STUDY OF A QUASIOPTICAL SUPERCONDUCTING INTEGRATED RECEIVER FOR IMAGING APPLICATIONS AT 400-700 GHz

Sergey V. Shitov [1)], Valery P. Koshelets [1)], Andrey M. Baryshev [1)], Lyudmila V. Filippenko [1)], Willem Luinge [2)], Jian-Rong Gao [2, 3)], and Petri Lehikoinen [4)].

[1)] Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Mokhovaya 11 Moscow 103907, Russia, *Sergey@hitech.cplire.ru, Sergey@sron.rug.nl*

[2)] Space Research Organization of the Netherlands, P.O.Box 800, 9700 AV Groningen, the Netherlands.

[3)] Department of Applied Physics and Materials Science Center, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands.

[4)] Helsinki University of Technology, Radio Laboratory, Otakaari 5A, FIN 02150 Espoo, Finland.

Abstract

An imaging array receiver for the submillimeter wavelength is being developed. Each of 9 pixels of the array receiver is a single-chip superconducting receiver with dimensions 4 mm x 4 mm x 0.2 mm and contains a planar antenna, an all-Nb SIS mixer, a superconducting local oscillator (FFO) and the necessary coupling circuitry. A prototype design of the array receiver block, its optics and magnetic shielding are discussed. Experimental data for the integrated receiver for high frequency range of 550-700 GHz are reported. A first sample has shown receiver noise temperature of 560 K (DSB) at 645 GHz with optics optimized for 500 GHz. Smooth and permanent tuning has been demonstrated for the integrated LO over frequency range 610-700 GHz. To obtain ultimate coupling for both signals from the antenna and from the integrated LO, the integrated receiver concept with a quasioptical balanced SIS mixer is suggested.

1. Introduction

The term 'Superconducting Integrated Receiver' has been introduced in 1992 with the first attempt to integrate a low-noise SIS mixer and a superconducting local oscillator to form a sensitive single-chip device [1]. Both the light weight and the low power consumption of the device are attractive features for radio astronomy from space, atmosphere monitoring from aircraft, etc. The small size of the integrated devices makes them particularly suitable for a mapping array receiver.

Since the SIS mixers are proven to be the most sensitive front-end detector for a receiver within frequency range of 100 - 700 GHz, and even up to 1000 GHz (see, for example [2] and [3]), our main efforts were put into the study of compatibility of the mixing device with a superconducting Josephson oscillator, in this case a flux flow oscillator (FFO). Such an integration seems not difficult because both devices can be fabricated using the same Nb/Al/Al_xO_y/Nb trilayer [1, 4]. On the other hand, the need for a strong magnetic field to suppress the Josephson effect in the micron-size SIS junction is inconsistent with demand for a relatively weak and stable magnetic field for proper operation of the Josephson oscillator. The solution has been found by integration of superconducting control lines into both SIS mixer and FFO in a way that the interference between two devices is reduced to very small values. Experimental tests at 500 GHz have shown the receiver noise temperature $T_{rx} \approx 150$ K (DSB) and the acceptable beam pattern of the integrated lens antenna [4, 5]. However, about half of the receiver noise is still associated with both imperfection of the coupling of LO power and signal loss towards the LO.

The main advantages of a flux flow oscillator (FFO) over other Josephson oscillators developed up to date, are its simplicity, frequency and power tunability up to 850 GHz [6]. Since the frequency of FFO is determined by an external magnetic field, an effective magnetic shielding has to be used similar to a SQUID magnetometer. Unwanted noise of (or interference to) the bias circuit may also change the voltage across the FFO resulting in a broader effective linewidth. With a frequency locking technique that has been developed and used for precise measurement of the FFO spectrum; a 200 kHz linewidth at 450 GHz has been measured [7]. It turns out that the linewidth is different for resonant and non-resonant regimes; linewidth is usually wider for a non-resonant regime [8]. The effect of frequency locking to a specific frequency of the tunable resonator is required similar to other oscillators, including the Gunn oscillator. Preliminary experiments on synchronization of the FFO with the external source are not finished yet, but encouraging so far [9].

