A Superconducting Planar Integrated Receiver for the Frequency Range 430-480 GHz

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Abstract

A planar receiver comprising a Josephson flux-flow oscillator (FFO), a double dipole antenna and a SIS mixer integrated on a single chip within an area of 3 x 3 mm has been realised in the frequency range of 400-500 GHz. RF tests have been performed at temperatures between 2 K and 4.2 K. A best DSB noise temperature of 595 K ± 20 K at 465 GHz was obtained for the receiver with the mixer pumped by the FFO. The width of the antenna beam has been measured referred to the input window of the cryostat and was about ± 4 degrees at the power level of about - 20 dB. The power consumption of the whole device is estimated to be 20 μW.

Introduction

Recent developments in the field of superconducting thin film technology and RF design resulted in sensitive SIS mixers for heterodyne receivers in both the mm and the submm wavelength regions (1). In addition, a number of important RF components such as two types of oscillators based on synchronous arrays of lumped Josephson junctions (2-4) and long Josephson junctions (5-8), SIS attenuators (9) and *dc* SQUID RF amplifiers (10), have been developed or improved recently and can be used in combination with SIS-mixers. New superconducting RSFQ elements (11) could also be used, for example, in a digital correlators for data processing. All these devices are fast enough and have very low power dissipation. Integration of these elements on a single chip to create a small size and low power consumption receiving system for airborne/ spaceborne astronomy and environmental monitoring at mm and submm wavelengths, is an important step to be done.

In order to realise a fully integrated receiver in the submm region one has to put close together an antenna feed, mixer element, local oscillator including a power injection system, IF-amplifier and preferably also a back-end spectrometer. It is clear that such a complicated device will consist of a number of chips. For example, the front end including the antenna, mixer and LO source could be on a single chip. There is no doubt that an SIS mixer must be used in an integrated receiver. However, the choice of the best suitable LO between existing superconducting oscillators still has to be made.

Both types of superconducting oscillators mentioned above are voltage tuneable sources according to the Josephson relation $f = V/\Phi_0$; $\Phi_0 = h/2e$. For the first type, the synchronous array, reasonable output powers (up to 40 μW) have been obtained at frequencies of about 400 GHz in a matched load (3); but no linewidth narrower than 10 MHz has been measured for a Josephson 10-junctions array (4). The synchronous array with a number of junctions of $N{\sim}10^3$ could provide a linewidth of about 100 kHz, but the device seems rather complicated and it has not been tested yet. The distance between adjacent junctions (or between compact groups of junctions) in the array should be equal to the wavelength λ in order to provide phase synchronisation; so the overall dimension of such a device is rather large. Another disadvantage of the synchronous arrays is its narrow range of frequency and power tuning.

For the second type of Josephson oscillator, the long tunnel junction, two different modes of oscillation can be used as a microwave source: i) resonant soliton motion (at weak magnetic field applied to the junction with low damping), whence this device is called the soliton oscillator; ii) unidirectional and viscous magnetic flux flow (at relatively large applied magnetic field) in a junction with high damping. The soliton oscillator has very narrow linewidth (5), and its frequency is strictly determined by the junction length. Only a relatively small power can be delivered to the load in this case.

At large magnetic field the unidirectional flow of the fluxons (flux quanta Φ_o) occurs in a long Josephson junction (6-7). Long means that the junction length $L >> \lambda_j$, while the width of the junction $W \leq \lambda_j$, where λ_j is the Josephson penetration depth. Under the influence of bias current and magnetic field H fluxons are created at one end of the junction. These fluxons form a Josephson vortex array that is driven to the opposite end by Lorentz force due to bias current. The fluxons annihilate at the end of the junction creating pulses of electromagnetic energy. This kind of fluxon motion manifests itself as a current step in the dc I-V curve, the so-called Flux Flow Step (FFS), at the voltage:

$$V_{FFS} = f_{FFS}\,\Phi_o = \upsilon N \Phi_o / L = \upsilon \Lambda H, \qquad (*)$$

where υ- the propagation velocity of electromagnetic waves in the Josephson junction (Swihart velocity), typically 1-2 % of the light velocity in the vacuum; N is a number of fluxons in the junction and $\Lambda=(\lambda_L+\lambda_L+t)$ is the magnetic thickness of the junction (λ_L is London penetration depth). It is possible to explain qualitatively the appearance of the FFS by an interaction of the oscillating Josephson current with the travelling electromagnetic pulses of the same frequency.

Using (*) one can see that the FFS voltage, and consequently the oscillation frequency of the Flux-Flow Oscillator (FFO) is directly proportional to the applied magnetic field. The FFO frequency can be tuned over a wide frequency range and is limited only by the superconducting gap frequency (6-8). Moreover, in the case of a strong enough field, the FFO provides a nearly sinusoidal output with low content of higher harmonics and sufficient power to pump a SIS array mixer. The phase-locking of the FFO with external oscillator seems to be possible (12). In summary, this is why the FFO seems the best choice for the local oscillator for submm integrated receiver.

Since all proposed components have *compatible fabrication processes*, the next step in the research of an integrated receiver is the development of new interfaces that make all components *compatible on the same substrate*. For example, the FFO integrated on the same chip with SIS mixer has to be controlled by a relatively weak magnetic field. But the strong field usually applied to a micron size SIS-junction by an external coil could disturb the operation of the FFO. The use of local magnetic fields concentrated near each device seems to be necessary in the case of a submm SIS-mixer and FFO integrated on a chip.

