Critical Temperature Dependence of the Noise Temperature and IF Bandwidth of Superconducting Hot Electron Bolometer Mixers

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Abstract—**We present a study of the critical temperature dependence of the noise temperature and intermediate frequency (IF) noise bandwidth of superconducting hot electron bolometer (HEB) mixers. We simulate the noise temperature of a superconducting niobium nitride (NbN) HEB mixer with different critical temperatures (T_c) by a distributed hot spot model. The simulation shows that the mixer noise temperature is the lowest at T_c approximately equal to 7 K~9.5 K, and increases beyond this range due to the decrease of conversion gain or the increase of output noise. To verify this result, three superconducting HEB mixers of different critical temperatures (i.e., 7.5 K, 8.8 K and 10.3 K) are measured (at 3.5 K) at 0.85 THz and 1.3 THz. A good agreement is observed between simulation and measurement. In addition, we also study the dependence of IF noise bandwidth of superconducting HEB mixers on T_c. It appears that the larger T_c, the wider the IF noise bandwidth is.**

I. INTRODUCTION

Superconducting hot electron bolometer (HEB) mixers are presently the most competitive devices for low-noise heterodyne detection at frequencies above 1 THz [1, 2], and they are increasingly being used on space- and ground-based telescopes for radio astronomical observations [3, 4]. Superconducting HEB mixers are essentially a microbridge made of an ultra-thin superconducting film such as niobium nitride (NbN), with a typical thickness of a few nanometres. When a superconducting HEB mixer is driven to its operating point by applying terahertz radiation from a local oscillator (LO) and a direct current (dc) voltage, a "hot-spot" region will be formed in the microbridge centre with the electron temperature close to the microbridge critical temperature T_c. It is known that the performance of superconducting HEB mixers, such as noise temperature and IF noise bandwidth, is closely related to the electron temperature and the microbridge critical temperature T_c. However, the dependence of noise temperature and IF noise bandwidth of superconducting HEB mixers upon the microbridge critical temperature T_c is yet to be fully understood. In this paper, we study the critical temperature dependence of the mixing performance of a superconducting HEB mixer by a distributed hot spot model [5, 6]. We also measure the receiver noise temperature and IF noise bandwidth of three superconducting HEB mixers fabricated from different batches of NbN films and with different critical temperatures (i.e., 7.5 K, 8.8 K and 10.3 K) at 0.85 THz and 1.3 THz. A detailed comparison between simulation and measurement is then given.

II. NOISE TEMPERATURE

We first modelled the critical temperature dependence of the noise performance of a superconducting HEB mixer (at a bath temperature of 3.5 K) by a distributed hot spot model [7]. It can be seen from Fig. 1 that the input noise temperature of the superconducting HEB mixer is the lowest at T_c approximately between 7 K and 9.5 K. We attribute the degradation of mixer noise performance to the decrease of conversion gain at low critical temperatures and to the increase of output noise at high critical temperatures.

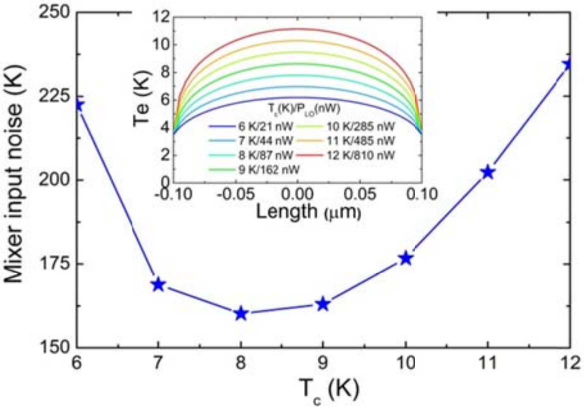

Fig. 1 Calculated input noise temperature of a superconducting HEB mixer with different T_c from 6 K to 12 K. The inset shows the calculated electron temperature profiles.

We calculated the conversion gain and output noise temperature (including Johnson noise and thermal fluctuation noise) of the superconducting HEB mixer as a function of critical temperature with a small signal model [8]. Fig. 2 shows the calculated results at the optimal bias point of the superconducting HEB mixer. Apparently, the higher critical temperature is, the higher the conversion gain and the higher the noise temperature appear. It should be pointed out that the conversion gain of the superconducting HEB mixer approaches nearly zero at critical temperatures close to the bath temperature and becomes saturated at high critical temperatures.

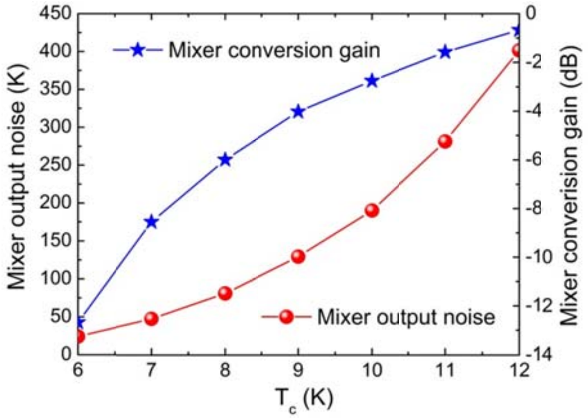

Fig. 2 Calculated output noise temperature and conversion gain of the superconducting HEB mixer as a function of critical temperature at the optimal bias point.