Recent development of wide-band SIS mixers [10] covering main part of the submm range (400 -700 GHz), makes the potential integration with widely tunable FFO even more attractive. The performance of the integrated receiver at highest possible frequency has not been tested yet. We report here first experimental results of integrated receiver near the gap frequency of Nb (600-700 GHz) where losses might become important. The prototype design of the imaging array receiver for 450-550 GHz is presented. New concept of a quasioptical balanced SIS mixer is discussed to realize maximum possible coupling of both signals from the antenna and from the integrated local oscillator.

2. Experimental Tests of the 650 GHz Receiver

a) Design of Chip and *dc/rf* Interface

All experimental chips are of the same dimensions 4 mm × 4 mm × 0.2 mm. This area contains a double-dipole antenna SIS mixer placed in the center, superconducting local oscillator and all necessary *dc*- and *IF*-interface. Eleven contact pads are located along the edge of the chip and wire bonded by *Al* wire to the printed circuit board (PCB). The PCB provides mechanical support for *dc*- and *IF*-connectors and also springs down the chip against the flat surface of the hyper-hemispherical lens providing sufficient heat contact to the liquid helium bath. Part of the wafer layout is shown in Fig. 1. The receiver chips for frequency range of 550-700 GHz (nominally tuned at 650 GHz) have a smaller size of antenna. The devices with a larger antenna for a frequency range of 400 - 500 GHz are used as a reference since their design has been tested before [5]. The integrated FFO is placed closer to the left-low corner of the chip. The LO power is supplied to the mixer via a superconducting micro-strip transmission line which contains a number of *dc*-blocking elements. For the fabrication procedure and for the details of the chip receiver design see [1, 4].

b) Mixer/Receiver Noise Temperature Test

The 650 GHz integrated mixers have passed two tests: a pre-test at *dc* and a *rf*-test with Fourier Transform Spectrometer (FTS). Both tests have demonstrated that SIS mixer is tuned at a central frequency of about 640 - 650 GHz and the integrated LO is providing mixer-coupled power of 60-70 nW. The pumped current-voltage characteristic (IV-curve) of the SIS mixer is presented in Fig. 2. The Josephson effect in the mixer is suppressed at about its first minimum by the integrated control line carrying *dc*-current of about 30 mA.

The complete test of the integrated receiver has been carried out in a vacuum cryostat with optical window. The chip mount and optics were the same as used for 500 GHz receiver experiments. The results reported are not corrected for a mismatch due to the optics and window. The data of *rf*-test with external and internal LOs for two temperatures of the LHe bath are presented in Fig. 3. Outside the region of best tuning, the noise temperature is higher for the internal LO that is caused by lack of the LO power.

The high frequency cut-off is found to be very close to the gap frequency of Nb (680 GHz at 4.2 and 700 GHz at 2.5 K, for our samples). The attenuation in the transmission micro-strip line which is carrying LO power from the FFO, becomes high at about gap frequency of Nb. At lower frequencies the pump was found to be low because the FFS become much "shorter" that means unstable operation of the FFO at higher bias current (at higher power).

The sharp drop of the noise temperature T_{rx} that one may expect from the FTS pre-test, was not found around 645 GHz for both internal and external LOs. It could be due to the presence of excessive noise picked up at the *input* of the mixer (i.e. this noise is not dependent on mixer's gain). A more thorough analysis seems necessary to find out whether losses in LO circuits at 645 GHz are crucial for low noise operation of the integrated receiver near the gap frequency of Nb.

c) Antenna Beam Pattern

The receiver antenna beam was formed by two printed dipole antennas integrated with the SIS mixer and two quartz lenses: hyper-hemispherical one (diameter 10 mm) and front lens f = 40 mm (diameter 24.5 mm). The antenna beam pattern was mapped in front of the dewar's window at the distance of about 45 cm. The mapping is based on detection of a broad-beam source which is being translated in front of the cryostat in the plane perpendicular to the receiver beam axis. The antenna beam pattern presented in Fig. 4 shows main sidelobes at the level of about -12...-15 dB. The beam is not perfectly symmetric. A small of misalignment of the antenna with respect to the center of hyper-hemispherical lens can explain the incomplete symmetry of the beam.

d) Integrated Local Oscillator

Since the frequency of Josephson oscillator has fundamental relation with *dc*-voltage across the tunnel barrier of SIS junction, the tuning range of the integrated LO has been tested via measuring the dependence of its bias *voltage* on control line current while the bias *current* of the FFO was kept constant. Figure 5 shows the experimental data on tuning of the FFO. The LO is showing a *continuous* tuning which is almost linear from 550 GHz up to 700 GHz. The point of limited stability indicated in Fig. 5 means that the bias current of the FFO has to be decreased to obtain continuous tuning over this point. The decrease of the bias current means lower output power of the LO.