The injection of LO power can be realised not only by quasioptical coupling of the beam to the antenna, but also via an integrated interface (transmission line) connected to the SIS-junction (or the array of SIS junctions). It should be mentioned that a SIS array usually needs more LO power. Significant losses of the incoming signal into the LO path could happen in case of strong coupling between the FFO and the mixer. However, reduction of LO coupling by more than -10 dB could cause lack of the mixer pump since the power available from the experimental FFO is of the order of 0.3 μW. An estimate of FFO power at bias point (I_{FFO}, V_{FFO}) is $kI_{FFO}\cdot V_{FFO}$, where $k \approx 0.15$, that has been evaluated from the experimental data (13),(14). Because of mentioned limitation of available LO power, a single junction design of SIS mixer looks more attractive.

Description of the experimental chip

The well-developed concept of a double-dipole antenna SIS-mixer (15) has been chosen as a basic approach. The point symmetry of the double-dipole design allows us to use additional leads as an interface between the mixer and other parts of the integrated receiver. A drawing of the central part of the experimental chip of full size 4x4x0.2 mm is presented in Fig.1. The SIS mixer comprises double dipole antenna and tuned 1 μm size SIS junction Nb-AlO_x-Nb. The FFO is on the same chip, but separated from the mixer by a choke structure that prevents leakage of the RF input signal from the antenna. The microstrip transmission line connecting the LO and the mixing junction lies on top of the choke structure. A simplified equivalent diagram of the device is presented in Fig.2.

A. SIS mixer

The single junction SIS mixer of an original design is featured by tuning strips used as the control line for the "internal" magnetic field. An SIS junction is placed in the center of the 3 μm wide strip which is connected to both dipole antennas (210 x 10 μm each) via two λ/4 microstrip transformers. The control current of the line I_{cl} produces the magnetic field applied to the junction. The size of the dipole antenna was chosen such that no counter reflector needs to be used. Of course, it is a compromise between sensitivity and simplicity of the device that was accepted for the first experiments. The use of both a movable backshort and a counter reflector is planned for a future development. Four contacts on the chip are used to control the SIS-mixer. Two of them, as usually, provide the bias current and pick-up the IF output signal, the two others are connected to the control line to suppress the Josephson noise (see Fig.1,2).

We use a quasi-optical mount containing two lenses. The sample is mounted on the flat back side of a fused quartz hyper hemispherical lens (R = 5 mm) with the double-dipole antenna being in the center. The hyper hemispherical lens is illuminated by a primary quartz lens (F ≅ 65 mm, D = 20 mm, effective) coated with antireflection Teflon film 100 μm thick. 8 pads on the chip and 10 pin contacts of the mounting are used to control the whole device. The mount is placed in vacuum on the cold plate behind an RF transparent window in cryostat with liquid helium.

SIS mixers with an "internal" magnetic field source passed preliminary RF tests that were performed in a mixer block of similar design and demonstrated good suppression of *ac* Josephson effect (Shapiro steps) when operated at 400-450 GHz. Receiver DSB noise temperature of about 300 K were measured with an external LO source (carcinotron) at 430 GHz (16).

B. Local oscillator

The FFO in the tested samples are designed in overlap geometry with length L = 450 μm and width W = 3 μm. The Josephson penetration depth was estimated to be $\lambda_j \cong 4$ μm. It is known that the "idle" overlapping strongly affect the FFO properties, i.e. the propagation velocity (17). We minimised the idle overlapping to 6-10 μm in the present design.

To avoid the self field effect that leads to inclination of the FFS, the bias current should be distributed in the same manner as supercurrent in the tunnel junction (6, 8). The improved bias is realized by employing a "tail" without direct current injection at the end of the junction where

