First Implementation of a superconducting integrated receiver at 450 GHz

Valery P. Koshelets, Sergey V. Shitov, Lyudmila V. Filippenko,
and Andrey M. Baryshev
Institute of Radio Engineering and Electronics, Moscow, Russia

Hans Golstein, Thijs de Graauw, Willem Luinge, Harry Schaeffer,
and Herman van de Stadt
SRON, Groningen, The Netherlands

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An integrated quasioptical receiver consisting of a planar double dipole antenna, superconductor-insulator-superconductor mixer and a superconducting local oscillator (LO) with matching circuits has been designed, fabricated and tested in the frequency range 360–490 GHz. A flux-flow oscillator (FFO) based on unidirectional and viscous flow of magnetic vortexes in a long Josephson tunnel junction, is employed as a local oscillator. All components of the receiver are integrated on a 4 mm×4 mm×0.2 mm crystalline quartz substrate using a single Nb–AlO$_x$–Nb trilayer. The lowest DSB noise temperature of 470–560 K has been achieved within a frequency range of 425–455 GHz. © *1996 American Institute of Physics.* [S0003-6951(96)01209-5]

The concept of a fully integrated superconducting receiver is attractive for sub-mm observations from space where low weight, low power dissipation and limited volume are required. Superconductor-insulator-superconductor (SIS) junctions are currently the most sensitive mixing elements available in the frequency range 100–1000 GHz; their noise is ultimately limited only by fundamental quantum value hf/k (see, for example, Ref. 1). At higher frequencies the lack of compact and easily tuneable local oscillators is a serious problem that motivates the attempts for direct integration of superconducting local oscillators with SIS mixers.

Flux flow oscillators (FFO) are based on the unidirectional and viscous flow of magnetic vortices in a long Josephson tunnel junction with high damping.[2,3] They have been successfully tested up to the gap frequency of Nb (from 250 up to 800 GHz).[2–4] A power level sufficient for pumping of a SIS mixer[4,5] has been demonstrated at 450 GHz. Continuous tuning of both frequency and power of the FFO has been demonstrated as well as moderate linewidth of the autonomous FFOs: about 1 MHz can be inferred from different mixing experiments.[3,4,6,7] These properties make this device the main candidate for a LO for a SIS quasioptical mixer in a planar submillimeter wave receiver (or imaging array) which could be used for space applications. At low frequencies a waveguide prototype of an on-chip integrated SIS receiver with a FFO has been successfully tested;[7] a DSB receiver noise temperature of 85 K has been realized at 140 GHz.

At least two problems should be solved for integration of a SIS mixer and a FFO on a single chip. The first problem is related to the coupling between the FFO and the SIS mixer. Since the RF power produced by a FFO is only one order larger than needed for optimal pumping of the SIS mixer, a quite strong coupling (not less than 10%) between local oscillator (LO) and mixer is highly desirable. On the other hand, stronger coupling may cause considerable leakage of the input signal to the LO circuit and thus an increase in noise temperature of the receiver. For the present design the coupling between FFO and SIS mixer is chosen at the level of about 25%–20% by using an impedance mismatch (see Fig. 1). Injection of the LO power into the SIS junction takes place in the center of the antenna. About 30%–35% of the input signal is lost toward the LO.

A second serious problem arises because quite different levels of magnetic field strengths are required for optimum operation of the SIS mixer and the FFO. Since the Josephson supercurrent in the SIS junction must be suppressed to achieve low noise operation of the mixer, a strong magnetic field has to be used for a small (about one micrometer) size junction. This field may exceed more than 100 times the optimal value for tuning of the FFO and thus may affect the performance of LO. Two separate control lines are used to provide the optimal magnetic fields to the SIS mixer and the

