

MICROWAVE MIXING AND IF BANDWIDTH IN SUB-MICRON LONG
HIGH- T_c HOT-ELECTRON BOLOMETERS

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Abstract

We have systematically measured both the length and temperature dependence of the intermediate frequency (IF) bandwidth of hot-electron bolometer (HEB) mixer made from a high- T_c superconductor (HTS). Mixer devices with lengths (L) between 50 nm and 1 μ m were fabricated from 25 - 35 nm thick YBCO films on $YAlO_3$ (YAO), MgO, and sapphire substrates. Bandwidth measurements were done using signal and local oscillator (LO) frequencies in the range 1 - 300 GHz. At low operation temperatures where self-heating effects occurred, the IF bandwidths were about 30 MHz, 100 MHz, and several 100 MHz for devices on YAO, MgO, and sapphire, respectively. The theoretically predicted L^2 -dependence of the IF bandwidths was not observed. At higher operation temperatures, where self-heating disappeared and flux-flow effects define the shape of the IV characteristic (IVC), the measured IF bandwidth increased significantly, while the overall conversion efficiency at low IF's decreases by several dB. Our data indicate that the temperature dependence of the HEB mixer performance may be influenced by vortex dynamics effects in HTS materials.

I. Introduction

The hot-electron bolometer (HEB) mixer made from a high- T_c superconductor (HTS) was introduced recently as a competing alternative to a Schottky-diode mixer. The HEB mixer would require 100-times less LO power and thus would be a desirable candidate for long-term atmospheric remote-sensing and planetary missions. The required operating temperatures between 65 K and 75 K can be achieved with available space-qualified coolers or even with passive radiative coolers.

The HEB mixer consists of a microbridge of HTS material between normal metal contacts (Fig. 1). Electrons in the microbridge can be heated by absorbed RF radiation and dc transport current. Nonequilibrium "hot" electrons (e^*) transfer their energy to the

lattice (ph^*) during a very short electron-phonon relaxation time τ_{e-ph} , which is about 1-2 ps at 80-90 K in $YBa_2Cu_3O_7$ (YBCO) [1-3]. The performance of the mixer depends strongly on the total thermal conductance for heat removal from the phonon sub-system. As shown in Fig. 1, this heat can be removed by escape of the phonons to the substrate (τ_{es}) or by diffusion of phonons to the normal metal contacts (τ_{diff}). In the case of the phonon diffusion, the mixer IF response would depend strongly on the microbridge length. In contrast, the heat removal through the film-substrate boundary is determined by the thermal boundary resistance and the heat diffusion in the substrate. Two substrates with good dielectric properties and high thermal conductivity on which high quality HTS films can be grown are magnesium oxide (MgO) and sapphire (Al_2O_3). MgO provides a low boundary resistance of about $5.3 \cdot 10^{-4} \text{ Kcm}^2/\text{W}$, while Al_2O_3 gives $1.1 \cdot 10^{-3} \text{ Kcm}^2/\text{W}$ [4].

Modelling of the performance of HTS HEB mixers was done by some of us and the results showed that single sideband mixer noise temperatures around 2000 K, optimum LO power levels in the range of a few μW , and IF bandwidths of several GHz could be possible [5]. However, this approach assumes that phonon diffusion into the normal metal contacts takes place and dominates for the heat removal out of the microbridge. Based on the calculations in [5], phonon diffusion could be a dominant thermal process, only if the length of the bolometer is less than a few hundred nanometer.

The aim of our experimental work was to fabricate sub- μm long HTS HEB mixer on MgO and sapphire substrates and to determine their intrinsic thermal relaxation times as inferred from the -3dB IF bandwidth. Available HEB mixers on YAO substrates were also measured in order to compare our results with the performance of devices on a perovskite substrate that has a good lattice match to YBCO but less favorable thermal properties [6].

