Invited Paper

Nonlinear THz Mixing in $YBa_2Cu_3O_7$ Thin Film Hot Electron Bolometers

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ABSTRACT

Small volume high-T_c super-conducting $YBa_2Cu_3O_7$ (YBCO) thin films are used as low power, very wide bandwidth mixers in the frequency range of 75 GHz to 2.5 THz. The YBCO films are patterned into lattice-cooled hot-electron bolometers (HEB) coupled to an integrated Au thin-film antenna and transmission line. Near 77 K, these mixers have responsivity as high as 780 V/W using only 8 nW of local oscillator (LO) power at 585 GHz. The responsivity can be shown to be truly bolometric. Direct heterodyne and homodyne down-conversion mixing using local-oscillator frequencies of 75 GHz and 585 GHz show overall conversion gains of -35 dB, which includes a -18 dB coupling loss, using only ~ 1 μW of LO power. The gain bandwidth shows a simple Lorentzian roll-off with -3 dB point of 5 to 8 GHz. The large gain bandwidth and small power requirements make these high-T_c superconducting mixers an attractive alternative to existing Schottky diode and conventional superconducting receiver technologies.

1. INTRODUCTION

Heterodyne reception of sub-millimeter wavelength radiation presents a technological challenge because of basic source and receiver limitations in this frequency band. Coherent continuous-wave THz local oscillators (LO) generally output only limited power, typically < 10 mW, so that receivers in this frequency range must be able to generate useful conversion gains at low LO powers, preferably << 1 mW. In addition, for fast communications and radar purposes, a receiver with a wide conversion gain bandwidth, ideally near 10 GHz, is desired. Schottky diode mixers are widely used for THz mixing. They have the advantage of room-temperature operation and very wide bandwidths, but generally require > 1 mW LO power. For low-power work, conventional superconductor-insulator-superconductor (SIS) tunnel junction mixers have been the devices of choice. Conventional superconductors offer the lowest power operation available, but must be maintained below liquid helium temperature (4.2 K) to achieve this. SIS mixers also face bandwidth limitations in the THz and present reactive coupling difficulties in high-frequency circuits.

There has recently been much interest in using superconducting hot-electron bolometers (HEBs) as heterodyne mixers at submillimeter frequencies. Like all bolometers, HEBs are broad band; they are not limited to sub-gap frequencies as (SIS) mixers are. Superconducting HEB mixers can also have large conversion gain bandwidths and may be able to mix using low local oscillator (LO) power, relative to semiconductor mixers. Recent work in HEBs have followed two schemes. The "diffusion-cooled" HEB proposed by Prober[1] and first fabricated by Skalare, *et al.*[2] achieves large intermediate frequency (IF) bandwidth by allowing hot electrons to diffuse out to a cold reservoir formed by the electrical leads. This process requires the inelastic mean free path to be larger than the sample size. At 2.2 K, such a Nb HEB has shown[3] conversion gain $\eta \approx -10$ dB and IF bandwidth of 6 GHz using

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10 nW of LO power. The "lattice-cooled" HEB proposed by Gershenzon, *et al.*[4] cools the hot electrons through phonon collisions. The geometry of the HEB removes hot phonons to the substrate to maximize IF bandwidth. Operating at 4 K, lattice-cooled NbN HEBs have shown[5] $\eta \approx$ -10 dB and IF bandwidth of 2.2 GHz, using 0.5 μW of absorbed power at 430 GHz.

The IF bandwidth of lattice-cooled HEBs is ultimately limited by the electron-phonon scattering rate; in NbN at 4 K this limit is < 10 GHz. Materials with faster inelastic scattering rate are thus desirable. In view of the high normal resistivities of the high-T_c superconductors, Gershenzon, *et al.*[6] proposed that $YBa_2Cu_3O_7$ (YBCO) could produce a very wide IF bandwidth in a lattice-cooled HEB operating at 77 K. Time-resolved optical measurements[7] of quasiparticle relaxation in YBCO films imply a possible IF bandwidth ≥ 50 GHz. Heterodyne mixing measurements using YBCO HEBs based on the design of Ref. 4 have been done at 1.5 μm[8] and 9.6 μm[9] wavelengths. The IF bandwidth observed was 18 GHz, limited by the instrumental bandwidth. However, a relatively large LO power (6 to 50 mW at 9.6 μm) was used, and the overall η was about -90 dB at 2 GHz IF using 6 mW of incident LO power. Excluding a -13 dB coupling loss, the intrinsic η was -77 dB with 0.3 mW of absorbed LO power. Recently, Karasik *et al.*[10] calculated that an optimal design in a small ($(0.1\ \mu m)^2 \times 10$ nm) YBCO HEB operating near 77 K could achieve an intrinsic η of better than -10 dB using 1 to 10 μW of LO power.

