements of most practical applications. The far field antenna beam has been measured as ≈ f/10 with sidelobes below - 16 dB that makes Integrated Receiver suitable for coupling to a real telescope antenna. A 9-pixel imaging array receiver with each pixel containing an internally pumped receiver chip has been developed and tested. Linewidth of a phase locked FFO as low as 1 Hz has been measured relatively to reference oscillator in the frequency range 270 - 440 GHz.

Keywords: superconducting integrated submm wave low-noise receiver, quasi-optical SIS mixer, double-dipole antenna, imaging array, phase locked flux-flow oscillator (FFO).

Introduction.

Lightweight and compact ultra sensitive submm Superconducting Integrated Receivers (SIR) [1-4] are very attractive for both radio-astronomical space applications and distant monitoring of the Earth atmosphere, where low weight, power consumption and limited volume are vitally required. New ambitious radio-astronomy multi-dish projects (like ALMA) would gain considerably by using single chip SIR due to their lower price and better serviceability compare to conventional approaches. A distant study of the atmospheric pollution is possible by detection of the spectrum lines of ozone, chlorine and other elements in submm wave range by onboard SIR. Presently the single-chip superconducting receiver comprises a SIS-mixer with quasioptical antenna and a superconducting local oscillator (LO). In future it could be followed by an intermediate frequency SQUID amplifier [5] and superconducting circuits for digitization of down converted signals and their real time processing [6]. In this memo we review the latest results of SIR study that were done in tight collaboration between Space Research Organization of the Netherlands (SRON-Groningen) and Institute of Radio Engineering and Electronics (IREE-Moscow).

A SIS mixer is proven to be the most sensitive heterodyne detector in the frequency range 100 - 1000 GHz. Noise temperature of the SIS receivers that are successfully used in radio astronomy for spectral observations is ultimately limited only by the fundamental quantum value hf/2k. For many applications the lack of compact and easily tunable submm local oscillators is a real bottleneck that motivates the direct integration of a superconducting LO with the SIS mixer. Flux-flow oscillator (FFO) [7], which is a most developed candidate for the integrated oscillator, is a long Josephson tunnel junction in which an applied dc magnetic field and a bias current drive a unidirectional flow of fluxons. In the past few years the FFO has been proven as a reliable wideband and easy tunable local oscillator suitable for integration with a SIS-mixer in a single-chip submm wave receiver [1, 2]. An integrated control line with current I_{CL} is used to generate the dc magnetic field locally applied to the FFO. According to Josephson relation the junction biased at voltage V oscillates with a frequency $f=(2\pi/\Phi_0)*V$), where Φ_0 is the magnetic flux quantum = $2\,10^{-15}$ Web (what corresponds to 483.6 GHz/mV). The velocity and density of the fluxons and thus the power and frequency of the emitted mm-wave signal may be adjusted independently by joint action of bias current and magnetic field. The FFOs based on Nb-AlO_x-Nb junctions have been successfully tested from about 120 to 700 GHz (gap frequency of Nb) providing power sufficient to pump a SIS-mixer (about 1 μW at 450 GHz) [2].

500 GHz Integrated Receiver- Design and Results.

A layout of the SIR microcircuit has been designed using original programs for computation and analysis of superconducting circuits. The micron size SIS junction (R_N = 15 – 25 Ω) placed in the center of the mixer is a shared load of two dipole antennas (Fig. 1). The LO power is supplied from FFO to the SIS junction via a microstrip transmission line of about 1 mm long. To avoid loss of the signal toward the LO path, this port has a high output impedance of about 60 O. It causes a significant reflection of incoming LO signal that requires a significant resource for the FFO power.