It has been found recently that the FFO has at least two distinctive regions of operation within the sub-mm range. Resonant operation takes place at bias voltages less than a *boundary* value of $V_{gap}/3$ that associated with a frequency range below 470 GHz [8]. This regime is characterized by presence of resonance Fiske steps (FS) because of low dumping of the junction cavity. The bias voltage of FFO is strongly locked to the FS that means limited tunability of the oscillator (operation is not stable between FS).

A continuously tunable flux flow regime might be realized at higher voltages (frequencies) where FS are dumped by quasi-particle loss, so flux flow steps (FFS) take place. The most important difference between these two regimes is the FFO linewidth (LW). The resonant regime is characterized by FS with much lower dynamic resistance, R_d, and the typical free running LW is relatively low (less than 1 MHz), but poor tunability is the price. In the non-resonant regime ($f \geq 500$ GHz) the dynamic resistance is much higher that is one of the reasons for broadening of LW. The experimental data of a free running FFO are presented in Fig. 6.

The data graph might be split into three regions. The first region has lowest R_d (0.001 - 0.02 Ω) that usually happens in the resonance regime at relatively low frequencies. Within this region the linewidth is following theoretical model [11] and might be associated with a constant fluctuation current of 0.2 μA. The second region is characterized by more sharp increase of LW that can be explained in terms of higher effective temperature. The estimated value of about 27 K is associated with external interference to the FFO. The much wider LW is measured in the non-resonant regime (presented by diamonds). The experimental value for the non-resonant regime is almost one order higher than LW of resonant regime for the same $R_d \approx 0.02$ Ω. This effect might be explained with the recent theory [12] in terms of elastic noise of the fluxon chain in absence of locking resonant conditions.

To realize the FFO operation with LW about (or smaller) than 1 MHz above the *boundary* voltage, two sets of experiments are in progress. In the first experiment devices have an integrated *rf* feed-back circuit to check whether it is possible to create quasi-resonant conditions for the FFO with high damping. The injection locking of the FFO to a 10 GHz synthesized source will be tested in the second set of experiments using an on-chip FFO-multiplier.

3. Imaging Array Receiver Design

The imaging array of 9 pixels in the frequency range 450-550 GHz is planned to be tested within one year from now. The sketch of the main receiving block is presented in Fig. 7. To achieve both dense packaging of the pixels and equal quality of all beams (f/10), use of diffraction limited silicon elliptic lens (diameter 10 mm) is planned in each individual pixel. Silicon elliptical lenses and their anti-reflection coatings from Stycast™ epoxy [3] are manufactured using precision diamond turning. Each pixel is designed to be the same optically, mechanically and electrically for easy replacement. The chip receivers fabricated on silicon substrates will be tested individually to guarantee *the best selection* for both main receiver and its replacement.

Since the FFO is a magnetic field sensitive device, the magnetic shielding is very important. Present design has two magnetic shields: an external tube from μ-metal and an internal one from superconducting material with option to heat it up in order to release trapped flux (see Fig. 7). To study the shield efficiency, the experimental chip receiver has been tested about 10 times during half-year showing reasonably stable and repeatable operation.

4. Balanced SIS Mixer Concept

Since a wide tuning range (400 - 700 GHz) and a reasonably good sensitivity have been demonstrated for a twin-junction double-dipole SIS mixer [10], there is an interest to combine this device with a Josephson LO into an integrated receiver of superior quality. However, it was found that injection of LO power via micro-strip coupling circuitry is not obvious for the twin-junction mixer. The extra problem of limited LO power is important because both junctions of the balanced mixer have to be pumped to the same level that means approximately twice more power must be coupled from the FFO. A balanced mixer basically allows complete coupling of both signal and LO power (Fig. 8). Two junctions of the mixer are connected in series to the LO, but they are in parallel to the signal coming from the antennas in such way that no leak of the in-phase signal power is possible to the LO path. The optimal signal coupling might lead to a factor of two *lower noise temperature* along with *extra power* coupled from integrated LO. We hope that an integrated receiver with balanced mixer might operate at the level of the best SIS receivers pumped by a 'traditional' LO. A few experimental samples of the balanced receiver are pre-tested at *dc* and ready for further *rf*-study. The bandwidth of the balanced mixer of present design supposed to be about the same as of a single-junction mixer (60 - 90 GHz). Next is the study of an integrated receiver with *balanced wide-band twin-junction mixer*.

