Submillimeter-Wave Mixing and Noise in HTS Josephson Junctions

M. Tarasov*, E. Stepantsov**, D. Golubev***, Z. Ivanov, T. Claeson
Physics Department, Chalmers University of Technology, S-41296 Gothenburg, Sweden
*Institute of Radio Engineering and Electronics of Russian Academy of Sciences
**Institute of Crystallography of Russian Academy of Sciences
***P.N.Lebedev Physical Institute of Russian Academy of Sciences

O. Harnack, M. Darula, S. Beuven, H. Kohlstedt
Institute of Thin Film and Ion Technology, Research Center Juelich, 52425 Juelich, Germany

Abstract— A Josephson quasioptical detector comprising YBaCuO junction on bicrystal MgO substrate, integrated log-periodic Au antenna, MgO extended hyperhemisphere lens attached to the substrate and 1.4 GHz cold amplifier with cold circulator has been designed, fabricated and experimentally studied. We fabricated several integrated Josephson junctions 1-2μm wide which at 4.2 K demonstrate RSJ IV curves with critical currents 100-300 μA and normal resistance of 10-20 Ω. The noise temperature (T_N) at 4.2 K and 430 GHz measured by a hot/cold load method in fundamental mixing mode with external BWO local oscillator brings T_N=1100 K for the junction shunted by low-inductance resistive shunt and T_N=1400 K without shunting. At bath temperatures of 20-40 K the noise temperature was in the range 1500-3000 K, at 50 K the noise temperature was below 2000 K, and at 60-70 K increased over 3000 K in the frequency range 410-586 GHz. The noise temperatures measured in the self-pumping mode vary between 580-2300 K with dc bias in the range 0.1-0.5 mV. The linewidth of Josephson oscillations has been extracted from a selective detector response and IF noise voltage dependence. The measured excess noise can be attributed to shot noise and multiple Andreev reflection in pinholes with Ss'S structure. We observed small subharmonic steps in IV curve and noise dependencies, which are typical for SNS junctions.

I. INTRODUCTION.

During last two decades the Josephson mixers (JM) have been extensively studied both theoretically and experimentally. The theoretical basis was developed by K. Likharev and co-workers [1]. Contrary to a classical resistive mixer, in a JM conversion losses can be decreased and become even negative, i.e. downward conversion with small (2-3 dB) power gain can be achieved. However, due to the presence of Josephson oscillations and their mixing with the intrinsic noise of the junction and LO, the noise temperature can be an order of magnitude higher than the value for the resistive mixer at the same temperature. The experimental results obtained for mixers with Josephson point contacts demonstrated noise temperatures of about 100 K at 130 GHz [2] and at 250 GHz [3] and were rather encouraging. However, the appearance of SIS mixers stopped the development of JMs for a long period. At present SIS Nb-based mixers approached their frequency limit at about 700 GHz. Recently studied Josephson mixing in shunted [4] and unshunted [5] SIS junctions demonstrated the possibility to improve impedance matching by use of integrated transformers, planar antennas and quasioptic technique to improve the JM performance. Progress in HTS Josephson junctions development brings possibilities to increase the signal frequency of JM over several THz due to the relatively high energy gap of HTS materials. High transition temperatures of HTS materials promise operation temperatures above 20 K. In addition, the low local oscillator power makes HTS Josephson mixer an attractive candidate for air and spaceborn receiver applications.

The calculations [6] predict for the signal frequency (f) above the characteristic frequency (f_c) of junction $f>f_c$ the $T_{Nmin}\cong 10.5\cdot T(f/f_c)^2$, while the minimum value of noise temperature $T_{Nmin}\cong 6T$ attains for $f\approx 0.3f_c$. In down-converter with self-pumping the input signal is mixed with the internal Josephson oscillations. In analysis of self-pumping JM it is necessary to keep in mind that JO have a fairly large linewidth about several Gigahertz. If the monochromatic signal is input to the junction, then the linewidth of the output signal at IF is the same as for JO, that can bring large conversion losses. However if the input signal is a noise signal with sufficiently wide bandwidth, the additional losses do not arise. The losses can be low also if we decrease the linewidth of JO by applying low-inductance resistive shunt. As a result the minimum value of a double sideband (DSB) noise temperature in JM with self pumping (see [6]) equals physical temperature T for $f<0.2f_c$, and decreases as $8(f/f_c)^2$ with frequency increase above f_c. A low-inductance resistive shunt improves noise temperature of mixer and resolution of Hilbert spectrometer which can be viewed as a self-pumped homodyne mixer in which external signal is mixed with internal Josephson oscillations and down converted.