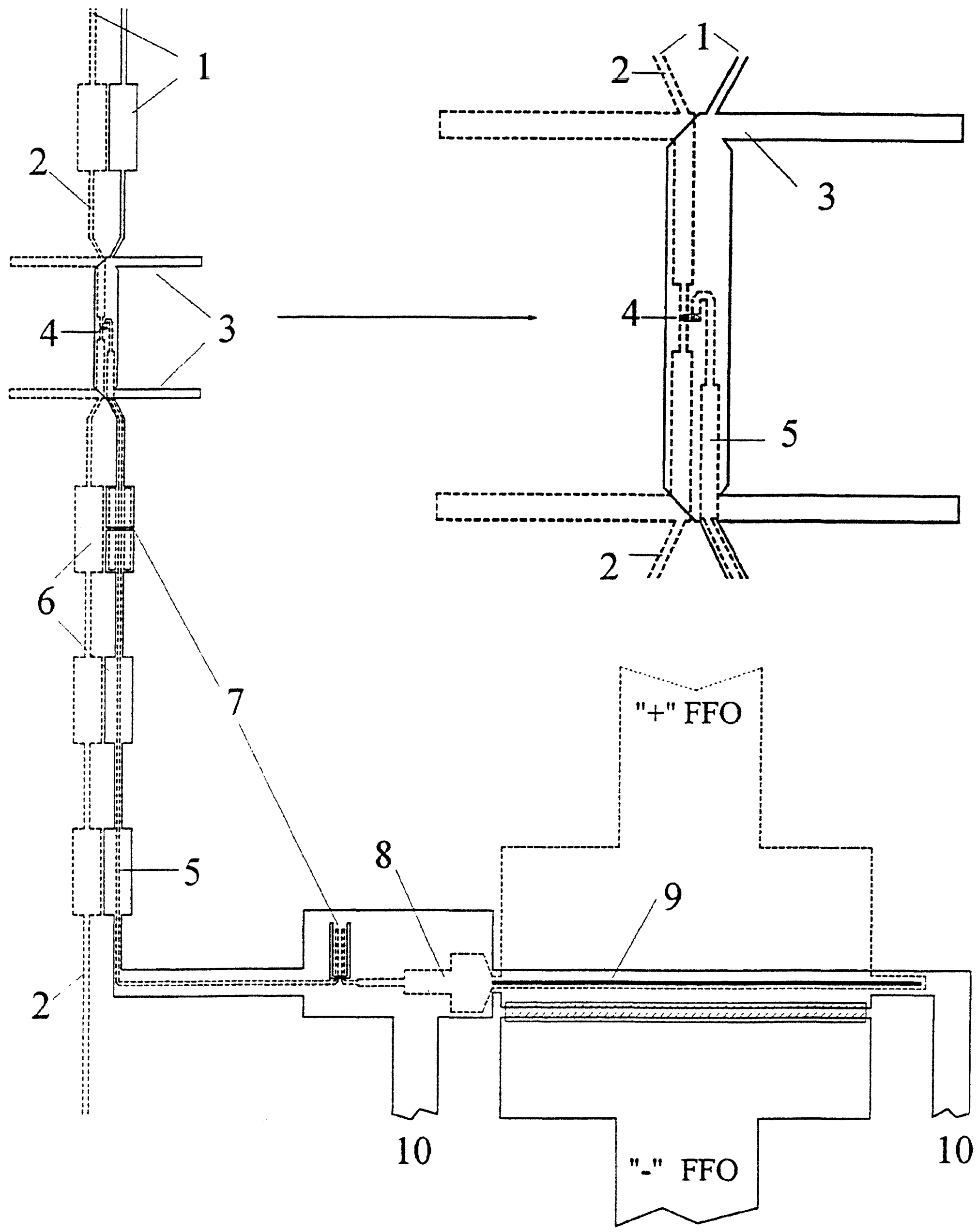

Fig.1 Drawing of the central part of the chip. Numbers in the figure are: 1- IF/DC leads; 2- SIS-mixer H-field control line, 3- double dipole antenna; 4- SIS junction; 5- LO feed line; 6- choke filters; 7- *dc* blocks; 8- Chebyshev transformer; 9- FFO junction; 10- FFO H-field control line.

fluxons are nucleated. The length of the unbiased tail was selected to be about $12\lambda_j$ (about 50 μm) for the optimal operation near 500 GHz.

To obtain uniform bias current injection along the junction, the finger-type *dc* feed with series resistors is used (18). The wide strip feed with spread resistor has been tested also for comparison. The resistors in the finger-type feed are intended to avoid trapping of the magnetic field near the junction. They also allow the junction base electrode to be used as a control line. To reduce the parasitic heating due to resistors, they are designed to be "vertical", i.e., the current is passing them in vertical direction. The nominal value of one resistor of size 10 x 10 μm was estimated as 0.01 Ω. Since no significant influence on the FFO operation has been found, the wide strip with the spread series resistor could be recommended as more simple to fabricate.

C. Matching circuits

The FFO output impedance to be matched to the SIS-mixer was assumed as the characteristic impedance of a Josephson transmission line with size of the junction. The value of the FFO output impedance about 0.4 Ohm was estimated. Three stages impedance transformer is used to couple the FFO output power to the microstrip line of 4 μm wide. The calculated characteristic impedance of the microstrip line is 14 Ohm. The Chebyshev three stages transformer has a compensated first (widest) section which is tapered with the angle of 120 degrees. To reduce the width of the first section, thinner insulating SiO layer of 230 nm is used.

Two dc blocks (breaks) are incorporated into the microstrip transmission line to separate the bias currents of the mixer and FFO and prevent leak of IF signal due to the capacitance of the matching circuit. Since FFO is intended to be frequency locked on harmonics of pumping source, the band-pass filter of high order (not shown in Fig.1) has to be used to prevent a leakage of the fundamental frequency to the mixer. The phase-locked 10 GHz and 70 GHz sources are planned to be used in future experiments around 500 GHz. The low loss performance of the band-pass filter has been proven within this frequency range experimentally.

A new design for dc block in a microstrip line using only two layers has been developed. The design principle has been verified successfully with a scale model in the frequency range 1-1000 MHz. In Fig.3 schematic pictures of the dc blocks as well as measured and calculated transmission of the design from Fig.3a are presented. The dc blocks are band-pass filters that use a combination of resonant microstrips and slots. The break from Fig.3a has been designed on a base of the folded slot line antenna. Because of high mutual inductance of the two half-slots excited in antiphase, the radiation loss in the dc-block is very low.