Summary

1. The integrated receiver on a base of niobium trilayer $Nb/Al/Al_xO_y/Nb$ is useful up to 700 GHz. Since 1992 integrated receivers of different design have been tested within frequency range 100-700 GHz showing noise temperatures better than 1 K/GHz close to the performance of 'traditional' SIS receivers with external LO.

2. The linewidth less than 1 MHz is typical for integrated LO within the frequency range below 450-470 GHz when operated in the resonant regime. However, much wider linewidth has been observed in the easy-to-tune regime of the FFO at higher frequencies. To improve the spectral resolution of the integrated receiver, tunable frequency- and phase-locking systems are under study.

3. The imaging array receiver of 9 integrated receiver pixels with elliptical silicon lenses is designed and will be complete within one year.

4. The new quasioptical balanced SIS mixer is designed using an advantage of the integrated *rf*-interface that provide complete coupling of power for both input signal source and the local oscillator. This approach may lead to ultimate quality of the integrated receiving device.

Acknowledgments

The work was supported in parts by Russian Program for Basic Research, the Russian State Scientific Program "Superconductivity," and ESA TRP contract No. 11653/95/NL/PB/SC.

References:

[1] V. P. Koshelets, A. V. Shchukin, S. V. Shitov, and L. V. Filippenko, *IEEE Trans. on Appl. Supercond., vol. 3, No. 1, pp. 2524-2527, 1993.*

[2] R. Blundel and C. E. Tong, *Proc. IEEE, vol. 80, pp. 1702-1720, Nov. 1992.*

[3] H. van de Stadt et al. *Proc. **6th** Int.Symp. on Space THz Techn., March 1995, Pasadena USA.* M. Bin, M. C. Gaidis, D. Miller, J. Zmuidzinas, T. G. Phillips, H. G. LeDuc, *Proc. **7th** Int.Symp. on Space THz Techn., March 1996, Charlottesville, USA, pp. 549-560.*

[4] V. P. Koshelets, S. V. Shitov, L. V. Filippenko, A. M. Baryshev, H. Golstein, Th. de Graauw, W. Luinge, H. Schaeffer, H. van de Stadt, *Appl. Phys. Lett. **68** (9), pp. 1273-1275 (February 1996).*

[5] S. V. Shitov, V. P. Koshelets, A. M. Baryshev, L. V. Filippenko, T. de Graauw, J.-R. Gao, W. Luinge, H. van de Stadt, N. D. Whyborn, P. Lehikoinen, *Proc. 7th Int.Symp. on Space THz Techn., March 1996, Charlottesville, USA, pp. 417-425.*

[6] 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, *IEEE Trans. on Appl. Supercond., **5**, 3057 (1995).*

[7] V. P. Koshelets, S. V. Shitov, A. V. Shchukin, L. V. Filippenko, and J. Mygind, *Appl. Phys. Lett. (July 1996).*

[8] 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". *Submitted to Phys.Rev.*

[9] V. P. Koshelets, A. V. Shchukin, I. L. Lapitskaya, and J. Mygind, *Phys. Rev B., (1995).*

[10] S. V. Shitov, A. M. Baryshev, V. P. Koshelets, J.-R. Gao, J. Jegers, W. Luinge, H. van de Stadt, Th. de Graauw, *Proc. 7th Int.Symp. on Space THz Techn., March 1996, Charlottesville, USA, pp. 525-535.*

[11] M. J. Stephen, *Phys. Rev. Lett., **21**, 1629 (1968).*

[12] A. A. Golubov, B. A. Malomed, A. V. Ustinov, *Phys. Rev. B, **54**, 3047 (1996).*

