Integrated Superconducting Submm Receivers

ABSTRACT The concept of a fully Superconducting Integrated Receiver (SIR) has been developed and experimentally proven in a tight collaboration between the Institute of Radio Engineering and Electronics (IREE-Moscow) and the Space Research Organization of the Netherlands (SRON-Groningen).

A single-chip submm wave receiver includes a planar antenna integrated with a SIS mixer, pumped by an internal superconducting FFO as local oscillator (LO). A DSB noise temperature below 100 K has been demonstrated around 500 GHz. A compact array of 9 SIRs has been developed and tested. Each pixel contains an *internally pumped* receiver chip, which is mounted on the back of an elliptical silicon lens.

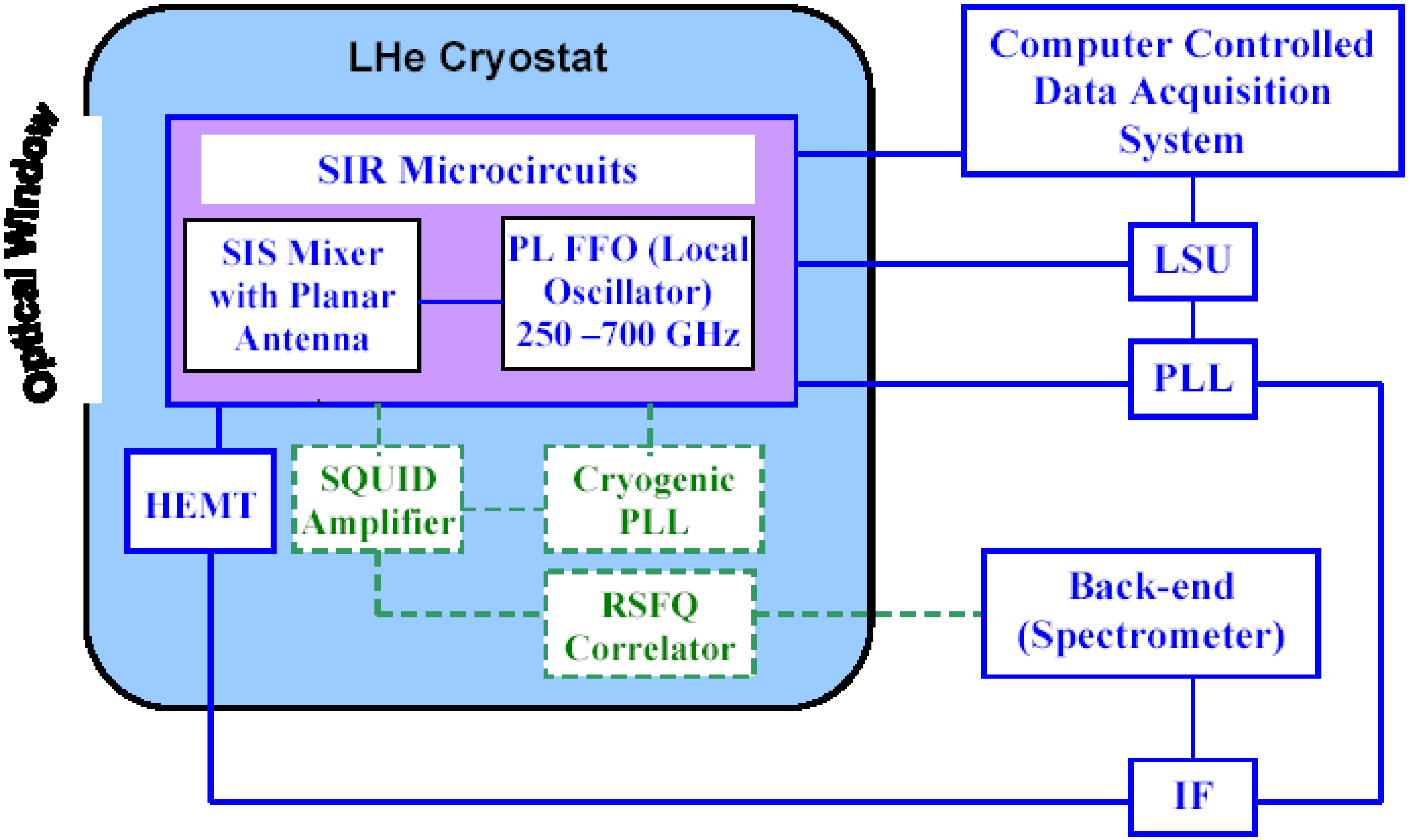
Local oscillators based on Nb-AlO_x-Nb FFOs have been successfully tested from about 120 to 700 GHz (gap frequency of Nb) providing enough power to pump an SIS-mixer (about 1 μW at 450 GHz); both the frequency and the power of the FFO can be dc-tuned. Recently a possibility of FFO phase locking has been experimentally proven for the first time for ANY type of Josephson oscillator. A breadboard of a superconducting integrated spectrometer with a phase-locked FFO has been tested showing the frequency resolution of the receiver as low as 10 kHz at 364 GHz. To demonstrate an ability of the spectral observations the effect of broadening of a spectral line of SO_2 gas was measured for a laboratory gas cell at 300 K within the pressure range of 0.03 - 1 mbar.

All these results made possible development of 550-650 GHz integrated receiver for the Terahertz Limb Sounder (TELIS) intended for atmosphere study and scheduled to fly on a balloon in 2005.

A lightweight and compact ultra-sensitive sub-mm superconducting integrated receiver (SIR) with low power consumption is of great interest for both radio-astronomical research and distant monitoring of the Earth's atmosphere. The new ambitious radio-astronomy multi-dish projects (e.g. ALMA) would gain considerably by using single-chip SIRs due to their lower price and better serviceability as compared to conventional approaches. A distant study of atmospheric pollution is possible using air- or satellite-borne SIRs for detection of the spectrum lines of ozone, chlorine and other elements in the sub-mm wave range. Currently the single-chip superconducting receiver comprises a SIS mixer with a quasioptical antenna and a superconducting local oscillator (LO). In future it could be followed by an intermediate frequency SQUID amplifier and superconducting circuits for digitization of down converted signals and their real time processing (see Fig. 1)

Fig. 1 Block Diagram of Superconducting Integrated Receiver

Already proven elements are shown by solid lines
Dashed lines show the elements being under development



Single-chip Superconducting Integrated Receiver (SIR)

Sub-millimeter wave spectrometers are currently of great interest for radio astronomy and for Earth study by monitoring the atmosphere chemistry. Most of advanced spectrometers nowadays employ ultra-low noise SIS mixers at the temperature of liquid helium. The sensor of an SIS mixer is a thin-film integrated circuit fabricated with micron accuracy so the tiny circuit may contain many SIS junctions. In contrast, conventional local oscillators used with SIS mixers are room temperature semiconductor devices. This approach makes difficult the integral packaging of the whole receiving system.

The 1-microWatt level superconducting Josephson flux-flow oscillator (FFO) is proven to be suitable for integration with a low-noise SIS mixer as a local oscillator (LO). Among the Josephson devices FFO has also an advantage of good tuneability in combination with relatively narrow free-running linewidth. Recent experimental study on phase-locking FFO up to 700 GHz is the good basis for development of a practicable submillimeter spectrometer.

The microcircuits of the submm Integrated Receivers are fabricated from Nb/AlO_x/Nb trilayer ($j_c \approx$ 5-8 kA/cm^2) at IREE (Moscow) using a specially developed technological procedure. Circuits are produced on a two-inch silicon wafer (0.5 mm thick) and then diced into chips of 4 mm $\times$ 4 mm. A double-dipole antenna SIS mixer is placed in the geometrical center of the chip where the incoming *rf* signal is focused by a coated silicon microwave lens. The FFO-based local oscillator (LO) is placed just outside the two-wavelength “hot” spot of the antenna and connected to the mixer with a microstrip transmission line, which contains a number of rf coupling and dc blocking elements. Both the SIS mixer and FFO are provided with local magnetic fields via integrated control lines [24]. All receiver elements are placed in the area of about 1 mm $\times$ 1 mm, but the chip dimensions are defined mainly by a size of contact pads which were chosen to be of about 0.8 mm for easier connection; eleven contact pads are provided for bond-wiring.

Two microphotographs of the SIR chip made with different magnification are shown in Fig 2.

a) Microphotograph of a central part of the silicon chip of sizes 4 mm by 4 mm. All main elements of the Integrated Receiver are presented; the back reflector is not yet installed on the double-dipole antenna. Some details of wiring and contact pads are out of the field of view, which is about 1 mm by 1.5 mm.

b) Microphotograph of a double-dipole antenna SIS mixer of the Integrated Receiver. Microstrip tuners for the antenna and a feeder of the local oscillator are shown. The field of view is about 100 μm by 150 μm.

The receiver chip is placed on the flat back surface of an elliptical silicon lens. The mixer block is mounted on the cold plate of a liquid helium cryostat with a Mylar or Capton window at 300 K and a crystalline quartz window at 80 K. A black polyethylene film at 4.2 K is used as a heat shield. All windows as well as the anti-reflection coating are optimized for a center frequency of 500 GHz. A cryoperm shield around the mixer block is applied to reduce the influence of external magnetic interference. A DSB noise temperature below 100 K has been demonstrated around 500 GHz. Heterodyne measurements have shown that the instantaneous bandwidth of the receiver is 15 – 20 %, which meets the requirements of practical applications. The double-dipole lens-antenna SIS mixer has an antenna beam ≈ f/9 with sidelobes below - 16 dB. This enables an efficient coupling of the SIR to a telescope antenna. The concept of a balanced SIR has been developed in which in principle no FFO power is lost to the antenna and no signal is lost to the FFO (see Fig. 3 – 6).

A compact array of 9 SIRs has been developed and tested (see Fig 7). Each pixel contains an *internally pumped* receiver chip, which is mounted on the back surface of an elliptical silicon lens. Each individual chip with size 4 mm × 4 mm × 0.5 mm consists of a SIS mixer incorporated in a double-dipole antenna and a FFO with matching circuits. The elliptical silicon lenses and their anti-reflection coating (Stycast™ epoxy) are manufactured using precision diamond turning. A "fly's eye" optical configuration has been used for the Imaging Array. This reduces both the inequality of beams as well as *rf* and magnetic cross-talk between pixels. 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. A noise temperature of about 150 K has been measured at 500 GHz using the internal FFO for the imaging array of Integrated Receivers.