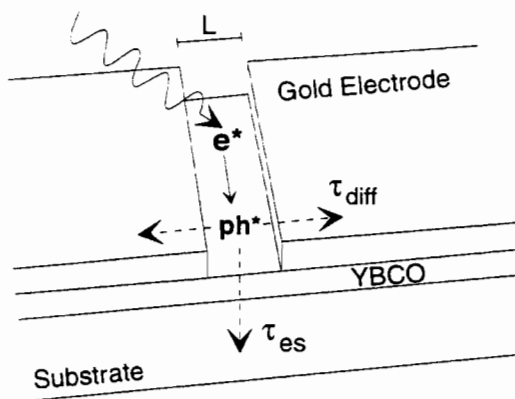


Fig. 1: Schematic of a HTS hot-electron bolometer mixer and possible energy-relaxation mechanisms for the heat removal (see text for details)

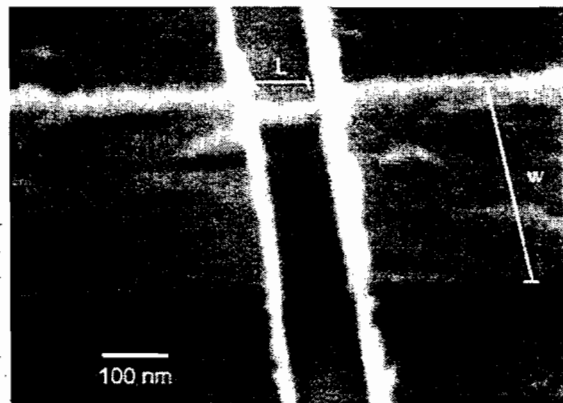


Fig. 2: Sub- μm YBCO HEB on MgO. The gold/YBCO sandwich electrodes are visible on the left and right. The YBCO strip which forms the microbridge is located in the center, $L=100 \text{ nm}$, $w=1 \mu\text{m}$.

II. Sample fabrication

For the fabrication of HEB mixers, YBCO films with thickness of about 20–40 nm were grown on MgO and sapphire substrates using the laser deposition method. In the case of sapphire we used a 30 nm thin CeO₂ buffer layer between the substrate and the YBCO film. The thin YBCO films were protected by an 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 $w \approx 1 \mu\text{m}$), with integrated bow-tie antennas, 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 using ion beam etching (IBE), a SiO_x protection layer was deposited by thermal evaporation. HEB mixers on YAO substrates were fabricated using a similar growth technique. However, for the lithographic steps a self-alignment process was used and for the gold removal a selective Cl₂ etch was applied (see ref. [7] for details). A finished HEB device on MgO is shown in Fig. 2.

III. IF bandwidth measurements at low operation frequencies

IF bandwidth measurements were done using two monochromatic signals in the frequency ranges 1–20 GHz, 100 GHz, and 300 GHz. The lowest frequency range was chosen due to the simplicity of the microwave circuits and readily available RF equipment. If the mixer relaxation properties are determined by the thermal properties of the HEB device only, one could assume that the IF bandwidth measured at low operation frequencies would be comparable with that at submillimeter waves. Low-frequency effects (e.g., because of possible Josephson weak links in the bridge) can certainly give a misleading picture of the HEB performance. Therefore, similar measurements at 100 GHz and 300 GHz are a necessary test for operation frequency dependent effects. In this way we expect to be able to get more data on the real HEB performance in the submillimeter wave range, rather than from mixer measurements at optical frequencies done earlier [8].

1. Setup for 1–20 GHz signal frequencies

As shown in figure 3, two sweep oscillators feed the LO signal (OSC 2) and a second, weaker signal (OSC 1) into a 12.4 GHz-broadband directional coupler (I d. c.). The output port was connected to a 18 GHz-broadband directional coupler (II d.c.) in order to use the same coaxial cable for the LO/signal input and the IF signal output. The coaxial