The low power characteristics of YBCO HEBs are of great interest in both applications and in understanding the principles underlying the non-linear electrodynamic response. Here we report on the low LO power responsivity and heterodyne mixing characteristics of antenna-coupled YBCO HEBs. These HEBs show low power video (30 - 100 Hz) responsivities at 585 GHz equal to the best values obtained in YBCO bolometric detectors, but with much higher response speeds. The responsivity can be used to provide direct verification of the assumed bolometric nature of the detection and mixing. As a heterodyne mixer, the overall η at 1.8 GHz IF is substantially higher than previous reported work using YBCO HEBs, and the estimated intrinsic η is close to calculated optimal values. At 1.8 GHz IF, intrinsic conversion gains as high as -16 dB were observed, after correcting for the external coupling loss. This showed the potential of the YBCO HEB as a useful mixer. We observe a single roll-off conversion gain bandwidth described well by the simple Lorentzian expected from classic bolometer theory[11] with -3 dB bandwidth of 5 to 8 GHz.

2. SAMPLE PREPARATION AND MEASUREMENT

The samples used were epitaxial YBCO films grown by off-axis single target sputtering[12] onto (100) MgO substrates. The films were initially 100 nm thick and were capped *in situ* with 10 nm of Au. The as-deposited films had T_cs of 85 - 87 K with transition widths typically ≤ 1 K. Prior to patterning, a further Au layer ≥ 2 skin depths thick (at the desired operating frequency) was evaporated onto the initial Au layer. The HEB was fabricated in the center of a 50 Ω coplanar transmission line feeding a double slot antenna (overall dimensions $0.34\lambda_0 \times 0.18\lambda_0$, λ_0 = free space wavelength) etched into the YBCO/noble metal film. The bolometer itself consisted of a single YBCO line, 1 μm x 2 μm, with its noble metal overlayer removed using a non-aqueous Au etch. This chemical etch did not affect the superconducting transition temperature or width and was found to be highly reproducible. We targeted room-temperature resistance values that would give 50 Ω somewhere in the superconducting transition. Finished bolometers had room temperature resistances of 300 to 600 Ω, T_cs near 87 K with transition widths of 2 to 4 K, peak dR/dT values of 80 to 100 Ω/K, and typical critical current densities at 77 K around 5×10^5 A/cm^2.

All measurements were done quasi-optically. Samples were clamped onto a silicon hyper-hemispherical lens and heat-sunk to a copper block. The equilibrium sample temperature could be varied between 77 and 93 K. For the 585 GHz responsivity measurements, radiation from a far-infrared gas laser was coupled into the cryostat through a Teflon window using external TPX lenses. Incident LO power was measured before the external optics. Coupling losses were determined by measuring the HEB current-voltage relation with and without LO power and using a standard bolometric power absorption model.[13] Wire grid diplexers were used to rotate the polarization and check the performance of the antenna. The samples were DC current biased, with the bias level adjusted to maximize the responsivity (typically $I_{bias} \sim 1$ mA). A mechanical chopper (30 to 100 Hz) modulated the incident radiation, and the coherent AC voltage response from the HEB was measured using a lock-in amplifier. For conversion gain measurements, two tunable Gunn diodes (80 - 95 GHz) were used as sources. The higher power source served as the LO, and the lower power source as the rf signal. Attenuators kept the total power ≤ 4 mW in all measurements. Incident LO and RF powers were measured at the position of the Si lens using a power meter. The determination of overall conversion gains include coupling losses between the Si lens and the HEB.