Manuscript received September 15, 1998
This work was supported in part by Swedish Royal Academy of Sciences, COPERNICUS foundation, Ministry of Sciences of Russian Federation, Russian Foundation for Basic Research, INTAS

1051-8223/99$10.00

II. Integrated Receiving Structure and Experimental Setup

The integrated receiving structure consists of YBaCuO Josephson junction formed on the bicrystal (100) MgO (ε_r= 9.6) substrate and Au complementary log-periodic antenna. YBaCuO film 80 nm thick was deposited by laser ablation. The 2 μm wide junction has a normal state resistance of 10 Ω and a critical current of 300 μA, measured at 4.2 K. A microphotograph of the structure is presented in Fig. 1, and the IV curves in Fig. 2. The remarkable feature of IV curves is the low excess current, a clear Fraunhoffer pattern in I_c dependence on magnetic field and correct oscillations of the critical current and Shapiro steps with applied LO power. To reduce the linewidth of Josephson oscillations and improve the mixer performance several types of low-inductance resistive shunts have been studied. The integrated shunt with resistance 0.87 Ω was not so effective as hybrid one, that was made of 50 μm Au wire bonded directly to the contact pads. The shunt single loop about 5 mm in diameter brings the resistance below 0.1 Ω at 4.2 K and inductance that does not shunt sufficiently the IF signal at 1.4 GHz.

The substrate with sample was attached to the MgO extended hyperhemisphere lens placed in the LHe cryostat with optical window. For feeding the radiation a 3-lens wideband gaussian beamguide was designed and fabricated [7]. Backward Wave Oscillators (BWO) in the frequency range 350-650 and 880-1250 GHz were used as a LO source for mixer measurements and receiving structure microwave evaluation. A broadband signal from a black body absorber was combined with the LO signal by using a simple polyethylene beam splitter. For filtering off infrared signal contributions we used black polyethylene and fluorogold cold filters. The IF signal from the junction was connected to a matching circuit and amplified by cooled down to 4.2 K amplifier with a cooled circulator at the input.

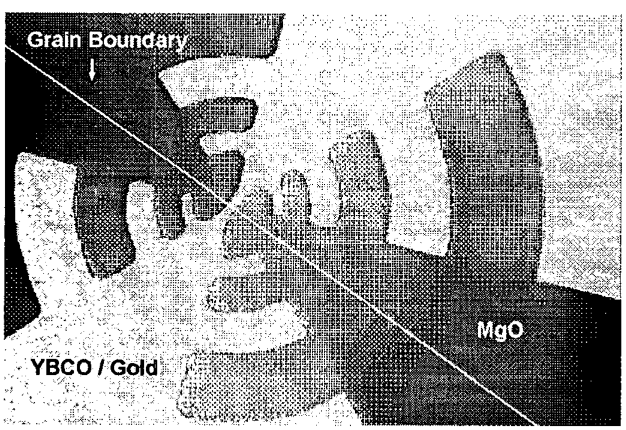

Fig. 1. Integrated receiving structure with a grain-boundary Josephson junction deposited on MgO bicrystal substrate.

III. Experimental Results

The IV curves and IF output signal measured at 300 K hot load (H) and 77 K cold load (C) as a source of signal radiation are presented in Fig 2 a,b. Results are presented for unshunted junctions measured at 4.2 K. The increase of temperature leads to appearing of a hump in the noise temperature in the range 20-40 K, then the noise temperature decreases at 50 K and rises again over 3000 K at temperatures 60 K and higher. The influence of LO radiation shows correlated features: the amplitude of the first Shapiro step decreased in the region of hump, then slightly increase at about 50 K and then again drops down. The temperature dependence for higher frequencies is even sharper: the 1000 GHz Shapiro step reduced at temperatures over 10 K.

The noise temperature measured in the self-pumping mode, when LO source was switched off, vary between 580 and 2300 K with the dc bias in the range 0.1-0.5 mV.

