YBaCuO HEB Hot-spot Model with Non-uniform RF Power Absorption: THz Mixing Frequency-dependent Performance

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***Abstract*—High-T_C superconductor (YBaCuO) hot electron bolometers (HEB) are promising THz mixers due to the large predicted bandwidth and the low local oscillator (LO) power requirement. Recently, we introduced the hot-spot model, initially dedicated to low-T_C NbN devices, to predict YBaCuO mixer performance. Major improvements to the model have been introduced: i) local description of the power absorption along the HEB constriction, ii) THz dependence of the resistive transition, iii) impedance matching between the THz antenna and the constriction. Mixer noise temperature T_N and conversion gain G were predicted up to 2.5 THz. For instance, T_N = 2700 K (DSB) and $G = -13$ dB are obtained with 9 µW of LO power at 1 THz.**

I. Introduction and Background

During the past decade, superconducting hot electron bolometers (HEB) have been the object of unceasing progress, especially for low-T_C devices. Efforts on high-T_C YBaCuO HEBs have been more limited, however, with few published results because ultrathin film YBaCuO technology has proven difficult due to chemical reactivity and aging effects. Besides, early predictions were encouraging, with noise temperature ~1000 K (DSB) at P_{LO} = 11 µW local oscillator (LO) power for a constriction (Fig. 1) of dimensions $L = w$ = 100 nm and θ = 10 nm [1]. This model was based on the "0-D" point bolometer approach that describes the system in terms of thermal reservoirs only, namely the (hot) electrons at temperature T_e and the phonons at temperature $T_p < T_e$.

Furthermore, the "1-D" hot-spot model that includes the spatial dependence along the superconducting constriction as $T_e(x)$, was implemented for low-T_C HEBs [2]. Our initial motivation was to extend this model to YBaCuO, while taking the high-T_C specificities into account [3]; furthermore, phonon diffusion along the constriction was introduced through the dependence $T_p(x)$ [4]. Our present objective is to introduce the influence of frequency and predict THz HEB mixer noise temperature and conversion gain.

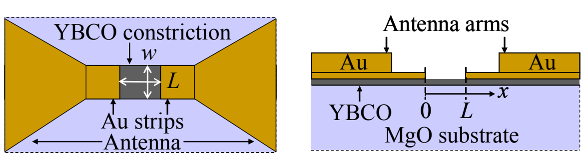

Fig. 1. HEB schematic views (not to scale) of a YBaCuO constriction tied to the arms of a planar antenna. Left: top view; right: cross-section. The constriction dimensions are: length L, width w, and thickness θ. The hot-spot model coordinate x is parallel to L.

II. Model Overview and DC Results

We have dropped the usual hypothesis that considers the LO power to be uniformly absorbed over the HEB constriction length L. We have substituted to it the major assumption that the THz current is now constant along the constriction, hence a non-uniform LO power absorption. The local electron temperature was obtained by solving the coupled electron and phonon thermal reservoir equations, which could be used to determine the local YBaCuO complex resistivity, hence the locally dissipated LO power. A modified two-fluid model description allowed deriving the frequency dependent superconducting impedance transition. In particular, the resistive transition (Fig. 2), is characterized by the mid-transition temperature shift (about −1% per THz) and transition broadening (about +20% per THz). Another outcome was the ability to introduce the impedance matching coefficient between the constriction and the antenna.

The constriction electrical simulations provided the DC current-voltage I-V maps under LO pumping (Fig. 3). These were in line with available experimental results (both low-T_C and high-T_C HEBs), and so confirmed the non-uniform LO power assumption [5].

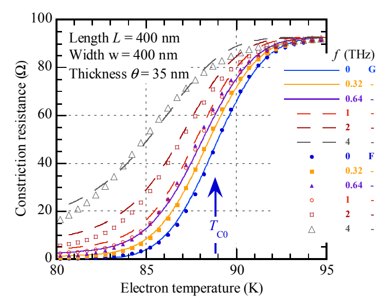

Fig. 2. Resistive transitions of an YBaCuO constriction, from DC to 4 THz. The lines labeled "G" apply to a Gaussian distribution function of the mid-transition temperature. The points marked "F" apply to a Fermi-Dirac like approximation of "G", as used for convenience in the numerical simulations. T_{C0} is the mid-transition DC critical temperature. After [5].

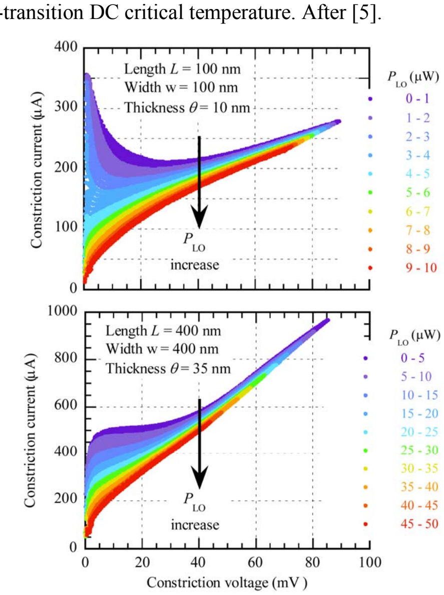

Fig. 3. DC current vs. voltage maps for small size (top) and medium size (bottom) YBaCuO constrictions, at various LO power levels. After [5].

