NOISE AND CONVERSION EFFICIENCY OF HIGH-T_c SUPERCONDUCTOR JOSEPHSON MIXERS

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Abstract

We report on experimental studies of the noise performance and conversion efficiency of high-T_c Josephson mixers at frequencies between 90 GHz and 550 GHz. The heterodyne mixing experiments have been performed by using $YBa_2Cu_3O_{7-\delta}$ step-edge junctions and bicrystal junctions on MgO ($\varepsilon \approx 9.6$) substrates. We studied the Josephson mixer performance for the case of internal pumping (self-pumping) and external pumping. Receiver noise measurements in a waveguide setup for the case of external pumping at 90-94 GHz gave formally calculated double-side-band (DSB) mixer noise temperatures (T_m) of about 2000 K at physical temperatures of 10 K. Similar measurements in a quasioptical setup at 4.2 K and at operation frequencies of 430 GHz and 546 GHz yielded mixer noise temperatures of 1200 K and 1100 K, respectively. Using the internal pumped mode, i.e. mixing without external local oscillator signal, we also obtained clear IF response in hot/cold-measurements. The formally calculated T_m were between 580 K and 2300 K.

I. Introduction

Mixers based on the Josephson effect have been shown to have low local oscillator power consumption and high conversion efficiencies in the millimeter-wave range. In contrast to classical resistive mixers, the conversion efficiency of a Josephson mixer can be higher than -3 dB, i.e. conversion gain is possible. Beyond this, a large bandwidth up to serveral tens of GHz at the intermediate frequency (IF) is expected. Conventional low-T_c superconductor-isolator-superconductor (SIS) mixers which utilize the quasi-particle tunneling effect are known to have the highest sensitivity, but their mixing performance degrades above 0.7 THz. High-temperature superconductor (HTS) Josephson junctions (JJ) are expected to operate as a heterodyne mixers up to some THz due to of the relatively high energy gap of the HTS materials. High transition temperatures of HTS materials promise operation temperatures above 20 K. In addition, the low local oscillator power consumption makes the HTS Josephson mixer an attractive candidate for air- and spaceborne receiver applications.

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It is known that the sensitivity of Josephson mixers is limited by the intrinsic junction noise and excess noise from Josephson oscillations. Theoretical studies of the noise properties of Josepshon mixer were performed by Likharev et al. [1]. Their analysis predicts for normilized frequencies $\Omega > 1$ a minimum noise temperature of $T_n = 10.5T(\omega/\omega_c)^2$, where $\Omega=\omega/\omega_c$ with $\omega_c=2I_cR_ne/\hbar$ is the characterisic frequency of the Josephson junction (I_c is the critical current, R_n the normal-state resistance of the Josephson junction). An even more optimistic prediction of $T_n = 6T$ was given for signal frequencies ω equal to ω_c ($\Omega = 1$). In the selfmixing mode, i. e. the junction is pumped by the intrinsic Josephson oscillations, the noise temperature was predicted to be equal to T for $\omega > 0.2\omega_c$.

Schoelkopf et al. [2] have recently clarified the origin and the magnitude of this noise by simulations based on the macroscopic resistively shunted junction (RSJ) model. They showed that the linewidth of the internal Josephson oscillation is comparable with the frequency at bias points near the critical current, yielding an excess noise floor at low voltages. Following this analysis the mixer noise temperature depends on the working temperature, the embedding impedances, and the normalized frequency Ω. Their result for the minimum DSB mixer noise temperature was $T_n = 20T$ for $\Omega = 0.5$. These calculations were done for a fixed RSJ fluctuation parameter, $\gamma = 0.01$, which is defined by $\gamma = 2ek_BT/\hbar I_c$. This parameter is the ratio of the thermal energy, k_BT, to the Josephson coupling energy, $\hbar I_c/2e$. In general, the noise temperature of a Josephson mixer increases with increasing γ.

Several groups have studied experimentally the mixing properties of HTS Josephson junctions in [3]-[5]. Chen et al. [6] have recently demonstrated frequency downconversion of relatively strong signals at terahertz frequencies using $YBa_2Cu_3O_{7-x}$ (YBCO) bicrystal junctions (BCJ). Noise measurements on YBCO Josephson mixers were performed by Shimakage et. al. [5]. They measured a receiver noise temperatures T_r (DSB) of 1800 K in the 100 GHz band and 1200 K in the 300 GHz band.