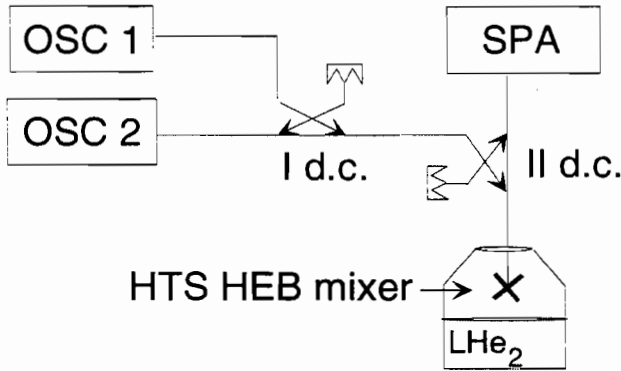


Fig. 3: Setup for IF bandwidth measurements, LO range 1-20 GHz, d.c. = directional coupler, SPA = spectrum analyzer

cable, the bias-tee, the voltage bias source and the mixer mount were assembled inside a dipstick in order to make measurements in a transport helium dewar at different temperatures. The IF bandwidth was measured by maintaining the signal frequency constant and sweeping the LO frequency. The LO level was adjusted for each data point in order to keep the amount of LO power coupled to the device constant. The whole measuring

process was computer-controlled. The biaspoint and LO level were adjusted in order to get stable mixing conditions. Oscillations which occur in the region of negative differential resistance in the IVC were avoided by biasing the mixer in the resistive branch close to the drop-back voltage. (Self-heating, i.e. the formation of a hot-spot across the microbridge, is the reason for the hysteric device behaviour. Inside the hot-spot, the electron temperature is higher than T_c).

We have to point out that we never adjusted the mixer for best conversion efficiency, since this would require a bias point very close to the hysteretic region where the device output noise becomes very large. Therefore, the absolute level of the low-IF conversion efficiency does not necessarily represent the best mixer performance. More important in our investigation was to get a measure of the IF dependence of the conversion efficiency.

2.a. HEB device on MgO substrates

Fig. 4 shows a set of IVCs of a 50 nm long YBCO HEB on MgO taken at different temperatures. Self-heating was observed in most of our devices below 70 K, flux-flow like IVCs were observed at temperatures above 70 K. The normal-state resistance of this device was about 50 Ω . Fig. 5 shows the result of measurements of the conversion efficiency at different temperatures. The data clearly show a temperature dependence of the IF bandwidth. At 50 K we measured a bandwidth of about 100 MHz. At the highest temperature (83 K) the bandwidth increased to about 2 GHz. Additional measurements with devices with lengths of 200 nm and 300 nm gave very similar results. This is a first indication that the length dependence of the IF bandwidth does not exist or reveal itself in our type of device (As a caveat, it should be noted that the resistance of our devices did

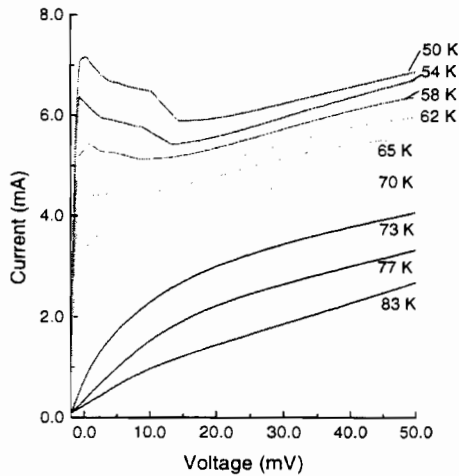


Fig. 4: IVCs at different temperatures of a 50 nm long HTS HEB on MgO, pumped at 1 GHz for optimum conversion

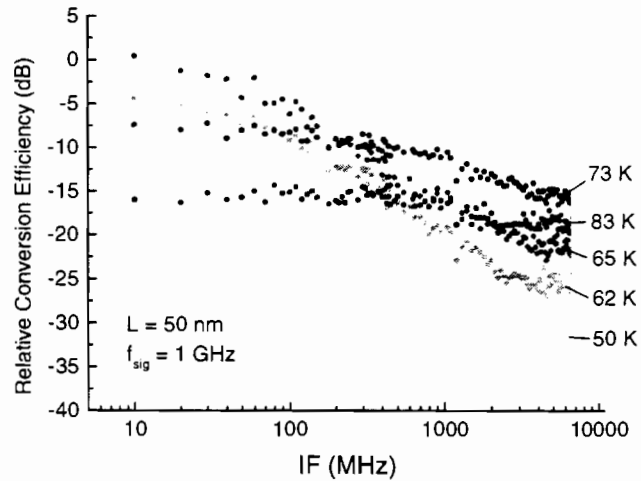


Fig. 5: IF bandwidth measurement at different temperatures using a 50 nm long HTS HEB on MgO