The conversion efficiency was estimated by dividing the variation of the input temperature 300-77 K by the related IF output power variation of about 10 K, compared to the IF amplifier noise temperature measured separately. This yields

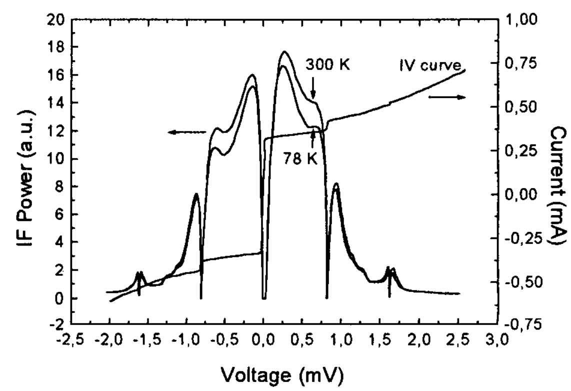

Fig. 2 a: Hot/cold measurement at 430 GHz

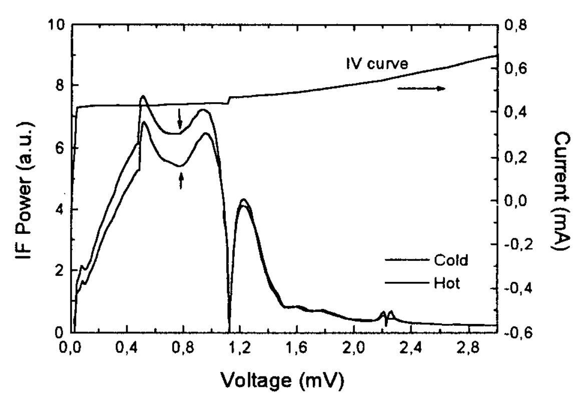

Fig. 2 b: Hot/cold measurement at 546 GHz an uncorrected conversion efficiency of -13.4 dB and a mixer input noise temperature of 55 K.

To estimate the total (integrated) noise of the Josephson junction at higher frequencies we have measured the selective detector response and IF noise under low LO power at frequencies up to 1250 GHz (see Fig. 3, 4). Measurements of the IF noise and the selective detector response are equivalent to evaluation of the Josephson radiation linewidth (see Fig. 4). The calculation of the spectrum from detector response of Josephson junction is known as Hilbert spectroscopy [8] and the proposed estimation from noise dependence is its modification that allows to simplify measurement technique and improve sensitivity and frequency resolution. At 500 GHz and 77 K the linewidth is 17 GHz in unshunted junction and 6 GHz in junction shunted by 0.1 Ω resistance. The configuration of measurement setup in this case is the same as for JM with self pumping.

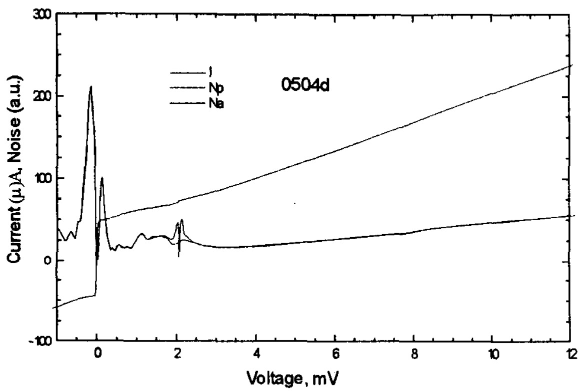

Fig. 3. Noise (Np, Na) and IV curve (I) measured under 1 THz irradiation (Np) and without radiation (Na).

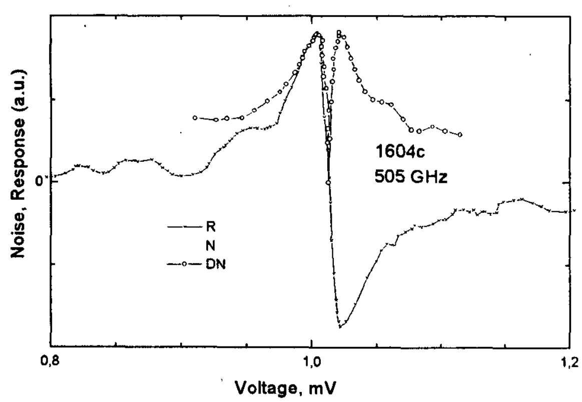

Fig. 4. Detector response R and noise DN, latter after deduction of autonomous noise and extraction the square root.