In this paper we present our experimental study of the noise and mixing properties of two different types of HTS grain-boundary junctions (GBJ): step-edge junctions (SEJ) and bicrystal junctions prepared on MgO substrates. The results of measurements of the mixer noise temperature and the conversion efficiency will be presented. The experiments were performed using a waveguide based setup for W-band frequencies and a quasioptical mixer for frequencies between 300 GHz and 600 GHz.

II. Fabrication of High-T_c Superconductor Josephson Junctions

GBJs, based on intrinsic barriers/interfaces, are specific for high-T_c superconductors and not known for conventional metallic superconductors. This class of Josephson junctions includes different GBJs like SEJs and BCJs. The former junction type can be realized by fabricating GBs at steep substrate steps. In the latter case, a grain boundary which is present in a bicrystal

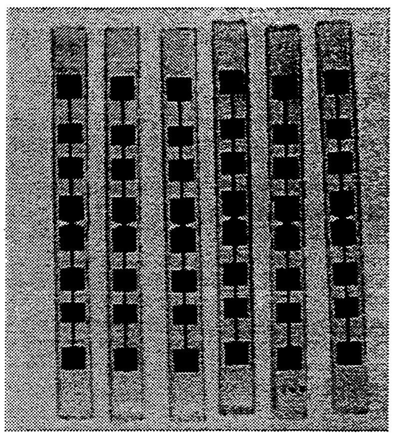

Fig. 1a: Step-edge Josephson junction mixers on MgO for waveguide mount

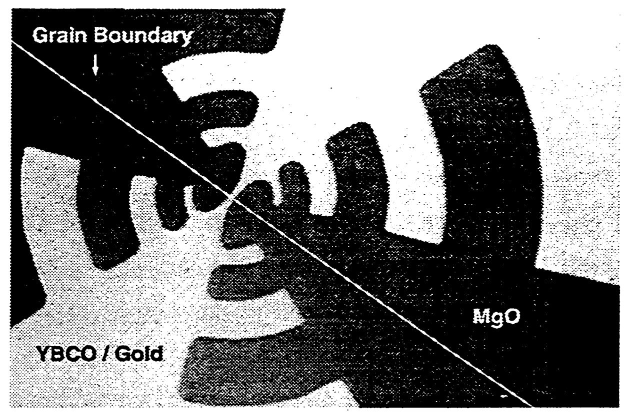

Fig. 1b: Logarithmic-periodic antenna for quasioptical mount with bicrystal junction in the center

substrate grows through the epitaxial HTS film during the deposition. A detailed review on HTS-JJs is given in [7].

For our studies, SEJs and BCJs were fabricated on (100) MgO substrates (ε_r = 9.6). Laser deposition method was used for fabrication of thin YBCO films with different thicknesses from 50 nm to 100 nm. After the deposition of the superconductor a approximately 50 nm thick gold layer was sputtered in-situ on the YBCO film. This layer is utilized as a low-loss antenna material and it is also used for electrical contacts. We used standard photolithographic processes and ion beam etching for patterning of the junction and the antenna structure. The Josephson junction consist of a 1 μm wide bridge which crosses a grain boundary (bicrystal junction) or a substrate step (step-edge junction). For step-edge junctions the standard step height was 250 nm and the thickness of the YBCO film was 200 nm. In order to remove the gold shunt from the top of the bridge we opened a window in the gold layer using ion beam etching. The junctions were integrated into bow-tie and logarithmic-periodic antenna layouts for measurements in a waveguide and a quasioptical setup, respectively (see Fig. 1a,b).

III. Waveguide Setup

A waveguide setup for measurements in the W-band was assembled as follows. The LO signal from a gunn oscillator is combined with a broadband noise signal from an absorber using a two grid diplexer. The combined signals are focussed through the teflon window of a cryostat. The mixer chip is mounted across a section of a rectangular waveguide inside a mixer block which feeds a circular, conical horn. A backshort and an e-plane tuner allow adjustment of the RF embedding impedance. The IF signal output of the mixer is connected to a bias-tee and a circulator which is located outside the cryostat. The IF signal is amplified by a 1.4 GHz IF HEMT amplifier with gain of 34 dB, followed by an amplifier with gain of 35 dB. The amplified signal passes a bandpass filter with a center frequency of 1.4 GHz and bandwidth of 400 MHz. The filtered signal is detected by a power meter. In order to introduce a broadband noise signal towards the mixer, we connected a noise diode to the circulator. The noise temperature T_{IF} of the IF chain was measured to be 230 K using the standard hot/cold load technique (Y-factor method).