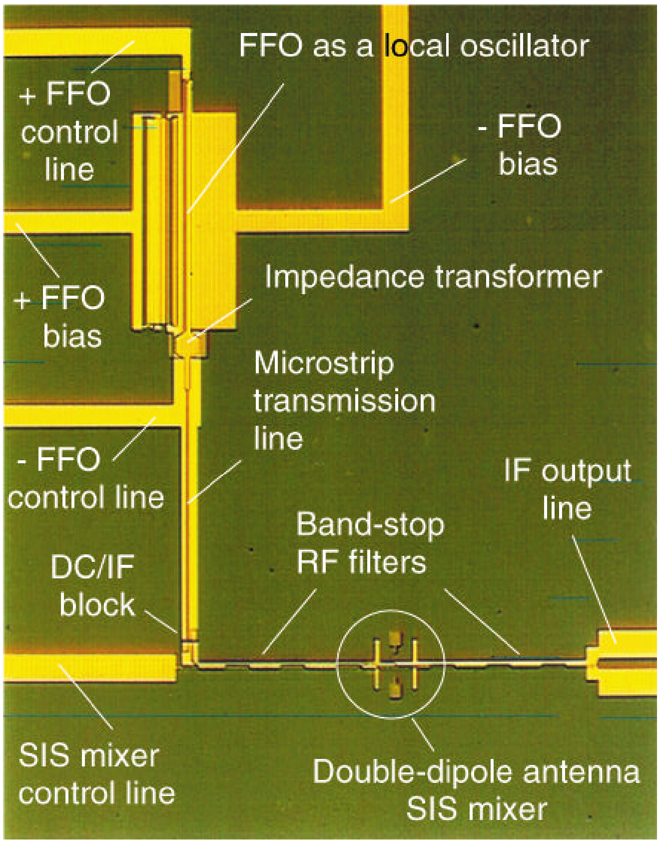

Fig. 1. Microphotograph of central part of the silicon Integrated Receiver chip; all main elements presented; some details of wiring and contact pads are out of the field of view.

The SIR microcircuits are fabricated on a crystalline Si substrate on the base of a high quality Nb-AlO_x-Nb trilayer. The SIR fabrication procedure has been successfully developed both at IREE (Moscow) and FDL-SRON (Groningen), this procedure does not require any additional equipment compare to conventional SIS junction technology. Each individual chip with size of 4 mm ? 4 mm ? 0.5 mm contains SIS mixer incorporated in double-dipole antenna and FFO with matching circuits. The receiver chip is placed on the flat back surface of the elliptical lens from silicon. To achieve a beam of high efficiency and good symmetry, a quarter-wave back reflector chip is installed at the double-dipole antenna so there is no backlobe radiation. The antenna produces a radiation pattern of good rotational symmetry. The lenses and their anti-reflection coating (Stycast? epoxy) are manufactured using precision diamond turning. The mixer block is mounted on the cold plate of a liquid helium cryostat with a Mylar or Capton vacuum window at 300 K and a crystalline quartz infrared filter at 80 K. A black polyethylene film at 4.2 K is also used as an infrared filter (Fig. 2). All these optical elements are optimized for a center frequency of 500 GHz. A cryoperm shield around the mixer block is mounted to reduce the influence of external magnetic interference.

