Performance Investigation of a Quasi-Optical NbN HEB Mixer at Submillimeter Wavelength

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***Abstract*—In this paper, the performance of a quasi-optical phonon-cooled NbN superconducting hot electron bolometer (HEB) mixer is thoroughly investigated. The variation of the receiver noise temperature and the conversion gain around 600 GHz with respect to DC bias voltage and LO pumping level has been measured. The lowest receiver noise temperature is 750 K and reduced to about 250 K after correcting the quasi-optical losses before the HEB mixer. We compared the measured results with the predictions according to one dimensional distributed hot spot model. A reasonable match between theoretical model and experiment is observed. In addition, the direct response of the HEB mixer (integrated with a log-periodic spiral antenna) is measured by using Fourier Transform Spectrometer (FTS). The stability of the receiver is also investigated by means of Allan variance time measurements performed with an intermediate frequency (IF) bandwidth of 40 MHz.**

***Index Terms*—NbN HEB mixer, noise temperature, conversion gain, frequency dependent response, stability.**

I. INTRODUCTION

EXPLORING the terahertz (THz) frequency range is crucial for astronomy since a wealth of spectral lines from molecules providing important information of planet and star formation fall into this range [1]. Detectors of high sensitivity and good stability are necessary to observe efficiently these spectral lines since the astronomical signals are generally very weak. Among all detectors available today, superconducting hot electron bolometer (HEB) mixers [2] have been proved to be the most competitive devices of coherent detection in the THz frequency range. Space or ground based projects such as TREND [3] and HIFI [4] have selected superconducting HEB mixers. In this paper, we have thoroughly investigated the DC characteristics and the noise performance around 600 GHz of a quasi-optical NbN superconducting HEB mixer through experiments and modeling. The receiver stability is also studied by measuring the Allan variance time at the LO frequency of 600 GHz.

II. HEB MIXER AND EXPERIMENTAL SETUP FOR HETERODYNE MEASUREMENT

The quasi-optical phonon-cooled NbN superconducting HEB mixer was fabricated in Moscow State Pedagogical University (MSPU). The HEB mixer itself is indeed a microbridge made up of an extremely thin superconducting NbN film deposited on a thick silicon substrate by DC reactive magnetron sputtering. The superconducting NbN microbridge is 0.15 μm long, 2.4 μm wide and 3.5 nm thick and is placed between the feed point of a log-periodic spiral antenna which couples RF and LO signals to the HEB mixer.

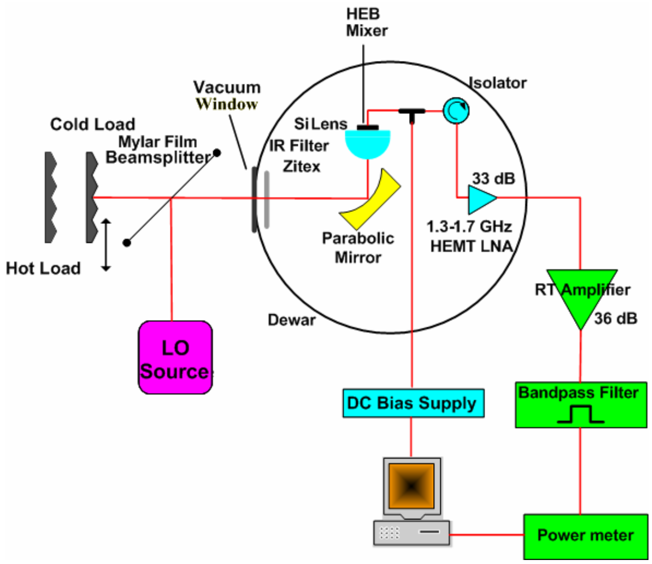

Fig. 1. Schematic diagram of the heterodyne measurement setup.

Heterodyne characterization of the quasi-optical superconducting HEB mixer was performed at frequencies near 600 GHz. The experimental setup is shown in Fig. 1. The HEB device was glued on the centre of a silicon hyper-hemispherical lens with a diameter of 12.7 mm, and then mounted in a copper mixer block fixed on the 4-K cold plate of the cryostat. The 600 GHz LO source is provided by a solid state source (Gunn oscillator and frequency multiplier). The LO and RF (hot or cold blackbody) signals are combined by a beamsplitter made of a 25 μm thick Mylar film, and then transmitted into the cryostat through a vacuum window (25 μm thick Mylar film) and an IR filter (Zitex G110). For signal focusing, a parabolic reflection mirror is situated in front of the mixer block on the plate of the cryostat. The HEB mixer's IF output signal is

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connected to a 0.1-10 GHz bias-tee, a 1.3-1.7 GHz cooled low noise HEMT amplifier (of 33 dB gain and 5 K noise temperature), a 36 dB gain room temperature amplifier, a 1.5 ± 0.02 GHz YIG bandpass filter, and finally detected by a power meter.