IV. Quasi-Optical Setup

For heterodyne mixing experiments in the frequency range between 300 GHz and 600 GHz a quasioptical setup was assembled at Chalmers University of Technology. A backward wave oscillator (BWO) generated the LO signal, and a broadband signal from a black body absorber was combined with the LO signal by using a simple polyethylene beam splitter. The beam was formed by a teflon lens and focussed thru the windows of a LHe cryostat. For filtering of infrared signal contributions we used black polyethylene and fluorogold filters. The mixer chip was mounted on the rear side of a hyperhemisperical MgO lens. The IF signal was connected to a matching circuit and amplified by a cooled amplifier with a circulator at the input.

V. Experimental Results

A. Response to External Pumping

The Josephson junction response to external pumping was investigated in the millimeter and the sub-millimeter wavelength range. Fig. 2 shows the response of a MgO bicrystal junction,

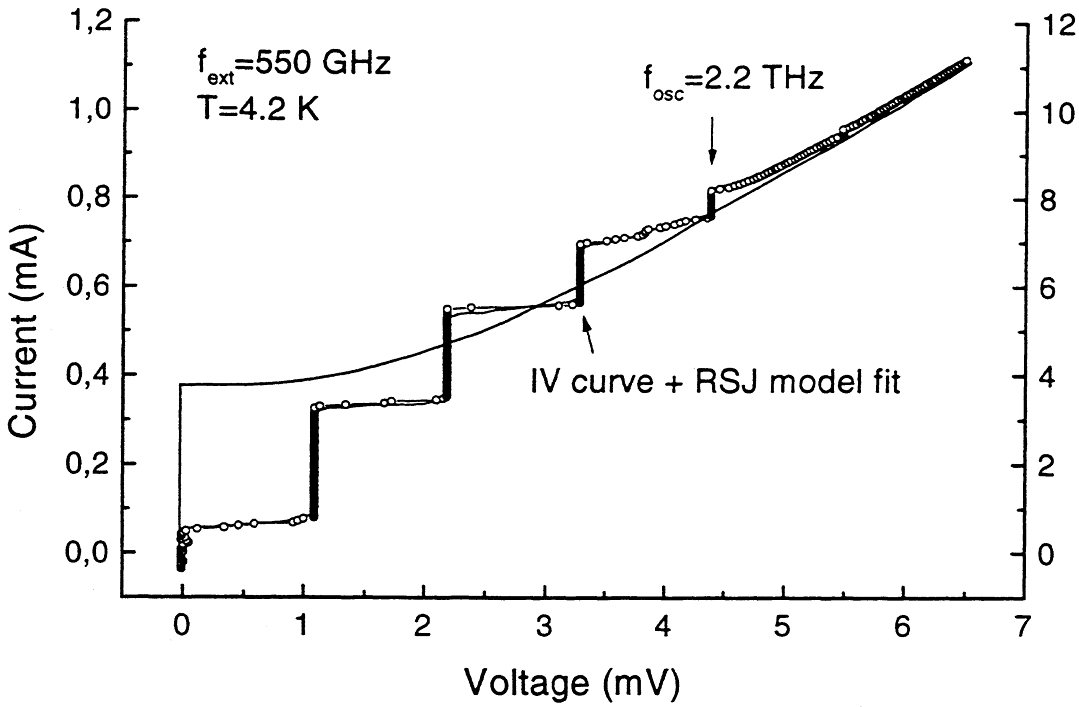

Fig. 2: External pumping of a BCJ on MgO at 550 GHz, with and without external pumping irradiated by 550 GHz radiation using the quasioptical configuration. In this experiment it was possible to suppress the critical current completely to zero (lack of excess current) and we obtained oscillation of the Shapiro step height with increasing power in accordance with RSJ model predictions. The calculated RSJ-model fit (Ω=0.5, β_c=0.8, γ=0.01) showed nearly perfect correlation with the experimental data. This means that the junction behavior can be completely descibted by the RSJ model - also at frequencies above 1 THz. Therefore we can assume that no parasitic effects, e.g. Cooper-pair breaking, occur.

