

# **YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> Hot-Electron Bolometer Mixer at 0.6 THz**

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## ***Abstract***

We present an investigation of hot-electron bolometric mixer based on a YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> (YBCO) superconducting thin film. Mixer conversion loss of -46 dB, absorbed local oscillator power and intermediate frequency bandwidth were measured at the local oscillator frequency 0.6 THz. The fabrication technique for nanoscale YBCO hot-electron bolometer (HEB) mixer integrated with a planar antenna structure is described.

## ***Introduction***

The hot-electron phenomenon has been proved to be an efficient mixing mechanism for the terahertz range [1]. Heterodyne receivers based on NbN and Nb hot-electron bolometric (HEB) mixers have reached a noise level as low as 20 quantum limits ( $h\nu/2$ ) for frequencies up to 5 THz with instantaneous bandwidth of 4 GHz to 9 GHz [2,3, 4]. At the present time they are the most sensitive broadband receivers for terahertz frequencies. Although HEB mixers based on high- $T_c$  films do not compete with low- $T_c$  mixers with respect to sensitivity, they have much larger instantaneous bandwidth and need much simpler (and, therefore, lighter) refrigeration systems, that makes it possible to use them in airborne and space radiotelescopes. Simple fabrication technology, real impedance, a possibility of low optimum local oscillator power (which is simply proportional to the mixer volume) makes YBCO HEB mixers to be competing with Schottky diode mixers.

The hot-electron phenomenon consists of the heating of electrons in a superconducting film by radiation. Beating of the local oscillator (LO) and the signal

waves causes oscillations of the electron temperature, and, therefore, of the load voltage, at an intermediate frequency ( $\omega_{IF}=\omega_{LO}-\omega_S$ ). Since the impedance of the HEB mixer is the dominantly real, the intermediate frequency (IF) bandwidth of the mixer is limited only by the electron temperature relaxation rate. For such superconductors as YBCO with strong electron-phonon coupling ( $\tau_{e-ph}=1.1$  ps [5]) and large phonon to electron specific heat ratio ( $c_p/c_e\approx 40$ ) electrons are effectively cooled via the electron-phonon interaction. The theoretically predicted IF bandwidth for a YBCO HEB mixer is  $1/(2\pi\tau_{e-ph})=140$  GHz. Due to the film-substrate boundary resistance significant phonon heating occurs in the film. In YBCO films this effect is much stronger than in low- $T_c$  films, since the complicated composition of YBCO does not allow fabrication of ultrathin films with high critical temperature and critical current density. This effect limits the IF spectrum on the lower side to 2 GHz, which can not be treated as a significant disadvantage of YBCO HEB mixers. A much more important effect of the phonon heating is an increase of the mixer conversion loss in the IF bandwidth of interest (i.e. 2-140 GHz). According to theoretical models of the HEB mixer phonon cooling rate could be increased reducing mixer in-plane size and film thickness. Mixer volume reduction also leads to a decrease of LO power request that is quite important in terahertz range where power of solid state radiation sources is quite limited.

### ***Device fabrication and measurement set-up***

In the paper we present a technology for fabrication of sub-micrometer size YBCO mixers integrated into a planar antenna structure. YBCO films on  $\text{LaAlO}_3$  substrates were deposited by a pulsed laser ablation technique in an oxygen atmosphere. The deposition occurred at the substrate temperature  $800^\circ\text{C}$  and the oxygen pressure 0.8 mbar. For the film oxidation the oxygen pressure was increased up to 1 bar and substrate temperature was ramped down with the rate  $15^\circ\text{C}/\text{min}$ . At the room temperature 20 nm gold layer was in-situ deposited. The critical temperature of the films was inductively measured and was around 88-89 K. Using an e-gun evaporation system 200 nm ex-situ gold layer was deposited to form an antenna and IF contacts. As an antenna we used self-complimentary spiral antenna design, which performed well with NbN HEB mixer and has good coupling efficiency with a Gaussian beam [6].

The thick gold layer has also to prevent any deterioration of superconducting properties of the YBCO film during the next fabrication steps. On top of YBCO/gold double-layer two small pads and two arm spiral structure were made using electron-beam lithography, titanium evaporation (40 nm) and standard lift-off procedure. At the next step with an e-beam lithography and a lift-off a carbon pad as thick as 50 nm was made inside the area marked by rectangular in Fig.1. With these Ti and C masks the gold and YBCO films were ion-milled down to the substrate. After that, the

carbon mask was removed in RF oxygen plasma and the substrate was moved into the ion-milling system again. During the second ion-milling process the gold layer between two small pads was removed down to YBCO film. SEM picture of the device is shown in Fig.1.