To simplify the SIR operation the data acquisition system IRTECON was developed for the *I*ntegrated *R*eceiver *Te*st and *Con*trol (see Fig. 8). One of the routines of IRTECON finds the best SIS bias minimizing the receiver noise temperature, T_{RX}, at a particular frequency. The pump level 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)

Fig. 2. Integrated Receiver Microcircuits

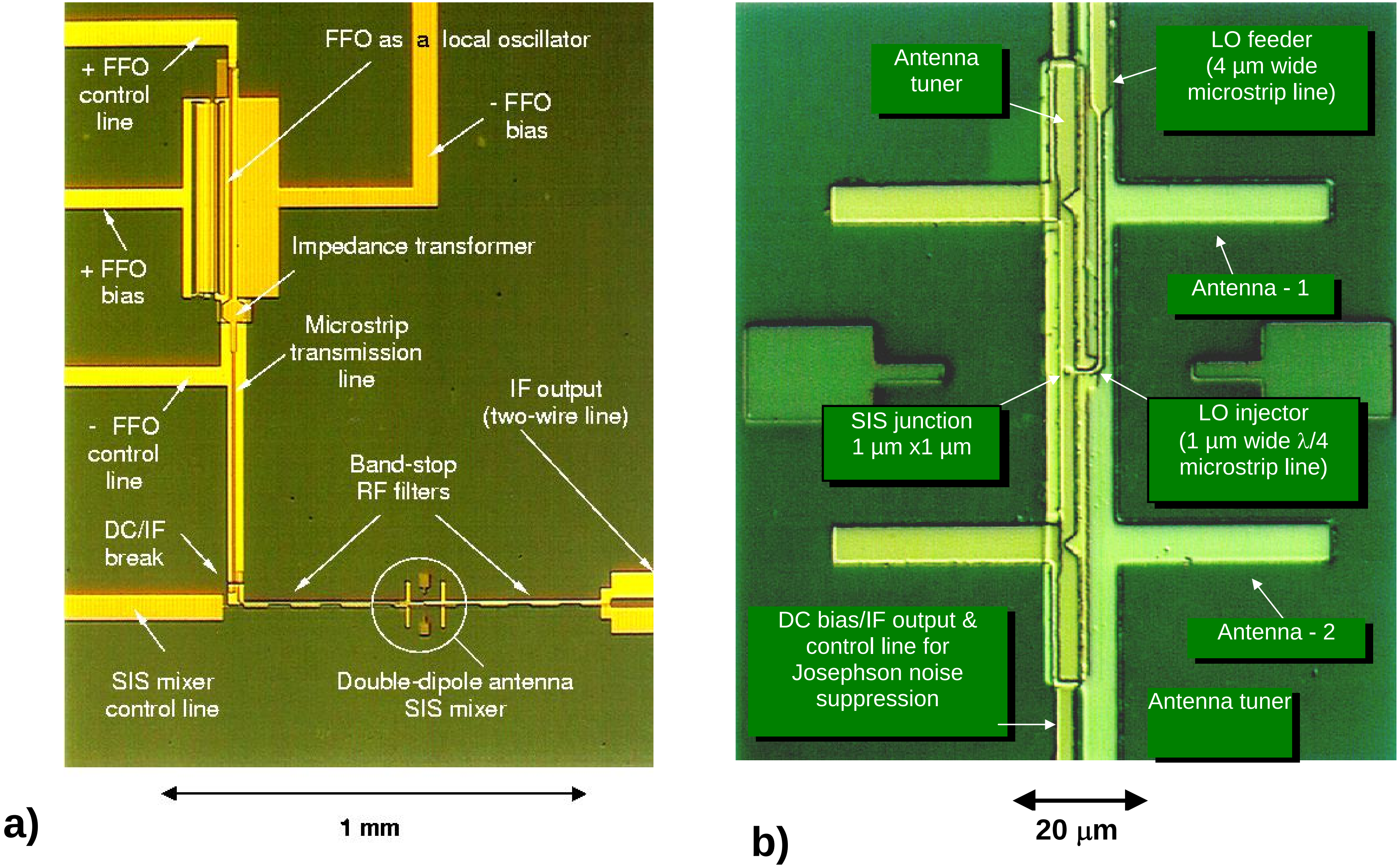
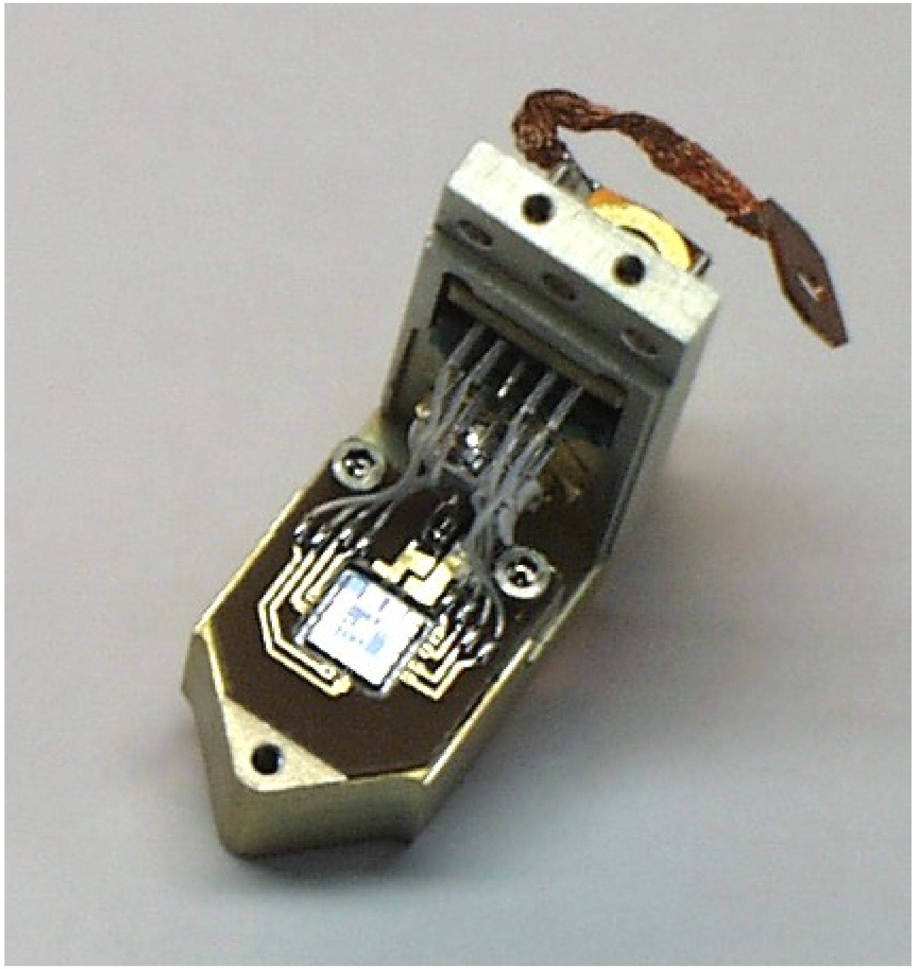


Fig. 3 Replaceable Module of the 500 GHz Imaging Array SIR

Replaceable element of the 9-pixel imaging array. (a) The unit is shown from the side of the receiver lens; (b) The unit is shown from the side of the receiver chip, which is mounted on the elliptical microwave lens and wire bonded to the printed circuit board.



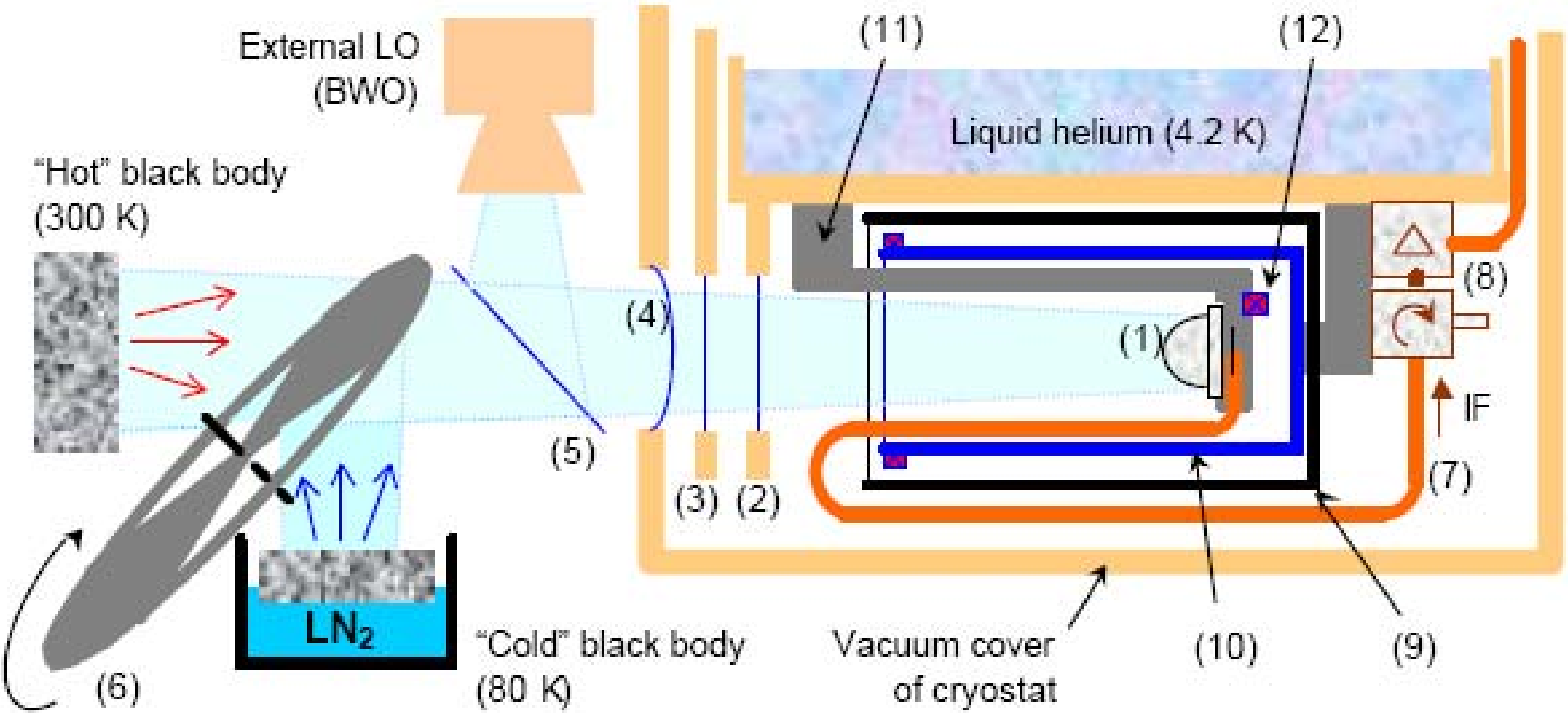


Fig. 4. Schematics of experimental setup for SIR tests including details of beam coupling, interior of cryostat and magnetic shielding: (1) silicon elliptical lens with antireflection coating; chip receiver is glued at its flat back, (2) Zitex infrared filter at 4.2 K, (3) resonant plate filter from Teflon or quartz at 80 K, (4) resonant vacuum window from Mylar or Kapton, (5) thin film beamsplitter (not used with internal LO), (6) chopper wheel switching "hot" and "cold" antenna loads, (7) semirigid coaxial IF cable, (8) shielded IF isolator and 30 dB IF amplifier (1.3-1.8 GHz), (9) external shielding layer (μ-metal), (10) internal superconducting shield, (11) holder (heat sink) from copper, (12) heaters for chip and superconducting shield.

