GAIN-BANDWIDTH CHARACTERISTICS OF HIGH-T_C SUPERCONDUCTING MILLIMETER-WAVE HOT-ELECTRON BOLOMETER MIXERS

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ABSTRACT

The conversion gain bandwidth characteristics of millimeter-wave mixers using high-T_c superconducting $YBa_2Cu_3O_7$ (YBCO) thin films are presented. The YBCO films are patterned into lattice-cooled hot-electron bolometers (HEB) coupled to an integrated antenna and transmission line. Direct heterodyne and homodyne down-conversion measurements using local-oscillator frequencies of 75 GHz and 585 GHz show overall conversion gains of -35 dB, which includes a -18 dB coupling loss. The gain bandwidth shows a simple Lorentzian roll-off with -3 dB point of 5 to 8 GHz. No second plateau in the gain spectrum has been observed, in contrast to other reports. The effective volume of the HEB is believed to be significantly smaller than the physical dimensions of the device.

Gershenzon, *et al.*[1] first proposed the design of a lattice-cooled superconducting hot-electron bolometer (HEB) for use as a low-power, wide-band-width heterodyne mixer at millimeter and submillimeter-wave frequencies. This idea has been successfully implemented using NbN[2], which shows a conversion gain as high as -15 dB using 1 μW of pump power at a temperature of 4.2 K. The ultimate speed and bandwidth of the lattice-cooled HEB is determined by the electron-phonon scattering rate. For this reason, Gershenzon[3] suggested that the high normal-state resistivity of the high-T_c superconductor $YBa_2Cu_3O_7$ (YBCO) could indicate a very fast electron inelastic scattering rate and so make this material an ideal candidate to produce a very wide instantaneous bandwidth lattice-cooled HEB operating at 77 K. The first reports of such mixers at 1.5 μm (Ref. 4) and 9.6 μm (Ref. 5) wavelengths showed a very low intrinsic conversion gain of -77 dB (excluding coupling losses) using a relatively large 0.3 mW of absorbed LO power. However, the gain bandwidth showed a two-plateau structure. A low frequency plateau near -77 dB rolled off near 1 GHz intermediate frequency (IF) but gave way to a second plateau near -90 dB that extended to at least 18 GHz, the upper limit of the measurement.

Karasik, *et al.*,[6] 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

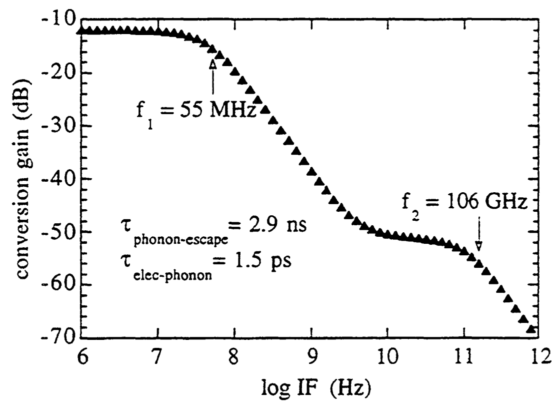

Figure 1: Calculation of the conversion gain bandwidth for a YBCO HEB mixer using the model of Ref. 6. An ideal 100% coupling of power to the HEB is assumed. The parameters used, including the phonon escape lifetime and the electron-phonon scattering time, are appropriate to YBCO with the nominal physical dimensions of the devices discussed in the text.

and noise temperature decreases for smaller bolometer volumes. The conversion gain bandwidth of the HEB is determined by the time it takes to remove heat from electrons via electron-phonon scattering and the escape 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. The first roll-off in the reported two-tiered bandwidth structure was interpreted as a consequence of the phonon escape time from the HEB, and the upper limit of the second plateau interpreted as 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. 1 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. 6. 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 first roll-off point f_1 of only 55 MHz.

We recently reported on the low power responsivity and conversion gain characteristics of small YBCO HEBs operating near 77 K.[8] A 60 dB improvement over previously reported values in the intrinsic conversion gain near 2 GHz IF demonstrated the potential of the YBCO HEB as a useful mixer. Here we address the conversion gain bandwidth characteristics of these mixers. In contrast to Refs. 4 and 5, we observe a single roll-off conversion gain bandwidth with -3 dB point of 5 to 8 GHz in these high-gain mixers. Based on the analysis of Ref. 6, this relatively high conversion gain, combined with the high resistance of the device, indicates that the effective volume of the HEB is significantly smaller than the nominal physical dimensions of the device.