not scale as expected with length, and this may effect the results). Additionally, at temperatures below 60 K, the hot-electron plateau was clearly seen starting around 2 - 3 GHz. This indicates that the relaxation mechanisms can be explained by the two-temperature model in this temperature range, similar to results reported earlier [8]. At temperatures above 70 K, where the measured IF bandwidth increased significantly, self-heating disappeared and we speculate that flux-flow effects began to dominate.

2.b. Temperature dependence of conversion efficiency

In order to get a better measure of the variation of the optimum conversion efficiency with temperature in the low-frequency limit, we biased the mixer very close to the hysteresis (but avoided any biaspoints at negative-differential resistance to keep the noise low) and adjusted the LO level for optimum output signal. As shown in Fig. 4 the shape of the IVC changes completely with temperature. At temperatures higher than 73 K we could not obtain a hysteresis any longer. In this regime it was possible to find an optimum biaspoint on the IVC without a large increase of the output noise. We attribute this regime to a vortex-flow mechanism inside the bridge. A similar shape of the IVC can be obtained also at lower temperatures by applying enough LO power. However, physical reasons for that could be different and in latter case a smooth IVC under strong pumping can be explained by the heating processes only.

Fig. 6 shows the optimum conversion efficiency versus operation temperature (same device as in section 2.a.). The IF was 10 MHz, the LO frequency was 1010 MHz and the

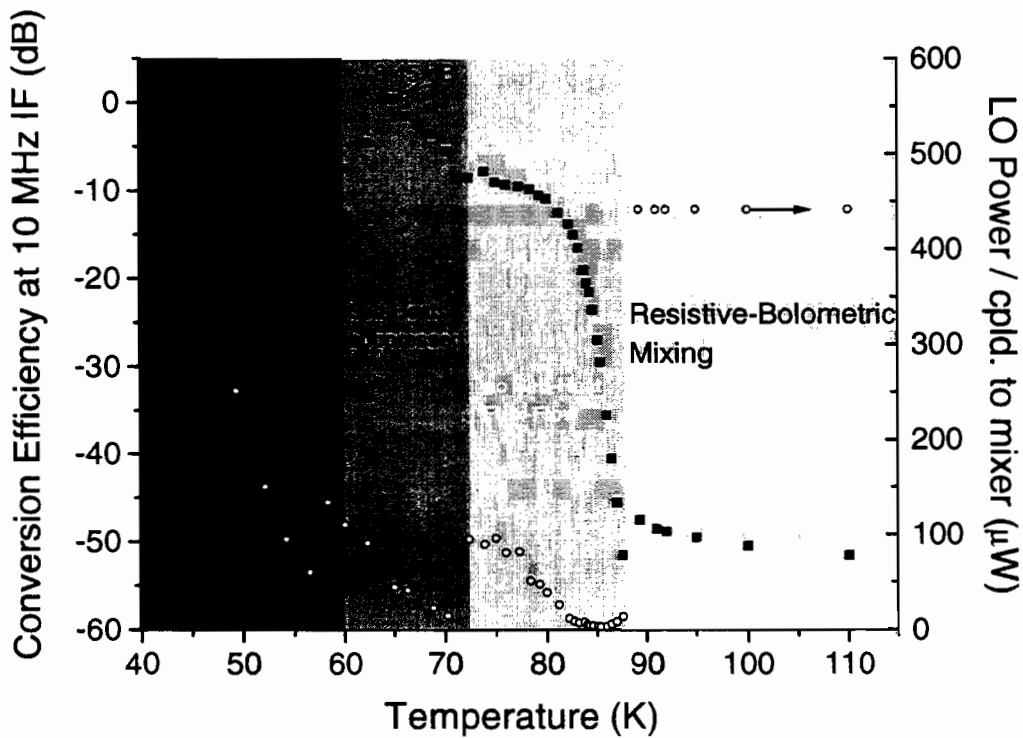


Fig. 6: Temperature dependence of maximum conversion efficiency of a 50 nm long HTS HEB on MgO

