Wide Bandwidth Far-Infrared Mixing using a High-T_c Superconducting Bolometer

Mark Lee, Richard C.-T. Li

Abstract **– We report on the gain bandwidth and noise characteristics of far-infrared mixers using high-*Tc* superconducting YBa2Cu3O7 (YBCO) thin films. The YBCO films are patterned into lattice-cooled hot-electron bolometers (HEBs) coupled to an integrated antenna and transmission line. Heterodyne and homodyne down-conversion using LO frequencies of 115 GHz and 585 GHz show a device conversion gain of as high as –9.5 dB at 66 K using 1 μW of LO power. *Y*-factor noise measurements show a double-sideband noise temperature of 3400 K at 66 K. Both gain and noise bandwidths show a single-pole roll-off with -3 dB point near 10 GHz.**

I. Introduction

Gershenzon, *et al.* [1] first proposed the design of a lattice-cooled superconducting hot-electron bolometer (HEB) for use as a low-power, wide-bandwidth heterodyne mixer at millimeter and submillimeter-wave frequencies. In principal, HEB mixers have several very attractive properties, including wide LO and IF bandwidths, low LO pump power requirements, reasonable noise figures, ease of fabrication, and freedom from capacitive parasitics. The lattice-cooled idea was first successfully implemented using NbN [2], which showed a conversion gain up to -15 dB using 1 μW of LO power at a temperature of 4.2 K.

The ultimate speed and bandwidth of a lattice-cooled HEB is determined by the electron energy relaxation rate, which in metals is presumed to be 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) implied 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 near liquid nitrogen temperatures. 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 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] did extensive calculations on the conversion gain and noise properties of lattice-cooled HEB mixers using a two-temperature model. They found that the conversion gain increases and noise temperature

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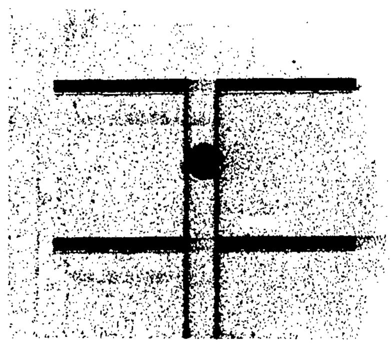

Fig. 1: SEM micrograph of a YBCO HEB coup-led to a 585 GHz double-slot antenna and a co-planar transmission line. The 1 μm x 2 μm HEB itself is at the intersection of the two tapers in the center of the picture. The width of the antenna arms is 175 μm.

decreases for smaller bolometer volumes. The 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 τ = 1.5 ps, leading to an upper IF bandwidth limit of $f_c = 1/2\pi\tau$ in excess of 100 GHz.

II. Device Structure and Measurement

Our HEB devices began with sputter-deposited (001)-oriented YBCO thin films nominally 100 nm thick covered with > 2 penetration depths (> 200 nm) of a gold overlayer, all on MgO substrates. A double-slot antenna and coplanar transmission line were then lithographically patterned and etched into the YBCO/Au using an Ar ion beam (see Fig. 1). A window over the area of the HEB was patterned, and the Au overlayer over the HEB was then removed using a non-aqueous iodine-based selective Au etch, which did not affect the superconducting transition temperature or width of the underlying YBCO film. The nominal dimensions of the HEB were 1 μm (width) x 2 μm (length) x 100 nm (thickness). The width and length dimensions were measured in an optical microscope. In practice, DC resistance measurements suggested that the thickness of the film was less than 100 nm, perhaps due to some etching into the YBCO film during the Au etch. Finished bolometers had room

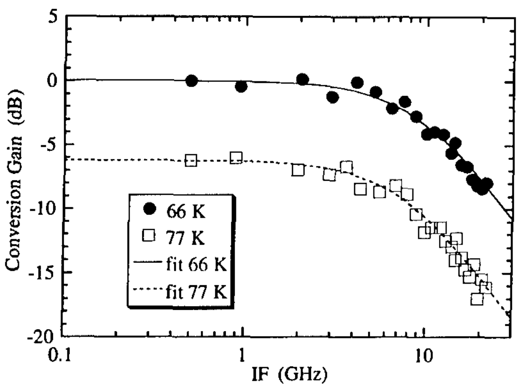

Fig. 2: Measured conversion gain bandwidth at two sample temperatures for 115 GHz LO frequency using 1.5 μW LO power. Data are normalized to the low-frequency gain at 66 K. The fits are simple Lorentzians, with -3dB points of 9 GHz (66 K) and 7.5 GHz (77 K).

temperature resistances of 100 to 300 Ω, transition widths of 1 to 2 K at around 85 K, and nominal critical currents at 77 K of ~ 0.1 mA.

All measurements were done quasi-optically. The HEB devices were clamped onto a high-resistivity 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 oscillators (115 to 145 GHz) were used. The LO was kept fixed at 115 GHz, and the rf source was varied. Attenuators kept the total incident power < 1 mW, with the rf power typically _10 dB below the LO power. At 585 GHz LO frequency, homodyne response was measured by using a Schottky diode in a corner cube to generate amplitude modulated sidebands onto the beam from a molecular gas laser. Sidebands could be detuned up to 20 GHz off the laser line. Sideband power (1 to 10 μW) was calibrated using a known Schottky diode receiver. In both cases, the intermediate frequency generated by the HEB was amplified using a cooled microwave amplifier with bandwidth of 20 GHz.