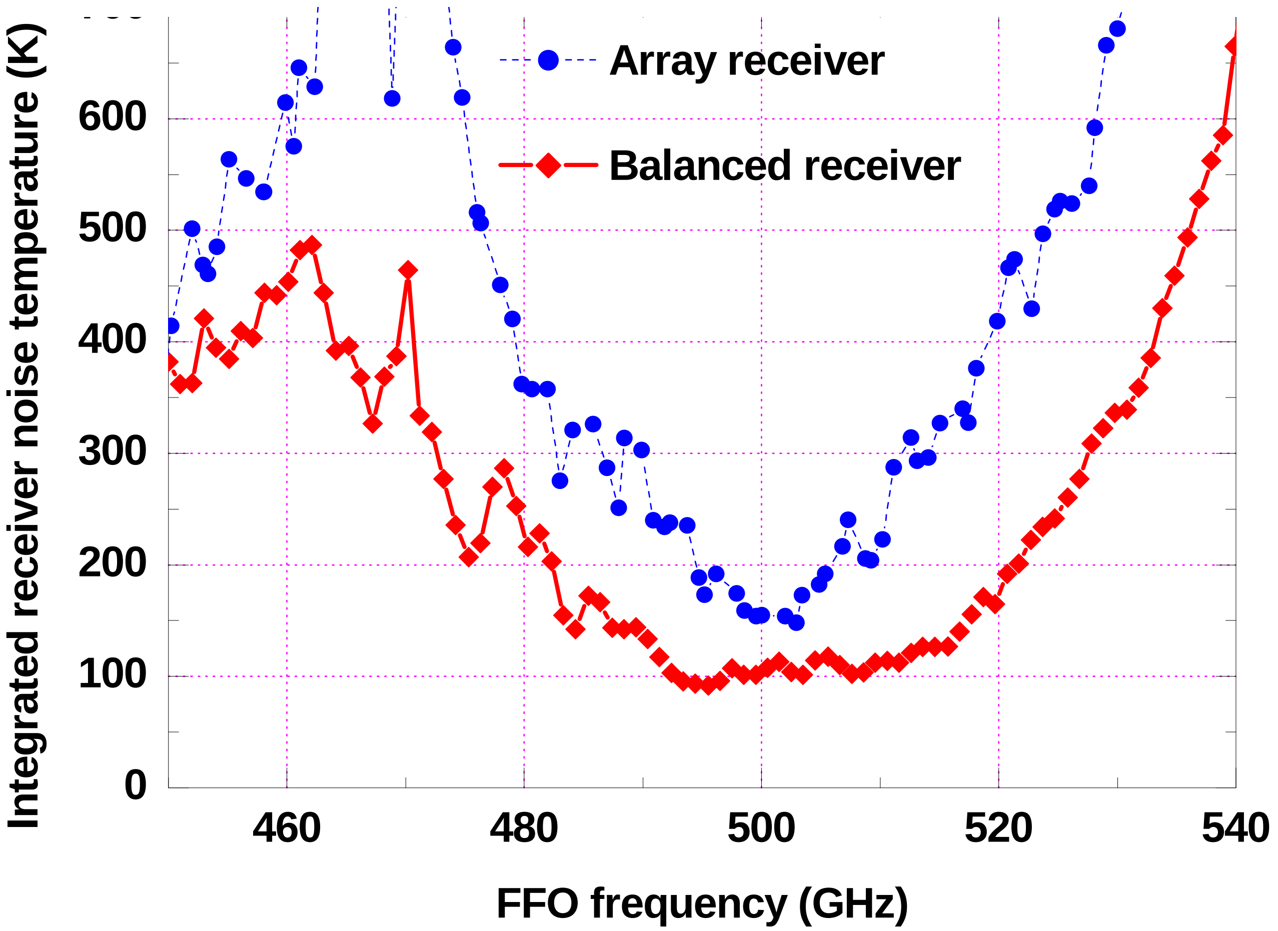


Fig 5. Experimental data on a typical single-junction pixel pumped by its internal FFO in 9-pixel array cryostat (circles). The data are collected automatically by the IRTECON system; ripples are associated with interference on a thick 80 K infrared filer. Data on a pixel with the double-junction *balanced SIS mixer* pumped by the integrated FFO (diamonds) measured in test cryostat.

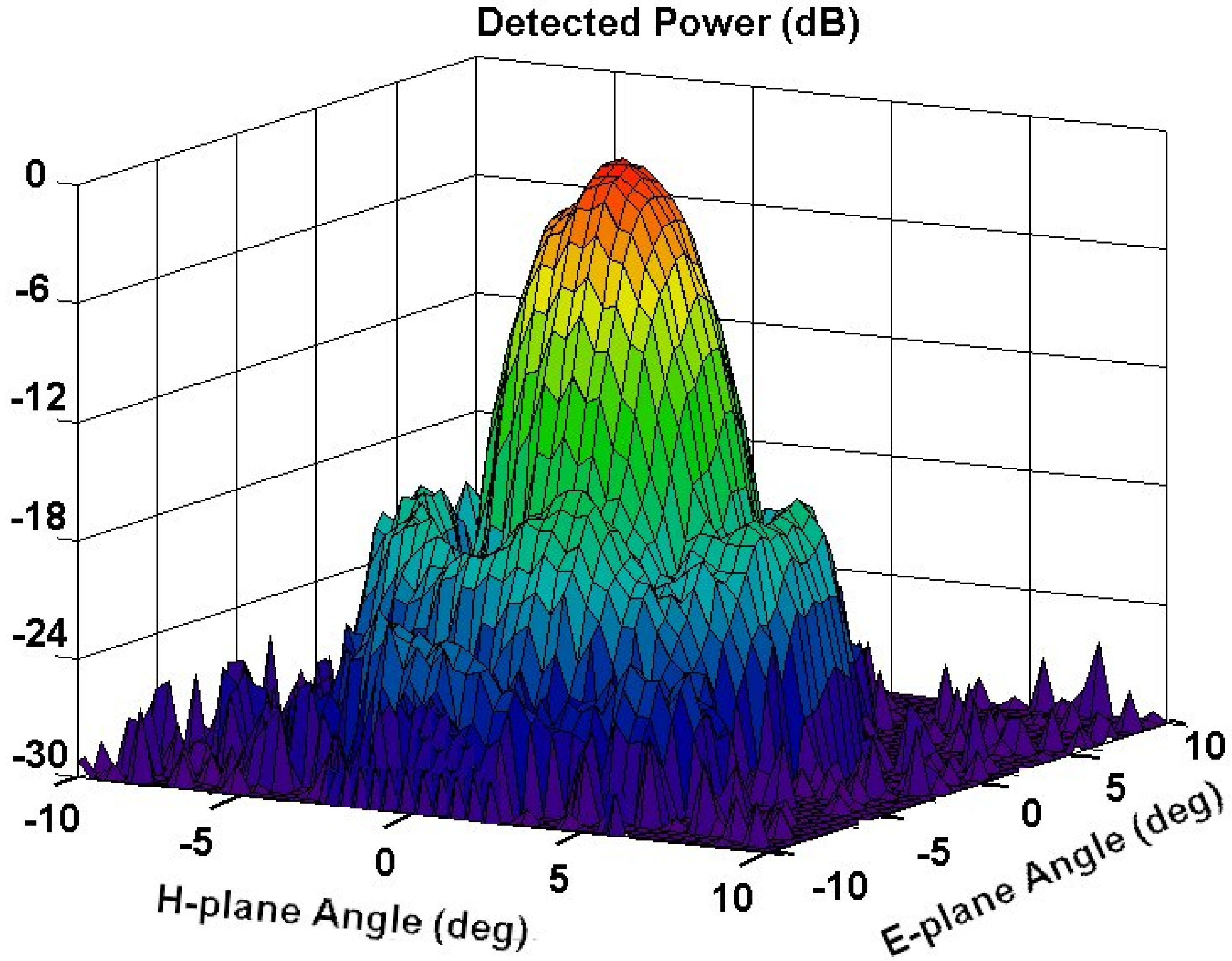


Fig 6. Antenna beam pattern of the SIR pixel measured at the distance of 400 mm from the cryostat window at 490 GHz. Data for the raster image are collected from area 100 mm by 100 mm. The equal power contours are placed with step of 1 dB. The first sidelobe found at -16 dB. Some asymmetry is assumed to be a result of sidelobes touching the shielding can.

Fig 7. Nine-pixel imaging array receiver block. Each pixel is an independent integrated receiver with its own internal local oscillator. The array mount is shown from the side of its input microwave lenses.

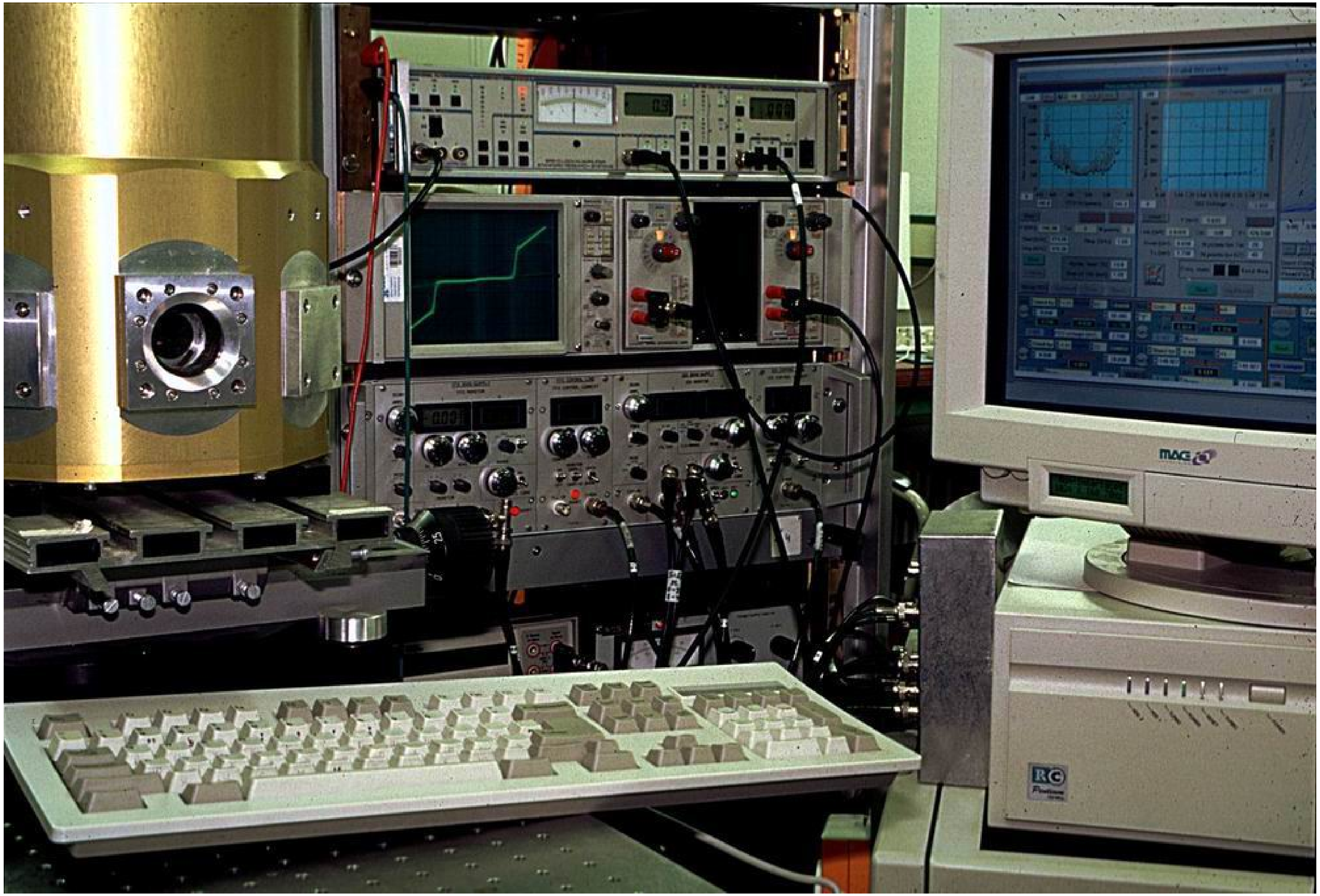


Fig 8. Photo of the experimental set-up controlled with IRTECON system: quasi-optical cryostat at the left, bias supply unit in the center (at the background) and data display at the right.

Properties of Flux Flow Oscillator.

The FFO is a *long* Josephson tunnel junction in which an applied dc magnetic field and a dc bias current, I_B, drive a unidirectional flow of fluxons, each containing one magnetic flux quantum, $\Phi_0 = h/2e \approx 2\ 10^{-15}$ Wb. Symbol h is Planck's constant and e is the elementary charge. An external coil or an integrated control line with current I_{CL} can be used to generate the dc magnetic field applied to the FFO. According to the Josephson relation the junction biased at voltage V oscillates with a frequency $f = (1/\Phi_0)*V$ (about 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 both the bias current and the magnetic field.

Long Josephson Nb-AlO_x-Nb junctions with overlap geometry are used as FFOs (see inset in figure 9). The FFO length, L, and the width, W, are about 500 μm and 5 μm, respectively. The value of the critical current density, j_c, is in the range 2 - 8 kA/cm^2 giving a Josephson penetration depth, $\lambda_J \approx 8$ - 4 μm. The corresponding specific resistance, $R_n*L*W \approx 100 - 25\ \Omega\ \mu m^2$. For the numerical calculations we use typical values of the London penetration depth ($\lambda_L \approx 90$ nm) and the junction specific capacitance ($C_s \approx 0.08$ pF/μm^2). The active area of the FFO (i. e. the AlO_x tunnel barrier) is usually formed in a long window in the relatively thick insulation layer (200-350 nm, SiO_2) between two superconducting (Nb) films (base and counter electrodes). The so-called "idle" region in the thick SiO_2 layer between the overlapping electrodes adjacent to the junction forms a transmission line parallel to the FFO. The width of the idle region is about the junction's width, which is limited by the alignment accuracy of the fabrication process. One of the electrodes of FFO is employed as a control line in which a dc current, I_{CL}, produces the applied magnetic field, B_{appl}.