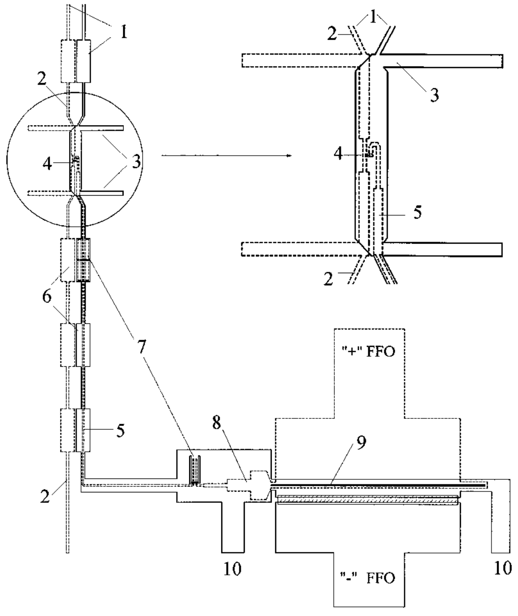

FIG. 1. Schematic drawing of the integrated receiver chip and enlarged view of the antenna with SIS mixer. "1" - SIS mixer DC/IF out; "2" - SIS control line; "3" - double-dipole antenna; "4" - SIS mixer with tuning circuits; "5" - microstrip line for coupling of FFO power; "6" - RF choke filters; "7" - DC & IF blocks; "8" - Chebyshev 3 stage transformer; "9" - flux flow oscillator; and "10" - FFO control line.

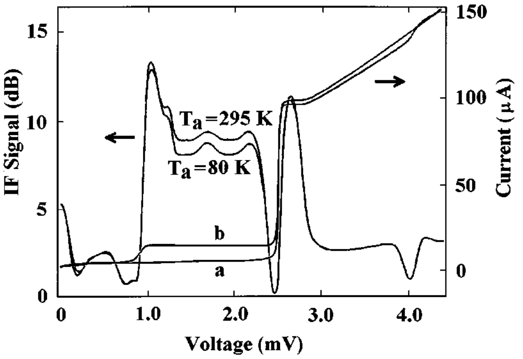

FIG. 2. *IV* curves of the SIS mixer of the integrated receiver: unpumped (a) and pumped by the FFO at 440 GHz (b). The IF output power is shown for both hot (295 K) and cold (80 K) loads as signal source at the receiver input.

FFO independently. The control current for the suppression of Josephson noise is introduced in such a way that no special circuitry is necessary: the tuning circuit of the mixer includes the role of a control line.

A slightly simplified layout of the receiver chip as well as an enlarged view of its center with antenna, mixer and matching circuitry are shown in Fig. 1. We use a single SIS junction as a mixing element located in the center of a double dipole antenna. The antenna and the tuning elements for the SIS junction are designed for a center frequency of 450 GHz. The symmetry of the antenna allows us to use similar coplanar choke filters on either side of the antenna. The upper leads are used for the DC/IF connections and contain RF choke filters with high reflection for the input signal frequency. The lower leads contain choke filters of a modified design with DC/IF blocks between the FFO and the SIS mixer, and a ground plane of the microstrip line transmitting LO power. A simplification of the DC blocks in the interconnecting line between the FFO and the SIS junction allows the use of only two superconducting layers. One of the lower leads is also used as a terminal for the control line of the SIS mixer.

The integrated circuit is fabricated on a crystalline quartz substrate with a technique developed earlier for producing high quality Nb–AlO$_x$–Nb SIS mixers and RSFQ digital devices.[8] Both SIS and FFO junctions are formed simultaneously from the same trilayer. The value of the critical current density is in the range of 5–8 kA/cm^2 which corresponds to a specific resistivity $R_n \times S = 40$–25 Ω μm^2. The SIS mixer junction has an area of 1–1.5 μm^2; a narrow strip (3–4 μm wide) in the top electrode is used as the control line. The long Josephson junction (FFO) has a length L of 450 μm and a width W of 3 μm. The base electrode layer of the long junction is employed as a control line to produce the magnetic field for the FFO. Two different layers of SiO insulation are used to provide the wide range of microstrip line impedance needed for different parts of the matching circuit.

The standard quasioptical double-lens SIS mixer setup was used (see, for example Refs. 9 and 10): A first fused quartz lens with an antireflection Teflon coating provides focusing of the incoming beam to a second hyper hemispherical quartz lens. The receiver chip is placed on the flat back surface of this lens. Ten springing pin contacts ∅ 200 μm are used to supply the chip with the necessary DC currents and to provide connection of the mixer output signal to the intermediate frequency (IF) amplifier which is a cooled low-noise HEMT operating over the frequency range of 1.1–1.7 GHz. The IF noise temperature is about 10 K as deduced from the SIS junction shot noise. The mixer block is mounted on the cold plate in the vacuum space of a liquid helium cryostat with TPX window at 300 K. A black polyethylene film and a resonant fused quartz plate are used as heat shields at 80 K. When an external oscillator is used, a 50 μm thick Kapton film serves as a beam splitter in front of the window of the cryostat.

