HTS Mixers Based on the Josephson Effect and on the Hot-Electron Bolometric Effect

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***Abstract*—We report on our experimental studies of high-T_C Josephson mixers and high-T_C hot-electron bolometric (HEB) effect mixers. Mixers based on high-T_C bicrystal Josephson junctions have been fabricated, and noise, conversion efficiency, and receiver bandwidth measurements have been performed in the frequency range between 90 and 550 GHz. The dependence of the mixer performance on the operation temperature has been studied. High-T_C HEB mixers have been fabricated on MgO and sapphire substrates. We successfully sized the dimensions of the effective device volume down and managed to fabricate 50-60 nm long devices. In such short structures phonon diffusion into the normal metal electrodes should significantly improve the mixer performance.**

I. INTRODUCTION

Mixers based on high-temperature superconductors (HTS) could be attractive candidates for millimeter and submillimeter wave receiver applications where operation temperatures above 20 K are required (e.g., earth remote-sensing observation from satellites). Low-temperature superconductive mixers utilizing quasiparticle tunneling are known to have a high sensitivity and low power consumption. However, all attempts to fabricate mixers based on quasiparticle tunneling in HTS junctions failed. Several reasons, such as short coherence length, nonconventional pairing mechanism, and sensitivity to processing, made it impossible to fabricate high quality tunnel junctions from HTS materials. The presently possible HTS mixers can utilize the Josephson effect or the Hot-Electron Bolometric (HEB) effect. We have investigated both types of mixers.

II. HIGH-T_C JOSEPHSON MIXERS

A HTS Josephson mixer consists of a grain boundary junction, which is intrinsically shunted due to the microscopic nature of the boundary. The nonlinear current-voltage characteristics of a pumped junction can be utilized for low-noise heterodyne mixing. HTS Josephson mixers have been investgiated in a number of studies [1]-[3]. The mixer noise temperature of 1200 K at 4.2 K operating temperature has been measured at 345 GHz using a quasioptical coupled HTS step-edge Josephson mixer [1]. We report on the noise and conversion performance of W-band waveguide Josephson mixers at operating temperatures above 20 K, based on bicrystal junctions on MgO substrates.

A. Fabrication

Step-edge (SEJ) and bicrystal junctions (BCJ) are specific for high-T_c superconductors. SEJs on MgO have been fabricated successfully [3], but problems with reproducibility and reliability have been found. It turned out that bicrystal junctions (BCJ) on MgO are much more stable and show higher I_cR_n products than SEJs. We have fabricated BCJs on 24° MgO bicrystal substrates ($\varepsilon_r = 9.6$). Pulsed laser deposition method was used for growing 50-100 nm thin YBCO films. In addition, a 50 nm thick gold layer was deposited in-situ on top of the YBCO film. We used standard photolithographic processes and ion beam etching (IBE) in combination with mass spectroscopy (in order to control the etching process) to define the junction and the antenna structure (YBCO etching rate $\approx$1nm/min). The junctions were integrated into bow-tie and log-periodic antennas. In order to remove the shunting gold layer from the top of the 1 μm-wide bridge, we lithographically defined a window across the bridge and milled the gold using an etching rate of 4 nm/min. The HTS bridges were passivated by evaporating a SiO_x layer.

B. Mixer Noise and Conversion Measurements

The RF setup consists of a mixer block for 80 GHz to 120 GHz with mechanical tuners, assembled inside a cryostat. A simple beam splitter was used to combine the signal and the local oscillator (LO) signal. For experiments at frequencies between 430 GHz and 550 GHz the junctions were mounted into a quasioptical setup using an extended hyperhemisphere MgO lens. The intermediate frequency (IF) signal was amplified by a cooled amplifier or by an external room-

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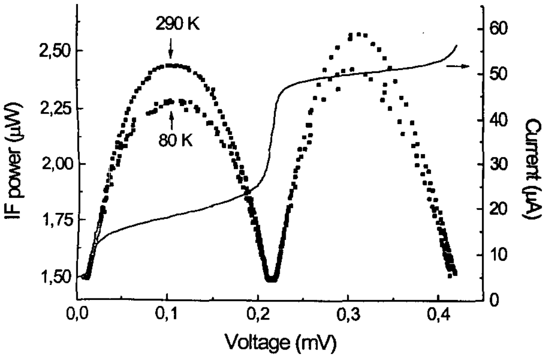

Fig. 1: IF power measurement at 90 GHz (LO) and 20 K using the standard hot/cold technique. The lowest receiver noise temperature was 2900 K.