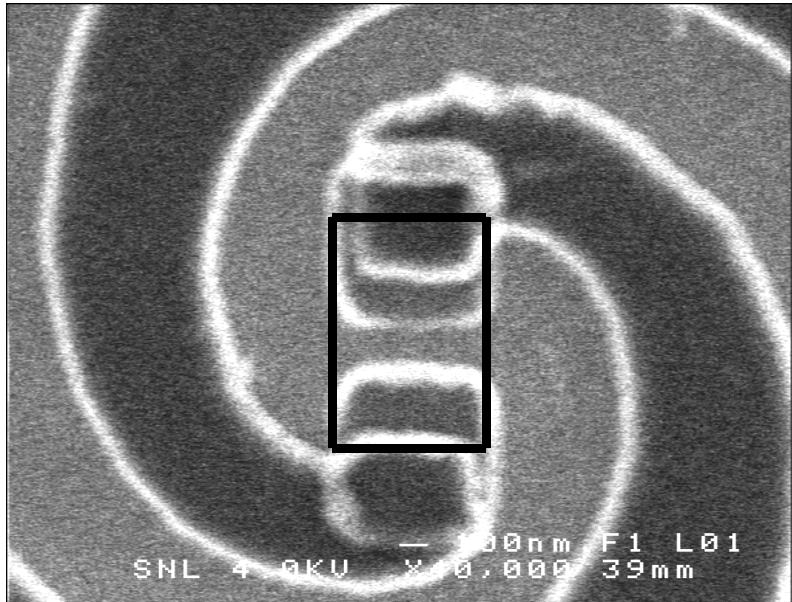


Fig.1 SEM image of a spiral antenna coupled YBCO mixer. The rectangular marks the bolometer area.

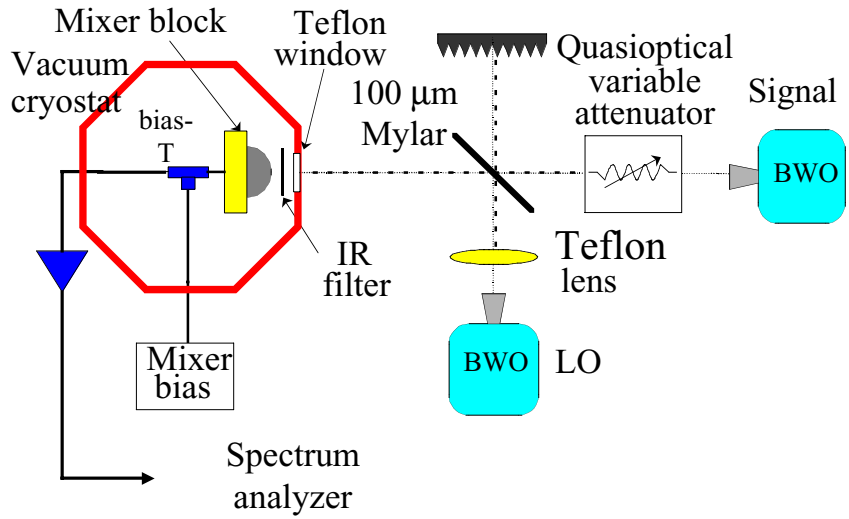


Fig.2. 600 GHz heterodyne measurements set-up.

For the heterodyne measurements we used a set-up, which is shown in Fig.2. The mixer was attached to a Si elliptical lens and mounted in a vacuum cryostat cooled by liquid nitrogen. Two backward wave oscillators (BWO) were used as a local oscillator and a signal source. The frequency of the signal BWO was fixed at 600 GHz and the LO frequency was tuned. At each frequency point the LO power was kept at the same level. For relative measurements of the LO power we used the same mixer as a direct detector. The LO radiation was chopped with low frequency (20 Hz) and a detected signal was measured by a lock-in amplifier connected into the bias circuit. The same technique was also used for the measurements of the signal power relatively to the LO power. The absolute absorbed LO power was measured by isothermal method, which is well described in [3]. The maximum absorbed LO power, which we could obtain was 8  $\mu$ W.

## ***Results***

Mixer IV-curves are shown in Fig.3. At temperature 77 K the mixer conversion efficiency increased considerably as the voltage exceeded 30 mV. But it was accompanied with a very high output noise level, which is attributed to the instability of the resistive state in that region (this region is not shown in the figure). At higher temperatures the output noise becomes smaller, but conversion efficiency decreases. We measured the mixer conversion loss (at the intermediate frequency 450 MHz) at different temperatures, which correspond to a reasonable noise level. The minimum conversion loss was 46 dB, which could be improved by decreasing the ambient temperature, but at the cost of an increase of the output noise. Conversion loss did not depend much on the bias voltage and in a quite large voltage region conversion loss did not drop more than 2 dB. We found that with a decreasing of LO power the IF signal goes down linearly, which shows that the LO power is far from the optimum point. An increasing of the LO power can improve conversion performance of the mixer.

