Noise and conversion properties of Y–Ba–Cu–O Josephson mixers at operating temperatures above 20 K

Oliver Harnack,[a] Marian Darula, Stephan Beuven, and Hermann Kohlstedt
Institute of Thin Film and Ion Technology, Research Center Jülich, 52425 Jülich, Germany

(Received 8 September 1999; accepted for publication 27 January 2000)

We have measured the noise performance and conversion efficiency of Y–Ba–Cu–O bicrystal Josephson mixers at operating temperatures between 20 and 60 K and at operating frequencies around 90 GHz. A double-sideband mixer noise temperature of about 1600 K and a conversion efficiency of −10 dB at 20 K operating temperature has been measured using the Y-factor method. The absorbed local oscillator power was in the range of 10 nW. The dependence of the mixer performance on the normalized frequency Ω and the fluctuation parameter Γ has been studied. In accordance with the resistively shunted junction model, the experimental data show the presence of excess noise. The temperature dependence of the mixer noise temperature can be explained by the variation of the linewidth of the Josephson oscillations with the operating temperature. © *2000 American Institute of Physics.* [S0003-6951(00)00113-3]

Mixers based on a single high-temperature superconductor (HTS) Josephson junction recently became attractive devices for receiver applications in long-term remote-sensing satellite missions. Low-noise operation utilizing the ac Josephson effect in the THz frequency range is expected at temperatures well above 10 K because of the large band gap of HTS superconductor materials. Additionally, the Josephson mixer requires only low local oscillator (LO) power levels on the order of several nanowatts, which can be considered to be a major advantage over Schottky diode mixers. Josephson mixers based on several different HTS junction technologies were reported for millimeter and submillimeter wave mixing.[1–3] Grossman *et al.* reported on mixing experiments at 30 THz using $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconductor–normal–superconductor Josephson junctions.[1] The mixer noise temperature T_M, the figure of merit of any mixer device, of 1200 K at $T=4.2$ K has been measured using a YBCO step-edge Josephson junction at 345 GHz.[2] Tarasov *et al.* have measured mixer noise temperatures of 1200 K at 430 GHz and 1100 K at 546 GHz and $T=4.2$ K using a YBCO bicrystal junction (BCJ).[3] However, the mixer noise performance at operating temperatures higher than 4.2 K is still unclear. The determination of the temperature dependence of the device noise is important for the identification of noise mechanisms that limit the mixer performance. The aim of our work was to measure the mixer noise performance of BCJs at operating temperatures above 20 K and to compare the experimental data with predictions by the resistively shunted junction (RSJ) model.

As shown in earlier studies, the Josephson mixer suffers from excess noise, which is believed to be self-generated due to the ac Josephson effect.[4,5] The mixer noise temperature is expected to exceed the thermal noise limit by several factors. After the RSJ model, the mixer noise depends on the fluctuation parameter, which is defined by $\Gamma=2ek_BT/\hbar I_C$, the ratio of the thermal energy k_BT to the Josephson coupling energy $I_C\hbar/2e$, where I_C is the critical current of the Josephson junction. Although the mixer noise can be assumed to exhibit no frequency dependence as long as the operating frequency does not exceed the gap frequency and $hf \ll k_BT$, the overall mixer performance is strongly frequency dependent, since the conversion efficiency η scales with the normalized frequency Ω, where $\Omega=\omega_{LO}/\omega_C$, ω_{LO} is the LO frequency, and $\omega_C=2eI_CR_N/\hbar$ is the characteristic frequency. In fact, ω_C is limited by the characteristic voltage $V_C=I_CR_N$, where R_N is the normal resistance of the Josephson junction. Assuming that the mixer is well matched to the radio frequency (rf) input and intermediate frequency (IF) output, the conversion efficiency of the Josephson mixer is given by $\eta=R_D/R_S(\partial I_C/\partial I_{LO})$,[6] where R_D is the differential resistance in the bias point and R_S is the rf resistance. A simple estimation shows that η is roughly $\eta\cong R_D\times R_S^{-1}\times\Omega^{-2}$ for $\Omega>1$.[4] Therefore, the overall mixer performance deteriorates as the square of the frequency for frequencies greater than the characteristic frequency. Based on RSJ model calculations, Schoelkopf *et al.* predicted a minimum double-side band (DSB) mixer noise temperature of $T_M=20$ T for $\Omega=0.5$, assuming $\Gamma=0.015$.[4] Likharev and Migulin calculated a minimum noise temperature of $T_M=10.5\cdot T\Omega^2$ for normalized frequencies $\Omega>1$, and $T_M=6$ T for ω_{LO} equal to $0.3\omega_C$ $(\Omega=1)$.[5] However, these models do not include any additional noise sources like noise generation by carrier transport mechanisms, and therefore these predictions certainly overestimate the Josephson mixer performance.