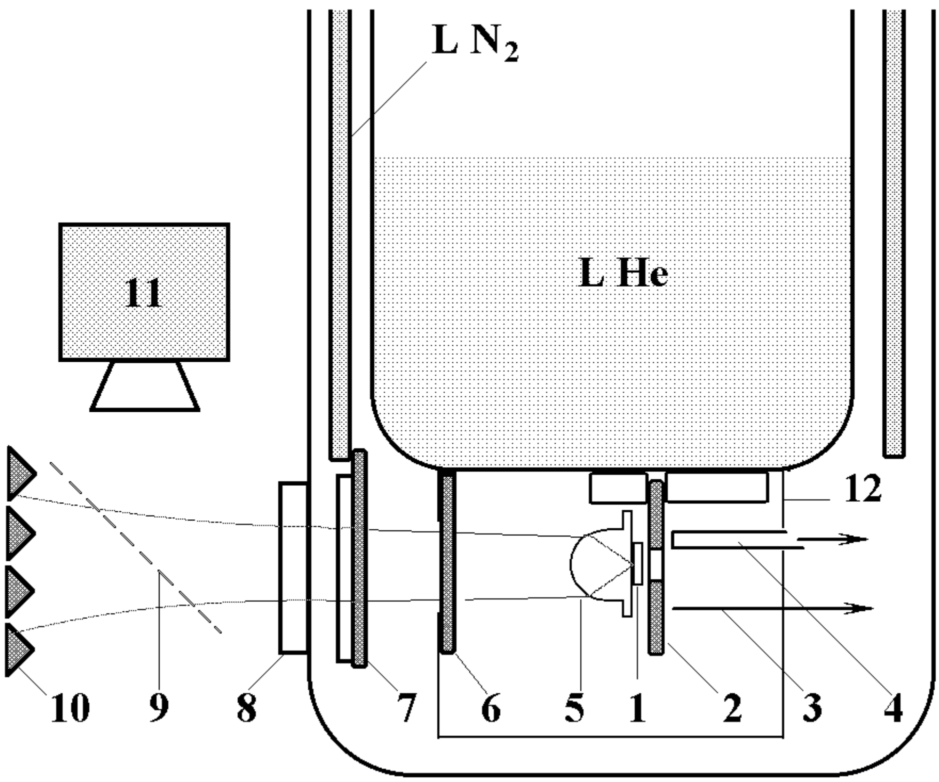

Fig. 2. Experimental setup for integrated receiver test: “1” - integrated receiver chip; “2” - bias plate with bonded contacts; “3” - DC wireing; “4” - IF output / SIS bias; “5” - elliptical silicon lens with anti-reflection coating; “6” - 4.2 K black polyethylene heat shield; “7” - 77 K heat shield; “8” - Mylar input window; “9” - 10 μ Mylar beam splitter; “10” - 300 K/77 K load; “11” - 420 - 490 GHz CSF-Thomson Carsinotron; “12” - cryoperm shield.

A receiver DSB noise temperature about 100 K has been achieved for SIR with the internal FFO operated over the frequency range 480 - 520 GHz, that is close to the quantum limit. The instantaneous bandwidth of about 15 % has been obtained in heterodyne measurements; that fits most astronomical applications. The level of the first-order sidelobe is about - 16 dB, the beam width is 3.7° and 6.7° at the -3 dB and -10 dB levels respectively [3, 4] (see Fig. 3). The first minimum in the radiation pattern occurs at approximately 4.5°. This corresponds roughly to a f/9.4 beam with a waist size $w_0 \approx 3.6$ mm. These figures confirm that the integrated receiver is suitable for coupling to a real telescope dish. Thanks to the noise contribution analysis it became possible to reduce a receiver noise temperature below 40 K at 475 GHz for a single-junction reference unit pumped by external LO [8]; that is the lowest value reported worldwide so far. A concept of a balanced SIR has been developed to avoid both FFO power and signal loss. The preliminary result is showing a noise temperature below 100 K over range of 480 - 510 GHz (see Fig. 4), which is comparable to the single mixer design.

