Dynamics of the response to microwave radiation in $YBa_2Cu_3O_{7-x}$ hot-electron bolometer mixers

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We present a systematic study of the intermediate frequency (IF) bandwidth of hot-electron bolometer mixers made from $YBa_2Cu_3O_{7-x}$ high-temperature superconductive thin films fabricated on substrates with high thermal conductivity (MgO and sapphire). At a local oscillator frequency of 100 GHz, a strong dependence of the IF bandwidth on the bias point and temperature has been experimentally found. Moreover, an unexpected IF bandwidth variation has been detected in a broad range of operating frequencies (1–480 GHz). Besides conventional bolometric mixing mechanisms associated with thermalization of electrons and phonons, the contribution of direct interaction between radiation and magnetic vortices in the $YBa_2Cu_3O_{7-x}$ film may be responsible for the observed effects. [DOI: 10.1063/1.1401095]

The hot-electron bolometer (HEB) mixer made from high-temperature superconductor (HTS) materials was introduced recently as a competing alternative to a Schottky-diode mixer.[1] It is an attractive candidate for long-term atmospheric remote sensing and planetary missions since the required operating temperature between 65 and 75 K can be achieved with available space-qualified coolers. Furthermore, this type of mixer requires 100 times less local oscillator (LO) power than the Schottky mixer, which is a clear advantage at THz frequencies. The lack of tunable local oscillators for the THz frequency range demands for large intermediate frequency (IF) mixer bandwidth. The physical limit of the IF bandwidth for HTS HEB is determined by the value of the inelastic electron–phonon scattering time in $YBa_2Cu_3O_{7-x}$ (YBCO) thin films ($\tau_{ep}\approx 2$ ps at $T\approx 85$–90 K),[2,3] and is about 100 GHz. Since at these temperatures the phonon heat capacity exceeds the electron one by 1–2 orders of magnitude, the mixer performance strongly depends on the total thermal conductance for heat removal from the phonon subsystem. The heat can be removed by phonon escape to the substrate (the characteristic time τ_{es} is proportional to film thickness d) or by diffusion of phonons to the normal metal contacts ($\tau_{diff}\propto L^2$, where L is the length of the mixer device). In order to provide useful IF bandwidths of the order of 1 GHz, devices with a thickness less than 30 nm and a length less than 300 nm are needed.[1] Previous studies of hot-electron effects in thin YBCO films on various substrates[4–12] showed that the predictions of the two-temperature model (2TM) (Ref. 13) apply at frequencies above 1 THz. Significant deviations from the model predictions are found at centimeter wavelengths.[14] In this letter, we describe systematic studies of the IF bandwidth at millimeter and submillimeter wavelengths using YBCO HEB mixer devices on substrates with high thermal conductivity (MgO and sapphire). In our work, we focus on the variation of the IF bandwidth with bias conditions, operating temperature, and LO frequency.

The HTS HEB mixer devices are fabricated on single-crystalline MgO and sapphire substrates. YBCO films with a thickness of about 35 nm are grown by laser ablation and patterned with optical lithography and ion-beam etching. The typical device geometry is a 1.5-μm-long and 1-μm-wide YBCO bridge between two gold contact pads (which act as the antenna). Typical values of the critical temperature and the superconducting transition width are about 85 and 3 K, respectively.

For IF bandwidth measurements, a 90–94 GHz Gunn oscillator and a 78–119 GHz tunable backward-wave oscillator are used. Both signals are fed into a waveguide dipstick, which is inserted into a liquid-helium transport dewar. The IF signal is measured by a spectrum analyzer, connected to the mixer chip by a semirigid cable and a broadband bias tee. The LO frequency, the LO output power, and the IF signal power are computer controlled and monitored. At higher frequencies (300 and 480 GHz) backward-wave oscillators and Schottky-diode frequency multipliers were used. During the IF spectrum measurements the mixer is biased by a constant voltage source.