A special integrated circuit comprising a well-coupled wide-band SIS detector is used to characterize the FFO as an rf source. Figure 9 shows a typical set of current-voltage characteristics (IVCs) of the FFO measured with incremented magnetic fields. Each IVC is recorded with a fixed control line current, I_{CL}, which is subsequently increased with a constant increment ΔI_{CL}. Simultaneously with the recording of the FFO IVCs, the pumped IV curves of the integrated SIS detector were measured by a newly developed data collection system (IRTECON). The magnitude of the pump signal is derived from the induced change in the subgap tunnel current, ΔI, of the SIS detector at $V = 2.5$ mV due to photon assistant tunneling normalized to the current rise, I_g, at the gap voltage (see Fig. 10). A ratio $\Delta I/I_g$ determines the color of the FFO IVC (0 corresponds to blue color, while all points where $\Delta I/I_g$ is more than 0.25 are red, with appropriate color pallet for intermediate pumping). From Fig 10 one can see that optimal pumping ($\Delta I/I_g = 0.25$) is obtained for FFO voltages from 200 to 1450 μV corresponding to the frequency range 100-700 GHz. Power of the FFO is proportional to bias current, so the power and frequency of the emitted mm-wave signal may be adjusted independently, and the FFO power can be precisely tuned at a fixed frequency.

IVCs of the SIS detector recorded at different setting of the FFO are shown in figure 10. Pronounced quasiparticle steps are clearly visible in the SIS IVC up to the FFO frequency of 670 GHz. Actually the useful frequency range is limited by the matching circuits and the SIS tuning structure rather than by the FFO itself. It is possible to change the frequency range of the integrated circuit by modifying the design of the matching elements. Implementation of an FFO based on superconductors with a higher critical temperature (higher gap voltage) results in a considerable increase of the maximum operational frequency.

The frequency resolution of a receiver (along with the noise temperature and the antenna beam pattern) is one of major parameters in spectral radio astronomy. In order to obtain the required resolution (of at least one part per million) the local oscillator must be phase-locked to an external reference. To ensure the phase locking, the free-running linewidth of the FFO has to be well below an effective regulation bandwidth of the PLL (of about 10 MHz).

Detailed measurements of the FFO linewidth were performed in a wide frequency range up to 700 GHz using a novel experimental technique based on an integrated harmonic mixer. A specially designed integrated circuit comprising an FFO, a harmonic SIS mixer, and the microwave circuit elements needed for the rf coupling is used for linewidth measurements (see figure 11). A Lorentzian shape of the FFO line has been observed both at higher voltages on the flux flow step (FFS) and at lower voltages in the resonant regime on the Fiske steps (FS’s), figure 12. It means that the free-running (“natural”) FFO linewidth in all operational regimes is determined by the wideband thermal fluctuations and the shot noise. This is different from many traditional microwave oscillators where the “natural” linewidth is very small and the observed linewidth can be attributed mainly to external fluctuations.

The FFO, as any Josephson junction, is a perfect voltage-controlled oscillator and hence its frequency can be stabilized and the FFO linewidth can be decreased by applying a phase-locked loop (PLL) system with bandwidth larger than δf_{AUT}. We have developed a special PLL unit utilizing an integrated SIS harmonic mixer to down-convert the FFO signal to a 400 MHz IF signal. After amplification the IF signal is compared to a 400 MHz reference signal in an analogue phase detector, the output of which is fed to the FFO bias supply. The new design of the FFO results in a decrease of the free-running FFO linewidth in the flux flow regime for $V > V_{JSC}$; it enables us to phase lock the FFO in the frequency range from 200 to 712 GHz, limited only by the gap value of the Nb-AlOx-Nb junction. Fig. 13 demonstrates spectra of the frequency and phase locked FFO operating at 707 GHz.

In order to find the “absolute” (total) phase noise of the phase-locked FFO one should add the noise of the reference oscillator multiplied by n^2 where n is the number used in the harmonic mixing (see Fig. 14). The absolute FFO phase noise is dominated by the reference oscillator noise for offsets < 1 MHz. Note that the measured phase noise already meets the requirements for single dish radio astronomy and atmospheric missions.

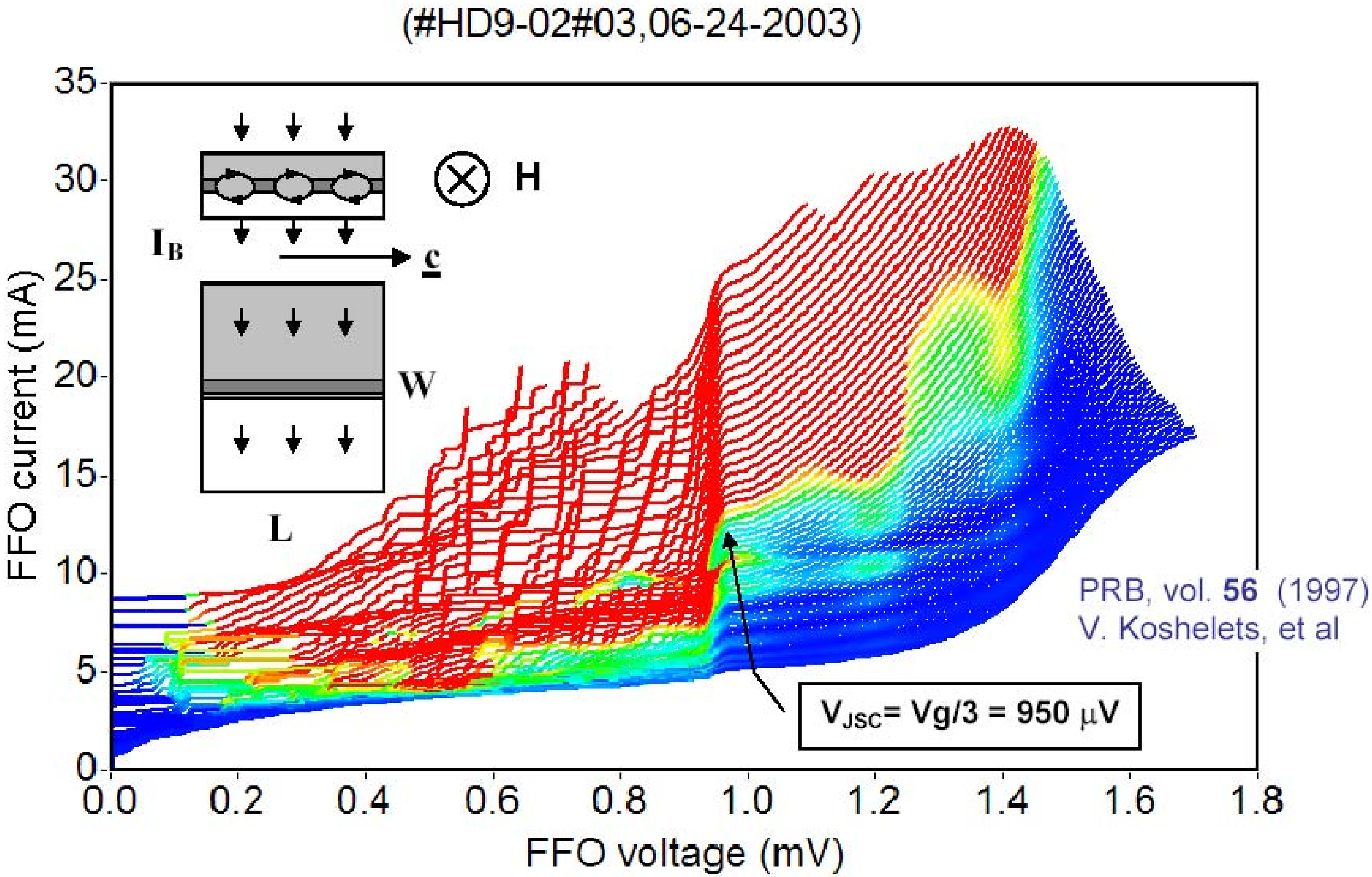


Fig 9. Typical set of IVCs for a Nb-AlO$_x$-Nb FFO recorded with incremented magnetic fields. Each IVC is measured for a fixed control line current, I_{CL} which is then incremented by $\Delta I_{CL} \approx 0.5$ mA before the next IVC is recorded. Note the abrupt change of the IVC at the boundary voltage $V_{JSC} \approx 950\ \mu$V, above which the voltage and thus the frequency of the FFO increases linearly with ΔI_{CL} (for fixed bias current I_B). Insets show the cross section of the long junction with driven vortices (top) and its overlap geometry (bottom).

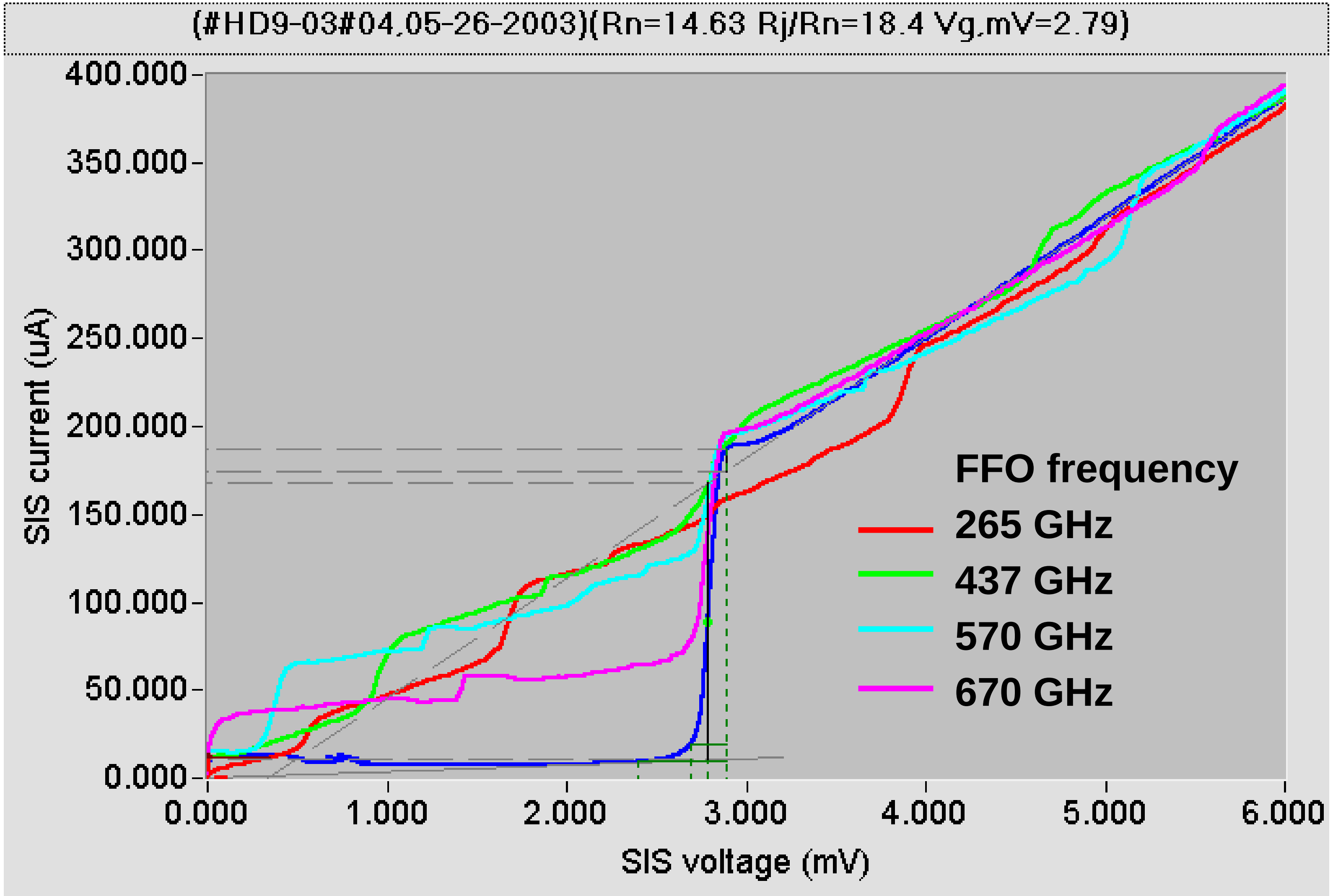


Fig. 10. IVCs of the SIS detector (wide band design) pumped by a FFO at different frequencies 265, 435, 570 and 670 GHz.