III. EXPERIMENT AND ANALYSIS

A. *Current-voltage characteristics*

We first measured the current-voltage characteristics of the HEB mixer for different LO pumping levels, as shown in Fig. 2. The critical current of this HEB device is about 80 μA. Fig. 2 also shows the current-voltage characteristics calculated by one dimensional distributed hot spot model [5], which is based on solving a heat balance equation for electron temperature along the superconducting microbridge. In this model, we adopted the measured temperature dependent resistance of the HEB device instead of a Fermi form assumption [6] to determine the resistance of the device. The effect of bias current on the critical temperature of the HEB is also taken into account as expressed by equation (1) [7]:

$$T_c(I_0) = (1-(I_0/I_c)^{1/\gamma})T_c(0) \qquad (1)$$

where I_0 and I_c are respectively the bias and the critical current of the device at $T=0$ K. γ is the exponent of the temperature dependence of the superconductor band gap and is estimated to be 0.8 for our HEB according to the measurement of the temperature dependent resistance at several bias currents, as shown in Fig. 3.

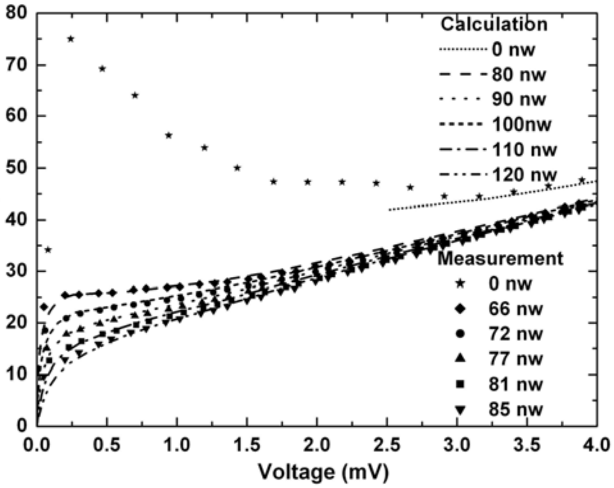

Fig. 2 I(V) curves of the HEB mixer for different LO heating powers.

According to Fig. 2, it is clear that the computed current-voltage characteristics are in good agreement with the measured ones over the whole bias range. Note that the measured LO power is determined by the isothermal technique. We attribute the difference between the predicted and measured LO power absorbed by the microbridge to imperfections of the isothermal technique, which is based on a lumped element model and is not capable of distinguishing the DC bias heating efficiency from that of LO power.

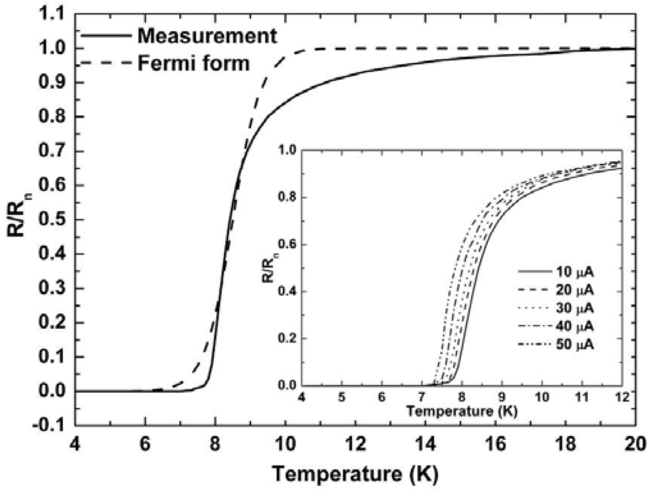

Fig. 3 R-T (resistance-temperature) curve of the NbN HEB mixer. The inset shows the effect of bias current on R-T curve.