signal frequency was 1000 MHz. We can clearly separate the temperature range by different shapes of the IVC. At temperatures below 60 K, the self-heating was still present at optimum LO level. At temperatures between 60 K and 73 K the hysteresis was still present without LO, but suppressed by the LO at optimum pumping. As mentioned before, at higher temperatures no self-heating was present.

The data show that the maximum conversion efficiency (≈ 0 dB !, corrected for coupling) can be found at 65 K in the range where self-heating can be suppressed by the LO. By increasing the temperature, the conversion efficiency starts to drop and reaches a plateau about 10 dB below the maximum value. At the same time the self-heating disappears and flux-flow type rounding starts to dominate the shape of the IVC. A further increase of the temperature results in a decrease of the conversion efficiency. At $T > T_c$ we obtained pure resistive-bolometric mixing, due to the temperature dependence of normal-conducting YBCO. Fig. 6 also displays the coupled LO power. In the range of maximum conversion

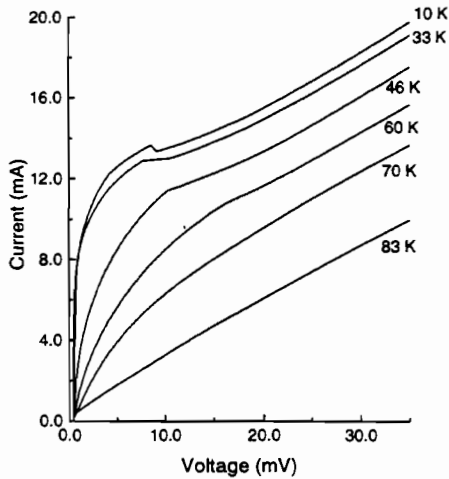


Fig. 7: IVCs at different temperatures of a 50 nm long HTS HEB on sapphire, pumped at 1 GHz

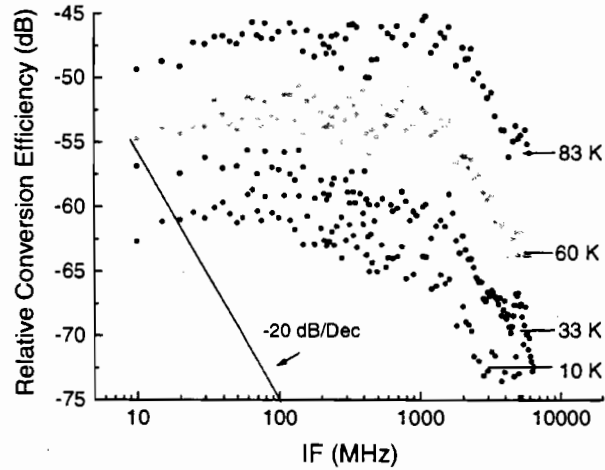


Fig. 8: IF bandwidth measurement at different temperatures using a 50 nm long HTS HEB on sapphire

efficiency, about $50 \mu\text{W}$ of LO power is needed to pump the mixer. In the flux-flow regime starting at 73 K, the optimum LO level increases by a factor of 10 reaching of about $100 \mu\text{W}$. This in fact indicates that the mechanism of mixing could have changed at this point. Also the unexpected high bandwidths would confirm this suggestion.