The IF spectrum of the mixer was measured in the range from 200 MHz to 6 GHz and the result is depicted in Fig.4. The hot-electron mode, when only the electron temperature is oscillating, is clearly observed in the range from 3 GHz to 6 GHz. The upper IF range was limited just by bandwidth of the bias-T.

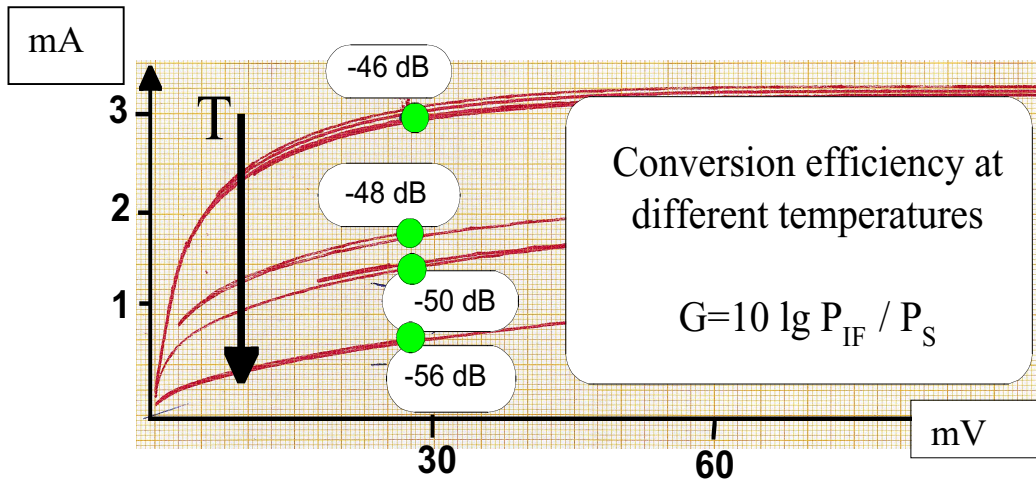


Fig.3 IV-curves of YBCO HEB mixer at different temperatures.

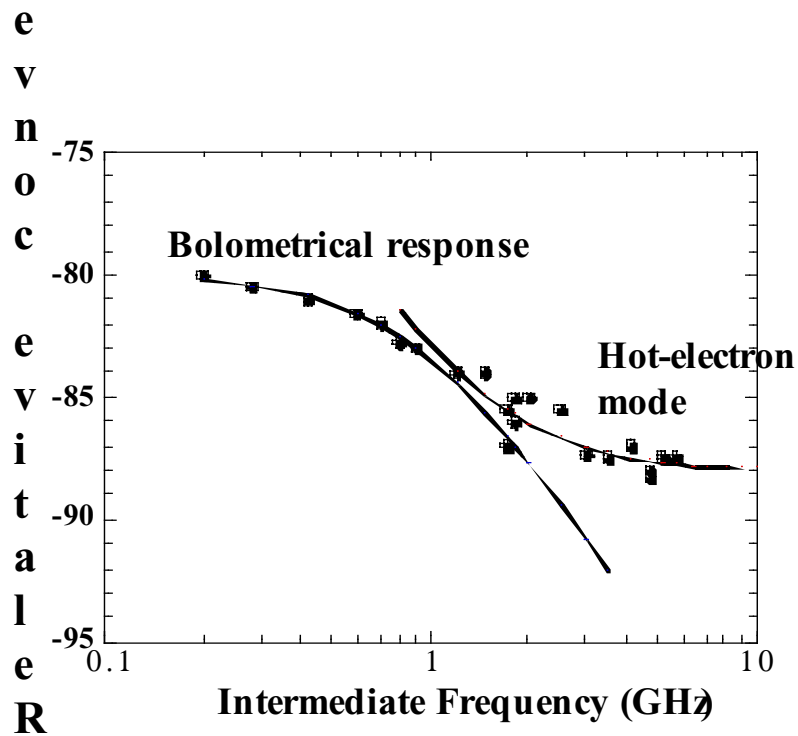


Fig.4. Intermediate frequency spectrum of YBCO HEB mixer measured at LO frequency 600 GHz.

## **Conclusion**

The mixer conversion loss 46 dB was obtained at 8  $\mu$ W LO power. The hot-electron mode in the IF spectrum, previously observed at IR range, is also observed at terahertz frequencies. The obtained results show that the YBCO HEB mixer can be used at the terahertz range.

## **References**

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