temperature amplifier at 1.4 GHz followed by a 65 dB amplifier stage and limited by a bandpass (Δf=400 MHz). We calibrated the noise temperature of the IF chain by using a heated 50 Ω load attached to the cold plate. A coaxial switch for connecting the mixer or the load to the IF system was used. The calibration yield IF noise temperatures (T_{if}) of 5 K for the cooled amplifier and 130 K for the room-temperature amplifier. The noise measurements were done by using the Y-factor method (300 K/77 K loads). From the related IF power levels we can determine the receiver noise temperature T_{rec}. The mixer noise temperature T_m, and the conversion efficiency η are related to T_{rec} by $T_{rec}= T_m+\eta^{-1}\ T_{if}$. Fig. 1 shows an IF power measurements in the waveguide setup with external pumping at 90 GHz. Receiver noise temperatures of about 2900 K at operating temperatures of 20 K and at an IF of 1.4 GHz were measured. The critical current (I_c) of this BCJ on MgO was 50 µA at 20 K and the normal resistance (R_n) was 14 Ω. The best conversion efficiency, not corrected for the IF impedance mismatch, was approximately -10 dB. The noise contribution by the room-temperature amplifier was relatively high (about 1300 K). The estimated mixer noise temperature is about 1600 K at 20 K. The absorbed local oscillator power of 4 nW was calculated from the value of the suppressed I_c[4].

C. *Temperature Dependence of T_{rec} and η*

Fig. 2 displays the measured dependence of the receiver noise temperature and the conversion efficiency on the operating temperature between 20 K and 60 K. The conversion efficiency was calculated in respect to the IF calibration described in section II B. The receiver noise temperature increases approximately linear in the temperature range from 20 K up to 35 K and increases dramatically at operating temperatures above 40 K. The conversion efficiency decreases linear with increasing temperature in the whole range. As expected from theory, the reduction can be well described by the increase of the normalized frequency Ω ($\eta \propto \Omega^{-1}$), where $\Omega=\omega/\omega_c$, ω is the signal frequency, and $\omega_c=4\pi I_c R_n e/h$ is the characteristic frequency. Since η drops linear with T, the nonlinear increase of T_{rec} above 40 K should be connected to a degradation of the mixer performance. This is most likely due to a change in the excess noise mechanism in the junction [5].

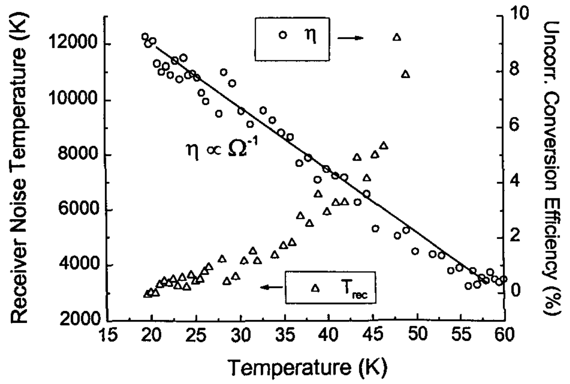

Fig. 2: Dependence of the receiver noise temperature and the conversion efficiency on the operating temperature at 90 GHz for the BCJ mixer which was described in section II B.

D. *Receiver Bandwidth Measurement*

In order to clarify the mode of side-band operation a receiver bandwidth measurement has been performed in the range 87-93 GHz. In this experiment the mechanical tuners have been adjusted for 90 GHz operation, the operating frequency has been changed after this, and the LO level has been adjusted for constant pumping at the same time. The measured characteristics of T_N and η shows that we can assume rather double-side-band (DSB) operation than single-side-band (SSB) operation, since the receiver performance is more or less constant within 90 GHz±1.6GHz (Δf=400 MHz). However, there is a clear evidence that we have a quite resonant tuning and about 2-3dB signal reduction in the lower side band. An optimization of the impedance matching between mixer and waveguide could improve the broad-band receiver operation.

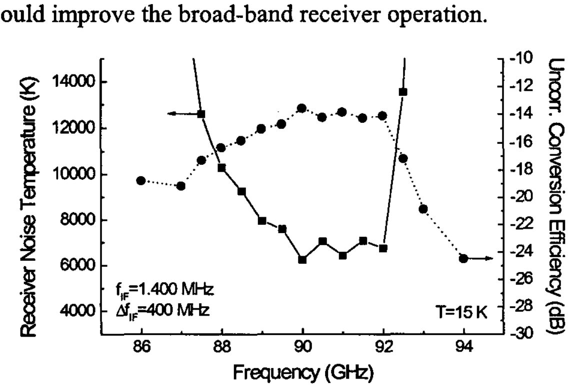

Fig. 3: Measurement of the receiver noise and conversion efficiency. The center frequency was chosen to be 90 GHz.