B. Mixer Noise Temperature

Receiver and mixer noise temperatures have been measured by using standard hot/cold load technique (Y-factor method) with 300 K (hot) and 77 K (cold) absorber loads.

1. Waveguide Mixer

For noise measurements in the waveguide setup, we fabricated SEJs on thin MgO substrates in order to reduce the high frequency losses. After the fabrication of several junctions on 10x10 mm^2

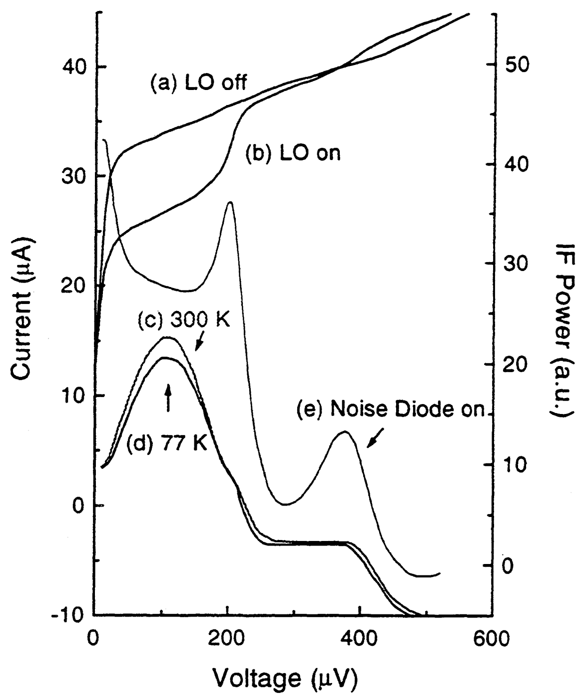

Fig.3: Waveguide mixer noise measurement

substrates, we reduced the substrate thickness down to approximately 150 µm and cutted each junction into a small 0.9 x 10 mm^2 strip (see Fig. 1 a).

The output noise of the mixer was measured at different current biaspoints. The best sensitivity of the receiver was obtained by maximizing the IF output power at biaspoints between the zeroth and the first Shapiro step with respect to tuner positions and local oscillator level. It is important to note that only a very narrow range of the tuner positions allowed a response of the mixer output to a change of the input absorber load temperature.

The results at a physical temperature of 10 K and 90-94 GHz LO frequency are displayed in Fig. 3. Curve (a) and (b) show the unpumped and the pumped IVC of the mixer, respectively. The characteristic voltage of this step-edge junction was 450 µV at 10 K corresponding to a characteristic frequency of 218 GHz and Ω_{90}=0.41. Curve (c) and (d) in Fig. 3 show the output noise of the mixer with a 300 K and a 77 K absorber load in front of the receiver, respectively. From this measurement, the calculated receiver noise temperature T_R was 3300 K. The mixer's conversion loss could also be determined using a reflection measurement method in order to get a measure of the reflection coefficient Γ which implies the impedance mismatch between mixer and IF amplifier. For this measurement, a broadband (DC-18 GHz) noise signal was introduced into one port of the circulator to be launched towards the mixer and reflected from the mixer into the input of the IF line. From the difference in IF power with and without the noise diode applied we can derive Γ [8]-[9].

Curve (e) in Fig. 3 displays the result of a reflection measurement. The differential resistance which determines the real part of the mixer's IF impedance was very close to the normal resistance R_n of 15 Ω of the junction at biaspoints between Shapiro steps. The best matching was obtained between the zeroth and the first Shapiro step with a Γ of approximately 0.47.

Knowing Γ and T_{IF}, we calculated a conversion loss of approximately -7.6 dB and an IF contribution to the receiver noise temperature of approximately 1300 K. The DSB mixer noise temperature is then estimated to be 2000 K including all front-end losses at the receiver input.

The fact that the differential resistance was close to R_n can be related to a high noise smearing of the IV curve. We expect a infinite (if noise current is zero) or high dynamical resistance between the Shapiro steps, since $\Omega_{90} < 1$ (unseparated steps). In contrast, in our experiment the noise current was 5 times larger than the thermal noise current at 10 K. We attribute this to a high external noise contribution, which also increased the mixer noise temperature.