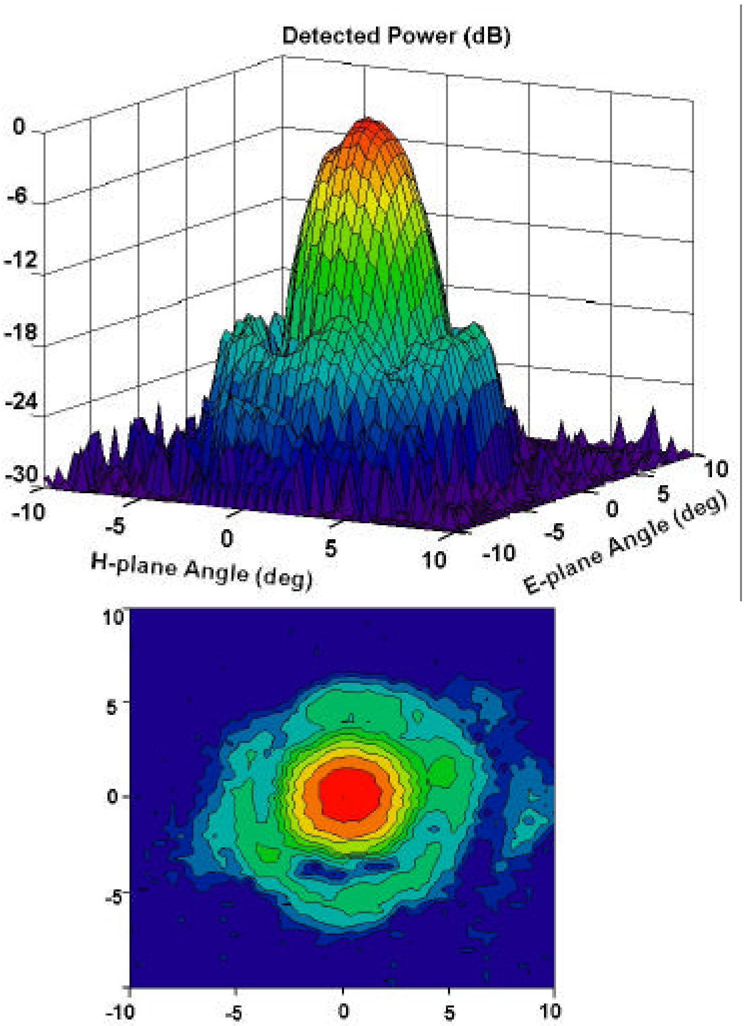

Fig. 3. Antenna beam patterns of the SIR pixels measured at the distance of 400 mm from the cryostat window at 500 GHz The equal power contours are placed with step of 1 dB. The first sidelobe found at -16 dB. Power in the mainlobe is about 89 %. Some asymmetry is assumed to be a result of sidelobes touching the shielding can.

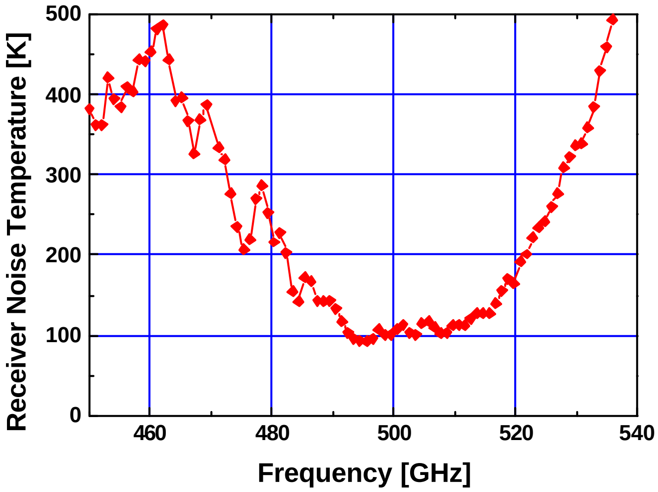

Fig. 4. Experimental data measured at T = 4.2 K for SIR with internal LO. The data are collected automatically by the IRTECON system.

An imaging array of nine Integrated Receivers has been developed and tested. To reduces both the inequality of beams as well as *rf* and magnetic cross-talk between pixels, the optical configuration "fly's eye" is used. An elliptical lens can be matched directly to a telescope simply by choosing the lens diameter according to the telescope f-number, and no intervening optics are needed. The elliptical silicon lenses (? ≈ 10 mm) are placed with the center-to-center separation of 13 mm that corresponds to an undersampling factor of about 4 (Fig. 5). Each lens carries its own individual receiver chip. No interaction between modules has been detected within the experimental accuracy, neither at *DC* magnetic fields nor at *rf*. This is important to mention that no degradation of the noise temperature was observed for the receiver chips fabricated more than 2 years ago.