Conversion gain measurements were done using both heterodyne and homodyne direct detection. For heterodyne detection, two tunable (75 to 95 GHz) Gunn diode oscillators were used, with one acting as a fixed 75 GHz LO source and the other acting as the rf signal source tuned from 75 GHz to 95 GHz. The difference or intermediate frequency (IF) generated by the HEB mixer was amplified by a cooled wide-bandwidth (0.5 to 20 GHz) microwave amplifier and recorded on a spectrum analyzer. The optimal LO power was found to be between 1 to 2 μW; the rf signal power was kept an order of magnitude lower than this. To measure conversion gain at an LO frequency of 585 GHz, homodyne detection of amplitude-modulated sidebands was used.[14] A microwave-biased Schottky diode in a corner cube reflector generated amplitude modulated sidebands on the 585 GHz line of a far-infrared gas laser. The HEB was used as a homodyne sideband detector. Sideband frequency could be varied from 1 to 15 GHz off the central laser line by tuning the microwave oscillator biasing the sideband generator diode. The rf power (0.1 to 1 μW) in the sidebands was calibrated at 1.8 GHz IF using a known Schottky diode receiver. However, the corner cube's conversion gain contained several absorption resonances in the tunable bandwidth, complicated interpretation of this data and limited the density of obtainable data points.

3. RESPONSIVITY AND CONVERSION GAIN CHARACTERISTICS

3.1 Responsivity

The current-voltage *(I-V)* characteristics from a HEB with a 585 GHz antenna are shown in Fig. 1 with no LO power and with 2 mW of incident power. The suppression of the supercurrent and the increase in the resistive slope are evident. Taking the difference between the two *I-V*s and using the thermal balance equation[15], we calculate that 260 μW was absorbed by the HEB, giving a coupling loss of -9 dB This figure fell by 18 dB when the polarization was rotated 90° from the optimal, showing the effectiveness of the antenna in enhancing the coupling.

Fig. 2 shows the video responsivity at 585 GHz LO and chopping frequency of 37 Hz as a function of the incident LO power. This sample had a dR/dT of 144 Ω/K in the center of its transition. Most striking is the large increase in responsivity as the LO power decreases. At 150 μW, the responsivity is 120 V/W. When the LO power drops to 8 nW, the responsivity rises to 780 V/W, comparable to that of some Schottky diode mixers and high-sensitivity YBCO infrared detectors,[16,17] but with much higher response speed. No plateau in responsivity was observed down to 8 nW.