III. THz Mixer Performance Results

We have considered the mixer performance for a typical medium size constriction of dimensions $L = w = 400$ nm and $\theta = 35$ nm. The DSB noise temperature T_{DSB} and the conversion gain G at 400 GHz are shown in Fig. 4 as color/gray scale levels on *I*-*V* maps. The RF power matching coefficient with the antenna was taken into account. The antenna being assumed as self-complementary, its impedance is purely real with resistance $R_A \approx 80\ \Omega$ for an MgO substrate (dielectric constant ~10) [6]. For the optimal value P_{LO} = 9 µW, minimum T_{DSB} = 2210 K is obtained at DC bias V = 12 mV (with associated $G \approx -11$ dB), whereas maximum $G \approx -10$ dB is obtained at DC bias V = 7 mV (with associated T_{DSB} = 2580 K).

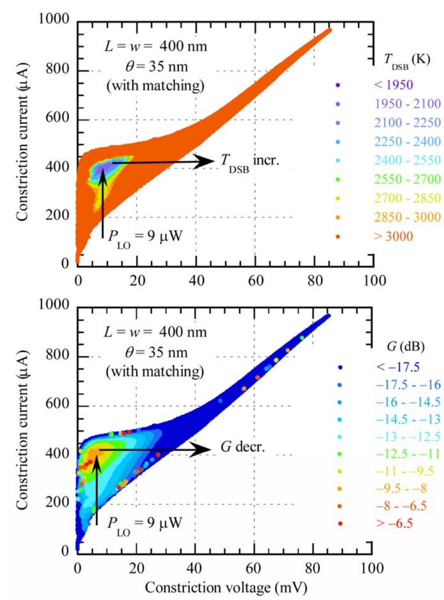

Fig. 4. For an YBaCuO constriction at 400 GHz, *I*-*V* maps exhibiting the DSB noise temperature (top) and conversion gain (bottom) values as level parameter. Impedance matching to the antenna was taken into account. The P_{LO} optimum areas are indicated.

Spanning the millimeter / THz wave range, at the same optimal LO power of 9 µW, minimum T_{DSB} (associated G) ranged from 1900 K (−10 dB) below 100 GHz, through 2700 K (−13 dB) at 1 THz, to 4150 K (−15 dB) at 2.5 THz, in reasonable agreement with published data. For instance, T_{DSB} = 3600 K and G = −11 dB were reported for a 1 µm × 2 µm, 100 nm thick constriction at 585 GHz with P_{LO} = 1 µW (a seemingly not optimized value) [7]. This also comforts the validity of the non-homogeneous LO power distribution, a key point of our present approach. With the usual homogeneous LO power assumption [4], we obtained T_{DSB} = 1600 K (G = −13 dB) at ~700 GHz with optimal P_{LO} = 35 µW (instead of 9 µW), which means that only 26% of P_{LO} would be effective in the hot-spot mixing process.

The maps in Fig. 5 were obtained without taking the RF power matching coefficient with the antenna into account (i.e., this coefficient was assumed frequency independent and arbitrarily equal to 1). Two inadequacies with respect to the correct approach (Fig. 4) appear: i) The mixer performance is significantly degraded, ii) the optimal performance areas are completely separated, with very different P_{LO} values.

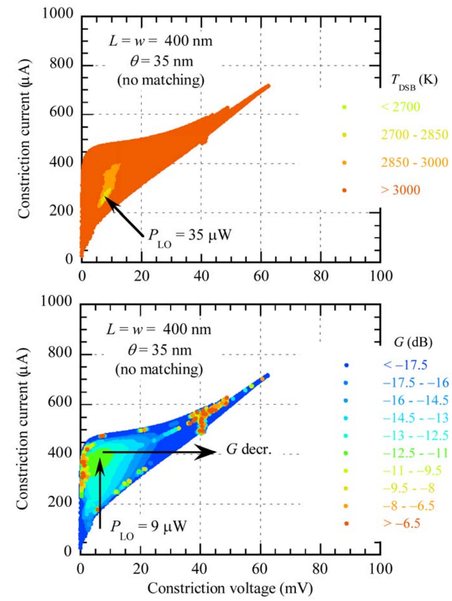

Fig. 5. For an YBaCuO constriction at 400 GHz, *I*-*V* maps exhibiting the DSB noise temperature (top) and conversion gain (bottom) values as level parameter. Impedance matching to the antenna was not taken into account. The P_{LO} optimum areas are indicated.

IV. Summary

In contrast with the usual assumption that the LO power is uniformly dissipated in the constriction volume, we have taken the more realistic assumption of a uniform RF current, hence a non-uniform RF and DC power dissipation. This approach has allowed introducing RF frequency effects in superconducting YBaCuO and predicting frequency dependent mixer performance.

Acknowledgment

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