In order to study the HTS Josephson mixer performance, W-band waveguide devices based on BCJs were fabricated on 24° MgO bicrystal substrates ($\epsilon_r=9.6$). The pulsed laser deposition method was used to grow 50–100 nm thick YBCO films. *In situ* dc sputtering was applied to cover the superconductor films by a thin layer of gold. We used standard photolithographic processes and ion beam etching to define the junction and the bow-tie antenna structure. Finally, the junctions were passivated by evaporating a thin SiO_x layer on top of the structure. The rf measurement setup

[a]Author to whom correspondence should be addressed; electronic mail: o.harnack@fz-juelich.de

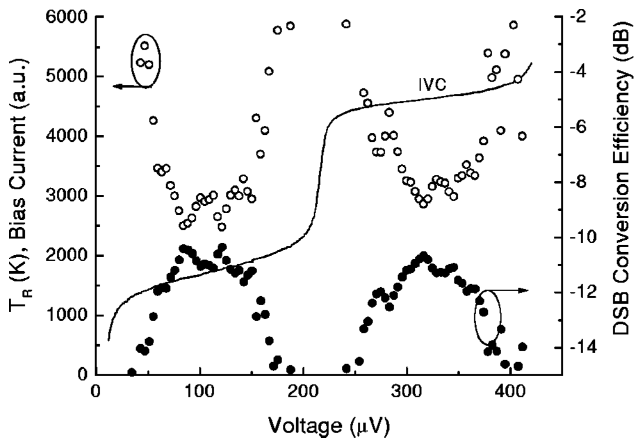

FIG. 1. DSB receiver noise and DSB conversion efficiency at different bias points. The LO frequency was 90 GHz and the operating temperature was 20 K. The best mixer performance can be obtained at bias points between the Shapiro steps.

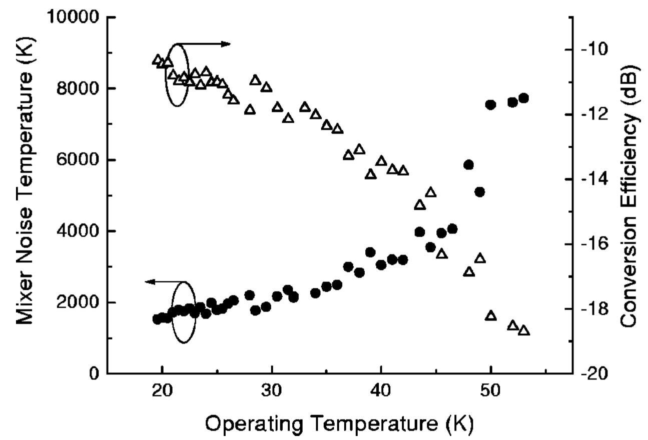

FIG. 2. Dependence of the DSB mixer noise temperature and DSB conversion efficiency on the operating temperature for a BCJ mixer. The LO frequency was 90 GHz.

consists of a mixer block with two mechanical tuners for 80–120 GHz, assembled inside a bath cryostat. For variable temperature measurements, the block was thermally isolated from the cold plate and attached to a resistive heater. Both a Martin–Puppett diplexer or a beam splitter were used to combine the signal and the LO signal. The IF signal was amplified by a room-temperature amplifier at 1.4 GHz, having a gain of 65 dB. The noise temperature of the IF chain ($T_{IF} \approx 130$ K) was calibrated by using a heated 50 Ω load as an adjustable thermal noise source. For the receiver noise temperature measurements 300 and 77 K absorber loads were used as radiation sources at the receiver input and from the related IF output power levels the receiver noise temperature T_R was calculated (Y-factor method). The LO level and the tuner positions were adjusted to get a minimum receiver noise temperature.

For our devices the lowest receiver noise temperature at $T=20$ K was about 2900 K (Fig. 1). I_C and R_N were in the range of 50 μA and 14 Ω, respectively. The best conversion efficiency η, not corrected for the IF impedance mismatch, was approximately -10 dB. An IF noise contribution of $T_{IF} \times \eta^{-1} \approx 1300$ K yields a mixer noise temperature of about 1600 K, which is about four times higher than predicted by Ref. 4 and about 13 times higher than predicted by Ref. 5. For the measured I_C at 20 K Γ was about 0.01 in this experiment (the RSJ simulations in Ref. 4 were made under the same condition). Also, the normalized frequency of this device at 90 GHz was ≈0.25, indicating that the estimation of Ref. 4 for the mixer noise temperature should apply here. A rf receiver noise bandwidth of about 3 GHz around 90 GHz was measured using the same device as in experiments reported earlier.[7] This fact proves that both sidebands (90 $\pm$1.4 GHz) were effectively terminated by the absorber load, hence the mixer operates in DSB mode. A coupled LO power of about 10 nW was roughly estimated from the required suppression of the critical current.[8] Figure 1 shows the measured receiver noise temperatures and the conversion efficiency at different bias points at $T=20$ K as a function of the bias voltage. Since the conversion efficiency is proportional to R_D the mixer performance deteriorates at the Shapiro steps where R_D is small. As shown in Fig. 1 the best mixer performance can be obtained at bias points in the middle between the Shapiro steps where the conversion is also most efficient.