3. HEB on CeO_2 /sapphire substrates

Fig. 8 shows the results of IF bandwidth measurements done by using a 50 nm long mixer on CeO_2 /sapphire at different temperatures. The normal resistance of this device was about 5Ω , which is consistent with its length and film sheet resistance. All curves show a clear roll-off with a -20 dB/Dec slope starting at about 2 GHz, as expected in the two-temperature model [5]. This slope does not change with temperature. In contrast to the data on MgO devices, we could not clearly obtain a comparable hot-electron plateau over our IF measurement range up to 8 GHz. Measurements at higher IF may be needed. At temperatures below 50 K the conversion at low IFs slightly increases due to self-heating, which leads to effectively lower IF bandwidths ($\approx 460 \text{ MHz}$ at 10 K). However, as the set of IVCs in Fig.7 shows, the self-heating at low temperatures is much weaker than was seen for a similar device on MgO. This indeed suggests that the heat removal on CeO_2 /sapphire substrates is more effective than on MgO, due to a lower thermal boundary resistance and/or higher thermal conductivity of CeO_2 /sapphire. Also, a longer device (80 nm) on CeO_2 /sapphire gave very similar bandwidth data.

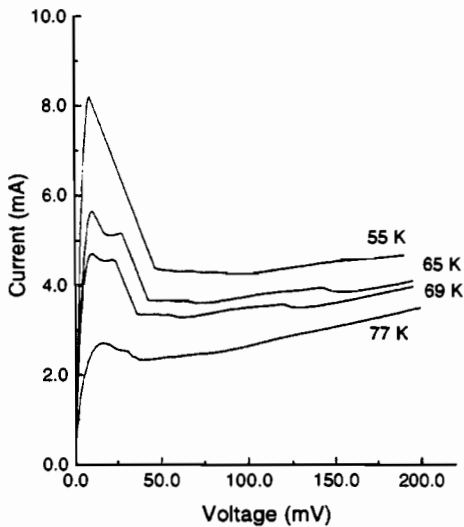


Fig. 9: Weakly pumped IVCs of a 1 μm long HTS HEB on YAO at different temperatures

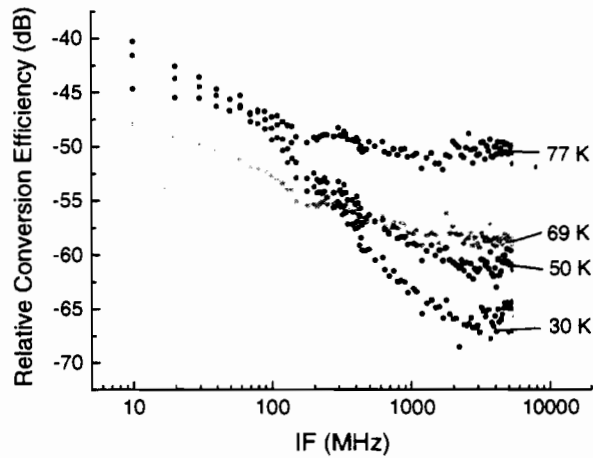


Fig. 10: IF bandwidth measurement at different temperatures using a 1 μm long HTS HEB on YAO

4. HEB on YAO substrates

Fig. 9 displays a set of IV curves for a 1 μm long HTS HEB on YAO. Note that self-heating effects are evident at temperatures up to 77 K, indicating that heat removal from the device is less efficient with this substrate than with MgO or sapphire. Fig. 10 shows the results of the IF bandwidth measurements. In contrast to the MgO and sapphire data, these IF characteristics show no low-frequency plateau, but instead a continuous drop of the conversion efficiency starting at the lowest frequency point of 10 MHz. This in general indicates that the heat diffusion into the substrate is a dominant heat removal process. This behaviour also was earlier reported for very large-area devices [8].

According to [5], the thermal resistance due to the diffusion in the substrate becomes important if the device area is large and/or the substrate has a poor thermal conductivity. Our devices were small enough to eliminate this effect for MgO and sapphire substrates but the thermal resistance was still significant for YAO substrates. Due to this fact, the IF bandwidth is in the range of a few 10 MHz in the low-temperature limit. At 77 K it is still around 100 MHz, however, the high-frequency (hot-electron-like) plateau which we also see in this device, moved up by about 16 dB. A similar dependence was measured on MgO, but not on CeO₂/sapphire.