E. Noise Measurements at 430 GHz and 550 GHz

Similar measurements were performed in a quasioptical setup. A 1 μm wide bicrystal junction with a current voltage characteristic without any excess current at 4.2 K was used. The mixer noise temperature at 4.2 K and 430 GHz measured in the fundamental mixing mode was 1200 K for the junction shunted by a low-inductance resistive shunt, and 1400 K for the junction with no shunt [6]. Measurements at 546 GHz gave noise temperatures of about 1100 K.

F. Discussion

The sensitivity of Josephson mixers is limited by excess noise, which includes intrinsic junction noise and noise generated by internal Josephson oscillations. Likharev et al. predicted a minimum noise temperature of $T_n = 10.5T(\omega/\omega_c)^2$ for normalized frequencies $\Omega > 1$ [7]. A more optimistic prediction of $T_n = 6T$ was given for signal frequencies ω equal to ω_c ($\Omega = 1$). Schoelkopf et al. have shown that the linewidth of the Josephson oscillations is comparable with the frequency at bias points close to the critical current [5]. This causes an excess noise floor at low voltages. Their simulations, based the resistively shunted junction model (RSJ), predict a minimum DSB mixer noise temperature of $T_n = 20T$ for $\Omega = 0.5$ assuming a fluctuation parameter $\gamma = 0.01$, which is defined by $\gamma = 4\pi e k_B T/hI_c$, the ratio of the thermal energy, k_BT, to the Josephson coupling energy, $I_c h/4\pi e$. In the experiment described in section II B, γ was about 0.015 and $\Omega < 0.5$. Under these conditions we would expect a DSB T_m of about 400 K at 20 K, which is about four times lower than the measured value of 1600 K. However, intrinsic material losses and additional sources of noise which are not modeled yet, could be responsible for higher mixer noise.

III. HIGH-T_{IC} HOT-ELECTRON BOLOMETRIC MIXERS

Another type of the mixer, which is most promising for operation in the THz regime, is the superconductive hot-electron bolometer (HEB) [8],[9]. In contrast to the Josephson mixer, HEB mixer are not limited by the energy gap. Other advantages of HEB mixers are the real device impedance and the insensitivity against magnetic noise. HEB devices usually consist of a ultra small volume of thin superconducting film which is connected to two normal metal electrodes. Absorbed rf power generates non-equilibrium „hot" electrons, which result in an increase of the resistance of the device and a related voltage response. Depending on intrinsic relaxation mechanisms, HEB can be fast enough to follow the IF oscillation of several GHz. Karasik et al. published a detailed theoretical analysis of the performance of HEB mixers based on YBCO [10]. HTS HEB mixer have been investigated in [11]-[13]. An optimized fabrication technique, which is obviously the most important issue, was described in [11]. However, there exist still only a few data on the noise performance of these devices. Karasik et al. showed that low-noise mixing (≈2000 K SSB) could be achieved, if relaxation mechanism like phonon diffusion could be made dominant by reducing the device length (L) down to a few hundred nm [10]. Here we report on the fabrication and device tests of sub-μm HEB mixers on MgO and sapphire substrates.

A. Fabrication of Sub-μm YBCO HEB Mixers

For the fabrication of HEB mixers, thin YBCO films of thickness of about 20-40 nm have been grown on MgO and sapphire substrates using the laser deposition method. In the case of sapphire we applied a 30 nm thin CeO_2 buffer layer between the substrate and the YBCO film. The thin YBCO films have been protected by in-situ sputtered gold layer. Inductive T_c-measurements showed critical temperatures of 89-90 K for YBCO films on sapphire substrates and 84-86 K for films on MgO substrates. The transition widths were in the range between 0.5 and 1 K. After patterning the microbridges (width of the bridge w≈1μm), integrated into bow-tie antennas for waveguide measurements, a small-area window (50 nm to 500 nm length and 1 μm width) was defined across the bridge by using electron beam lithography. After removing the gold layer from the window by using IBE, a SiOx protection layer was applied by evaporation. We observed no significant degradation of the critical current density (J_c) and the R(T) characteristics.