To compare with the predicted results, three superconducting HEB mixers with different critical temperatures (i.e., 7.5 K, 8.8 K and 10.3 K) were chosen for measurements. The inset of Fig. 3 shows the measured receiver noise temperature of the superconducting HEB mixers as a function of bias voltage. Their lowest receiver noise temperatures are about 650±50 K at 1.3 THz for mixer No. 1, 500±50 K at 1.3 THz for mixer No. 2 and 800±50 K at 0.85 THz for mixer No. 3. The uncertainty is mainly attributed to the temperature fluctuation and mechanical vibration of the 4 K cooler. In order to understand the critical temperature dependence of mixer intrinsic noise performance, we corrected the noise contributions of the quasi-optical components. Fig. 3 shows the measured input noise temperature of the superconducting HEB mixers as a function of critical temperature together with the calculated one. Clearly, the measured result is in good agreement with the calculated one. Superconducting NbN HEB mixers do have the lowest noise temperature in the critical temperature range from 7 K to 9.5 K.

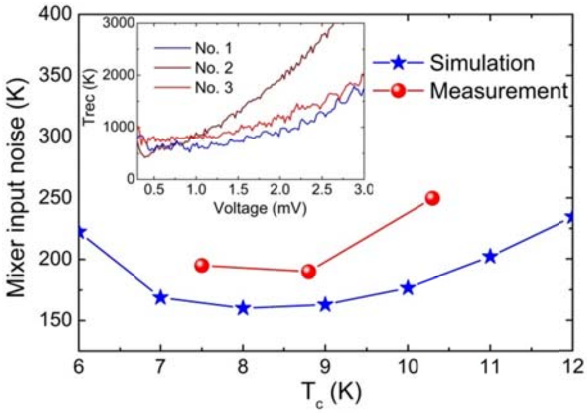

Fig. 3 Measured input noise temperature of the superconducting HEB mixers together with the calculated one. The inset shows the measured receiver noise temperature of the superconducting HEB mixers as a function of bias voltage.

III. IF NOISE BANDWIDTH

Fig. 4 shows the calculated IF noise bandwidth of the superconducting HEB mixer as a function of critical temperature. Also shown is the measured IF noise bandwidth of the three superconducting HEB mixers used above for the noise measurements. The inset of Fig. 4 shows the measured receiver noise temperature of the three superconducting HEB mixers as a function of IF frequency. It can be seen from Fig. 4 that the calculated and measured IF noise bandwidths show the same dependence on the critical temperature, i.e., the IF noise bandwidth of the superconducting HEB mixers gets wide at high critical temperatures. However, the calculated IF noise bandwidth is roughly two times higher than the measured one. We think this difference is likely due to the imperfect interface between the superconducting NbN microbridge and Au contact pads (200 nm thick) in our superconducting HEB mixers. Using a proximity effect model based on the Usadel theory [9], the interface transparency of the superconducting HEB mixers is estimated to be ~0.1 from their measured R-T curves. This estimated interface transparency is still smaller than the value of ~0.15, which is expected from the Fermi velocity mismatch using $\nu_f=1.39\times10^6$ m s^{-1} [10] for Au and $\nu_f=5.7\times10^4$ m s^{-1} [11] for a superconducting NbN film. In addition, the diffusion of hot electrons may be partly restricted due to the Andreev reflection since the energy gap of the superconducting microbridge becomes wide in the direction of heat diffusion.

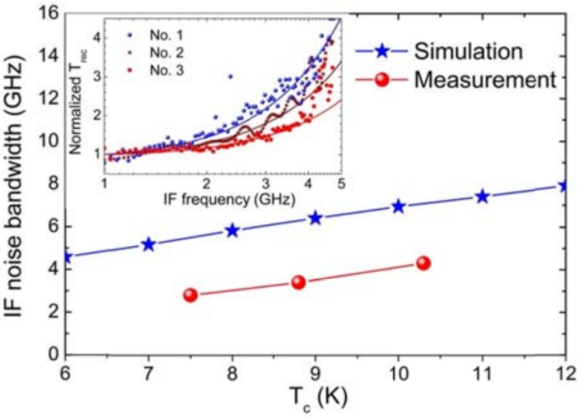

Fig. 4 Calculated and measured IF noise bandwidth as a function of critical temperature. The inset shows the measured receiver noise temperatures of the superconducting HEB mixers with different critical temperatures as a function of IF frequency. The solid lines are the fitting results using $T_{rec}\sim(1+(f/f_{IF})^2)$.

IV. CONCLUSIONS

In summary, we have studied the noise temperature and IF noise bandwidth of superconducting NbN HEB mixers with different critical temperatures by a distributed hot spot model. The modelling has shown that superconducting HEB mixers have the lowest noise temperature when their critical temperature is in the range from 7.0 K to 9.5 K, and the IF noise bandwidth of superconducting HEB mixers gets wide due to the reduction of phonon cooling time and diffusion cooling time at high critical temperatures. We have also measured the noise performance of three superconducting HEB mixers with different critical temperatures at 0.85 THz and 1.3 THz. A good agreement has been observed between modelling and measurement.

ACKNOWLEDGMENT

We acknowledge G.N. Gol'tsman and B. Voronov of MSPU for providing superconducting NbN films. This work was supported by CAS under Grant No. XDB04010300, NSFC under Grant Nos. 11127903, 11190012, and 11473075, and the CAS Joint Key Lab for Radio Astronomy.

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