The LO power is coupled from the transmission line to the mixing junction via the two stages transformer situated inside the mixer. The transformer raises the impedance of the LO source up to 50-60 Ω. The mismatch between the LO source and the mixer is used to get the LO coupling at the level of 25-30%. A small 2 Ω resistor is used at the place of connection of the LO circuit to the SIS junction. This resistor is to prevent decrease of current density in the mixer control line near the SIS junction.

Experimental Data and Discussion

To make the technological run shorter and more reliable, both the mixing and FFO junctions have been formed on the base of the same trilayer Nb-AlO_x-Nb (19, 20) on a crystalline quartz substrate. Because of good thermal conductivity of the crystalline quartz, better heat sink of the chip can be achieved in the vacuum cryostat. The substrate 15x24x0.2 mm contains 8 chips of slightly different design and two well-defined SIS junctions of size about 20 μm^2 which are used to check

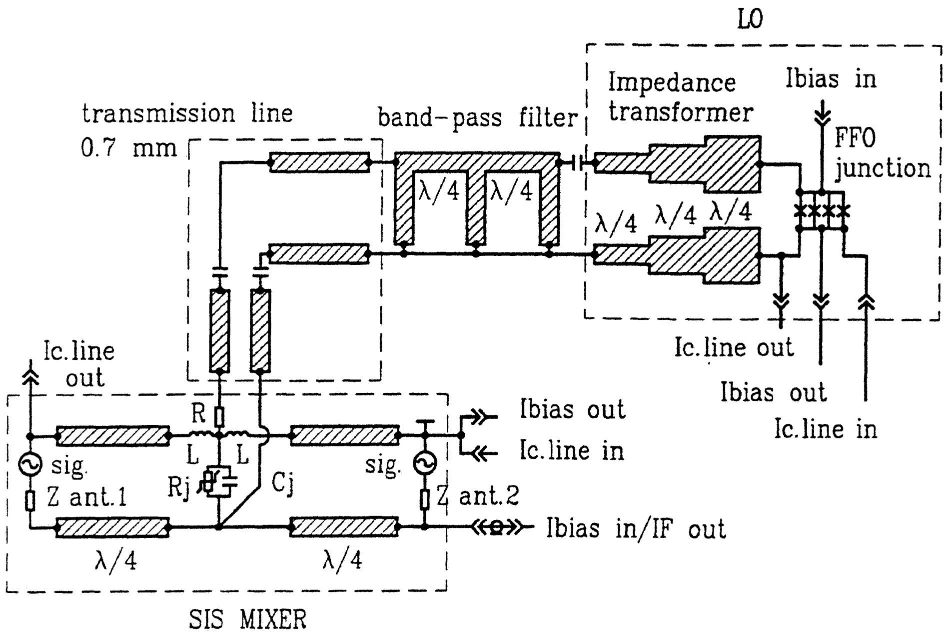

Fig. 2 Simplified equivalent diagram of the integrated receiver.

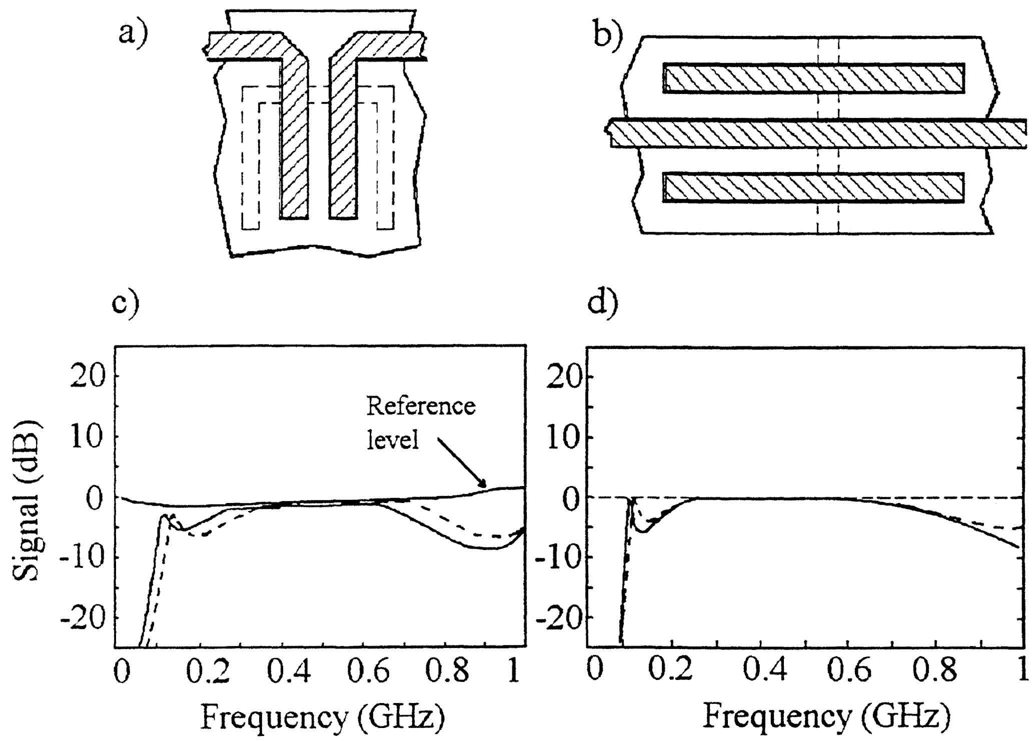

Fig.3 The dc-blocks in the micro strip line use only two metal layers: a) dc-break in the line; b) dc-break in the ground; c) measured transmission with scale model (1:1000) for different length of the microstrip stubs; d) calculated transmission for two cases: lossless slot-line (dashed) and radiative slot-line (solid).