B. DC Characteristics of Sub-μm YBCO HEB Mixers

Fig. 4 shows a SEM picture of the central part of our HEB mixer which has a device length of about 100 nm. The DC

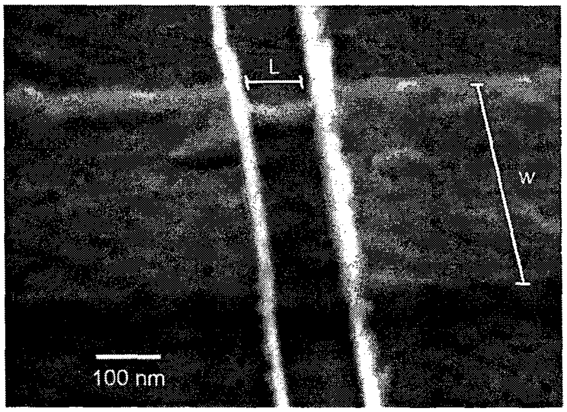

Fig. 4: Sub-μm YBCO HEB structure on MgO. The gold/YBCO sandwich electrodes are visible on the left and right hand side. The uncovered YBCO strip is located in the center between both electrodes, L=100 nm, w=1μm.

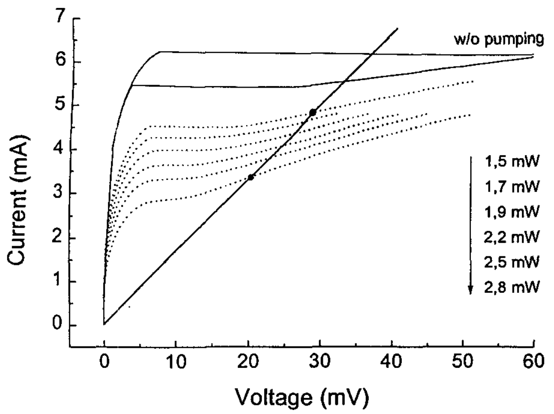

Fig. 5: DC characteristics of a YBCO HEB, L=0.05 µm, w=1µm, d=30nm; The dotted lines show the IVCs at different input levels at 90 GHz.

characteristics of a similar device on MgO with a smaller device length of 50-60 nm is displayed in Fig. 5 (film thickness 30 nm, device width 1 µm). The R_n was about 10 Ω and the I_c was 6.5 mA at 67 K. A thermal hysteresis which is related to self-heating of the device was visible at temperatures below 76 K. The dotted curves displays the response of the pumped device at different levels at 90 GHz and at 67 K. Comparing the dissipated electrical power along the constant resistance line and the applied microwave power, we estimated input losses of about 15 dB.

C. Heterodyne Mixing and Conversion Efficiency

Heterodyne mixing experiments have been performed at temperatures around 67 K and at 90 GHz. Fig. 6 displays the result of a mixing experiment using two monochromatic sources at 90 GHz (signal) and 91.4 GHz (LO). The overall conversion efficiency at 1.4 GHz was measured to be -25 dB. The same value was measured at an IF of 3 GHz, which is slightly better (5dB) than earlier experiments with longer devices ($L \approx 1$-2 µm) have shown [14]. This might be already an evidence that phonon diffusion plays a significant role in our sub-µm devices, but bandwidth measurements have to be done in order to clarify this more exactly. Additionally, the process of phonon escape from the film into the substrate could be improved by reducing the film thickness down to 15-20 nm. At the same time, the required LO power would be lowered.

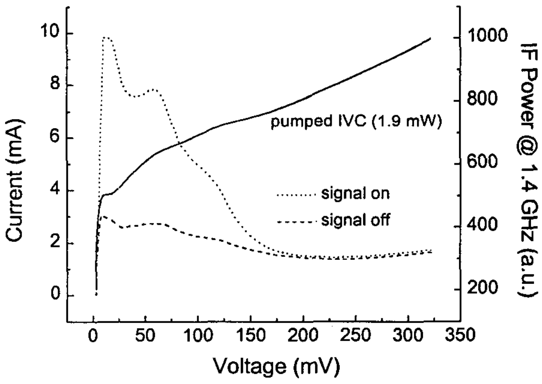

Fig. 6: Heterodyne mixing experiment at 90 GHz and 67 K using the sub-µm HEB mixer described in section III.B.

IV. CONCLUSION

We demonstrated that low-noise mixing is possible with HTS Josephson mixers at temperatures above 20 K. The measured mixer noise is about four times higher than predicted by the RSJ model. The required LO power was in the range of a few nW at 90 GHz. We successfully fabricated HEB mixers with device lengths between 50 nm and 0.5 µm and demonstrated heterodyne mixing at 90 GHz.

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