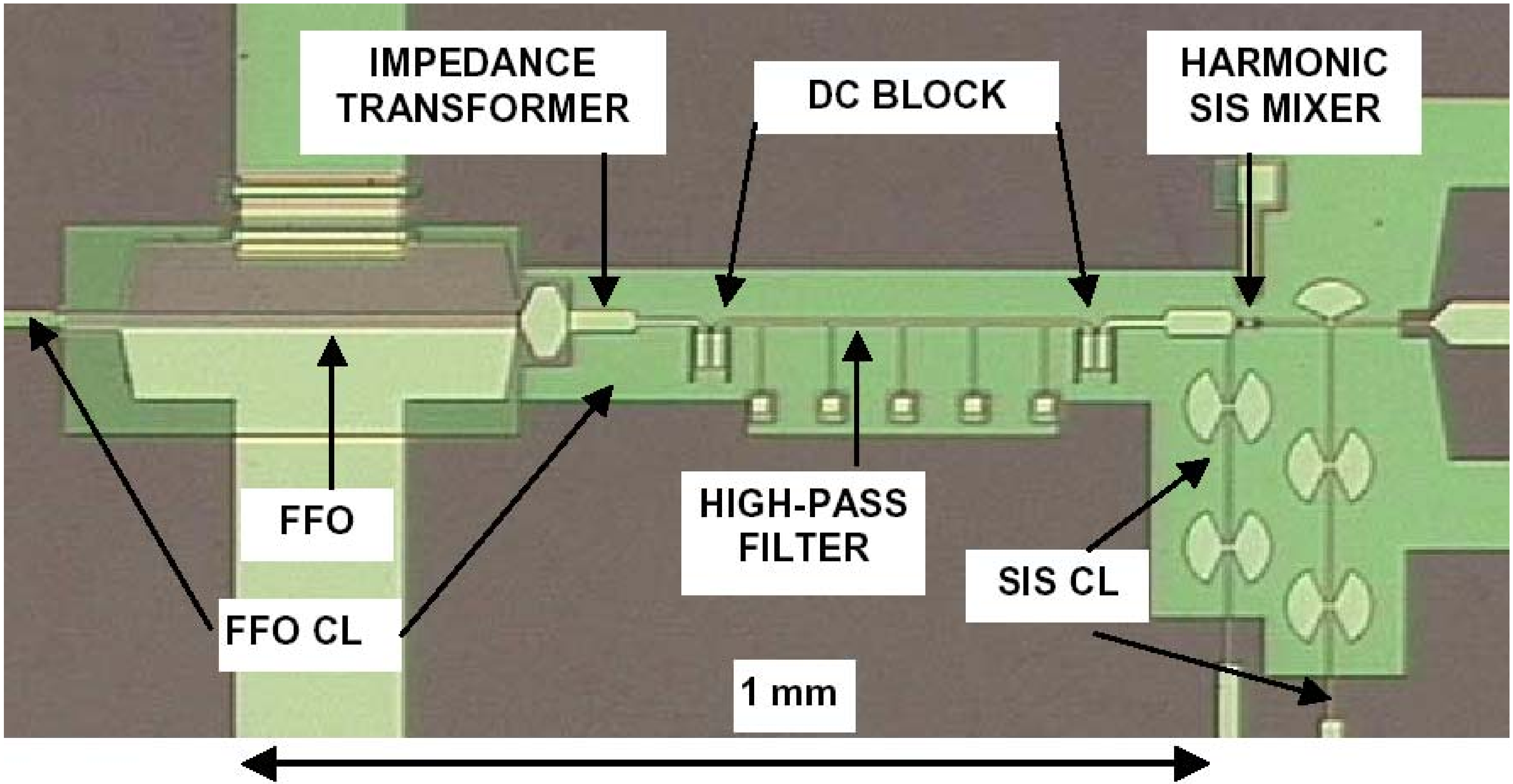


Fig. 11. Central part of the microcircuits used for FFO linewidth measurements.

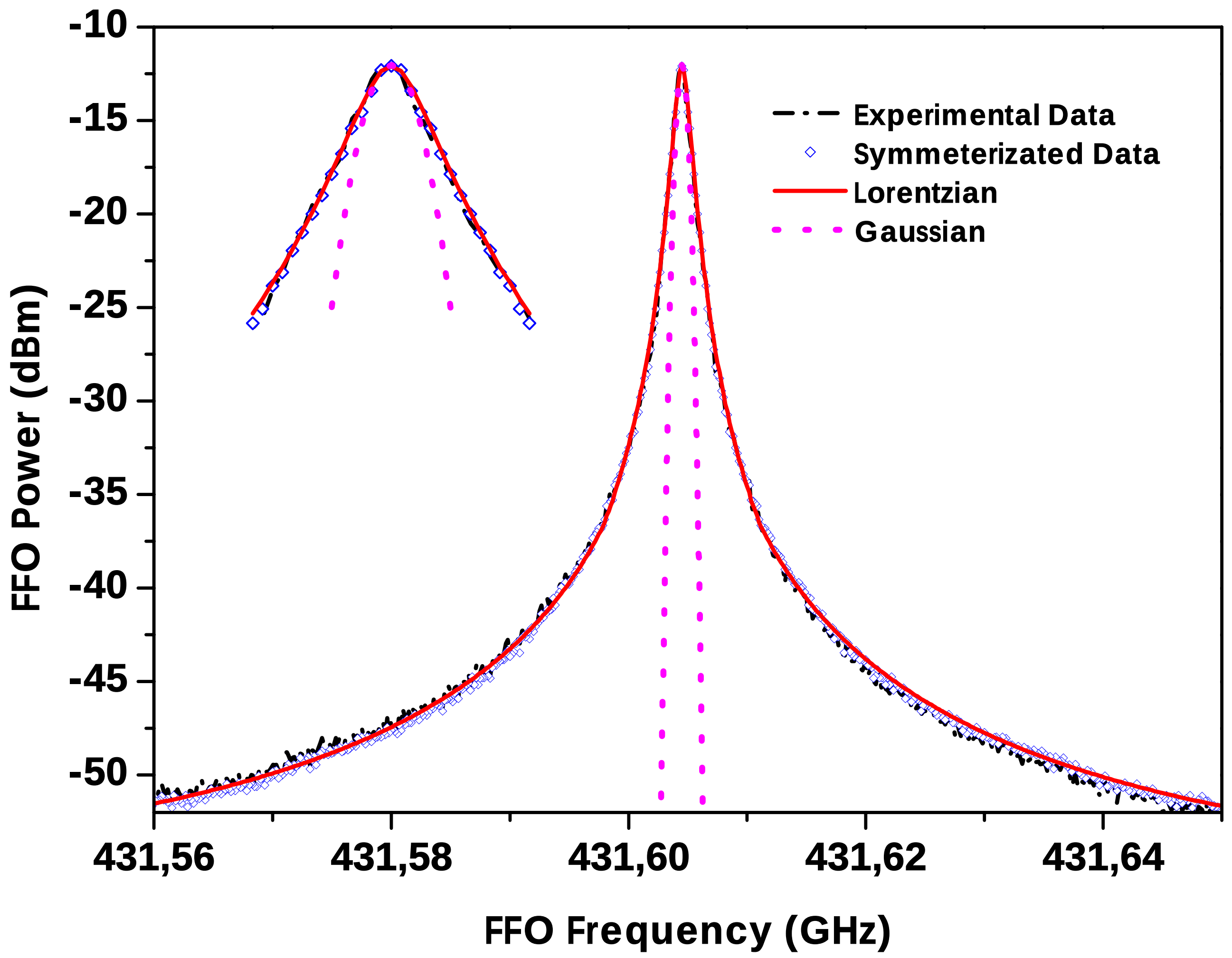


Fig. 12. FFO spectrum measured at 431 GHz (δf_{AUT} = 1.2 MHz) – dash-dotted line. The symmetrizated experimental data are shown by diamonds. Fitted theoretical Lorentzian and Gaussian profiles are shown by solid and dotted lines, respectively. The inset shows a zoom-in on the central peak with the frequency axis multiplied 5 times.

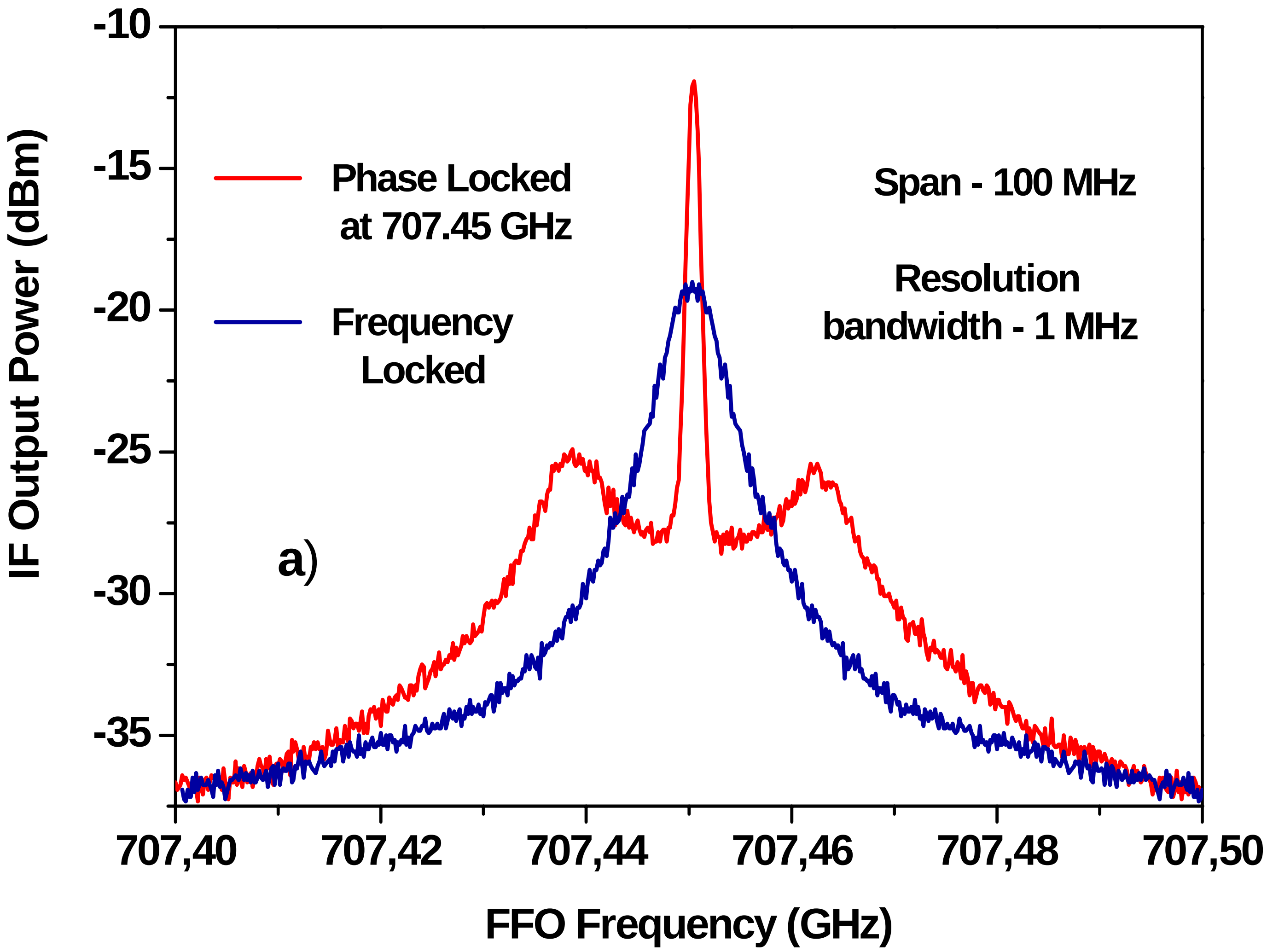


Fig. 13 a. Spectra of the frequency locked and phase-locked FFO operating at 707.45 GHz; the free-running linewidth is δf_{AUT} = 6.3 MHz, spectrum analyzer span 100 MHz.