The linewidth at 4.2 K and 1000 GHz is 34 GHz for a 20 Ω junction, 28 GHz for a 4 Ω junction, and 4.5 GHz for a 0.7 Ω shunted junction. These values are about 6-8 times over the simple estimations according to RSJ with Johnson noise as the main source of fluctuations $\Delta f[\mathrm{MHz}]=40(R_d^2/R_n)T[\mathrm{K}]$, see [1].

IV. Discussion

The measured noise temperatures of Josephson mixer are comparable with the best Schottky barrier diode mixers (SDM) [9]. The DSB mixer noise temperature of SDM is about 4000 K at frequencies in the range 300 - 500 GHz and 11000 K at 2500 GHz. Using relatively inexpensive 50 K refrigerator and HTc Josephson mixer the receiver noise temperature can be decreased twice.

The strong and non-monotonic temperature dependence of noise temperature and Shapiro step amplitude reflects the specific absorption of microwave radiation in thin HTS film. The losses became much higher when the central part of antenna is made of YBaCuO. To improve the receiving structure parameters we made the antenna of Au film, and even a small part of HTS film in the apex of antenna brings high and temperature-dependent microwave losses.

According to our measurements the linewidth of Josephson oscillations exceeds the value calculated from simple model based on Johnson noise as a main source of fluctuations. The spectral density of voltage fluctuations due to the Johnson noise can be given as

$$S_V(V) = R_d^2(V)\cdot S_I \cong \frac{2R_d^2(V)\cdot kT}{R_0} \qquad (1)$$

where R_0 is a junction dynamic resistance with no radiation. The noise voltage maximum in this relation coincides with the voltage position of R_d maximum. Position of the latter can be deduced from analytic expression for the IV curve near Shapiro step in presence of Johnson noise of a normal resistance R_0. The step smearing is characterized by dimensionless parameter

$$\gamma = 2ekT/\hbar I_{st}$$

where I_{st} is the step halfwidth in the absence of noise. Exact analytic calculations according to [1] are rather complicated, but for practical estimations simplified relations can be deduced:

$$\Delta V \cong 1.92 R_0\sqrt{2ekTI_{st}/\hbar} \quad \text{for } \gamma\le 1 \qquad (2a)$$

$$\Delta V \cong 4\sqrt{3}kTR_0/\hbar \quad \text{for } \gamma\ge 1 \qquad (2b)$$

The IV curve in Fig.1 corresponds to $\gamma=0.05$ and $\Delta V=6$ μV at 4.2 K, whereas experiment brings 30 μV. For other samples the step smearing was 1-3 times above the values calculated according to (2). Excess stepwidth can be explained by shot noise at relatively high bias voltages 1 and 2 mV. Shot noise can be accounted by simple substitution kT by

$$kT_{ef} = \frac{eV}{2} \coth \frac{eV}{2kT} \tag{3}$$

in relation (2). This brings an increase of 1.5 - 2 times in linewidth which is proportional to signal frequency.

The possible mechanism for the noise increase can be multiple Andreev reflection in normal channels via defects (pinholes) in the grain boundary barrirer. The shot noise in junction with mixed tunneling (SIS) and direct (SNS or Ss'S) conductivity, according to [10] can be presented as:

$$S_v = 2eI_{tun}R^2 + \frac{4\Delta}{eV} I_d R^2 \tag{4}$$

When the last term dominates, formulae (4) can be simplified to the relation for the noise temperature $4kT_nR=4\Delta R/e$, or $T_n=\Delta/ke$. The exact calculations in [11] determines the value of $T_n=\Delta/3ke$ for the noise temperature in pure SNS junctions. In the case of HTc junction it brings the noise temperature 300 K. For low excess currents this value can be determined by the ratio of the excess current to the critical current I_{ex}/I_c. If we assume that about 10% of current is carried by SNS or Ss'S channels, then the excess noise delivered by this mechanism brings about 30 K of extra noise temperature that is in a good correlation with the measured value. The presence of small subharmonic steps clear observed in noise dependencies is supporting the model of such current transport and noise [12]. This analysis demonstrate that excess noise in Josephson mixer can be attributed to the quality of JJ and can be improved by optimisation of the fabrication process.