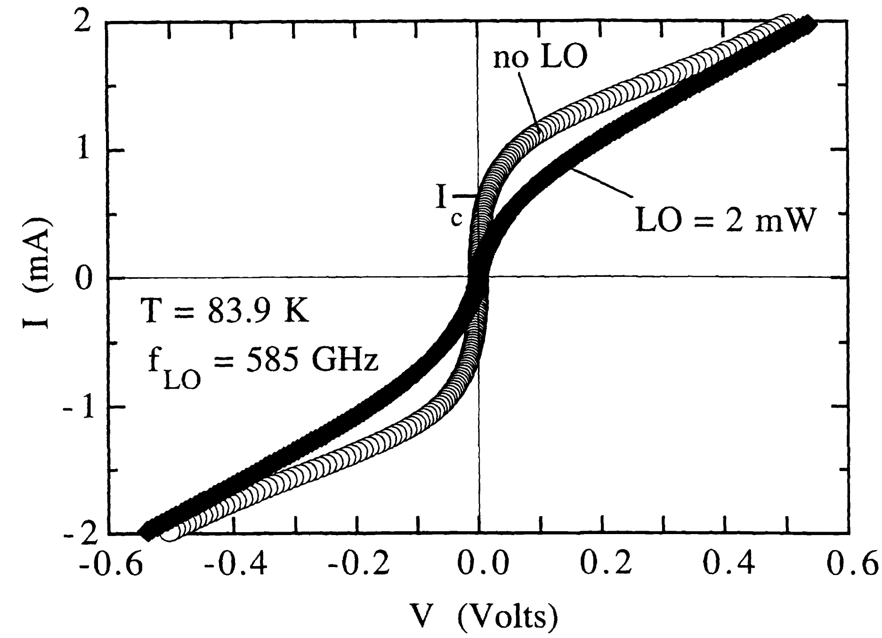
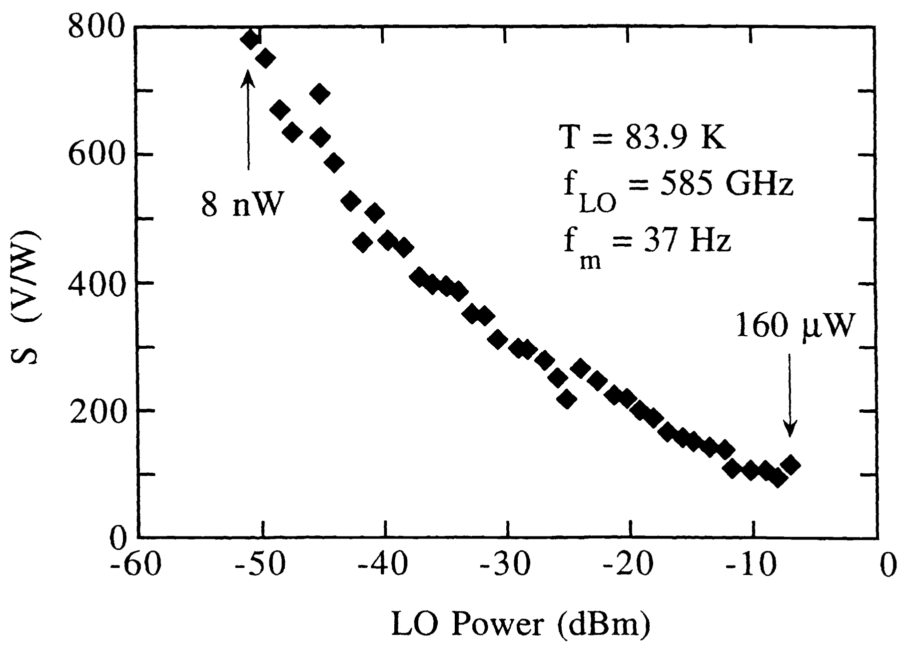


Fig. 1. Current-voltage characteristics of a YBCO HEB with and without LO illumination. The quoted LO power is the incident power, uncorrected for coupling losses.



Fig,. 2. Power dependence of the video responsivity S at a modulation frequency of 37 Hz.

3.2 Conversion Gain

Fig. 3 shows the overall η (including the coupling losses but with the amplifier gain removed) at 1.8 GHz IF as a function of incident LO power, using an incident rf power of 14.8 μW. The current bias was adjusted to maximize η. η increases approximately linearly[18] at low LO power as expected for bolometric mixing, reaching -47 dB at 3.3 mW. Onset of saturation can be seen at the highest LO powers. A figure of more significance in the development stage of YBCO HEB mixers is the intrinsic conversion gain of the bolometer, i.e. taking out the extrinsic coupling losses. The coupling loss in this measurement at the optimal bias point, estimated from the sample's pumped and unpumped *I-V*s in the same manner as done with the data of Fig. 1, was -36 dB for the LO and -31 dB for the RF. Thus about 1 μW of LO power and 11 nW of RF power were actually absorbed by the bolometer. At that power level, the intrinsic conversion gain is estimated to be -16 dB at 1.8 GHz IF. The coupling loss in the 75 GHz mixing measurement was much worse than in the 585 GHz responsivity measurements for three main extrinsic reasons: 1.) the Si lens was designed for operation at ≥ 200 GHz; at 75 GHz its effective aperture was smaller than desired, 2.) no attempt was made to shape the 75 GHz beam waist or convergence angle to match the radiation pattern of the antenna, and 3.) the mixing sample had resistance of 10 Ω at optimal bias, creating internal reflection losses between the HEB and the 50 Ω antenna and co-planar transmission line.