III. Data and Analysis

Fig. 2 shows the measured conversion gain bandwidth at two different temperatures for one of the YBCO HEBs using 1.5 μW of LO power at 115 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 9 dB from pumped and unpumped *I-V* curves, [8] the device conversion gain to is approximately _9.5 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 7.5 GHz at 77 K and 9 GHz at 66 K. Fig. 3 shows similar gain bandwidth data in a homodyne measurement at 585 GHz LO frequency. The device conversion gain here is _11 dB at the lowest frequency, with a -3 dB point of 7 GHz.

Fig. 4 shows the IF output vs. DC bias current data from a *Y*-factor noise temperature measurement. The LO

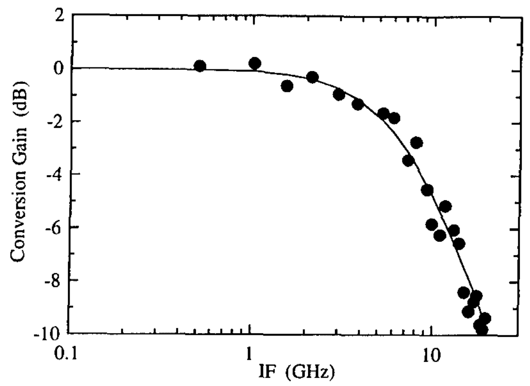

Fig. 3: Homodyne conversion gain bandwidth at 66 K for 585 GHz LO frequency using 1 μW LO power. Data are normalized to the low-frequency gain at 66 K. The fit is a Lorentzian, with -3dB point of 7 GHz.

is 585 GHz. The rf signal is derived from one of two blackbody radiators, one at room temperature (300 K) and the other at 77 K. The IF signal is amplified by a cooled 2.0 GHz tuned low-noise amplifier (noise temperature of 45 K operating at 77 K) and measured with a tuned power meter. Note that the IF output of the bolometer mixer is zero for any bias smaller than the critical current. The inset shows the time-domain IF power signal when the rf is chopped between the two blackbodies at 35 Hz. The DC bias is set to maximize the signal. From the difference in the IF output power, we obtain the double-sideband noise temperature at the input of the device to be about 3600 K.

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. 6. The low-frequency plateau shows a maximum device conversion gain of -12 dB, dropping to -50 dB at the second plateau. The first, lower frequency roll-off reflects the phonon escape rate from the film to the substrate heat sink. Because of the relatively large (100 nm) nominal thickness of the films used, the slow phonon escape lifetime leads to an f_1 of only 55 MHz. The

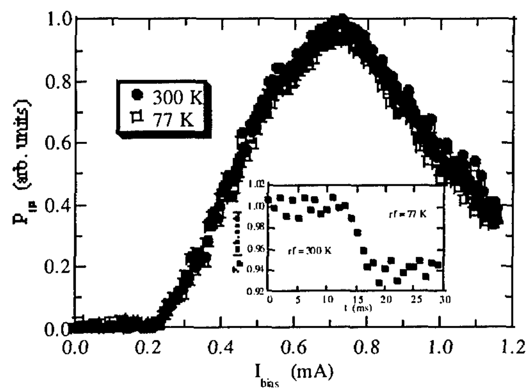

Fig. 4: Hot/cold load response of HEB mixer at 585 GHz LO. Shown is the output power at 2.0 GHz IF using rf blackbody sources at 300 K and 77 K. Inset: time domain response to a chopped 300 K / 77 K rf source.

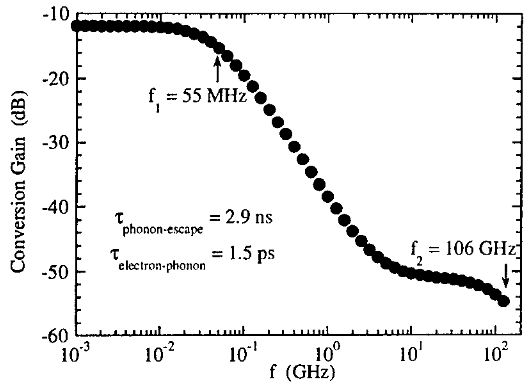

Fig. 5: Numerical calculation of YBCO HEB conversion gain bandwidth using the model of Ref. 6 and the nominal physical dimensions of our device. The phonon escape time is set primarily by the film thickness. The electron-phonon scattering time is taken from the reported data of Ref. 7.

second, higher roll-off f_2 that is due to electron-phonon scattering is well beyond the measurement bandwidth of our experimental apparatus.

Clearly, the data measured for our HEB mixer is inconsistent with the numerical results. First, the maximum device conversion gain measured is larger by roughly a factor of two than that predicted. More importantly, the roll-off frequency measured is over 100 times higher than the f_1 calculated based on the HEB's nominal dimensions. The larger conversion gain can be explained by an effective device thickness somewhat smaller than the nominal dimension. However, because the roll-off frequency increases approximately linearly with a decrease in film thickness in this model, there is no way the effective thickness can be made small enough to account for the factor of 100 discrepancy in 3 dB frequency between model and measurement. A 1 nm effective film thickness is smaller than the unit cell lattice constant in the (001) direction and would not superconduct at all. Some mechanism other than phonon escape is thus responsible for the observed roll-off frequency, but what this might be is currently unknown.

IV. CONCLUSION

Superconducting YBCO hot-electron bolometers have been demonstrated for use as far-infrared mixers operating near liquid nitrogen temperatures. These mixers have a device conversion gain as high as _9.5 dB, gain bandwidths near 10 GHz, and input noise temperatures around 3600 K at 585 GHz LO and 1 μW pump power. The gain bandwidth is much higher than models of the HEB mixing predict, but the origin of the discrepancy is currently unknown.

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