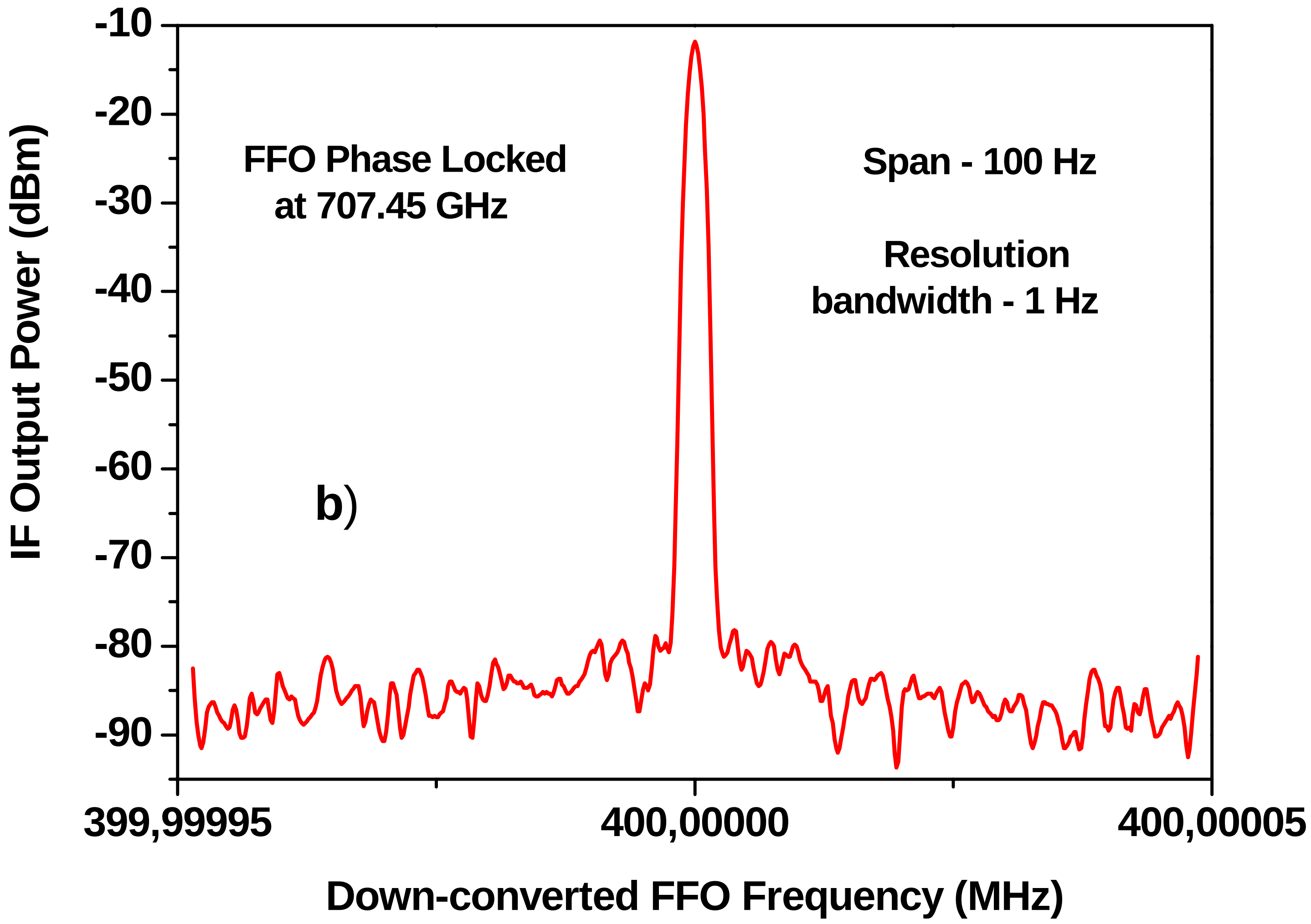


Fig. 13 b. Down-converted spectrum of the FFO phase locked at 707.5 GHz, measured relative to the reference oscillator (spectrum analyzer span 100 Hz, T = 4.2 K)

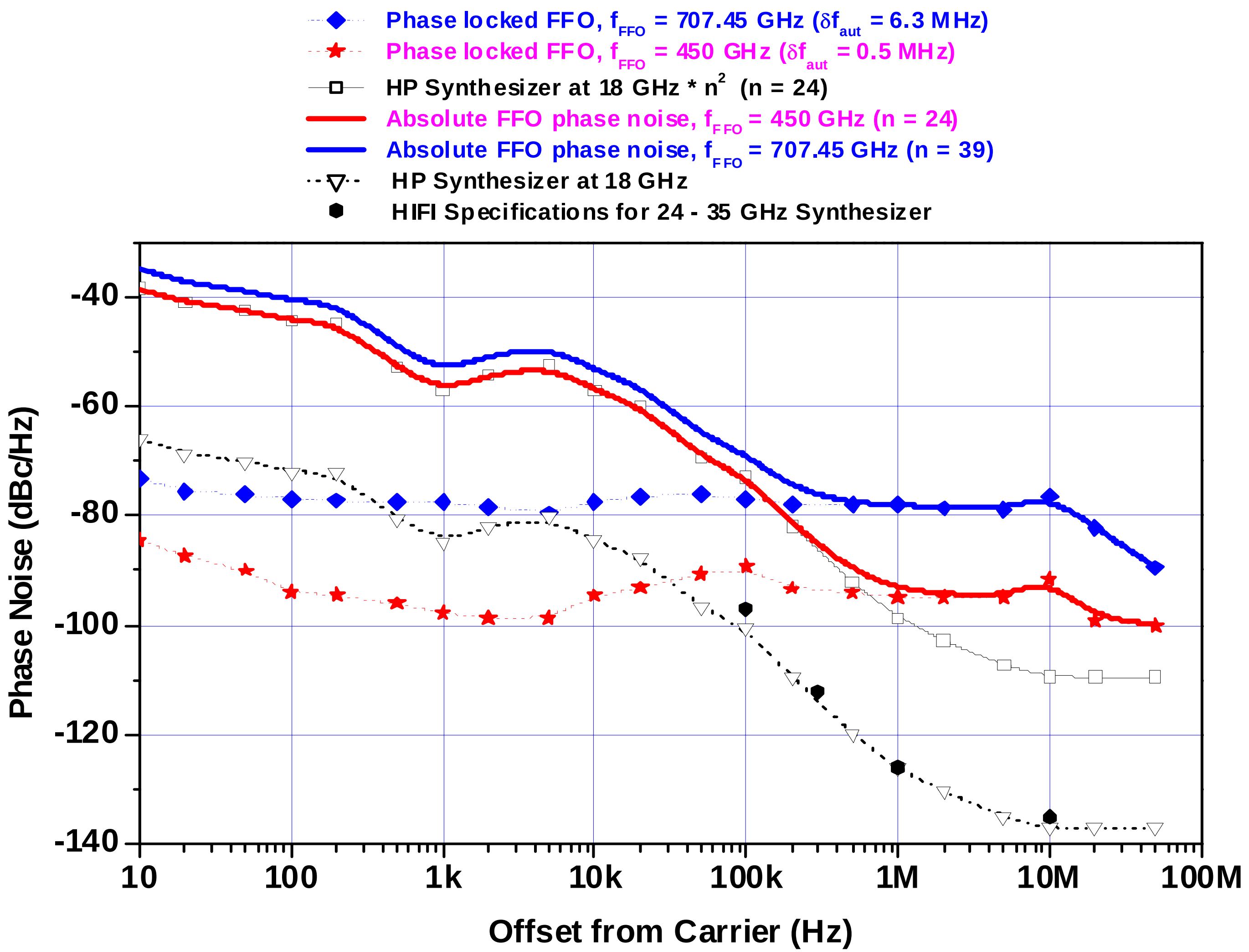


Fig. 14. Phase Noise of the PL FFO. Note that the phase noise at 700 GHz is -80 dBc/Hz at the 1 MHz offset

SIR with Phase-Locked FFO; TELIS Project.

Recent results on phase locking of an FFO to an external reference oscillator have been used to develop an integrated receiver with phase-locked loop: a 350 GHz receiver chip containing a phase-locked flux flow oscillator, and two SIS mixers (a quasioptical SIS mixer, incorporated in a double-dipole antenna for signal detection, and a harmonic SIS mixer for FFO phase locking) has been designed, fabricated and successfully tested. The FFO is phase-locked to the n-th harmonic of a 10 GHz synthesizer source ($n \approx 30 - 35$). Room temperature PLL electronics is used along with a synthesized reference source at about 10 GHz. The microphotograph of the PLL SIR chip for 320-370 GHz band is presented in Fig. 15. The chip is mounted on the flat surface of the silicon microwave lens with antireflection coating; the chip mount is placed inside a magnetic shield. The signal from an external semiconductor harmonic multiplier driven by a different synthesizer has been used to test the integrated receiver with a spectral resolution as low as 10 kHz (see Fig. 16). Very recently a PLL integrated receiver has been tested successfully as a laboratory spectrometer using AOS as a back-end (see Fig. 17 - 20). Broadening of the SO_2 spectral line by increasing the gas pressure in a one-meter long gas cell has been measured in absorption at 326.867 GHz. This is the first demonstration of a spectrometer driven by a Josephson oscillator, which can be tuned precisely and locked at the frequency of a desired spectral line.

As a prelude to future spaceborne atmospheric sounding missions a number of European national institutes joint their efforts to develop a high sensitivity, balloon borne atmospheric sounder that will allow simultaneous measurement of key molecular constituents within the stratosphere. The instrument is called TELIS (TErahertz and submm LImb Sounder) and will provide measurement of atmospheric constituents including OH, O_3, N_2O, CO, HCl, HOCl, ClO, and BrO that are associated with the depletion of atmospheric ozone and climate change (see Fig. 21). The 650 GHz channel is being developed in cooperation between IREE and SRON and is based on a single-chip phase-locked SIR. Details of the SIR-TELIS developments will be discussed in a separate presentation (will be distributed in the beginning of April).

List of the basic publications for all three presentations: “SIR”, “TELIS”, “Towards 1 THz FFO” is given at the end of this document. Most of these publications are available on the web site:
http://www.cplire.ru/html/lab235