the current density and size of small mixing junctions. High current density j_c=5-8 kA/cm^2 of the trilayer was used. The R_nA product (R_n is the normal state resistance of SIS junction; A is its area) could be treated as the most natural τ-parameter to characterise a quasiparticle mixer since specific capacitance C_s varies slightly in comparison to R_n (1). The R_nA in the range of 25 - 40 $\Omega \cdot \mu m^2$ was used and $C_s \cong 80$ fF/μm^2 was assumed for the samples tested. The mixing junctions have an area of 1-1.2 μm. The cross-windows process is used to fabricate the junctions of 1 μm size with high definition using standard optical lithography (20). Two layers of SiO (230 nm and 140 nm) are used. The FFO junction is formed with single 230 nm thick insulating layer of SiO.

The Ti film with the surface resistance of 5 Ω is used to form the resistors in the FFO *dc* feed and LO injection circuit. Contact pads are gold plated. The full technological process uses 8 layers.

A. Dipstick tests

The experimental SIS-mixers integrated with FFO have been tested first at *dc* in a dipstick to select candidates for the real RF experiment. The typical IV-curve of the mixing junction is presented in Fig.4. The specific resonance at the IV-curve at about 800 μV indicates tuning frequency of the mixing junction around 400 GHz. In the inset of the Fig.4 a control line characteristic is presented. It was found that the control current through the tuning strips of the SIS mixer produces a magnetic field that is strong enough to suppress Josephson supercurrent down to the second minimum in the 1 μm size junction.

To realise viscous flux flow state in the long Josephson junction (i.e. FFO regime), one should avoid the resonant soliton oscillations by increasing the junction length and damping that is inversely proportional to the quality factor Q_j :

$$Q_j = \{\alpha_{qp} + \beta(f_{FFS} / f_p)^2 \}^{-1}, \qquad (**)$$

where β is surface loss of the films; f_p is plasma frequency of the junction. In Fig.5 the IV-curve of typical FFO is presented. The estimated quasiparticle losses α_{qp} is very low for our junctions (typically $\alpha_{qp} \sim 0.01$) and we have no "pure" flux flow regime below V = 900 μV. Because of insufficient damping the IV-curve in this voltage region consists of a number of small amplitude Fiske resonances, exited by electromagnetic waves reflected from the ends of the junction. At higher voltages (higher frequency) the surface losses β become dominant. The "tail" geometry of the junction seems to be efficient since steady and near vertical FFS at V $\geq$ 900 μV are obtained (see Fig.5). The linewidth of the FFO estimated with an external carcinotron (mutual linewidth of two oscillators, actually) did not exceed 1 MHz as measured with a spectrum analyser.

The horizontal bars on the IV-curve indicate regions where pumping of the mixing SIS junction with $\alpha > 1$ has been obtained in the dipstick measurements. As it was expected, the efficient pump takes place around tuning frequency of the SIS mixer. The vertical branches at voltages above 0.8 mV are the repeatedly recorded traces of FFS that moves with the magnetic field changed. The tuning range of about 200-750 GHz is available with the control current adjusted from 4 to 15 mA for the most normally operated FFO.

B. RF tests in vacuum cryostat

The RF tests in the vacuum cryostat usually started with Fourier Transform Spectrometer (FTS) in video detection mode to check frequency of the best sensitivity of the SIS mixer. Typical RF response obtained in FTS experiment as well as calculated coupling of the signal and LO power to the SIS mixer are presented in Fig.6. Reasonable agreement between the experimental and the

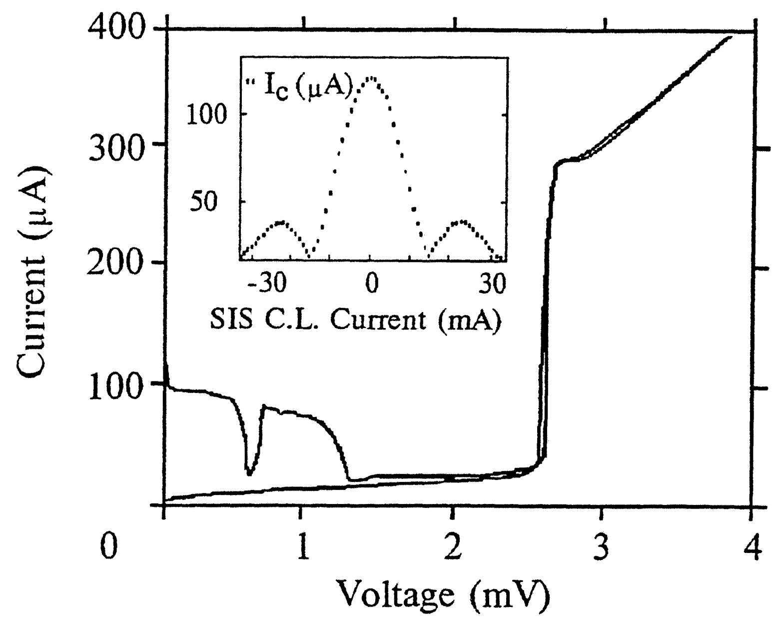

Fig.4 IV-curve of the mixing junction. The two curves are with and without magnetic field applied. The resonance feature at about V=0.8mV is due to the tuning structure. The dependence of the critical current I_c on the current through the control line is presented in the inset