2. Quasi-Optical Mixer

Measurements in the quasi-optical configuration showed DSB mixer noise temperatures of 1200 K at 430 GHz (Fig. 4a) and 1100 K at 546 GHz (Fig. 4b) including all front-end losses. The operation temperature was 4.2 K. The critical current of the BCJ on MgO was 300 μA and the normal resistance was about 10 Ω. This yields a formally calculated IcRn procuct of 3 mV and normalized frequencies of Ω_{430}=0.29 and Ω_{546}=0.37. The conversion efficiency was estimated by dividing the variation of the input temperature 300-80 K = 220 K by the related IF output power variation of about 10 K (compared to the IF amplifier noise temperature measured separately). This yields a uncorrected conversion efficiency of -13.4 dB and a mixer input noise temperature of approximately 50-54 K.

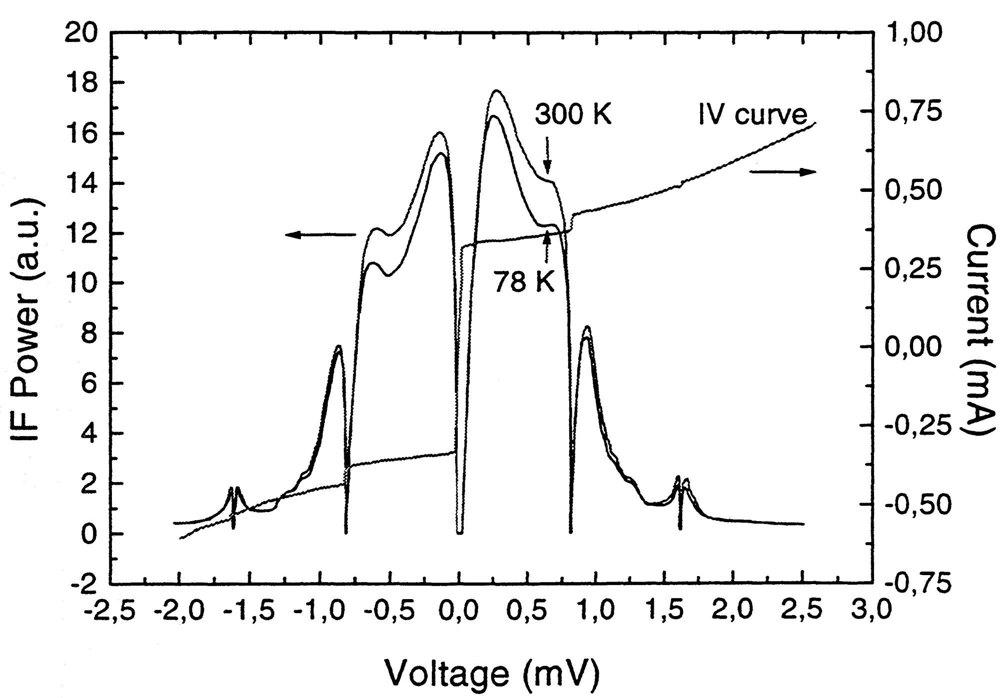

Fig. 4 a: Hot/Cold noise measurement at **430 GHz** using a bicrystal HTS Josephson junction, $T_{m, DSB} \approx 1200$ K.