Fig. 4 shows the measured conversion gain bandwidths from 0.5 to 20 GHz IF for a 75 GHz mixer at two sample temperatures, 77 K and 66 K. The gains are all normalized to the lowest frequency conversion gain at 66 K, which was -35 dB (uncorrected for a -18 dB coupling loss in this measurement). Also shown are simple Lorentzian fits to the data, using a single fitting parameter, the -3 dB bandwidth f_{3dB}, for each temperature. In the 75 GHz data, the overall gain and the bandwidth are both increased slightly at the lower temperature. Similar behavior was observed with the 585 GHz

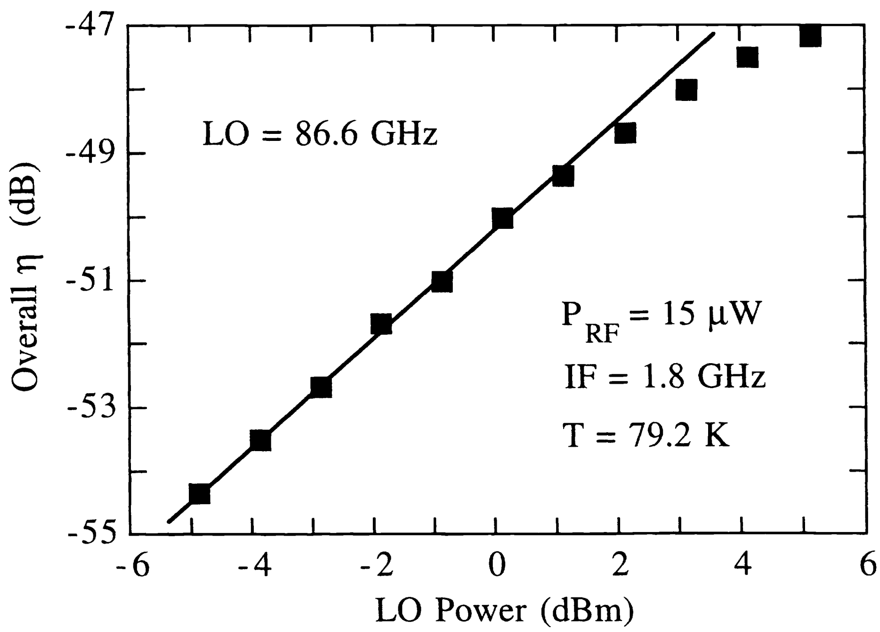


Fig. 3. LO power dependence of the overall conversion gain at a fixed IF frequency of 1.8 GHz. The rf power quoted is the incident power. Power and η are uncorrected for coupling losses.

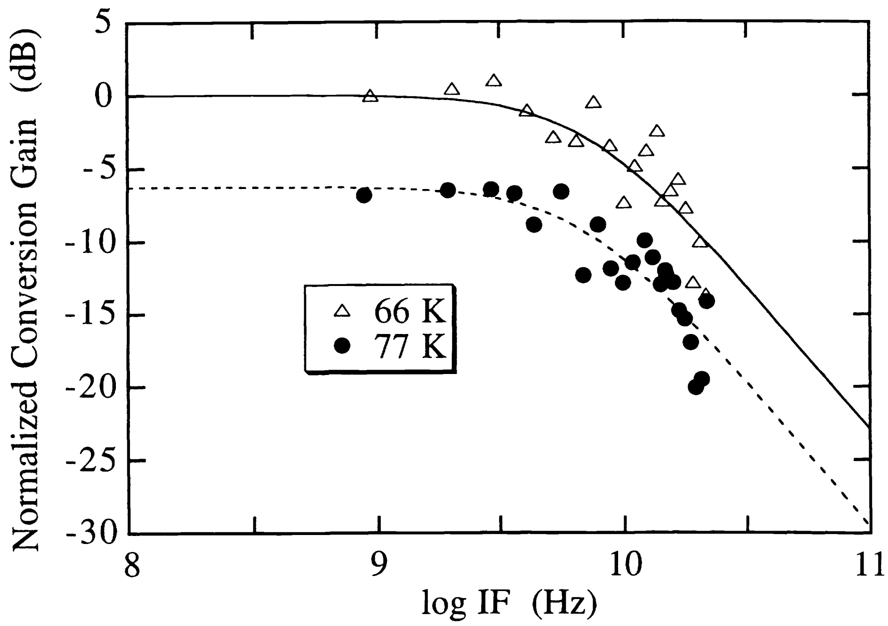


Fig. 4. Conversion gain bandwidths for one 75 GHz HEB mixer at two different temperatures. The curves are simple Lorentzian fits to the data.

