Superconducting Integrated Circuits for Submillimeter Heterodyne Receivers

S.V. Shitov

***Abstract*—A few aspects of integration of SIS junctions into a complete heterodyne receiver are discussed; a number of practical solutions are presented. The concept of perfect match for SIS mixers assumes proper integration of multiple junctions using series-parallel connection. Our recent progress in study of Josephson-type oscillators up to 1 THz is based on their integration with SIS mixers, dc-break filters and high-ratio impedance transformers. Fine adjustment of *rf* power from such integrated source is realized via controllable absorption by tunneling quasiparticles. A few variants of a quasioptical Superconducting Integrated Receiver comprising an integrated SIS mixer, FFO as a LO and optional harmonic SIS mixer in the PLL loop are demonstrated. A multi-channel concept of SQUID amplifier allows for a wide-band *if* chain, which accomplishes the traditional set of devices used for a heterodyne SIS receiver.**

I. Introduction

SIS junctions are unique devices combining two fundamental phenomena, the superconducting pairs tunneling (Josephson effect [1]) and the quasiparticle tunneling (Giaver effect [2]). This allows for use the same type of junction (e. g. Nb-AlO_x-Nb) either in a quasiparticle mode (for the quantum noise limited mixing or for the photon counting detection [3]) or in Josephson mode (for high frequency oscillators or for SQUID sensors, *rf* amplifiers, and digital devices [4]). This is why studies in SIS junction integration are of great importance for lightweight and low power consuming electronic applications.

II. Optimization of SIS Mixer Circuit

The most serious problems of mixing with a SIS junction are its low effective resistance at *rf* ($R_{rf}<<R_n$) caused by the junction's capacitance and high output resistance ($R_d>>R_n$). To realize high *rf* impedance, an array of N series connected junctions can be used. However, series-biased array mixers suffer from unequal bias voltage due to junction inhomogeneity and from poor *if* coupling due to very high output resistance.

It was suggested, analogous to Josephson arrays, to supply all N junctions with equal bias voltage via high inductive superconducting feeds [5], [6]. Such arrangement allows for *increased input*, $R_{rf}(N) = R_{rf}(1)N$, and *decreased output* resistance, $R_d(N) = R_d(1)/N$ [7]. The optimum number N for *desired* input and output resistance, R_s and R_L, we estimate as

$$N = (R_S/R_L)^{1/2}(R_d(1)/R_{rf}(1))^{1/2} \qquad (1).$$

To obtain good *rf* coupling, capacitance of the junction has to be tuned out. Such compensated two-junction cell was suggested in 1982 [8]. The prototype cell contains two SIS junctions looped by an inductor, which resonates with the junctions' capacitance. These junctions are connected in parallel at *dc* and *if*, but one can chose how to connect the *rf* source – in parallel to one of the junctions for $R_s=R_{rf}/2$ or in parallel to the inductor for $R_s=2R_{rf}$. It is easy to demonstrate that twin-SIS mixers [9]-[11] fit to this integration principle, which is tested experimentally up to N=11 at mm wavelength [12]. Practicable SIS mixers demonstrated receiver noise temperature, T_{RX}, as low as 20 K at 100 GHz with waveguides [12], 40 K at 470 GHz [13] and 245 K at 935 GHz with integrated lens-antennas [14]. Promising results are obtained at sub-THz frequencies with a resonant SIS mixer [15], which is the asymptotic solution for a twin-SIS mixer at high frequency.

III. Test Circuits for Josephson Oscillators

The efficiency of *dc*-to-*rf* conversion of a shunted SIS junction is limited by the shunt resistor, which provides *dc* stability and, unfortunately, damping most of the oscillator power. A pure resistive shunt is difficult to realize especially at THz frequencies [6]. This is why in most experiments the large-N array oscillators are operating in a resonant mode.