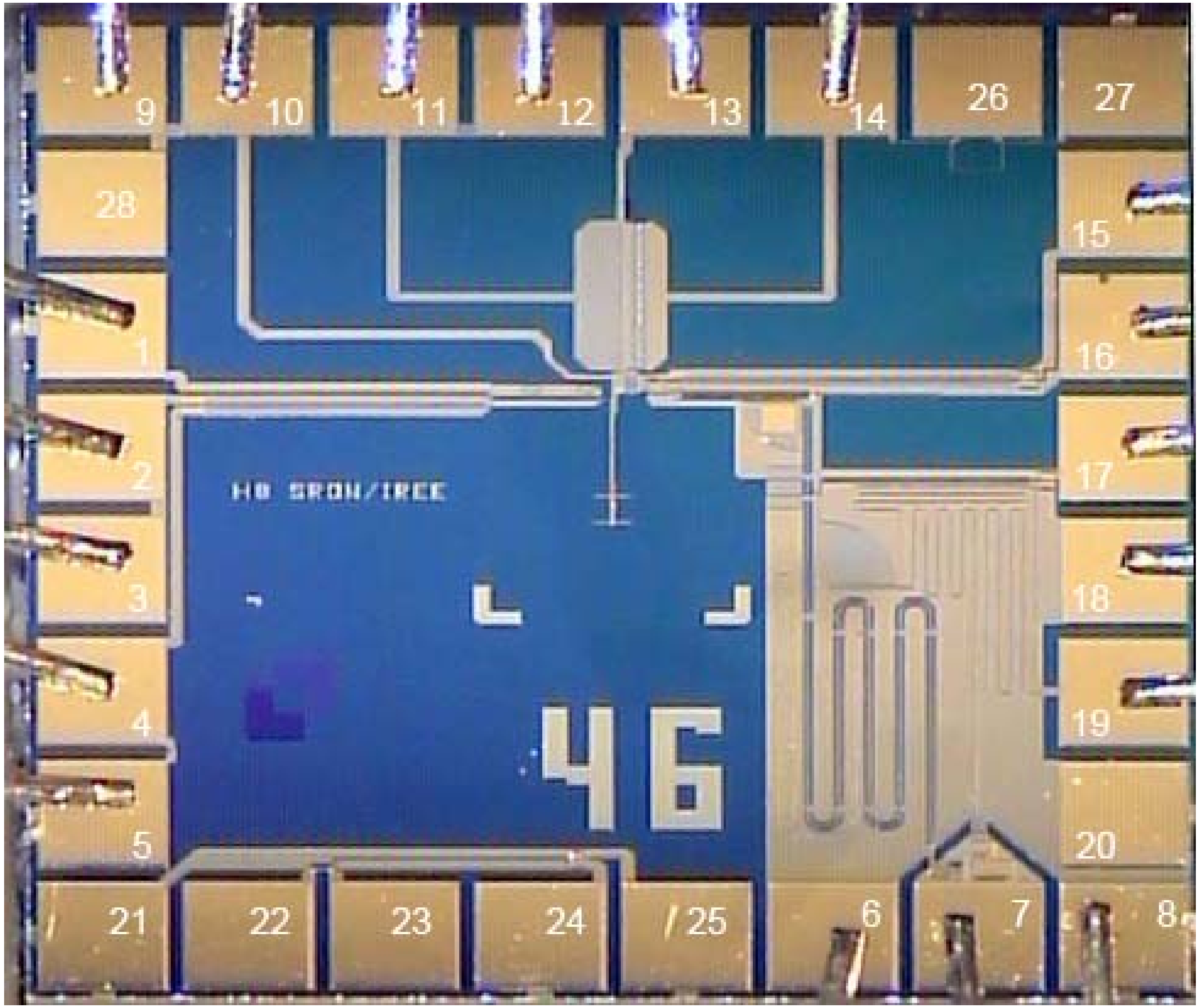


Fig. 15. Microcircuit of the superconducting integrated receiver with phase-locked Josephson oscillator. The chip size is 4 mm by 4 mm.

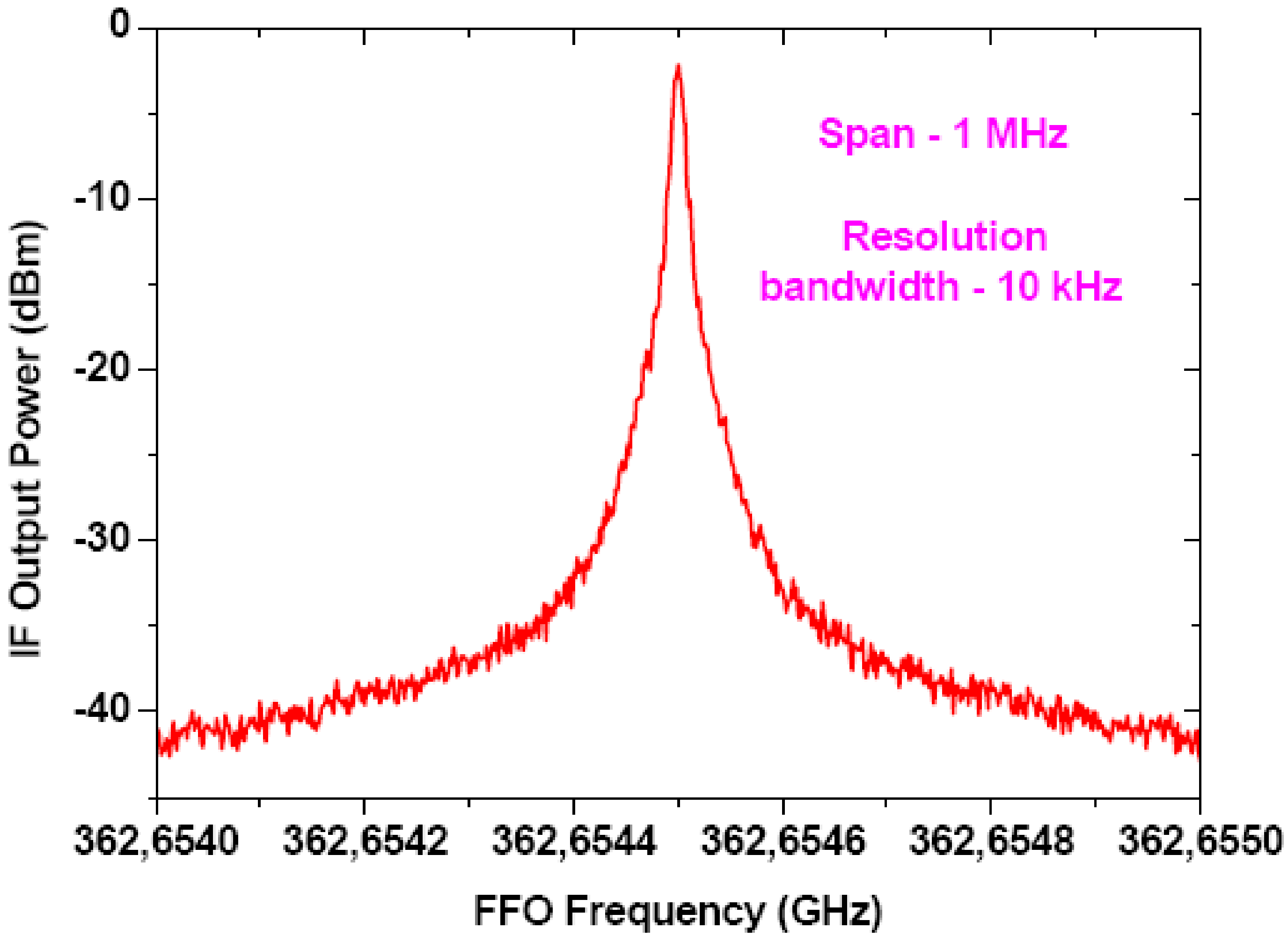


Fig. 16. The signal emitted by an external harmonic multiplier driven by synthesizer, the signal is measured by the integrated receiver with phase-locked FFO at 364.0545 GHz (IF = 1.4 GHz, low sideband).