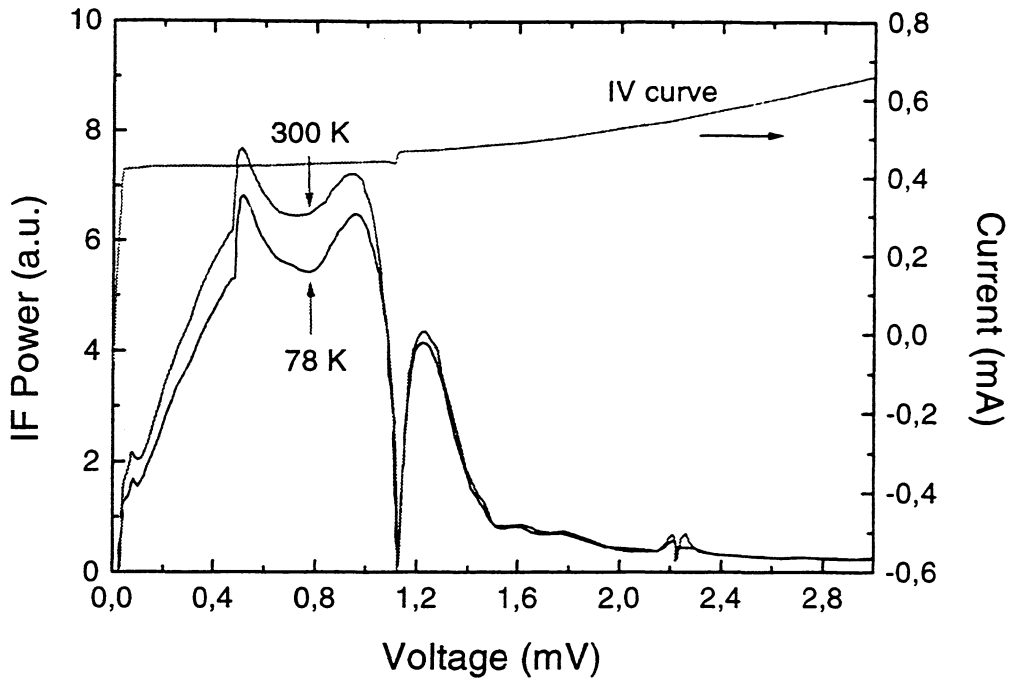

Fig. 4 b: Hot/Cold noise measurement at **546 GHz** using a bicrystal HTS Josephson junction, $T_{m,\,DSB} \approx 1100$ K.

C. Selfpumped Mode

We also performed mixer noise measurements in the self-pumped mode. For these measurements we closed the input window of the cryostat by hot and cold absorber. It is important to exclude any direct detection effects, i.e. the IV curve of the mixer should not respond to the absorber load. Fig. 5 shows the result of a noise measurement in the self-pumped mode at 4.2 K. The mixer is the same device as in the experiments with external pumping. From this data we extract a mixer noise temperature of 580 - 2300 K in the dc bias range 0.1-0.5 mV. Interesting features are the clearly visible minima and maxima in the IF output signal which are related to geometrical resonances of the "teeths" of of the logarithmic-periodic antenna (Fig. 1b). The differential resistance is reduced at the point of a resonance what results a change of the mixer impedance matching selfpumped mode.

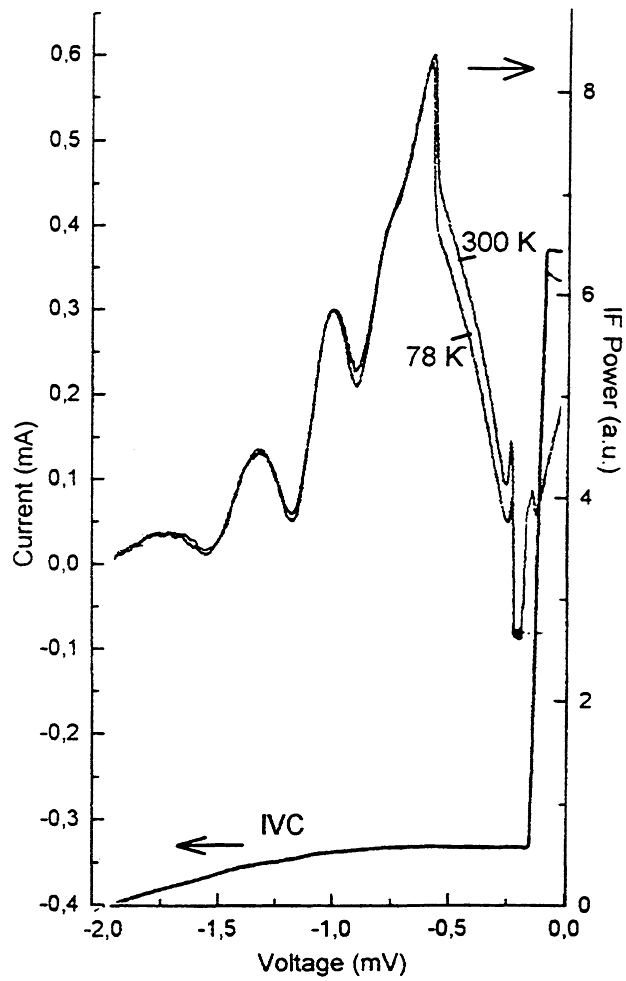

Fig. 5: Hot/Cold-measurement in the to the IF amplifier.