V. Conclusion

We have fabricated a HTS Josephson mixer and tested it in submm-wave range. A DSB mixer noise temperature of about 1100 K was measured at 430 GHz. The mixer performance was improved by using junctions with low-inductance resistive shunt. In a self-pumping operation mode a noise temperature of 1000 K and less was measured. The noise temperatures of HTc Josephson mixer are 2-4 times as low compared with the best Schottky barrier diode mixers. The use of HTc Josephson mixer with large I_cR_n products will allow to increase the receiver frequency above 1-2 THz. This makes Josephson mixers a promising candidate for radioastronomy and atmosphere monitoring. A novel method for estimation of Josephson radiation linewidth from the IF noise dependence has been suggested. This method is modification of the Hilbert spectroscopy method and allows to simplify the measurement technique and to improve the sensitivity.

Acknowledgment

This work is supported by European Community under Grant N IC15-CT96-0806 (INCO-Copernicus project), INTAS under Grants N 731 and 268, Swedish Academy of Sciences, Russian Ministry of Science and Russian Foundation for Basic Research.

References

[1] K.K. Likharev, V.V. Migulin, "Josephson effect millimetre range receivers", Radio Engineering and Electron Physics, v. 25, pp. 1-18, June 1980.

[2] J.H. Claassen, P.L. Richards, "Point contact Josephson mixers at 130 GHz", J.Appl. Phys., v. 49, N 7, p. 4130-4140, 1978.

[3] J. Edrich, D.B. Sullivan, D.G. Mac Donald, IEEE Trans. MTT, v. 25, N 6, p. 476, 1977.

[4] R.J. Schoelkopf, J. Zmuidzinas, T. Phillips, H.G. Le Duc, J.A. Stern, "Measurements of noise in Josephson-effect mixers", IEEE Trans. MTT, 43, N 4, (1995), pp. 977-983.

[5] M.A. Tarasov, G.V. Prokopenko, S.W. Jacobsson, V.P. Koshelets, S.A. Kovtonjuk, C.N. Holmstedt, L.V. Filippenko, I.L. Serpuchenko, S.V. Shitov, A.N. Vystavkin, E.L. Kollberg, "Experimental studies of Josephson mixing in SIS junctions with 500 GHz band local oscillator", 3 Int. Conf. on MM-Wave and Far Infrared Science and Technol., Aug. 22-26, 1994, pp. 149-152.

[6] V.P. Zavaleev, K.K. Likharev, "Performance limits of Some Wideband Devices with Josephson Junctions", Radio Engineering and Electron Physics , v. 23, 1268(1978).

[7] M. Tarasov, A. Shul'man, O. Polyansky, A. Vystavkin, E. Stepantsov, E. Kosarev, Z. Ivanov, H. Ekstrem, T. Claeson, E. Kollberg, "Quasioptical integrated YBaCuO receiver for direct detection and Hilbert spectroscopy in 350-850 GHz band", 6th Int. Superconducting Electronics Conf., ISEC'97, June 25-28, 1997, Berlin, Germany.

[8] Yu.Ya. Divin, O.Yu. Polyansky, A.Ya. Shul'man, "Incoherent radiation spectroscopy by means of the Josephson effect", Sov. Tech. Phys. Lett., 6(9), 454-455, 1980

[9] I.Galin, A high-performance 318 GHz subharmonic balanced mixer, Ninth International symposium on Space Terahertz Technology, 17-19 March 1998, Pasadena, Ca., pp. 181-186.,

B.J.Maddison, R.J.Martin, M.L.Oldfield, et al, A compact 500 GHz planar Schottky diode receiver with a wide instantaneous bandwidth, ibid, pp. 367-372.

C.M.Mann, Mixers for the millimetre, submillimetre and Terahertz regions, 28 EuMC, Amsterdam, 1998, pp. 741-746.

[10] P. Dieleman, T.M. Klapwijk, "Shot noise beyond the Tucker theory in niobium tunnel junction mixers", Appl. Phys. Lett., 72, N 13, 1653-1655 (1998).

[11] E.V. Bezugly, E.N. Bratus, V.S. Shumeiko, G. Wendin, "Multiparticle tunneling and enhanced current noise in mesoscopic SNS structures", Gothenburg Mesoscopic Days, April 17-18, 1998.

[12] M. Tarasov, D. Golubev, V. Shumeiko, E. Stepantsov, O. Harnack, Z. Ivanov, T. Claeson, "Subharmonic Shapiro steps and noise in high-Tc Josephson junctions", JETPh Lett., v. 68, N 5, 1998