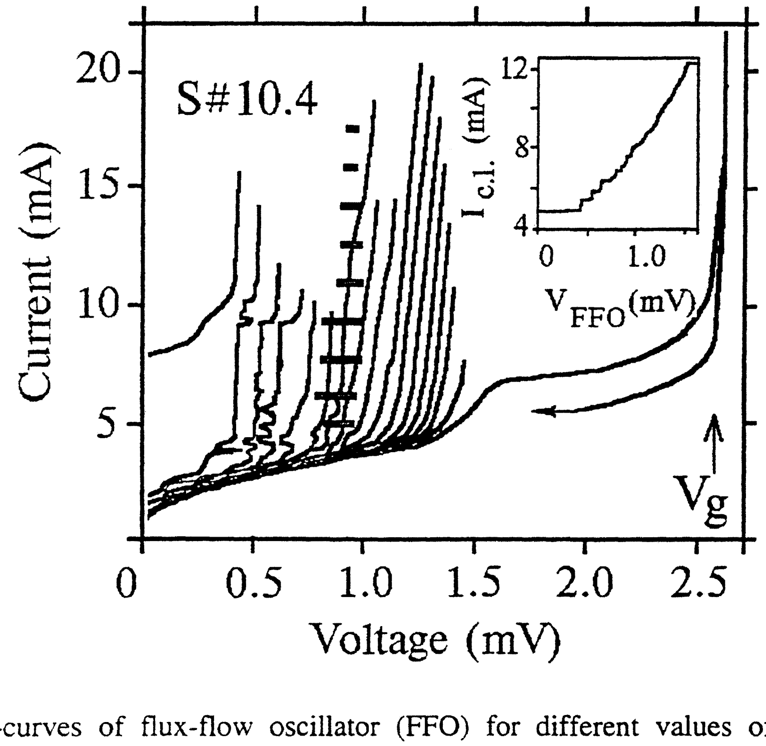

Fig.5 IV-curves of flux-flow oscillator (FFO) for different values of the control current. The horizontal bars show regions of efficient pump of SIS mixer. The dependence of the bias voltage V_{FFO}(oscillator frequency) on the current through the control line $I_{c.l.}$ is presented in the inset.

calculated data is seen. However, the horizontal bar, which is the experimental low estimation for the SIS mixer pump over tuning range of the FFO, was obtained in a dipstick experiment since the pump is significantly lower in the case of vacuum cryostat. A clear overheating of the FFO junction as well as decrease of the mixing junction gap voltage from 2.75 mV to 2.5 mV was observed in the vacuum cryostat at 4.2 K. Moreover, the pump levels for the cases of the dipstick (4.2 K) and the extra cooled vacuum cryostat (about 2 K) were still different. This effect is probably due to a local overheating of both the FFO junction and the nearest interface because of insufficient heat sink. The details of the problem are not clear yet. As a result the RF tests were performed at the temperature of LHe bath about 2 K.

In Fig.7 the experimental IV-curve of the SIS mixer pumped by FFO and the response for hot/cold antenna at IF = 1.5 GHz are presented. It is clearly seen that Shapiro steps are completely suppressed with the magnetic field produced by the control line. In Fig.8 the summary for the integrated receiver tuned with FFO frequency in the range of 404-490 GHz is plotted. On the top of the Fig.8 the integrated receiver noise temperature T_r is presented for two cases of internally and externally pumped SIS mixer. On the bottom the bias current of the mixing SIS junction is plotted for the same two cases. It is necessary to mention that the T_r obtained with the external LO are corrected for the beam splitter loss, but no correction should be done for T_r of integrated receiver since no beam splitter is used in front of the window of the cryostat.

One can see that the closest values of T_r take place for the closest pumping currents of the mixer (see Fig.8). The region of the lowest T_r within frequency range 460-470 GHz is rather an exception. In this specific region the gain of the mixer is arbitrary high and T_r is much less dependent on the pumping level. The shift between the region of the lowest T_r and highest pumping level could be explained by the difference in tuning frequencies of the mixer and the output transformer in LO coupling interface. Nevertheless the receiver has demonstrated wide band operation with DSB noise temperature <1500 K in the frequency region 428-482 GHz.

C. Power consumption analysis

Four separate bias sources have been used in the experimental tests. A voltage source was used to bias the SIS mixer. Three current sources were used for bias the FFO, its control line and the control line of the SIS mixer. It is important to mention that the main heat production is originated from the FFO. Typical values for the power dissipation loading the helium bath are summarised in Table 1.