For measurements at different operating temperatures, the mixer block was heated and temperature stabilized, and the LO power level was adjusted for best noise temperature at each temperature. Figure 2 displays the measured dependence of T_M and η on the operating temperature between 20 and 55 K. T_M increases approximately with a rate of 50 K per Kelvin of operating temperature in the temperature range from 20 to 35 K, then increases dramatically at $T>45$ K. η decreases as the operating temperature is increased because: (a) R_D decreases [less rounding of the current–voltage characteristics (I-VC)] along with the fluctuation parameter Γ and (b) Ω increases as I_C decreases along with the temperature. Our data give a power law dependence of $\eta \sim \Omega^{-1.5}$ at temperatures lower than 40 K and a $\eta \sim \Omega^{-2.5}$ dependence at temperatures above. We do not observe the predicted $\eta \sim \Omega^{-2}$ dependence throughout the whole temperature range, since the condition $\Omega > 1$ is not fulfilled at $T<40$ K for the measured device. The increase of Γ additionally reduces the conversion efficiency at high temperatures.

Figure 3 shows the dependence of the mixer noise temperature on Γ deduced from the measured data. The data

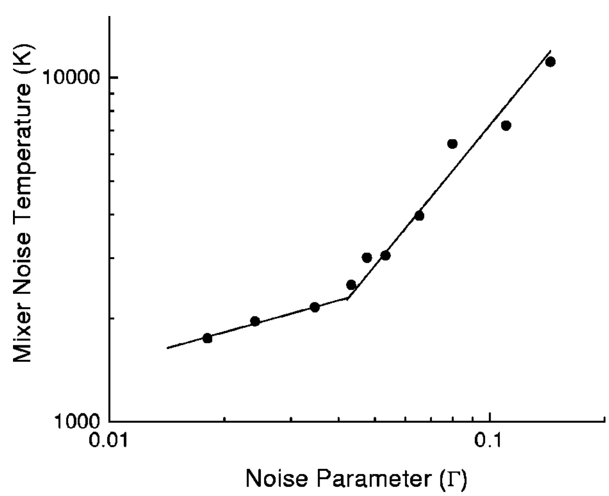

FIG. 3. Dependence of the mixer noise temperature on the fluctuation parameter Γ. For $\Gamma > 4 \times 10^{-2}$ the dependence of T_M on Γ is stronger than for $\Gamma < 4 \times 10^{-2}$.

points can be separated into two regimes where the $T_M(\Gamma)$ dependence exhibits two different slopes. As shown in Fig. 3 the fits indicate a weaker dependence of the mixer noise temperature on Γ in the range $\Gamma < 4\times10^{-2}$ and a transition to a stronger dependence in the range $\Gamma > 4\times10^{-2}$. This dependence suggests that a temperature-independent noise contribution starts to dominate the mixer noise at low operating temperatures. Moreover, the observed $T_M(\Gamma)$ dependence supports the assumption that internal oscillations of the ac Josephson effect are the main source of excess noise in a Josephson mixer. The linewidth of these oscillations is proportional to the low-frequency voltage spectral density S_v of fluctuations, which is $S_v \sim R_D^2 k_B T$ in the case of Johnson noise associated with the normal resistance. At very large fluctuations (high operating temperatures, $\Gamma \approx 1$), the nonlinearity in the I-VC is destroyed and R_D approaches the normal-state resistance. For $1 > \Gamma > 4\times10^{-2}$, the nonlinearity is still weak in comparison with the Johnson noise and the noise temperature varies linearly with Γ. As Γ is further reduced by decreasing the temperature, R_D increases, which keeps the linewidth large, even as the input Johnson noise fluctuation level decreases. As known from simulations, in this range of large differential resistance the Josephson oscillations are very broad and incoherent.[4] Therefore, the noise at low frequencies and at the rf sidebands is dominated by the Josephson fluctuations. Since the total power in these oscillations does not depend on the level of thermal fluctuations (but on I_C and R_N), the noise of the mixer is less dependent on Γ in this particular range. However, as RSJ model simulations showed at much lower values of Γ, e.g., in the range below 10^{-3}, the linewidth decreases effectively with decreasing thermal fluctuations. Since a narrow linewidth contributes less power to the sidebands of the mixer, the amount of noise is reduced and the mixer performance is raised.[4] (However, the range $\Gamma < 10^{-3}$ was not accessible in our experiments because of the junction parameters at low temperatures).