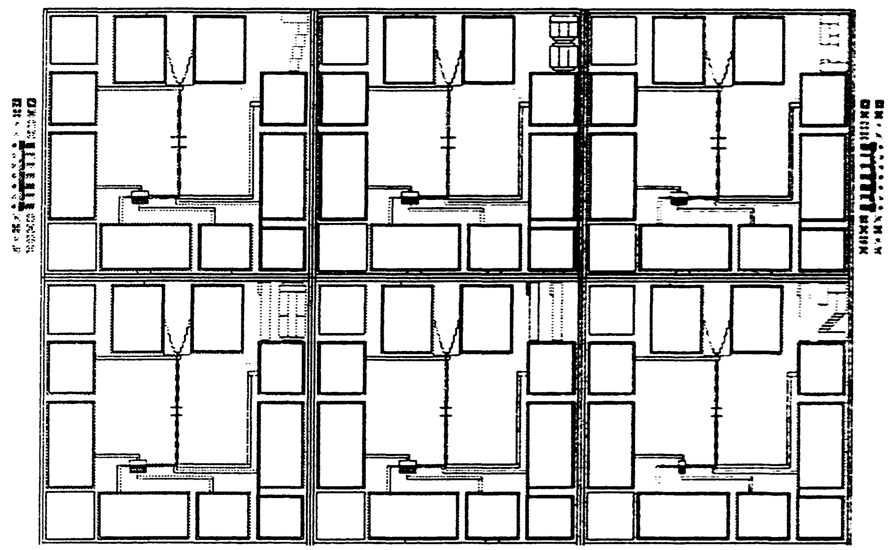

Fig. 1. Layout (partial view) of the quartz wafer containing 15 integrated receiver (only 6 chips are shown). The chip dimensions are 4 mm × 4 mm × 0.2 mm including the area of contact pads (0.7 mm × 0.7 mm). The double-dipole antenna SIS mixer is in the center of each chip; local oscillator (FFO) is at low-left from the mixer. The receivers for operation within 400-550 GHz (larger antennas) and 550-700 GHz (smaller antennas) are fabricated at the same wafer.

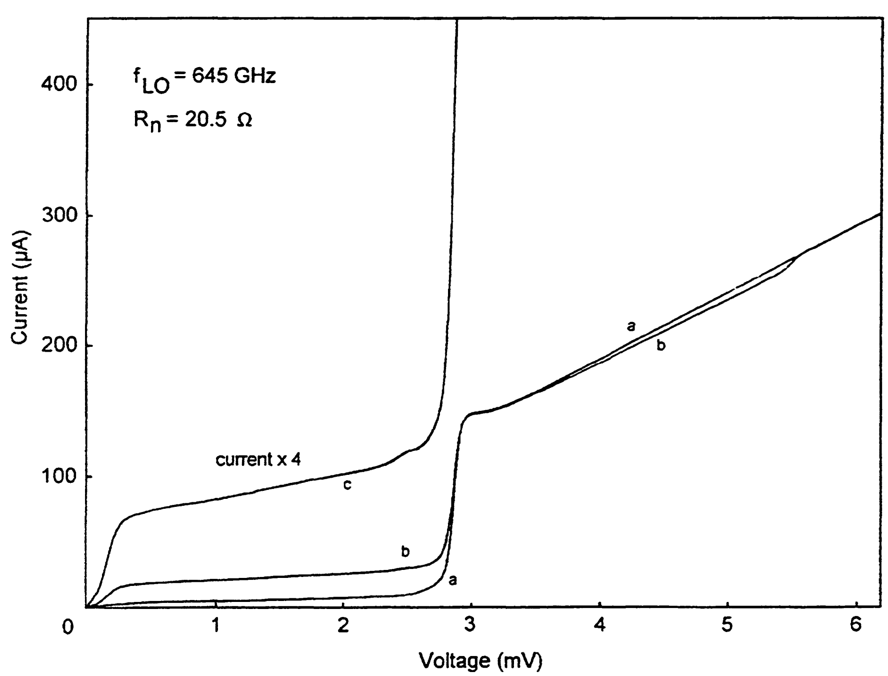

Fig. 2. Unpumped (a) and pumped (b) IV-curves of SIS mixer. The integrated LO at 645 GHz is used. The curve (c) is the same as (b), but it is magnified four times (× 4) in vertical scale.