The flux-flow oscillator (FFO) is a long (distributed) *non*-shunted SIS junction with Josephson effect spatially synchronized by moving Josephson vortices [16]. Another example is a two-dimensional (2D) array oscillator of *non*-shunted SIS junctions above the ground plane [17]-[19]. For accurate measurement of power, tuning range and emission spectrum, we integrated oscillators with wide-band twin-SIS detectors. The detectors can be used either for power measurement or as harmonic mixers of a PLL system. Special coupling elements are developed for such circuits: wide-band high-ratio impedance transformers (250-750 GHz, 1/100), a few types of *dc*-blocking filters (150-850 GHz) and integrated control lines for local magnetic field (up to 30 kA/m). Using this integration approach, the *non*-shunted oscillators with

S. V. Shitov is with the Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow 125009, Russia.

This work was supported in parts by RFBR projects 92-02-3484, 00-02-16270, 03-02-16748; INTAS projects 94-1783, 97-1712, 01-0367; ISTC projects 1199, 2445; ESA TRP Contract No.11/653/95/NL/PB/SC, 7898/88/NL/PB/SC; AFOSR Grant No.F49620-98-1-0072; NATO Linkage Grant 921040; JSPS S-01527, STA 49919, and Danish Science Foundation.

dc-to-*rf* conversion efficiency above 10% (up to 30%) at 150 GHz are demonstrated [18]. A number of interesting experimental results are obtained: detailed spectrum of free-running and locked Nb FFO up to 700 GHz [20], frequency doubling in stacked FFOs [21], THz-band emission from NbN FFO up to 900 GHz [22] and evidence of a coherence threshold in 2D array oscillators [17]-[19]. To adjust *rf* power from a fix-tuned integrated oscillator, the electronically controlled absorption by quasiparticles was suggested; the SIS attenuators are developed and tested at 70 GHz and 325 GHz with integrated FFO [23].

IV. Integration of a Receiver

Superconducting integrated receiver (SIR) is as a chip device containing sensitive (SIS) mixer coupled with its signal port to a waveguide or to a quasioptical antenna and with its LO port - to an integrated Josephson oscillator (FFO). The signal loss is unavoidable, if the simple T-junction power combiner is used. For the balanced scheme, the signal can be transferred from antenna to the mixing element without loss.

The first waveguide SIR at 140 GHz [24] was built as quartz chip 5.3 mm x 0.5 mm x 0.15 mm using the simple scheme and the prototype two-junction cell SIS mixer [8]. The noise temperature less than 85 K was demonstrated. For the range 400-700 GHz the layout is changed: the quasioptical (QO) SIR is built around a double-dipole lens-antenna SIS mixer with an elliptical silicon lens as the only optical element. Balanced and single junction versions of QO SIR at 500 GHz demonstrated T_{RX}=90 K and 140 K respectively [25]. An imaging receiver is developed and tested with nine pixels each one being an independent and replaceable QO SIR; the same pixel element is implemented in a compact probe-type laboratory sub-mm receiver [26]. A chip spectrometer at 330 GHz is developed as a combination of the QO SIR and PLL FFO circuits; the integrated LO is feeding now two mixers [27]. The frequency resolution as good as 10 kHz is measured along with fine detection of SO_2 gas absorption spectrum at 326867 MHz.

V. DC SQUID Based *IF* Amplifier

It was demonstrated that *dc* SQUID can be used as an *rf* amplifier (SQA) with noise temperature at the level of 100 mK [28], but its bandwidth (BW) is hardly exceeding 10%. To attain wide-band performance, a concept of multi-channel SQA is developed [29]. We demonstrated that BW up to 2 GHz can be achieved for the 4-channel SQA. The channel design is based on the experimental SQA, which is developed via extensive scale modeling and tested in the frequency range 3.0-4.6 GHz demonstrating single-stage gain 12.0±1.0 dB, 3-dB bandwidth of 500 MHz and noise temperature 1.0±0.25 K. The input saturation power in terms of the noise temperature normalized to 1 GHz input bandwidth is measured as 55 K*GHz for 1 dB gain compression point that fits to low-signal applications.

VI. Conclusion

The experimental results are quite encouraging and the methods developed can be recommended as the guidelines for superconducting integration technology at *rf*. The research continues now towards a practicable integrated (imaging) PLL receiver for radio astronomy and monitoring of atmosphere.

Acknowledgment

Author would like to thank for their collaborative efforts V. P. Koshelets, A. N. Vystavkin, S. A. Kovtonyuk, An. B. Ermakov, G. V. Prokopenko, L. V. Filippenko, I. L. Lapitskaya, P. N. Dmitriev; Th. De Graauw, P. Wesselius, W. Luinge, H. van de Stadt, H. Golstein, A. Baryshev, G. de Lange, B.D. Jackson, P. Lehikoinen; E. Kollberg, C.-O. Lindstrom, N. D. Whyborn; T. Klapwijk, G.-R. Gao, N. N. Iosad; A. Braginsky, A. Ustinov, H. Kohlstedt; C. Lobb, P. Barbara, B. Vasilic; J. Mygind, G. Fisher; A. Shoji, S. Kohjiro, M. Maezawa, and Z. Wang.