B. *Noise temperature and conversion gain*

The receiver noise temperature T_{rx} of the HEB mixer was obtained from conventional Y-factor measurement using a room-temperature (295 K) and a cold (77 K) blackbody as input signal source. Fig. 4 shows the measured DSB receiver noise temperature at the optimal LO pumping level (66 nw) over the whole bias range of interest. Biased at 0.8 mV and 26 μA, the HEB mixer demonstrates a lowest DSB receiver noise temperature of 750 K. After correcting the noise contributions of the quasi-optical components, we found that the lowest noise temperature was reduced to 250 K. The conversion gain G_{mixer} of the same mixer was characterized by U-factor method. The U factor is defined as the ratio of the IF output powers at the operating bias and the zero dc bias without LO pumping, and is given by

$$U = \frac{P_{295}}{P_{sc}} = \frac{2(T_{295}+T_{rx})}{(T_{bath}+T_{if})}G_{total} \qquad (2)$$

where T_{295} and T_{bath} are the effective radiation temperatures determined from their own physical temperatures by the Callen-Welton formulation, T_{if} is the equivalent input noise temperature of the IF chain (assumed to be 10 K), and G_{total} is the total conversion gain of the receiver. By reducing the contributions of the quasi-optical components (- 3.8 dB in our case) from G_{total}, the conversion gain of the NbN HEB mixer can be obtained. We compared the measured results with the predictions by one dimensional distributed hot spot model, and found that predicted conversion gains are about 3.5 dB higher than the measured ones (inset of Fig. 5) while similar trend is observed. This result implies that the hot spot model would have overestimated the IF current ΔI produced by incident signals and there would be some still unknown intrinsic losses of the HEB mixer or unconsidered losses in the IF circuit [8]. Here we introduced a tuning factor of 0.65 to the IF current ΔI in the hot spot model, and the computed conversion gains are found in better agreement with the measurements over the whole bias range (see Fig. 5).

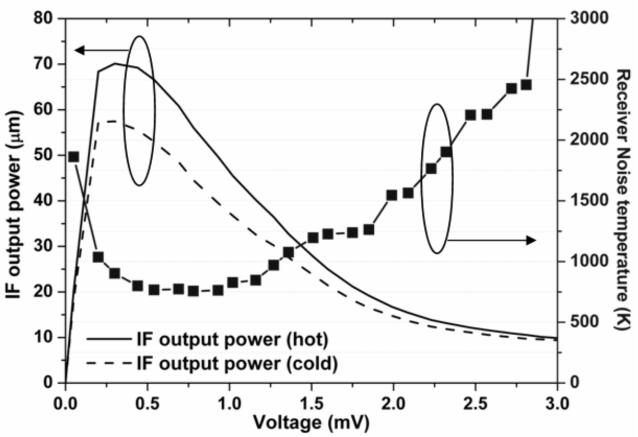

Fig. 4 Measured IF output powers responding to the hot and cold load (left axis) as well as the DSB receiver noise temperature (right axis) at the optimal LO pumping level for different bias voltages.

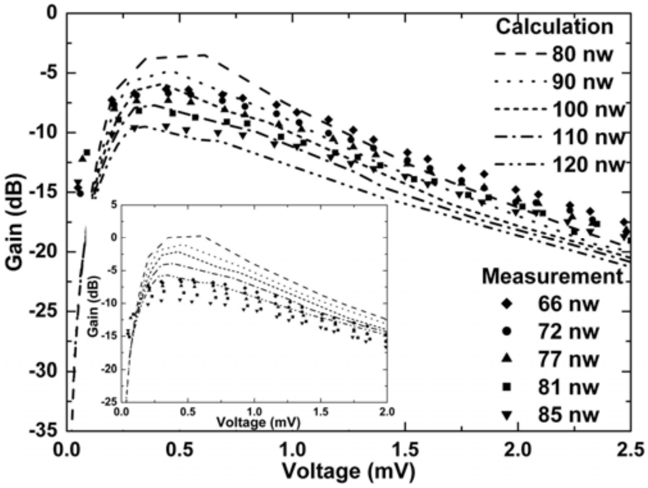

Fig. 5 Conversion gains of the HEB mixer for different bias voltages and LO pumping levels. The inset shows the calculated conversion gains without applying the tuning factor of 0.65.