The results obtained for the devices on MgO and sapphire substrates are similar, so in the rest of the letter we only discuss devices on MgO substrates. Figure 1 shows the current–voltage characteristic (IV curve) and IF bandwidth measurements of a device on a MgO substrate at 85 K. Figure 1(b) shows the IF spectra for four different bias points,

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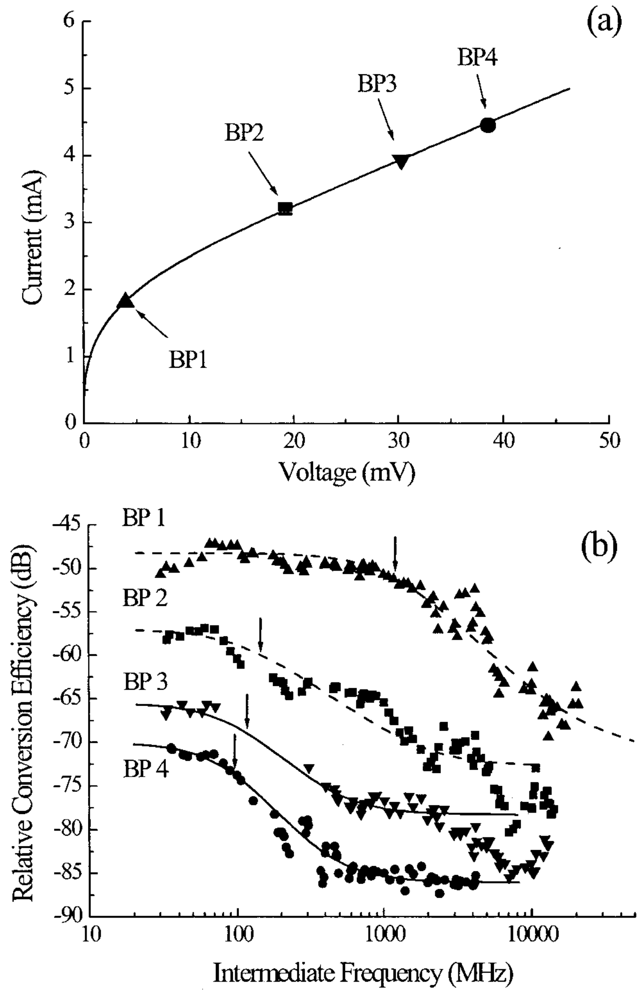

FIG. 1. (a) *IV* curves of a HTS HEB mixer on MgO at 85 K and bias points (BP) for IF bandwidth measurements; (b) IF spectra measured at 100 GHz at bias points marked (a). Arrows indicate the position of the −3 dB roll-off frequency. Solid lines are the fitting using Eq. (1). The dashed lines are to guide the eye.