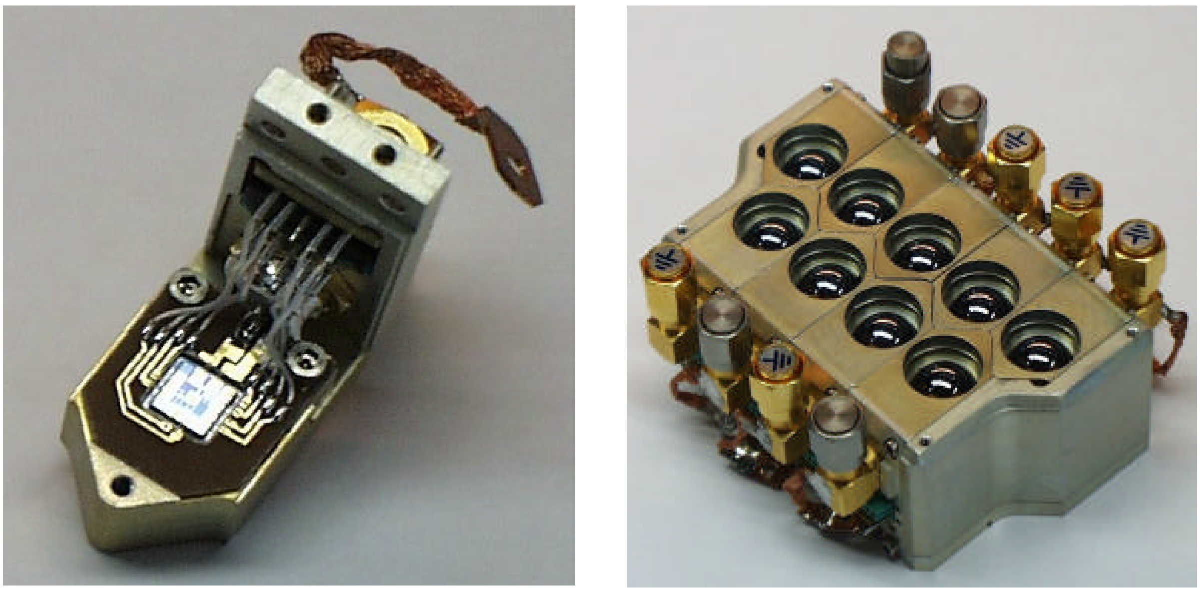

Fig. 5. a) Replaceable element of the 9-pixel imaging array. The unit is shown from the side of the Si chip which is mounted on the elliptical lens and wire bonded to the PCB. b) Nine-pixel imaging array. The array mount is shown from the side of its input microwave lenses.

To simplify the operation of SIR, the data acquisition system IRTECON was developed for the ***I***ntegrated ***R***eceiver ***Te***st and ***Con***trol. One of the routines of IRTECON finds the best SIS bias 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 (i.e. FFO control line current). For the SIR imaging array the noise temperature of about 150 K has been measured at 500 GHz using internal FFO.

FFO linewidth; Phase Locking to External Reference Oscillator.

Frequency resolution of a receiver (along with the noise temperature and the antenna beam pattern) is one of the major parameters in spectral radio astronomy. The resolution is determined by both the instant linewidth of the local oscillator and its long-time stability; it should be much less than 1 ppm of the center frequency. A reliable technique for linewidth measurements has been developed [9] and an autonomous FFO linewidth of a few hundred kHz was measured. A simple model based on Josephson radiation self-coupling was introduced [9] to explain the experimentally measured FFO linewidth dependencies. According to the theory a radiation linewidth is determined by both the noise and the differential resistance of the FFO at low frequencies, $f < \Delta f_{AUT}$, where Δf_{AUT} is an autonomous FFO linewidth. Therefore FFO linewidth can be changed by an external phase locking (PLL) system with a bandwidth larger than Δf_{AUT}.