The LO circuit in the integrated receiver chip (see Fig. 1) has been designed to provide coupling of about −7 dB between LO and SIS mixer. A near optimal pumping level of $\alpha \geqslant 1$ is realized over the FFO tuning range Δf of 50–100 GHz around the center frequency of about 450 GHz, as follows from the test measurements in a dipstick. The RF output power of the FFO is tuned by the bias current while the frequency is kept constant by fine adjustment of the magnetic field. The critical current and the first Shapiro step on the IV curve of the SIS mixer junction have been measured at a frequency $f_{\mathrm{FFO}}=450$ GHz and the data have been evaluated as a function of the DC power P_{DC} consumed by the FFO. The calculations indicate that the RF power coupled to the junction is about $P_{\mathrm{RF}}=0.26$ μW for a FFO DC power $P_{\mathrm{DC}}=7$ μW.

Complete suppression of the Josephson supercurrent in a SIS mixer can be realized with a DC current not exceeding 100 mA. The second minimum of the critical current of the SIS junction can usually be realized before the 3–4 μm wide control line is switched to the normal state. An example of

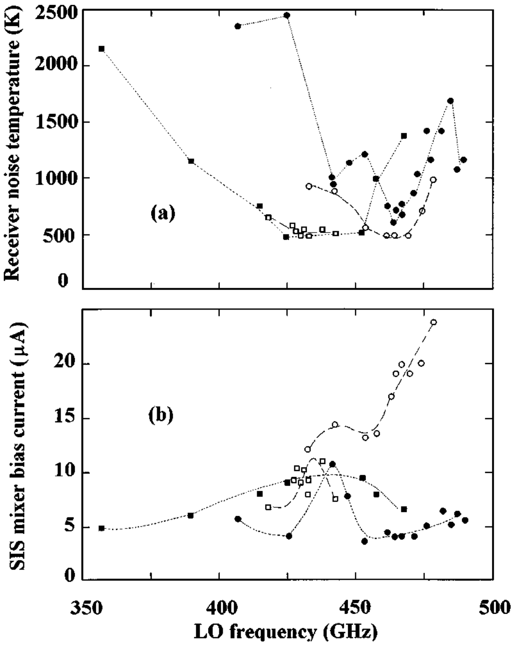

FIG. 3. The noise temperature (a) and "induced" bias current of SIS mixer vs frequency of LO for two integrated receivers, Receiver 1 (circles) and Receiver 2 (squares), measured by two different LOs: integrated FFO (solid symbols) and external oscillator (open ones). The lines connecting the experimental points are drawn as a guide to the eye. The noise temperatures are corrected for a beamsplitter loss in the cases of external LO.

the *IV* curve of a SIS mixer with suppressed Josephson effect is presented in Fig. 2.

In Fig. 2 curve ''a'' is an unpumped *IV* curve of the SIS mixer; curve ''b'' is measured when SIS is pumped by the FFO oscillating at 440 GHz. The IF output power of the receiver with a hot (295 K) and a cold (80 K) load as a source at the cryostat input window is also shown in Fig. 2. The DSB noise temperature of the integrated receiver versus FFO frequency is presented in Fig. 3(a) by solid circles for Receiver 1 and by solid squares for Receiver 2; the best values are 600 K near 465 GHz and 470 K near 425–440 GHz, respectively. The data obtained for the same receivers using an *external* LO are presented by open circles and squares in Fig. 3(a). Clearly, the range of frequency tuning of the integrated FFO is about 100 GHz.

The noise temperature of the Receiver 1 pumped by the internal FFO is higher than for an external LO at the same frequency. The difference is caused mainly by insufficient power delivered by the FFO. To confirm this assumption we measured the value of the SIS mixer bias currents in the operation points as shown in Fig. 3(b). The data marked by open circles and squares correspond to the ''optimal'' pumping at given frequency, provided by an external LO to obtain the lowest possible noise temperature. One can see that only at a frequency around 440 GHz the FFO of Receiver 1 pumps the SIS mixer to a level approaching the optimal one. At this frequency the noise temperatures are rather equal both for internal FFO and external LO: see Fig. 3(a). For Receiver 2, which has a pump level from the FFO closer to the optimal one, the corrected noise temperature obtained with an external LO is nearly the same as the lowest value of 470 K obtained with the internal FFO.

In conclusion, the design of a planar integrated receiver with superconducting LO has been described. Several chips with complete quasioptical on-chip receiver have been fabricated and tested successfully at submillimeter wavelengths. DSB noise temperatures of 600 K at 465 GHz and 470 K at 425–440 GHz for two samples of the integrated receiver have been achieved.

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