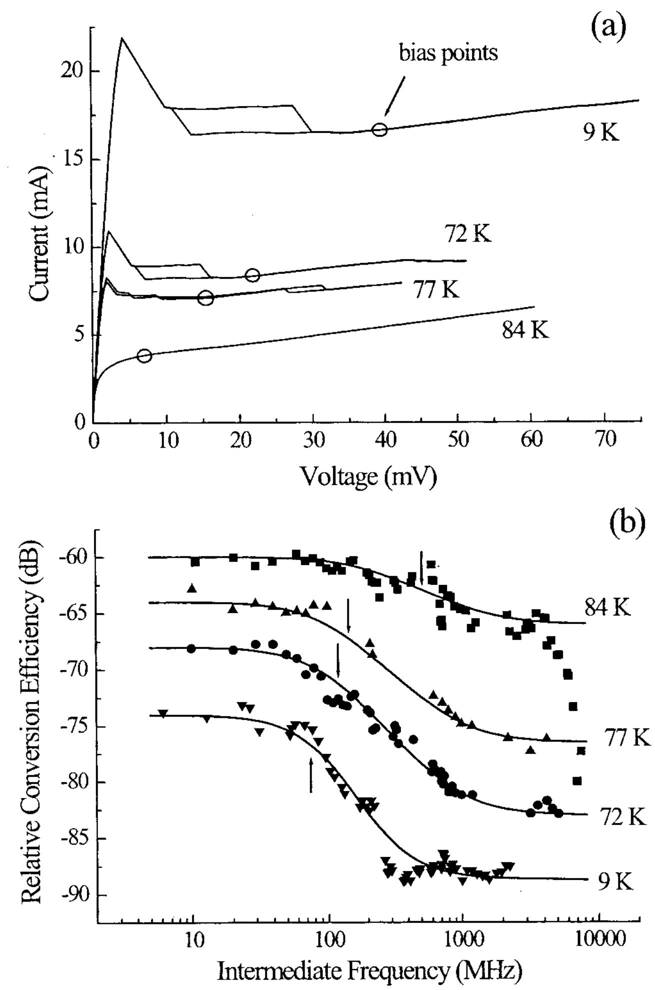

FIG. 2. (a) *IV* curves of a HTS HEB mixer on MgO at different temperatures; (b) corresponding IF spectra measured at 100 GHz. Arrows indicate the position of the −3 dB roll-off frequency. The line is to guide the eye.

indicated as BP 1–4 in Fig. 1(a). The spectra are vertically shifted for clarity. Obviously, the shape of the IF spectrum strongly depends on the bias point. All spectra have plateau up to several tens of MHz. At higher frequencies the IF response decreases, where the slope and roll-off frequencies depend on the bias voltage [arrows in Fig. 1(b)]. The value of the roll-off frequency (defined as the IF frequency corresponding to a 3 dB drop of the conversion efficiency) decreases from about 1.2 GHz for BP1 down to 90 MHz for BP4.

We tried to fit the experimental data for the conversion efficiency η to the theoretical frequency dependence given by the 2TM:[1]

$$\eta(f)\propto\sqrt{\frac{1+(2\pi f\tau_{\mathrm{pe}})^2}{[1+(2\pi f\tau_{\mathrm{ep}})^2][1+(2\pi f\tau_{\mathrm{es}})^2]}}. \qquad (1)$$

Here, $\tau_{\mathrm{pe}}=\tau_{\mathrm{ep}}\times c_p/c_e$ is the phonon–electron relaxation time, $c_p\approx0.65\ \mathrm{J\,K^{-1}\,cm^{-3}}$, and $c_e\approx0.025\ \mathrm{J\,K^{-1}\,cm^{-3}}$ are the heat capacities of phonons[15] and electrons,[16] respectively. The spectra for BP3 and BP4 follow the qualitative prediction of the model, but the inelastic phonon–electron scattering time found as a fitting parameter of Eq. (1), turns out to be an order of magnitude longer ($\approx$400 ps) than expected ($\tau_{\mathrm{ep}}\approx1.6$ ps at $T\approx90$ K).[2] The phonon escape time for a film with thickness d on a MgO substrate is given by $\tau_{\mathrm{es}}=33\times d$ (nm) ps.[17,18] For a film thickness of 35 nm this corresponds to a bandwidth $\Delta f_{\mathrm{es}}=(2\pi\tau_{\mathrm{es}})^{-1}\approx140$ MHz, which is in close agreement with the experimentally measured roll-off frequency for BP4. Thus, the phonon escape process dominates the relaxation process in our mixer in this particular bias regime.