Recently the feasibility of phase locking the Josephson FFO to an external reference oscillator is demonstrated experimentally [10-12]. A FFO linewidth as low as 1 Hz (determined by the resolution bandwidth of the spectrum analyzer) has been measured relatively to reference oscillator in the frequency range 270 - 440 GHz (Fig. 6). This linewidth is far below the fundamental level given by shot and thermal noise for a free-running tunnel junction. The residual phase noise of the phase locked FFO (measured relatively to the reference synthesizer) is plotted in Fig. 7 (data from Fig. 6) as a function of the offset from the carrier. Based on these results, a concept of a single-chip fully superconducting integrated receiver with a phase-locked loop is developed [10, 12]. Along to this concept a SIR for a frequency of about 350 GHz containing a quasioptical low-noise SIS mixer, a phase-locked flux-flow oscillator, a harmonic

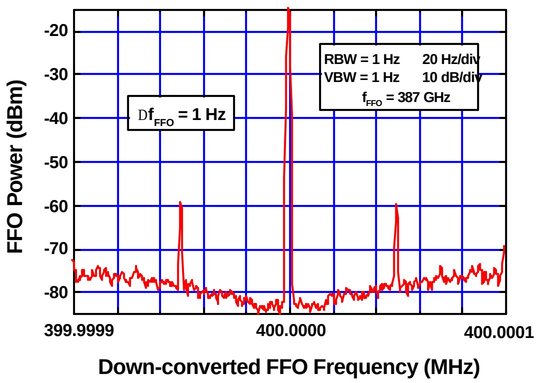

Fig. 6. Down-converted IF power spectra of the phase locked FFO (f = 387 GHz) recorded relatively to the reference oscillator.

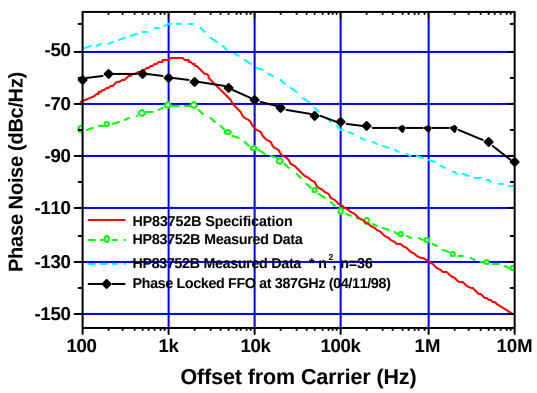

Fig. 7. Experimentally measured phase noise of the phase locked FFO at 387 GHz in comparison with the data for the HP synthesizer.

SIS mixer and a SIS multiplier as a source for the harmonic mixer (optional) has been designed, fabricated and pre-tested recently [13]. The FFO has to be phase-locked to the 35th harmonic of a 10 GHz synthesized source using custom-design room temperature electronics with the PLL loop bandwidth of about 10 MHz. For operation of the phase locked SIR at frequencies up to 700 GHz an additional efforts should be undertaken to decrease the initial FFO linewidth. Also an ultra-wide-band PLL system with sufficiently low phase noise is needed. Since the fundamental possibility of FFO phase locking is proven [10-12], all remaining problems seem to be of a technical nature.

Conclusion.

The combination of narrow linewidth and wide band tuneability makes FFO a perfect on-chip local oscillator for integrated submm wave receiver intended for spectral radio astronomy and aeronomy applications. Implementation of the single-chip Superconducting Integrated Receiver for new radio-astronomy projects based on a multi-receiver approach (e. g. ALMA) is especially advantageous due to lower price and better serviceability of the single-chip SIR as compared to conventional SIS receiver with a Gunn oscillator and multipliers. It is important to note that ultimate performance of the quasi-optical SIR is basically the same as for waveguide SIS receivers in the frequency range 400-600 GHz while the convenience of electronically controlled local oscillator and wide band tuneability of FFO offer an extra advantage of SIR over a regular SIS receiver.

Acknowledgement.