Table 1 Power consumption of some elements of the integrated receiver.

element of integrated receiver	bias current, mA	bias voltage, mV	power dissipation, μW
SIS mixer	0.005-0.012	1.5-2.5	0.0075-0.03
control line of SIS mixer	15-50	0 (superconducting)	0
Flux-Flow oscillator (FFO)	5-20	0.8-1	4-20
resistor(s) in FFO bias circuit	5-20	0.01-0.04	0.05-0.8
control line of FFO	5-20	0 (superconducting)	0

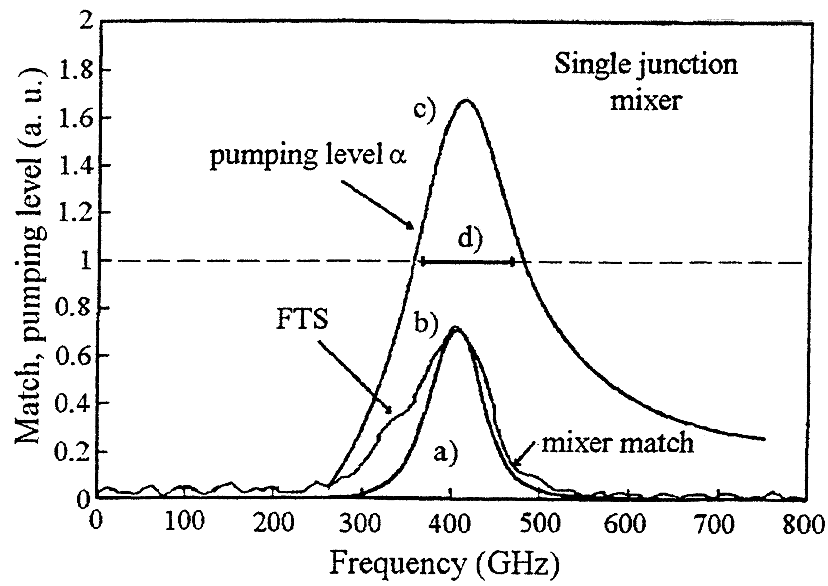

Fig.6 Coupling parameters for the integrated receiver: a) calculated match to the mixing junction; b) fitted to the video response of the mixer obtained with Fourier transform spectrometer; c) predicted pump level $\alpha=V_{RF}/hf$; d) the horizontal bar presents the region of pump level exceeding $\alpha=1$ (estimated from dipstick measurements).

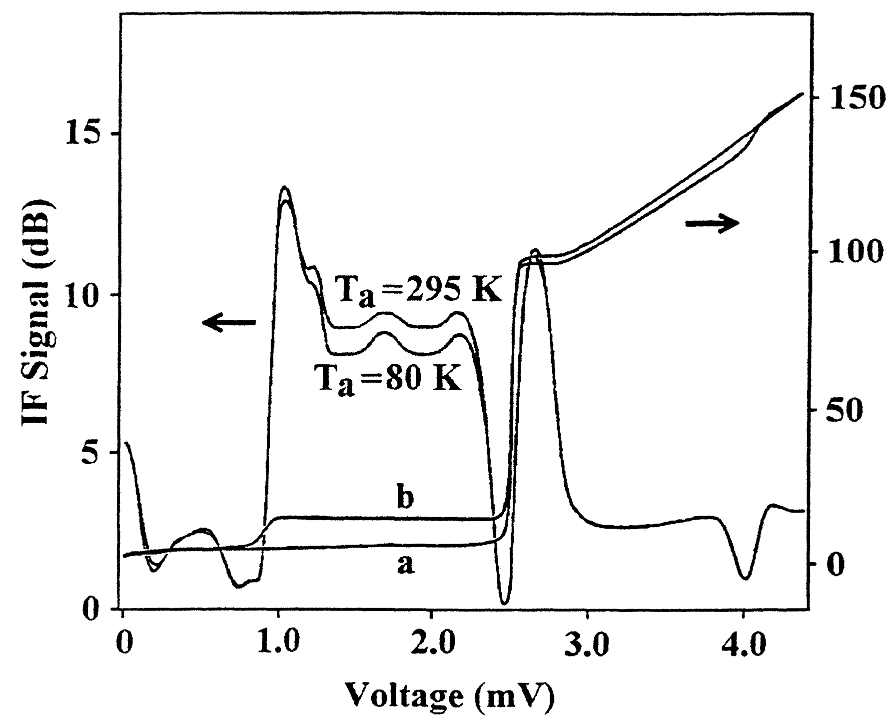

Fig.7 IV-curve of the unpumped mixer (a) and the pumped mixer (b). The IF power output at IF=1.5 GHz is given for blackbody radiators with temperatures of 80 K and 295 K.