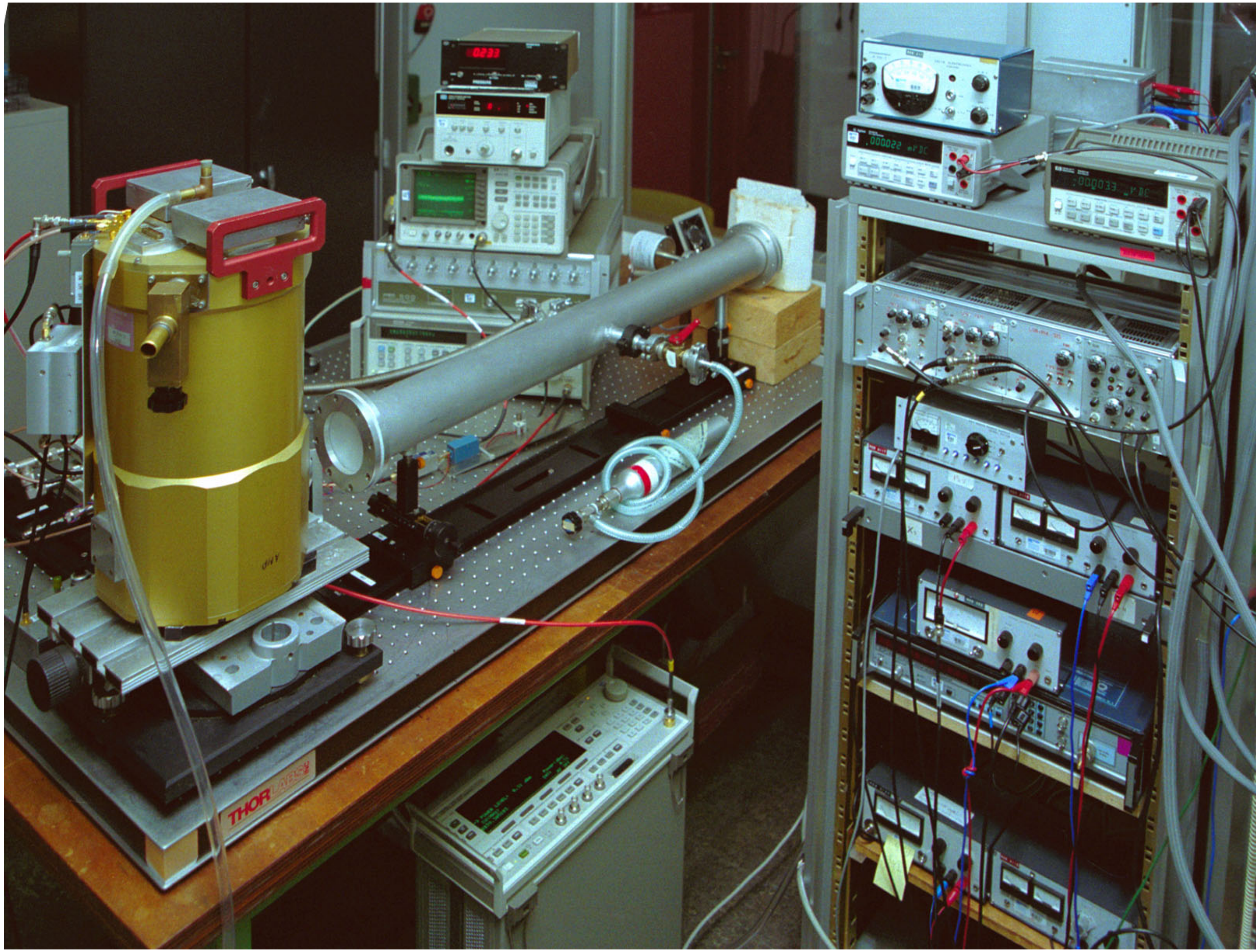


Fig. 17. Gas-cell setup for test of the phase-locked SIR

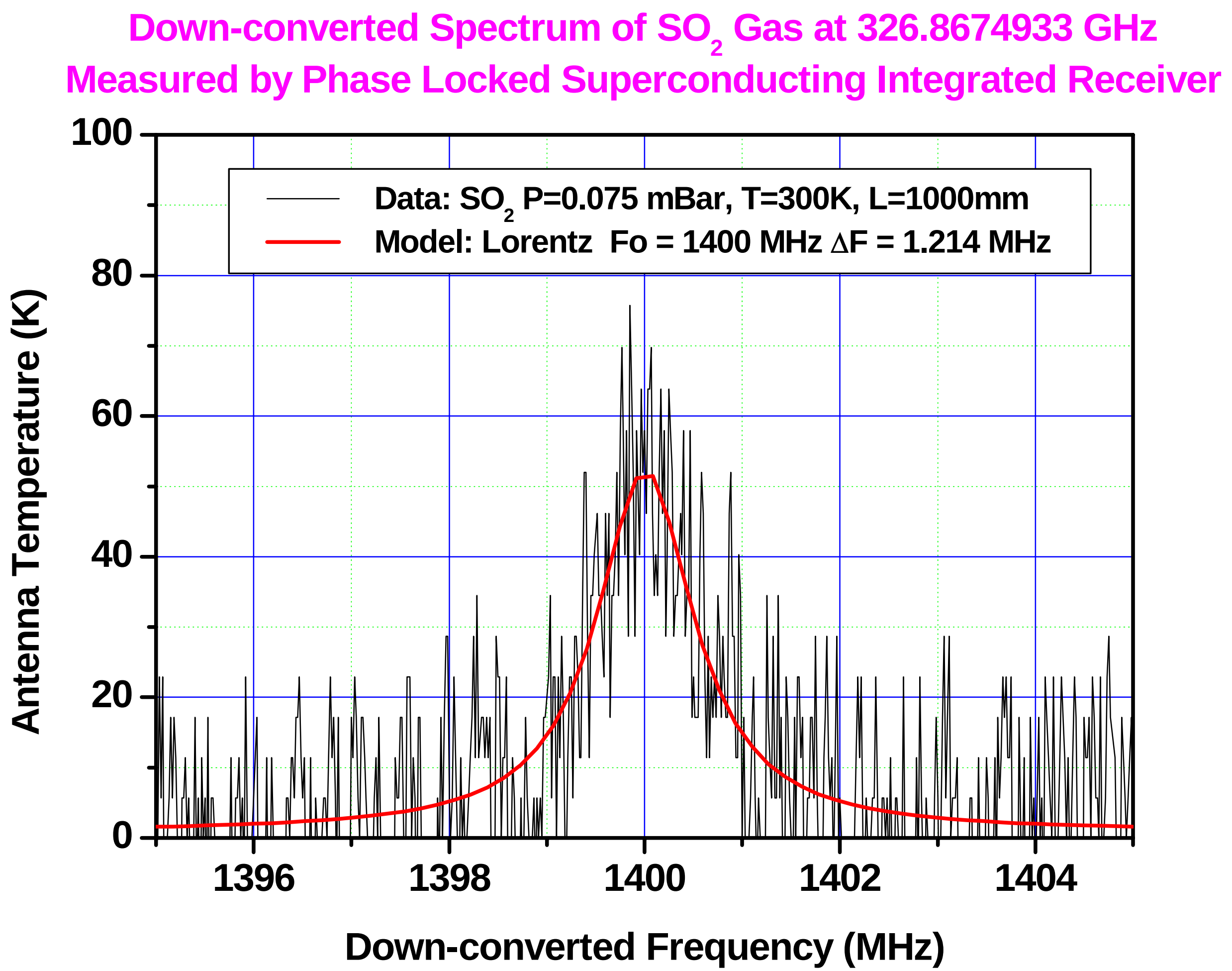


Fig. 20. Spectral line of SO_2 gas at pressure 0.075 mbar measured by superconducting integrated receiver with phase-locked FFO. Fitted theoretical Lorentzian profiles is shown by red solid line.

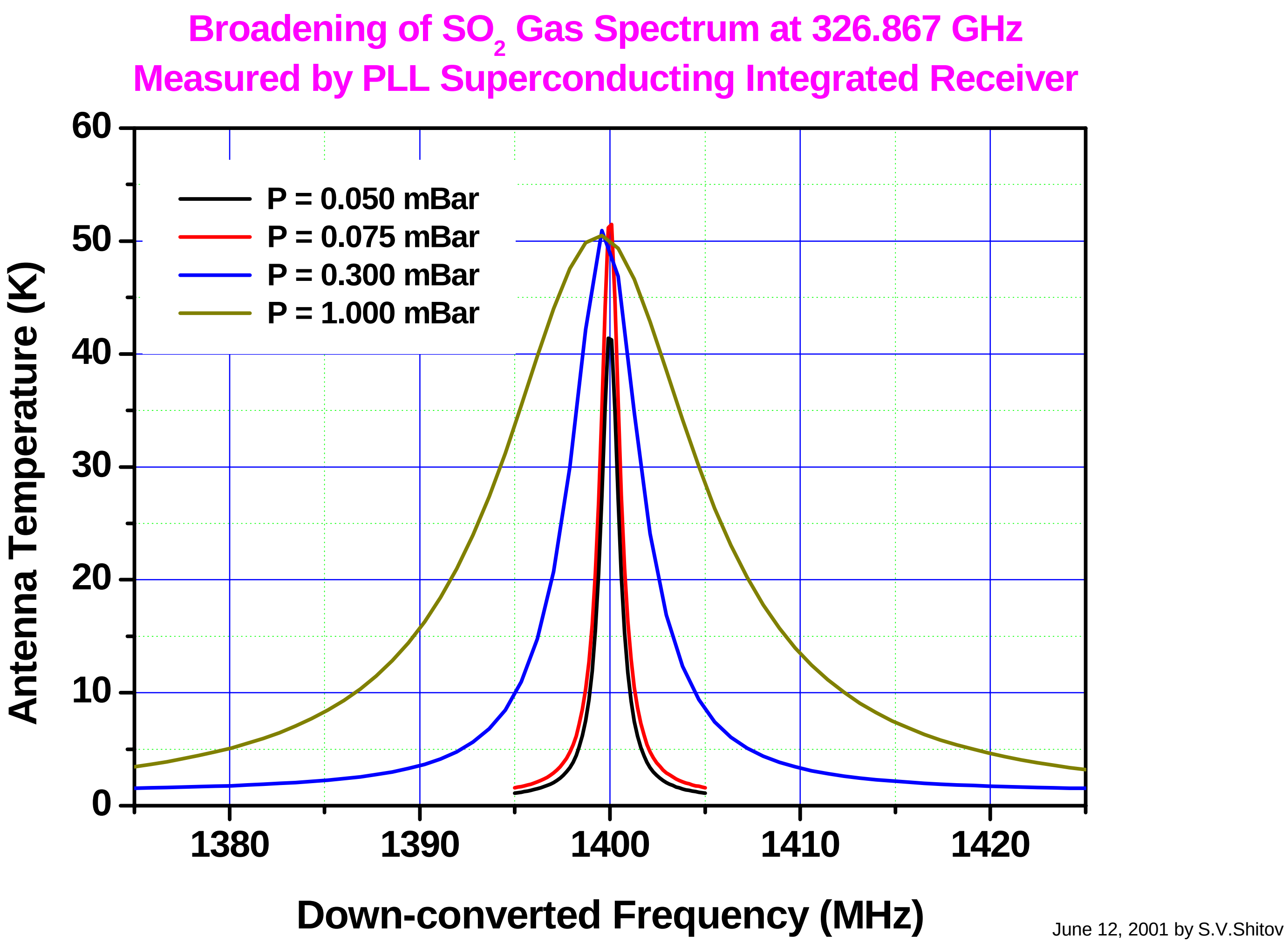


Fig. 20. Effect of broadening of SO2 gas absorption spectrum at 326.867 GHz measured by PLL superconducting integrated receiver. The Lorenzian fit to experimental data is used.

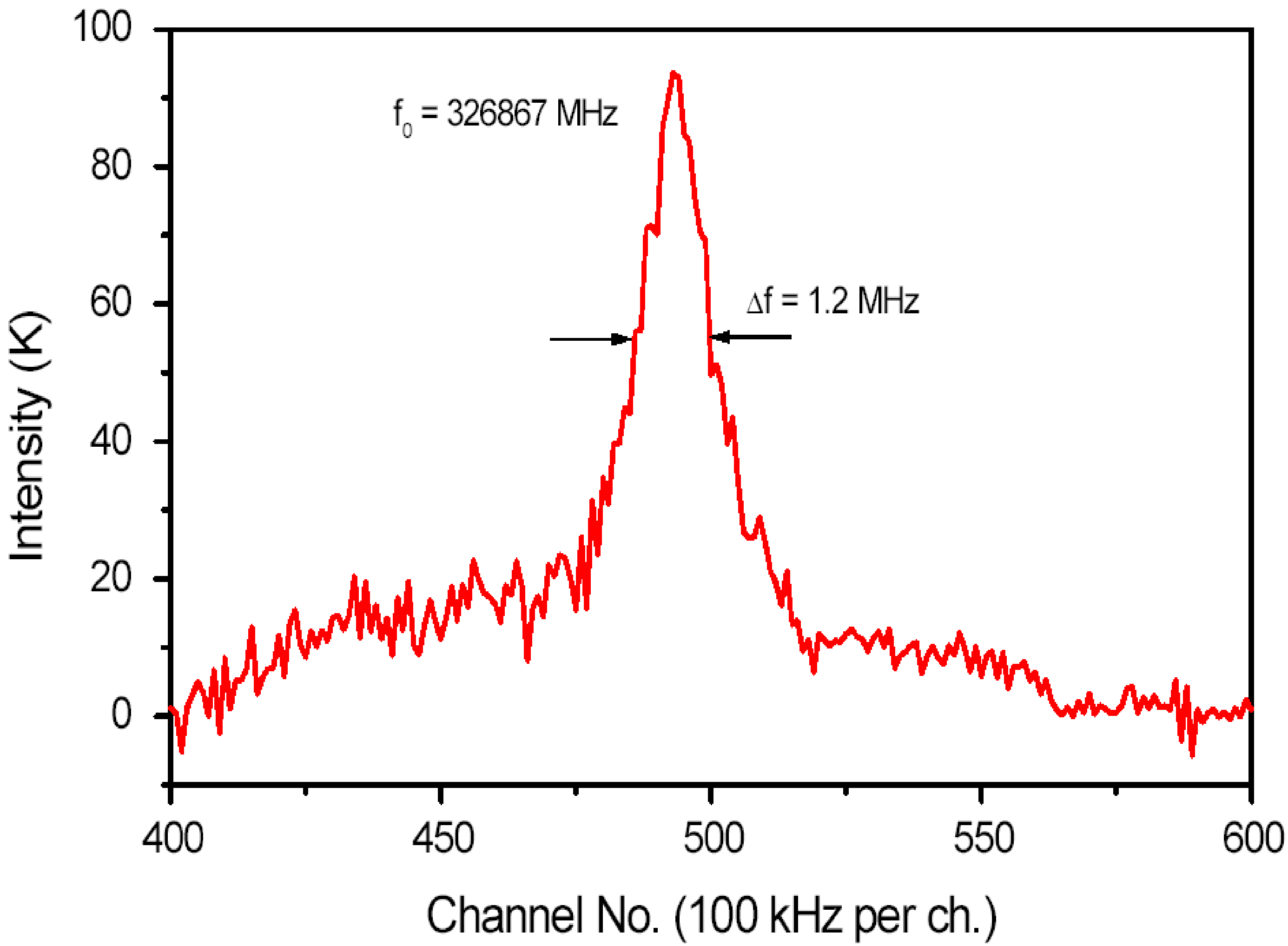


Fig. 20. Spectral line of SO_2 gas at pressure 0.03 mbar detected by superconducting integrated receiver with phase-locked Josephson oscillator (FFO). The data are processed using acousto-optical spectrometer.

Fig. 21. TELIS (TErahertz and submm LImb Sounder)

LIST OF THE BASIC PUBLICATIONS

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2. V.P. Koshelets, S.V. Shitov, A.M. Baryshev, I.L. Lapitskaya, L.V. Filippenko, H. van de Stadt, J. Mess, H. Schaeffer, T. de Graauw, "Integrated Sub-MM Wave Receivers" presented on ASC-94, Boston, USA, report ER-3, (1994). IEEE Trans. on Appl. Supercond., Vol. 5, No. 2, pp. 3057-3060 (June 1995).

3. V.P. Koshelets, S.V. Shitov, A.V. Shchukin, L.V. Filippenko, I.L. Lapitskaya, J. Mygind, "Integrated Flux-Flow Oscillators for Sub-MM Wave Receivers" Proceedings of the International Conference on Nonlinear Superconducting Devices and HTc Materials, Capri, Italy, (1994), Proceedings pp 383 - 401, (1995).

4. V.P. Koshelets, A.V. Shchukin, I.L. Lapitskaya, and J. Mygind. "Spectral Linewidth of Autonomous and Injection Locked Flux Flow Oscillators", Phys. Rev B., vol. **51**, No 10, pp 6536 - 6541, (1995).

5. S.V. Shitov, V.P. Koshelets, A.M. Baryshev, I.L. Lapitskaya, L.V. Filippenko, T. de Graauw, H. Schaeffer, H. van de Stadt, W. Luinge "A Superconducting Planar Integrated Receiver for the Frequency Range 430 - 480 GHz" Proceedings of 6th Space TeraHertz Technology Conference, Pasadena, March (1995)

6. V.P. Koshelets, S.V. Shitov, A.M. Baryshev, A.V. Shchukin, L.V. Filippenko, T. de Graauw, W. Luinge, H. Schaeffer, H. van de Stadt, and J. Mygind, "First Implementation of the Fully Superconducting 500 GHz Receiver with Integrated Flux Flow Oscillator" presented at EUCAS'95, Edinburgh, Great Britain, report OSB1, July (1995). Inst. of Phys. Conf. Ser. Number 148, pp 731-736, (1995).

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