IV. IF bandwidth measurements at 100 GHz and 300 GHz

1. Setup

IF bandwidth measurements at 100 GHz and 300 GHz were performed inside a vacuum cryostat with optical windows. The mixer was a 50 nm long HEB device on MgO. The signals were generated by multiplied solid-state sources (100 GHz, 300 GHz) and by a backward wave oscillator (300 GHz). The mixer chip was glued with the backside to an elliptical lense made from high-resistivity silicon and the IF signal was coupled to a coaxial cable and directly monitored with a spectrum analyzer.

2. IF bandwidths

Fig. 11 shows a set of IF characteristics taken at 100 GHz and 300 GHz in the low and high-temperature limit. The most important result is that the IF bandwidth in the high-temperature limit (≈ 450 MHz at 77 K) is not as large as it was at operation frequencies in the 1-20 GHz range (≈ 1.4 GHz at 78 K). The bandwidth of about 200 MHz is even lower at a signal frequency of 300 GHz.

This indicates that the mixing mechanism responsible for the large IF bandwidth does not continue to operate well or at least does not couple to the radiation well at high RF. Of course flat response with RF would be expected in the case of bolometric mixing. In contrast to this, in the low-temperature limit the IF bandwidth seems to increase slightly

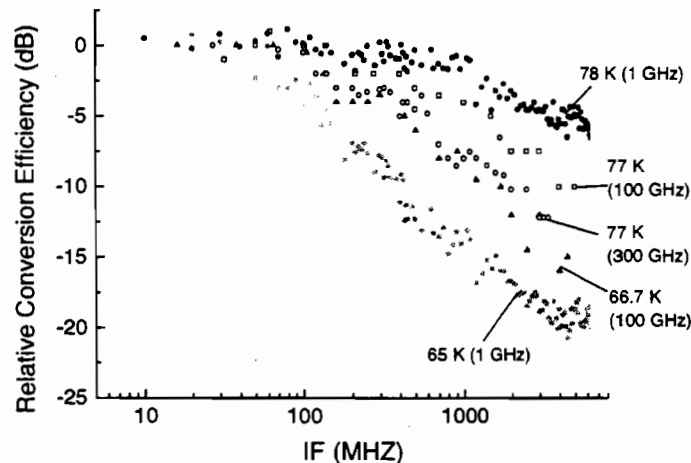


Fig. 11: IF bandwidth measurements at different operation frequencies using a 50 nm long HTS HEB on MgO in the low-temperature limit (around 65 K) and high-temperature limit (around 77 K)

with increasing operation frequency. However, the absolute conversion efficiency could not be estimated from these experiments, as the RF coupling efficiency is both poor and unknown.

VI. Discussion and Conclusion

For practical mixer applications, IF bandwidths larger than 1 GHz are desired. Our data show that HTS HEB mixers can meet this requirement. The measured bandwidths are lower than expected and a dependence on the device length was not found in a first set of devices. These facts suggest that phonon diffusion may not effectively decrease the energy relaxation times in our mixers. The reason for this and whether it depends on the specific device geometry is still under investigation.

However, the bandwidth performance of the HTS HEB even without heat diffusion into the contact is already encouraging. Thinner films may make the phonon escape into the substrate faster and enhance the bandwidth. Devices on CeO₂/sapphire have shown the best bandwidth performance. Mixer noise measurements have to be done in order to get a direct measure of the device performance. In fact, first noise measurements (to be discussed in a later publication) already indicate that the HTS HEB mixer performance agrees well with a model which does not include phonon diffusion.

Whether mixing in the high-temperature limit gives any advantage also depends on the device noise in this regime. The corresponding experimental data and analysis will be published soon [9]. The discovered temperature dependence of the IF bandwidth can probably account for previously reported unexpectedly high bandwidth of HTS mixers [10]. The origin of mixing in the flux-flow regime at high-temperatures, which obviously give larger IF bandwidths - but lower conversion efficiency, needs to be studied.

Acknowledgments

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