As shown in Fig. 4 the normalized mixer noise temperature T'_M, which is the mixer noise temperature divided by the operation temperature, does not depend linearly on the operating temperature, but exhibits a flat minimum around 30 K. Below 30 K, a further decrease of the operating temperature gives a higher T'_M. The temperature dependence of the mixer output noise inferred from T_M multiplied by η is also plotted in Fig. 4. As expected, the output noise decreases as the mixer performance deteriorates at high operating temperatures and nearly reaches the thermal noise limit at around 60 K. In summary, the $T'_M(T)$ dependence and the measured features of the $T_M(\Gamma)$ dependence can be attributed to a temperature-independent noise mechanism associated with the internal Josephson oscillations. The device noise is obviously dominated by the temperature-independent excess noise at low temperatures, rather than by

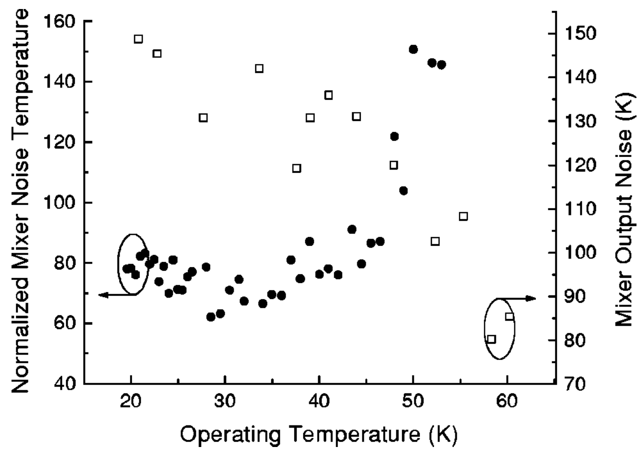

FIG. 4. Dependence of the normalized mixer noise temperature $T'_M = T_M/T$ on the operating temperature (left axis); T'_M shows a minimum around 30–35 K. Dependence of the mixer output noise on the operating temperature (right axis).

the underlying thermal noise. The origin of the disagreement in the experimental data and the theoretical predictions for the mixer noise remains unclear. Fluctuations generated by carrier transport through localized states[9] and multiple Andreev reflections via defects in the grain boundary barrier in HTS junctions[3] are believed to significantly increase the low-frequency voltage noise (i.e., for the linewidth of the Josephson oscillations to be raised). Further studies are necessary in order to understand these contributions to the HTS Josephson mixer noise in detail.

The authors would like to thank M. Siegel, J. Scherbel, D. Diehl, and P. Zimmermann from Radiometer Physics GmbH for useful help and fruitful discussions. This work is supported by the German Ministry of Education and Research (BMBF) and in part by the European Community (INCO–Copernicus project).

[1] E. N. Grossman, L. R. Vale, D. A. Rudman, K. M. Evenson, and L. R. Zink, IEEE Trans. Appl. Supercond. **5**, 3061 (1995).
[2] H. Shimakage, Y. Uzawa, M. Tonouchi, and Z. Wang, IEEE Trans. Appl. Supercond. **5**, 2801 (1997).
[3] M. Tarasov, E. Stepantsov, Z. Ivanov, O. Harnack, M. Darula, S. Beuven, and H. Kohlstedt, IEEE Trans. Appl. Supercond. **9**, 3761 (1999).
[4] R. J. Schoelkopf, Ph.D. dissertation, California Institute of Technology, 1995; R. J. Schoelkopf, T. G. Phillips, and J. Zmuidzinas, IEEE Trans. Appl. Supercond. **3**, 2250 (1993); R. J. Schoelkopf, T. G. Phillips, J. Zmuidzinas, and J. A. Stern, IEEE Trans. Microwave Theory Tech. **4**, 977 (1995).
[5] K. K. Likharev and V. V. Migulin, Radio Eng. Electron. Phys. **25**, 1 (1980).
[6] Van Duzer and C. W. Turner, *Principles of Superconducting Devices and Circuits* (Elsevier, New York, 1981), p. 199.
[7] O. Harnack, S. Beuven, M. Darula, H. Kohlstedt, M. Tarasov, E. Stephantsov, and Z. Ivanov, IEEE Trans. Appl. Supercond. **9**, 3765 (1999).
[8] K. K. Likharev, *Dynamics of Josephson Junctions and Circuits* (Gordon and Breach, New York, 1986).
[9] A. Marx and R. Gross, Appl. Phys. Lett. **70**, 120 (1997).