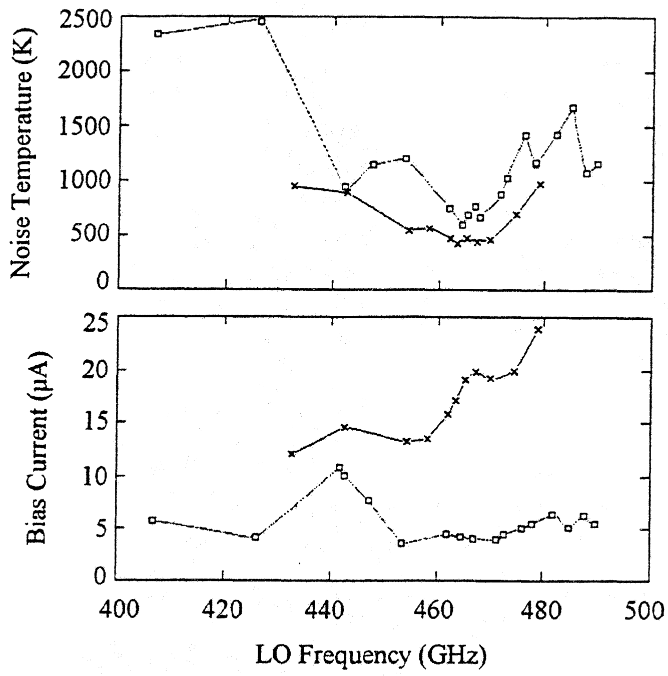

Fig.8 Noise temperatures of the integrated receiver and the LO induced bias current through the junction. Crosses refer to the use of an external oscillator, boxes refer to the use of the FFO.

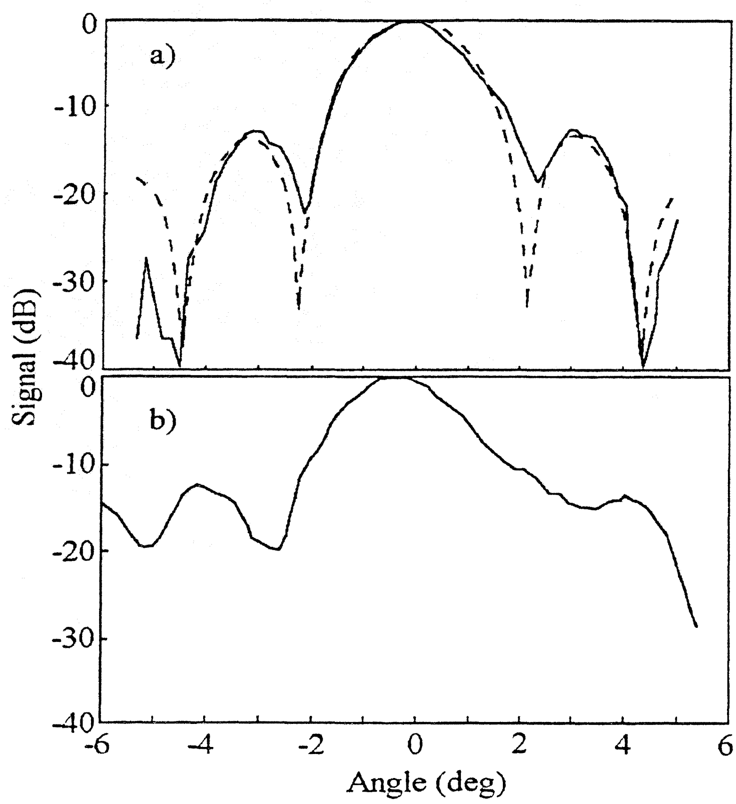

Fig. 9 Antenna beam patterns of the integrated receiver: a) in horizontal plane (solid); b) in vertical plane. The dashed line in a) is a calculated diffraction limited pattern.

D. Antenna beam

The antenna beam pattern of the receiver is presented in Fig.9. The data have been obtained in the video detection mode of the externally chopped CW signal at 465 GHz by tilting the cryostat around the phase center of the beam. The measured beam has width ± 4 degrees at the level of -20 dB in the horizontal plane (the dipoles of the antenna are vertical). The comparison between the experimental data and calculated diffraction pattern demonstrates that the size of the fitted diffraction hole is R = 9.7 mm. It is in reasonable agreement with the size of the primary lens (R = 10 mm). However, the beam is less symmetric in the vertical plane. The most probable explanation is the effect of asymmetric feed of the antenna because the central part of the mixer is large enough and the connection to the antennas is realised via asymmetric microstrip line.

Conclusion

A planar receiver consisting of a double dipole antenna, SIS mixer and a flux flow Josephson oscillator as LO integrated on a single chip, has been tested successfully in the frequency range of 400-500 GHz. Extensive experimental and numerical studies have been performed to match the FFO and the SIS mixer on the same chip. The data of the experimental test are in good agreement with predicted parameters of the integrated receiver that confirm the numerical method used for design and analysis of the device.

To avoid interference between the mixer and LO, novel integrated control lines have been used to produce the two localised magnetic fields for suppression of the Josephson noise in the mixer and for tuning the frequency of the FFO. High efficiency of the mixer control line is demonstrated by a second order minimum of the Josephson supercurrent in 1 μm size SIS junction. Hence the compatibility of SIS mixer and FFO in the submm region has been proven experimentally.

The integrated LO of the receiver has demonstrated good tuneability over the frequency range 400-500 GHz by adjusting the magnetic field applied to the FFO. The intrinsic linewidth of the free-running FFO is estimated experimentally as 1 MHz.

A number of original wide-band dc-breaks, impedance transformers and filters have been developed especially for the integrated receiver that allow to use only two metal layers. Hence the whole device has been fabricated with a reduced number of superconducting layers: one trilayer Nb-AlO_x-Nb and only one superconducting wiring layer. The single chip receiver has demonstrated wide band operation with DSB noise temperature <1500 K over the frequency range of 428-482 GHz and a minimum of T_r=595±20 K at 465 GHz.

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