HEB. It is clear that a simple Lorentzian line shape describes the data reasonably well. The -3 dB frequencies from the fits are 6.5 GHz and 8 GHz for the 75 GHz mixer at 77 K and 66 K respectively, and 5.5 GHz for the 585 GHz mixer at 66 K.

4. BOLOMETRIC ABSORPTION MODEL

4.1 Two-Temperature Model

Karasik, *et al.*,[10] have done extensive calculations on the conversion gain properties of lattice-cooled HEB mixers for different mixer dimensions, using a two-temperature model. They found that the conversion gain increases and noise temperature decreases for smaller bolometer volumes. The conversion gain bandwidth of the HEB is determined by two time scales: the time it takes to remove heat from electrons via electron-phonon scattering and the escape time of phonons from the bolometer. The latter is the slower time scale and is determined primarily by the bolometer thickness, with thinner bolometers leading to faster response times. These two characteristic times lead to a two roll-off structure in the conversion gain bandwidth. The first (lower frequency) roll-off is interpreted as a consequence of the phonon escape time from the HEB, and the second (upper frequency) roll-off is caused by the electron-phonon relaxation rate. Time-resolved measurements[7] of the electron-phonon relaxation rate in YBCO show a relaxation time of 1.5 ps, leading to a calculated upper bandwidth limit of order 100 GHz. Fig. 5 shows the calculated two-tiered conversion gain bandwidth for a YBCO HEB with the nominal physical dimensions of our device, using the model of Ref. 10. The low-frequency plateau shows a maximum intrinsic conversion gain of -12 dB, dropping to -50 dB at the second plateau. Because of the relatively thick (100 nm) films used, the slow phonon escape lifetime leads to a calculated first roll-off point f_1 of only 55 MHz.

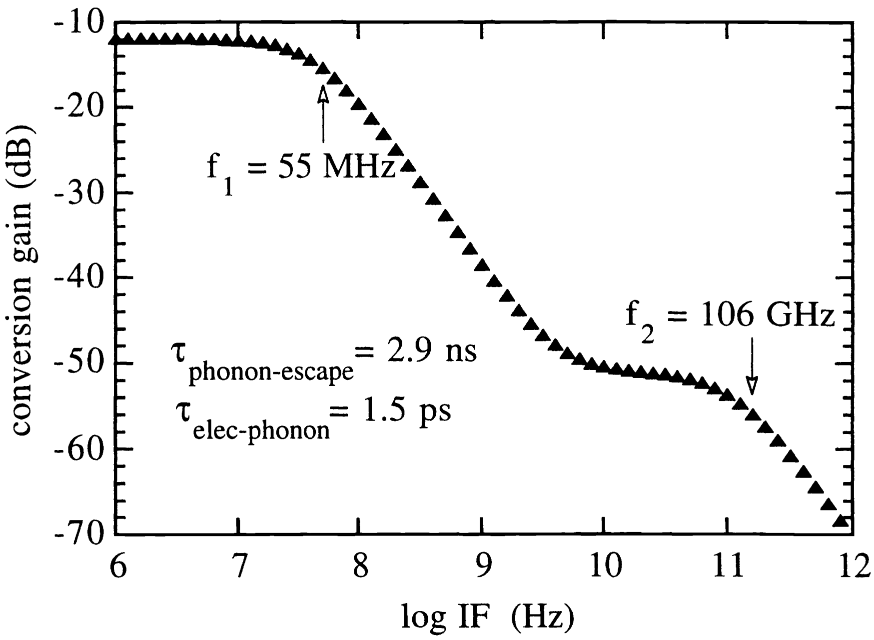


Fig. 5. Calculated conversion gain bandwidth behavior for a YBCO HEB using the two-temperature model of Ref. 10 and the nominal physical dimensions for the devices in this paper. The characteristic times chosen are obtained from independent measurements on YBCO films reported in Ref. 7.