References

[1] Josephson B D 1962 *Phys. Lett.* **1** 251-253.
[2] Giaver I I960 *Phys. Rev. Lett.* **5** 147-148.
[3] Tucker J R, Feldman M J 1985 *Rev. Mod. Phys.* **4** 1055-1113.
[4] Likharev K K 1986 *Dynamics of Josephson Junctions and Circuits* (New York: Gordon and Breach Science Publisher).
[5] Wan K-L, Jain A K, Lukens J E 1989 *IEEE Trans. Magn.* **25** 1076-1079.
[6] Kawakami A, Wang Z 1998 *IEICE Trans. Electron*. **E81-C** 1595-1600.
[7] Ermakov An B, Koshelets V P, Kovtonyuk S A, Shitov S V 1991 *IEEE Trans. Magn.* **MAG-27** 2642-2645.
[8] Vystavkin A N, Gubankov V N, Konstantinyan K I, Koshelets V P, and Obukhov Yu V 1982 *Physica 109 & 110 B* 2064-2066.
[9] Noguchi T, Sunada K, Inatani J 1992 *Proc. 39th Spring Meeting Japanese Society Appl. Physics, Tokyo, Japan*, 76.
[10] Belitsky V Yu *et al.* 1993 *Proc. 4 Int. Symp. Space Terahertz Technology*, Los Angeles, UCLA, USA, 538.
[11] Zmuidzinas J, LeDuc H G, Stern J A, Cypher S R 1994 *IEEE Trans. Microwave Theory Tech*. **42** 698-706.
[12] Shitov S V *et al.* 1991 *Supercond. Sci. Technol.* **4** 406-408.
[13] Baryshev A, Luinge W, Koshelets V, Shitov S, Klapwijk T, unpublished.
[14] Shitov S V *et al.* 2002 *Physica C* **372-376** 374-377.
[15] Uzawa Y, Wang Z, Kawakami A, Miki S 2001 *in Proc. 12 Int. Symp. Space Terahertz Technol*., San Diego, USA, 352-362.
[16] Parmentier R D 1978 Fluxons in long Josephson junctions *in Soliton in action*. Ed. K.Lonngren and A.C. Scott (New-York: Academic) 173-199.
[17] Barbara P, Cawthorne A W, Shitov S V, Lobb C J 1999 *Phys. Rev. Lett.* **82** 1963.
[18] Vasilic B, Barbara P, Shitov S V, Lobb C J 2001 *IEEE Trans. Appl. Supercond.* **11** 1188-1190.
[19] Vasilic B, Shitov S V, Lobb C J, Barbara P 2001 *Appl. Phys. Lett.* **78** 1137-1139.
[20] Koshelets V P *et al.* 2002 *Physica C* **367** 249-255.
[21] Shitov S V, Ustinov A V, Iosad N N, Kohlstedt H J 1996 *Appl. Phys.* **80** 7134-7137.
[22] Kohjiro S *et al.* 2002 *in Proc. 13-th Int. Symp. Space Terahertz Technol.* Harvard Univ., Cambridge, MA.
[23] Koshelets V P *et al.* 1993 *Appl. Phys. Lett.* **63** 3218-3220.
[24] Koshelets V P, Shchukin A V, Shitov S V, and Filippenko L V 1993 *IEEE Trans. Appl. Supercond.* **3** 2524-2527.
[25] Shitov S V *et al.* 1999 *IEEE Trans. Appl. Supercond.* **9** 3773-3776.
[26] Shitov S V *et al.* 2001 *IEEE Trans. Appl. Supercond.* **11** 832-835.
[27] Shitov S V *et al.* 2000 *IOP Conf. Ser.* **167-2** 647-650.
[28] Muck M, Kycia J B, Clarke J 2001 *Appl. Phys. Lett.* **78** 967-969
[29] Prokopenko G V, Shitov S V, Mygind J 2002 *Physica C* **372-376** 229-232.