With the same device, we also measured the IF spectra at several operating temperatures. The results of the IF spectra measurements at 100 GHz LO frequency and at operating temperatures between 9 and 84 K are presented in Fig. 2(b) along with the corresponding *IV* curves [Fig. 2(a)]. In these measurements, the bias voltage and the LO power are adjusted to get the highest conversion efficiency. The obtained temperature dependence of the IF bandwidth at 100 GHz is very similar to that reported previously for lower LO frequencies at 1–10 GHz.[14] At low temperatures (<77 K), the optimal bias point is at voltages above the hysteretic region in the *IV* curve, i.e., where the self-heating is significant. At these temperatures the IF spectra have a clear onset of the hot-electron plateau and in general look similar to those predicted by the 2TM. At higher operating temperatures the

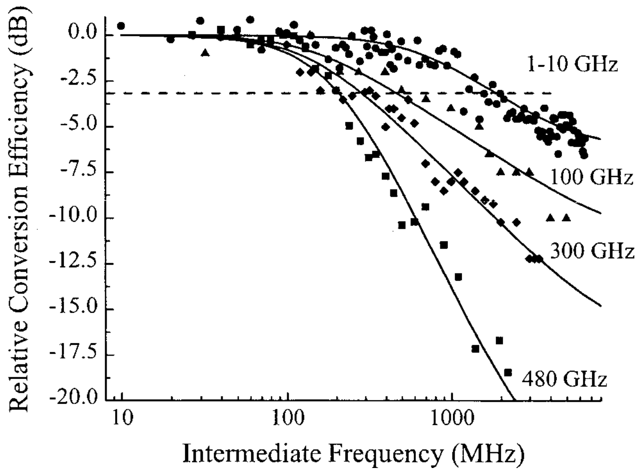

FIG. 3. IF spectra of a mixer response (MgO substrate) at different operating frequencies between 1 and 480 GHz at $T=77$ K. Dashed horizontal line indicates the position of the -3 dB roll-off frequency. The solid line is to guide the eye.

self-heating region disappears and the IF bandwidth becomes broader. At operating temperatures close to the critical temperature the bandwidth is 1–2 GHz. The observed IF bandwidth dependence on temperature correlates well with the bias-point dependence at fixed temperature: the IF bandwidth is significantly larger at low-voltage bias points, at low temperature the optimal bias points are at high voltages so the bandwidth is smaller.

The bias and temperature dependencies of the IF bandwidth were also studied at higher LO frequencies. The devices similar to those measured at 100 GHz were tested at 300 and at 480 GHz. Figure 3 shows the IF spectra measured at 1–10 (previous work),[14] 100, 300, and 480 GHz. The spectra were taken in the high-temperature limit (about 77 K). A gradual decrease in IF bandwidth is observed with increasing LO frequency. At 480 GHz the IF bandwidth does not depend on both temperature and bias point.

The obtained results suggest that the mixing mechanism responsible for large IF bandwidth in YBCO mixers on MgO and sapphire substrates becomes inefficient at high LO frequencies. The experimentally observed bias voltage, temperature, and LO frequency dependence of the IF bandwidth may be attributed to a presence of a nonbolometric mixing mechanism, coexisting with the frequency-independent bolometric one. This mixing mechanism is possibly related to the vortex dynamics. Vortices are known to provide various types of nonlinear behavior as long as the radiation frequency is low enough to allow the vortex motion to follow the electromagnetic wave phase.[19] This would explain the frequency dependence of the IF bandwidth below 500 GHz and is also the reason why this mixing process was not observed previously in optical mixing experiments. Furthermore, the observed nonbolometric phenomena practically vanish as soon as the self-heating starts, i.e., when hot spots define the shape of the *IV* curve and no vortices exist.

At THz frequencies the vortex mixing process is unlikely to be important and further HTS HEB mixer development should concentrate on the bolometric mixing effect and the optimization of the thermal properties of the devices and substrates.

In conclusion, we have studied the dynamics of the mixing response in YBCO bridges on MgO and sapphire substrates in a broad range of radiation frequencies, bias voltages, and temperatures. The observed variation of the IF bandwidth can be explained by a combined effect of the frequency-independent bolometric mixing and the mixing due to interaction of magnetic vortecies with radiation. The latter mechanism is efficient only at frequencies below 500 GHz and unlikely plays any role at THz frequencies and above.

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