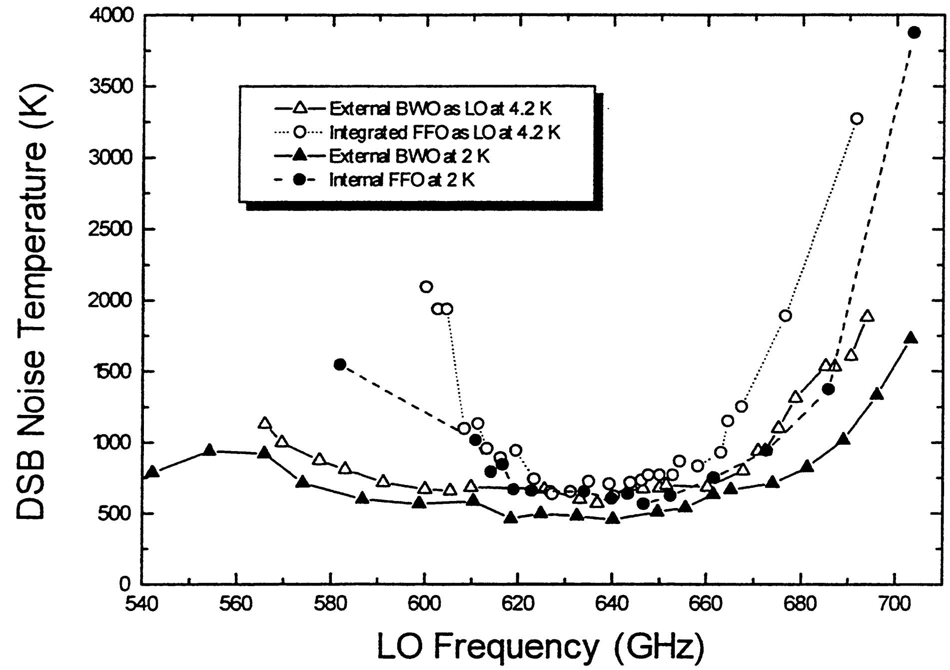

Fig. 3. Noise temperature for the integrated receiver within frequency range 540-705 GHz for both external and internal (integrated) local oscillators at two temperatures of the liquid helium bath.

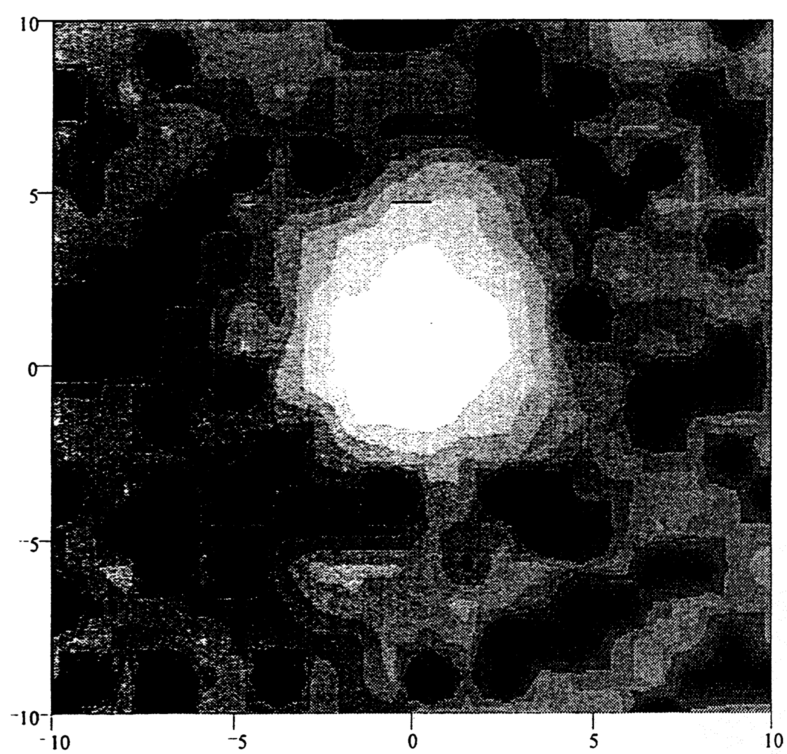

Fig. 4. Contour plot for the antenna beam pattern of the integrated receiver measured in front of the cryostat at 645 GHz. The step of gray scale is 3 dB. Both axes are in angular degrees.