C. *Direct response*

To get the direct response of the quasi-optical HEB mixer, Fourier Transform Spectrometer (FTS) measurement is performed when the HEB mixer is heated to its resistive state. The FTS measurement system consists of a Michelson interferometer with a chopped Hg lamp providing broadband THz radiation. The cryostat is placed in front of the FTS output and the biased signal of the HEB is connected to a lock-in amplifier that was synchronized with the chopper. The FTS system is operated in a step and integration mode. Performing the Fourier transform on the measured interferogram would give us the frequency spectrum. In this measurement, the maximum span and the minimum step size of the movable mirror was chosen to be 15 mm and 50 μm, which gives a frequency resolution of 10 GHz and a frequency range of 1.5 THz, respectively. Fig. 6 shows the normalized spectrum response of the mixer. We find that the direct response of the HEB mixer is in the frequency range from 200 to 1000 GHz. For frequencies higher that 1000 GHz, the response of the HEB mixer becomes weak due to the strong absorption by water (dash line in Fig. 6) although the log-periodic spiral antenna (originally designed for the 850 GHz band) should operate in that frequency region.

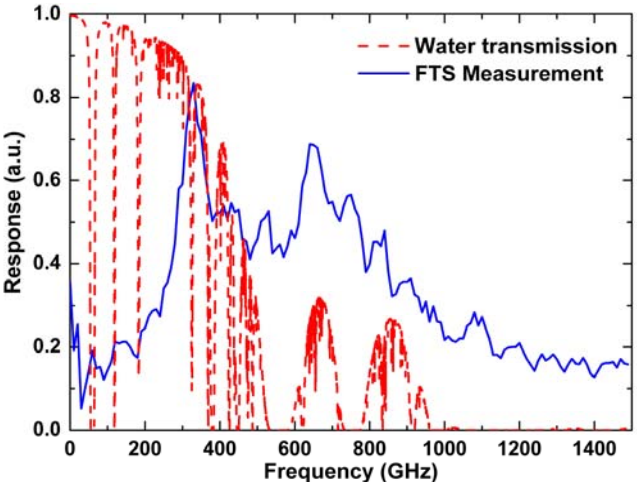

Fig. 6. Frequency dependent response of the quasi-optical HEB mixer.

D. *Stability*

One of the important parameters for heterodyne receivers is the receiver stability. A general method to determine the receiver stability is to measure so called Allan variance as a function of integration time. In order to obtain the Allan variance plot, we sampled the IF output power of the HEB mixer at the rate of 100 readings per second. Note that the IF output power of the HEB mixer is filtered by a YIG filter with a 40 MHz bandwidth centered at 1.5 GHz. According to the well known radiometer equation [9], the effective bandwidth determines the contribution of the white noise, and consequently determines the Allan variance time. Fig. 7 shows the Allan variance plot of the HEB mixer. In this case, the HEB mixer was biased at its optimum operating point and the IF output power used to obtain the Allan variance plot has been divided by its mean value. According to Fig. 7, the minimum Allan variance is on the order of 10^{-6} and the Allan variance time is about 0.3 s, which is close to published results [10].

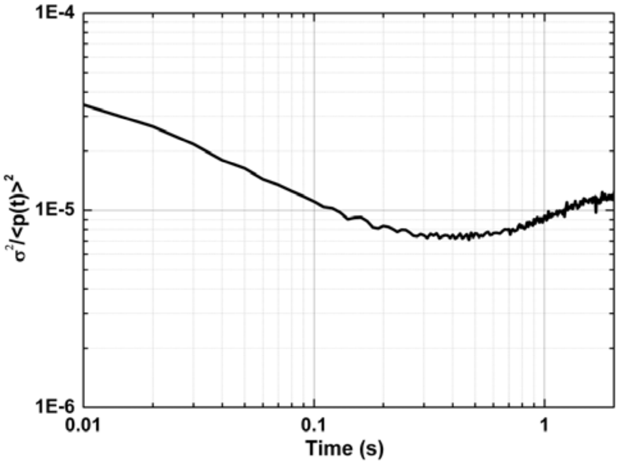

Fig. 7. Allan variance of the quasi-optical HEB mixer when it was biased at its optimum operating point.

IV. CONCLUSION

We have thoroughly investigated the performance of a quasi-optical phonon-cooled NbN superconducting HEB mixer. The measured lowest DSB receiver noise temperature is 750 K at 600 GHz, and down to 250 K after correcting the noise contributions of the quasi-optical components. Compared to the predictions by hot spot modeling, a good agreement has been observed with respect to current-voltage characteristics and conversion gains of the HEB mixer. In addition, the direct response of the HEB mixer has been investigated by means of FTS measurement and is found to be in the frequency range from 200 to 1000 GHz. The stability of the HEB mixer has also been studied and the Allan variance time is about 0.3 s.

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