VI. Discussion and Conclusion

The experimental results show that with high-T_c grain boundary Josephson junctions frequency conversion is possible at large IF bandwidths, high working temperatures, and low LO power levels which are important requirements for mixer applications in the mm and sub-mm wavelength range.

Following the analysis of Likharev et al., the best expectable mixer noise temperature should be approximately 26 K and 60 K at a physical temperature of 4.2 K and 10 K, respectively. In fact, the condition $\Omega < 0.5$ was satisfied in all of our experiments. The analysis of Schoelkopf predicts a best DSB mixer noise temperature of 84 K at 4.2 K and 200 K at 10 K for γ=0.01. The measured noise temperatures differ by a large factor from the theoretical predictions. However, we have to keep in mind that the measured values were not corrected for any kinds of receiver input losses. For the quasi-optical experiments, these losses include all losses of the beam splitter, window, and lens. The impedance mismatch between the mixer and the logarithmic-periodic antenna was quite large, since the required junction impedance was about 60 Ohm for this antenna on MgO. In contrast, the normal resistance of the mixer used in the quasi-optical measurement was 10 Ohm.

Additionally, the beamwidth was not optimized and consisted of two comparable lobes what gives about 2-4 dB losses. The broaden beam and the tilted polarization of the antenna with variation of frequency gave also 300 K influence from the sidelobes (3-4 dB losses). In fact, we have reflections from the MgO-vaccum interface, from the fluorogold-vaccum, and from the teflon window-air interface that gives about 2 dB losses in summary. The back lobe of the antenna on MgO gives about 1 dB more losses. These simple calculations of about 8-11 dB input losses, which can be reduced, show that our experimental results underestimate the performance of the Josephson mixer.

Other sources of noise are more of physical nature: 1/f noise which includes a number of different noise mechanisms (telegraph-like noise, fluctuations of critical current and resistance) could contribute to the overall mixer noise. In the RSJ model simulations only the presence of thermal noise was assumed and up to now, no other sources of noise were included. Indeed, at present we have no clear understanding how the intrinsic junction noise influences the mixer performance.

However, the experimental results demonstrate, that the Josephson mixer noise temperature is more or less independend of the operation frequency. We expect this behaviour as long as the normilized frequency $\Omega=\omega/\omega_c$ can be held constant for higher operation frequencies. The characteristic frequency ω_c is connected to the energy gap of the superconducting material. Due to the high energy gap of HTS material we expect that HTS Josephson mixers will prove to be useful for receiver applications at high working temperatures in the THz frequency range.

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References

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

[2] R. J. Schoelkopf, J. Zmuidzinas, and T. G. Phillips; R.J. Schoelkopf, Ph.D. dissertation, California Institute of Technology, 1995 (unpublished)

[3] J. P. Hong, H. R. Fetterman et al., *Appl. Phys. Lett.*, **62,** 22, 1993

[4] Y. Fukumoto, R. Ogawa and Y. Kawate, *Jpn. J. Appl. Phys.,* **32**, 1993

[5] H. Shimakage, Y. Uzawa, M. Tonouchi, Z. Wang, *ASC'96*, Pitsburg 1996

[6] J. Chen, H. Myoren, K. Nakajima, T. Yamashita, P. H. Wu, *Appl. Phys. Lett.*, **71** (5), 1997

[7] R. Gross, L. Alff, A. Beck, O. M. Froehlich, D. Koelle, A. Marx, *IEEE Trans. on Appl. Supercon.*, Vol. 7, No. 2, June 1997

[8] R. J. Schoelkopf, J. Zmuidzinas, T. G. Phillips, H. G. LeDuc, and Jeffrey A. Stern, *IEEE Trans. on Microw. Theor.*, Vol. 43, No.4, April 1995

[9] R. J. Schoelkopf, T. G. Phillips, and J. Zmuidzinas, *IEEE Trans. on Appl. Supercon.*, Vol. 3, No.1, 1993