The HEBs began as YBCO thin films nominally 100 nm thick covered with ~ 2 penetration depths of a gold overlayer, all on MgO substrates. A double-slot antenna and co-planar transmission line were then etched into the YBCO/Au using an ion beam (see Fig. 2). The Au overlayer was removed over the area of the HEB itself, which had nominal physical dimensions 2 μm (width) x 2 μm (length) x 100 nm (thickness), using a non-aqueous iodine-based Au etch which did not affect the superconducting transition temperature or width

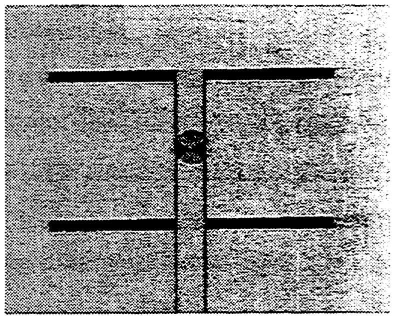

Figure 2: SEM micrograph of a YBCO HEB coupled to a 585 GHz double-slot antenna and a co-planar transmission line. The 2 μm x 2 μm HEB itself is at the intersection of the two tapers in the center of the picture. The width of the antenna arms is 175 μm.

and was found to be more reliable than the timed argon ion beam milling previously used. Finished bolometers had room temperature resistances of 300 to 600 Ω, transition widths of 2 to 3 K at around 85 K, and nominal critical currents at 77 K of ~ 0.1 mA.

Measurements were done quasi-optically. Samples were clamped onto a silicon hyper-hemispherical lens and heat sunk to a copper block. Sample temperature could be varied from 66 to 93 K. For direct heterodyne conversion gain measurements, two tunable Gunn

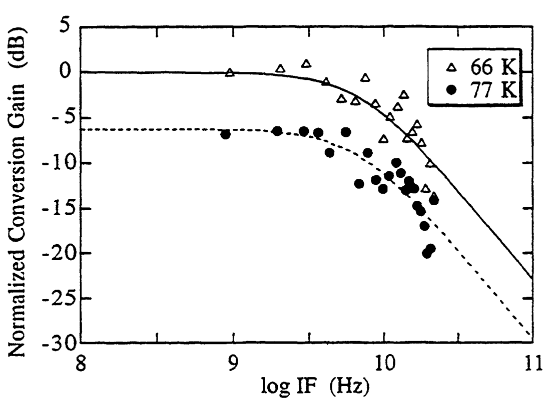

Figure 3: Measured conversion gain bandwidth at two sample temperatures for 75 GHz LO frequency using 2 μW LO power. Data are nomralized to the low-frequency gain at 66 K. The fits are simple Lorentzians, with -3dB points of 8 GHz (66 K) and 6.5 GHz (77 K).

diodes (75 to 90 GHz) were used. Attenuators kept the total power ≤ 1 mW in all measurements. The difference frequency generated by the HEB was amplified using a cooled microwave amplifier with bandwidth of 20 GHz. At 585 GHz, homodyne response was measured by using a Schottky diode in a corner cube to generate amplitude modulated sidebands onto the beam from a gas laser. Side-bands could be tuned up to 20 GHz off the laser line. Sideband power (1 to 10 μW) was calibrated using a known Schottky diode receiver.

Fig. 3 shows the measured conversion gain bandwidth at two different temperatures for one of our YBCO HEBs using 2 μW of LO power at 75 GHz. The rf power was kept at 0.1 μW and was tuned upward from the LO. Data are normalized to the low-frequency gain at 66 K. Estimating a coupling loss of 18 dB from pumped and unpumped *I-V* curves,[9] the intrinsic conversion gain to be compared with Fig. 1 is approximately -17 dB at the lowest frequencies at 66 K. The conversion gain is slightly lower and has a lower frequency roll-off at the higher temperature. At both temperatures, the data are well fit by a simple Lorentzian with -3 dB roll-off of 6.5 GHz at 77 K and 8 GHz at 66 K. There is no sign of a second plateau in the spectrum up to 20 GHz IF. Similar Lorentzian bandwidths were observed with other samples in the homodyne measurements at 585 GHz LO frequency. Typical -3 dB frequencies measured with 585 GHz were ~5 GHz.

There are several important differences between the data shown above and the data of

Refs. 4 and 5 and the calculation of Ref. 6. Most markedly, we do not observe a two-plateau gain-bandwidth structure. Using smaller LO power, the single Lorentzian bandwidth shown in Fig. 3 has an overall conversion gain two orders of magnitude larger, and a -3 dB roll off at frequencies 5 to 8 times higher, than the comparable values reported in Refs. 4 and 5. 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 the calculated low-frequency plateau conversion gain of -12 dB in Fig. 3, rather than the -50 dB gain of the second plateau. 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.

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. 6. 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 super-current, 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 at least 5×10^5 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. 6 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.

In summary, we have reported on conversion gain bandwidth measurements for high-T_c super-conducting YBCO hot-electron bolometer mixers. Using LO frequencies of 75 GHz and 585 GHz, simple Lorentzian bandwidths were measured with -3 dB IF roll-offs between 5 to 8 GHz. This is in contrast to two-tiered roll-offs reported by others. The larger bandwidths we observe may be due to a faster phonon escape time resulting from a smaller superconducting cross-section than the nominal dimensions of the device indicate, as well as alternate phonon escape routes. The DC resistance of the device, the critical current, and noise temperature measurements also support a smaller effective volume.

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