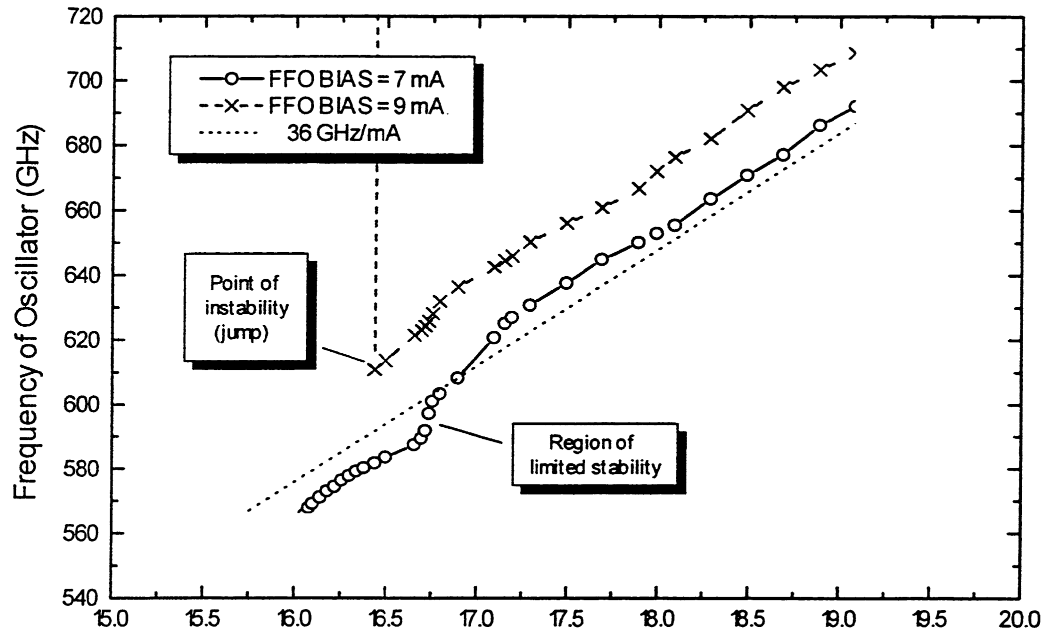

Fig. 5. Tuning characteristic of the superconducting flux flow oscillator (FFO) at about the gap frequency of niobium.

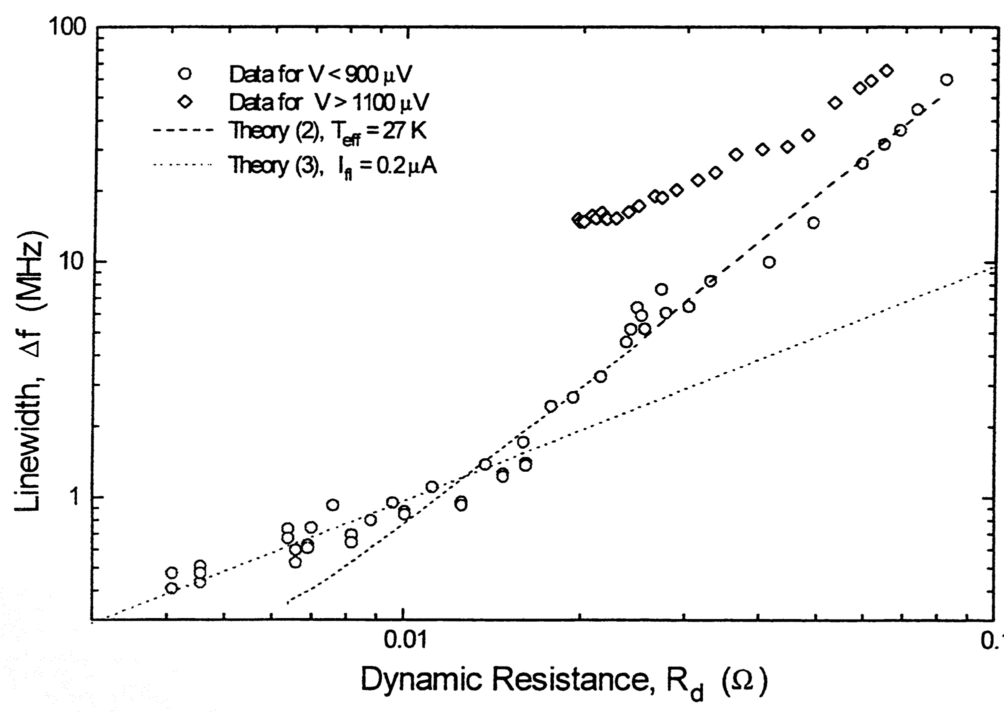

Fig. 6. Experimental data on FFO linewidth for different operating regimes.