4.2 HEB Effective Volume Analysis

There are several important differences between the data shown in Sect. 3 and the calculated behavior in Fig. 5. Most markedly, we do not observe a two-plateau gain bandwidth structure. The single Lorentzian bandwidth shown in Fig. 4 has a low-frequency intrinsic conversion gain very comparable to the calculated one, but with a -3 dB roll off frequency 100 times higher. While we have not observed evidence of a two-plateau structure, it is possible that the restricted frequency range of the measurement allows us to observe only one of the two plateaus. If so, the measured intrinsic conversion gain of -17 dB agrees much more closely with the calculated low-frequency plateau conversion gain of -12 dB in Fig. 5, rather than the -50 dB gain calculated for the upper frequency plateau in Fig. 5. This suggests that of the two frequency plateaus, the lower frequency one whose roll-off is set by the phonon escape time is being measured.

However, the bandwidth of the first plateau was calculated to be only 55 MHz given the nominal 100 nm thickness of the YBCO film, compared to the measured bandwidth of 5 to 8 GHz. It is possible that the larger bandwidth we observe pushes out the first plateau far enough to obscure a clear observation of the second plateau within our measurement limits, although we have no clear evidence that this takes place.

The higher than expected bandwidth implies, within the two-temperature model, a faster phonon escape time. This can result from a combination of a thinner HEB than the nominal dimensions indicate, and the presence of effective phonon escape routes from the HEB other than to the substrate. If phonons escaped only to the substrate, to obtain a first roll-off of 5 GHz would require a bolometer thickness of ~1.5 nm within the model of Ref. 10. Such a small thickness is inconsistent with the good superconducting transition in the DC resistance of these devices. The idea of having a smaller effective superconducting bolometer volume is consistent with the high normal-state resistivity of the device. Given the nominal dimensions of the bolometer and an upper bound on the room-temperature resistivity of 300 μΩ-cm for YBCO films showing a good superconducting transition, the device is expected to have a room-temperature resistance of less than 30 Ω, while we measure ≥ 300 Ω routinely. Because the entire device shows a DC supercurrent, the entire length of the bolometer must superconduct. The high resistance must then come from a decrease in the supercurrent-carrying cross-sectional area. Similarly, a good YBCO film should have a critical current density of $> 5 \times 10^5$ A/cm^2 at 77 K, while the measured values for our devices indicate critical current densities ten times lower using the nominal width and thickness. Based on the resistivity and the critical current, we estimate the effective superconducting thickness of the HEB to be closer to 15 to 20 nm. It is quite possible that etching damage to the top and edge surfaces can degrade the exposed YBCO and leave only a smaller region in the center of the patterned film with good superconducting properties.

The decrease in sample cross-section is actually fortuitous. Higher resistance makes it easier to obtain a 50 Ω impedance match to the antenna and transmission lines when operating the bolometer in the superconducting transition. Also, the smaller effective thickness and volume gives a faster phonon escape time to the substrate and provide alternate phonon escape paths to the damaged non-superconducting material at the edges and sides. The decrease in the escape time leads naturally to a higher conversion gain bandwidth. Finally, the calculations of Ref. 10 indicate that the mixer noise temperature should decrease with smaller HEB volumes. Preliminary measurements of the mixer noise show an input noise temperature of around 5,000 K for our best (highest conversion gain) samples at the optimal operating point. This noise figure is also much lower than expected for an HEB of the nominal physical dimensions we use, but is consistent with a mixer of significantly smaller superconducting volume.

5. CONCLUSIONS

Small volume YBCO superconducting HEBs are promising alternatives to existing mixer technology in the THz frequency spectrum. These devices require significantly less LO power (~ 1 μW) compared to Schottky diode mixers (~1 mW), with comparable bandwidth and responsivity. Compared to conventional superconductor mixers, the high-T_c mixers operate at liquid nitrogen rather than liquid helium temperature, have wider IF bandwidths, and have wider total bandwidths compared to SIS mixers. The YBCO HEBs also have the practical advantage of presenting primarily a real, rather than reactive, load to the antenna and waveguides at microwave frequencies. At present, the conversion gain of the YBCO HEBs is not as good as Schottky diodes or conventional superconductor mixers. The best intrinsic conversion gain measured for YBCO HEBs is -16 dB. An improvement of approximately 6 dB is needed before the conversion gain is competitive with existing THz mixers.

6. ACKNOWLEDGMENTS

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