The work was supported in parts by the Russian SSP "Superconductivity", INTAS project 97-1712, the Netherlandse Organisatie voor Wetenshappelijk Onderzoek (NWO) grant and ESA TRP contract 11/653/95/NL/PB/SC. Authors thanks Dr. Wolfgang Wild for suggesting this memo for the ALMA memo series and very valuable comments. We also deeply appreciate the participation in the development and study of the Integrated Receiver all members of the large international team, especially Andrey Baryshev, Andrey Ermakov, Lyudmila Filippenko, Petri Lehikoinen, Willem Luinge, Jesper Mygind, and Vladimir Vaks. Authors thank Thijs de Graauw, Herman van de Stadt, Nick Whyborn, Peter de Maaght and Martin van der Vorst for fruitful and stimulating discussions as well as H. Golstein, H. Smit, J. Evers and D. Van Nguyen for help in the experiment.

References

1. V. P. Koshelets, S. V. Shitov, L. V. Filippenko, 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. V.P. Koshelets, S.V. Shitov, L.V. Filippenko, A.M. Baryshev, W. Luinge, H. Golstein, H. van de Stadt, J.-R. Gao, T. de Graauw, “An Integrated 500 GHz Receiver with Superconducting Local Oscillator”, *IEEE Trans. on Appl. Supercond*., vol. 7, pp. 3589-3592, 1997.

3. 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.

4. S.V. Shitov, A.B. Ermakov, L.V. Filippenko, V.P. Koshelets, A.B. Baryshev, W. Luinge, Jian-Rong Gao, "Superconducting Chip Receiver for Imaging Applications". *IEEE Trans. on Appl. Supercond.*, **v.9,** No 2, pp. 3773-3776, (1999).

5. G.V. Prokopenko, D.V. Balashov, S.V. Shitov, V.P. Koshelets, and J. Mygind, "Two-stage S-Band DC SQUID Amplifier", *IEEE Trans. on Appl. Supercond.*, **v.9,** No 2, pp. 2902-2905, (1999).

6. A.V. Rylyakov, D.F. Schneider, Yu.A. Polyakov, “A fully integrated 16-channel RSFQ autocorrelator operating at 11 GHz”, *IEEE Trans. on Appl. Supercond.*, **v.9,** No 2, pp. 3623-3626, (1999).

7. T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida, "Flux Flow type Josephson oscillator for millimeter and submillimeter wave region", *J. Appl. Phys*. vol. 54, pp. 3302-3309, 1983; see also Pt. II, *J. Appl. Phys*,. vol. 56, pp. 3284, 1984; Pt. III, *J. Appl. Phys.*, vol. 58, pp. 441, 1985; Pt. IV, *J. Appl. Phys*., vol. 63, pp. 1130, 1988.

8. A.M. Baryshev, et all; to be published.

9. V.P. Koshelets, S.V. Shitov, A.V. Shchukin, L.V. Filippenko, J. Mygind and A.V. Ustinov, ”Self-pumping effects and radiation linewidth of FFO," Phys. Rev. B, vol. 56, pp. 5572- 5577, Sept. 1997.

10. 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". *IEEE Trans. on Appl. Supercond*., **v.9,** No 2, pp. 4133-4136, (1999).

11. V.P. Koshelets, S.V. Shitov, L.V. Filippenko, V.L. Vaks, J. Mygind, A.B. Baryshev, W. Luinge, N. Whyborn, "Phase Locking of 270-440 GHz Josephson Flux Flow Oscillator", Rev. of Sci. Instr., **v.12**, (1999).

12. V.P. Koshelets, A.M. Baryshev, J. Mygind, V.L. Vaks, S.V. Shitov, L.V. Filippenko, P.N. Dmitriev, W. Luinge, N. Whyborn, "Externally Phase Locked Sub-MM Flux Flow Oscillator for Integrated Receiver ", presented at EUCAS’99, report 8D-2, Barcelona, September (1999).

13. S.V. Shitov, V.P. Koshelets, L.V. Filippenko, P.N. Dmitriev, A.B. Ermakov, V.L. Vaks, A.M. Baryshev, W. Luinge, N.D. Whyborn, J.-R. Gao, “A Superconducting Integrated Receiver With Phase-Lock Loop”, presented at EUCAS’99, report 6-100, Barcelona, September (1999).