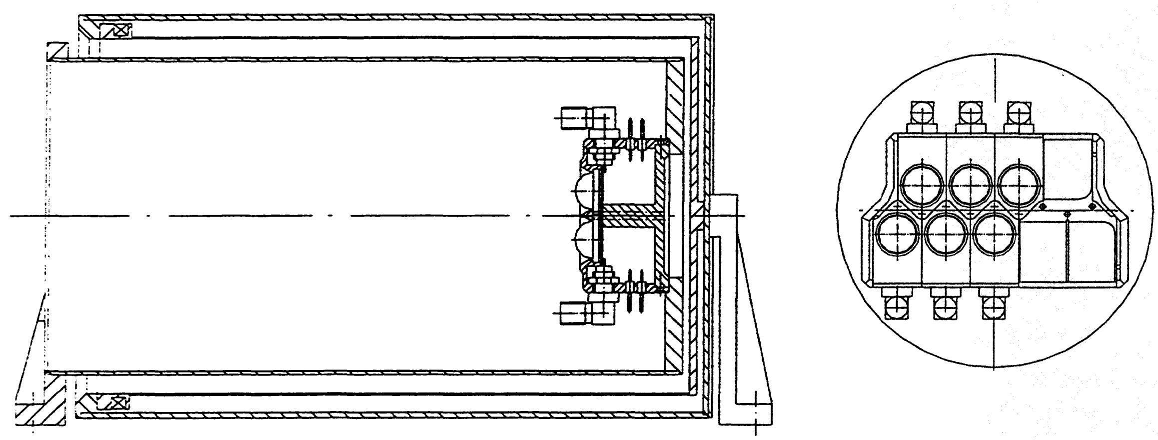

Fig. 7. Design of a prototype imaging receiver with individual silicon single-lens optics at each of 9 pixels. The two-layer shielding is used with the external cylinder from μ-metal and internal one from a superconducting material.

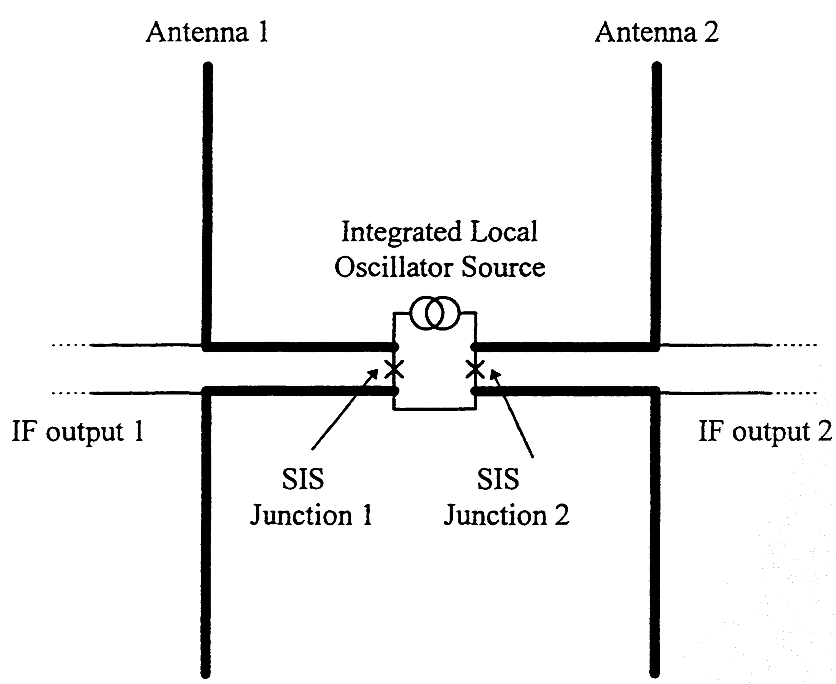

Fig. 8. Schematics of a quasioptical balanced double-dipole antenna SIS mixer. The mixing SIS junctions are connected to the integrated LO in series. Two output signals at IF are phase-shifted (180°) and have to be combined in-phase.