Development of a Quasi-Optical NbN Superconducting HEB Mixer

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Abstract—**In this paper, we report the performance of a quasi-optical NbN superconducting HEB (hot electron bolometer) mixer measured at 500 and 850GHz. The quasi-optical NbN superconducting HEB mixer is cryogenically cooled by a 4-K close-cycled refrigerator. Measured receiver noise temperature at 850 and 500GHz are 3000K and 2500K respectively with wire grid as beamsplitter, while the lowest receiver noise temperature is found to be approximately 1200K with Mylar film. The theoretical receiver noise temperature (taking into account the elliptical polarization of log-spiral antenna) is consistent with measured one. The receiver noise temperature and conversion gain with 15-μm Mylar film as the beamsplitter at 500GHz are thoroughly investigated for different LO pumping levels and dc biases. The stability of the mixer's IF output power is also demonstrated.**

***Index Terms*—Close-cycled 4K refrigerator, NbN HEB mixers, wire grid, elliptical polarization, U-factor**

I. Introduction

Superconducting HEB mixers have demonstrated good performance at terahertz frequencies. The DSB noise temperature of phonon-cooled superconducting HEB mixers is approaching eight times the quantum limit ($8h\nu/k$) [1] and the required LO power is as low as one microwatt. Some ongoing projects (including ground-based TREND [2], airborne SOFIA [3], and spaceborne Herschel [4]) will benefit from the technology of superconducting HEB mixers.

To suit long-period operations such as astronomical and atmospheric observations, it is of particular interest to investigate the behaviors of superconducting HEB mixers cooled by a close-cycled 4-K refrigerator. It has been indeed demonstrated that phonon-cooled NbN superconducting HEB mixers can survive such a cooling circumstance [5]. In this paper, a quasi-optical NbN superconducting HEB mixer is measured at 500 and 850GHz with a close-cycled 4-K refrigerator. The theoretically calculated receiver noise temperature as a function of the wire angle of wire grid was in good agreement with the measured one due to the elliptical polarization of log-spiral antenna [6]. Its performance is thoroughly investigated for different LO pumping levels and dc biases at 500GHz. In addition, the stability of IF output power of the quasi-optical NbN superconducting HEB mixer is examined.

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II. Measurement Setup

As shown in Fig. 1, the quasi-optical NbN superconducting HEB mixer measured is made up of a log spiral antenna and an ultra-thin NbN film bridge across the antenna's feed point. The log spiral antenna couples the RF and LO signals to the thin NbN film bridge, where mixing happens via some heat exchanges between electron and phonon. The thin NbN film, measuring about 3.5-nm thick, was deposited by dc magnetron sputtering on a heated high resistivity silicon substrate, while its bridge area, measuring 0.2-μm long and 2.4-μm wide, was fabricated through e-beam lithograph. The thin NbN film bridge had a normal resistance of 100 Ω and a critical current of 190 μA at 4.2 K. And its critical temperature and transition width were 9.6 K and 0.9 K, respectively.

The quasi-optical NbN superconducting HEB mixer was firstly glued onto a hyper-hemispherical silicon lens (of a diameter 12.7 mm, with no anti-reflection layer). The silicon lens with the superconducting HEB mixer was then put into a copper mixer block, which includes a 50-Ω microstrip line with its one port connected to the HEB mixer chip (via Indium)

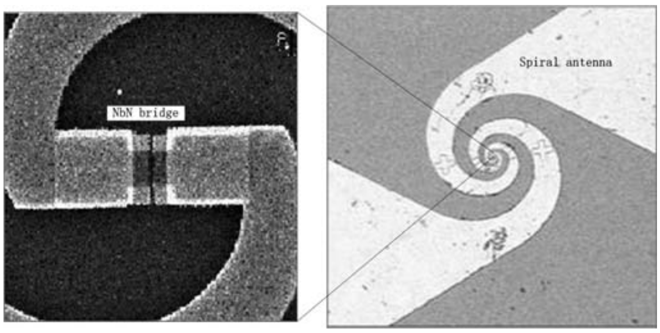
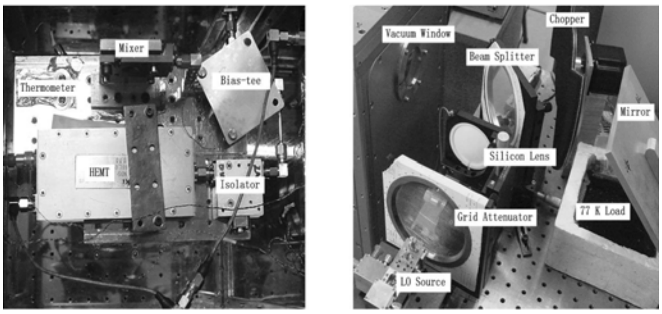


Fig. 1 Photograph of a quasi-optical NbN superconducting HEB mixer chip. The NbN bridge measures 2.4-μm wide, 0.2-μm long and 3.5-nm thick.



(a) (b)

Fig. 2 Photograph of the measurement setup, with (a) inside the cryostat and (b) outside view.

and the other to the IF&DC output port. The whole mixer was mounted onto the 4-K cold plate of the close-cycled cryostat (as shown in Fig. 2a).

We used the conventional Y-factor method to measure the noise performance of the quasi-optical NbN superconducting HEB mixer. The measurement setup is shown in Fig. 2b. A beam splitter made of a 15-μm thick Mylar film or wire grid couples the RF signal from a chopper (indeed a 295-K and 77-K blackbody) and the LO signal from a 850-GHz BWO or 500-GHz solid state source (Gunn plus x6 multiplier). The RF and LO signals are incident onto the hyper-hemispherical silicon lens through a vacuum window (100-μm Mylar film on the 300-K shield of the close-cycled cryostat) and an IR filter (two layers of Zitex G108 on the 40-K shield). The hyper-hemispherical lens focuses the RF and LO signals to the HEB mixer chip. The IF output signal goes through a bias-tee, a 1.2-1.8 GHz cooled HEMT low noise amplifier (including an isolator on the 4-K cold plate), a room-temperature amplifier (45-dB gain), a bandpass filter (1.55±0.085 GHz), and is finally detected by a square-law detector of a sensitivity of 1 mV/μW.

III. MEASUREMENT RESULTS

3.1 Noise temperature at 850GHz with BWO

Since the output power of our BWO at 850 GHz was too small to pump the I-V curve, we chose wire grid (fabricated from tungsten with wire diameter and space of 10 μm and 25 μm respectively) as beamsplitter to measure the receiver noise temperature. The measured optimal DSB receiver noise temperature was 3000K at the point 0.75mV and 36μA (shown in Fig. 3). During the experiment we found that the IF output power was not so stable, so we measured the correlation between the IF output power and BWO cathode voltage by measuring the voltage across a 500-Ω resistor in series with BWO (shown in Fig. 4). The IF output power is in good agreement with the voltage across the 500-Ω resistor in series with BWO during the period of 10 minutes, which led us to measure the receiver noise temperature at 500GHz.

3.2 Noise temperature at 500GHz with wire grid as beamsplitter

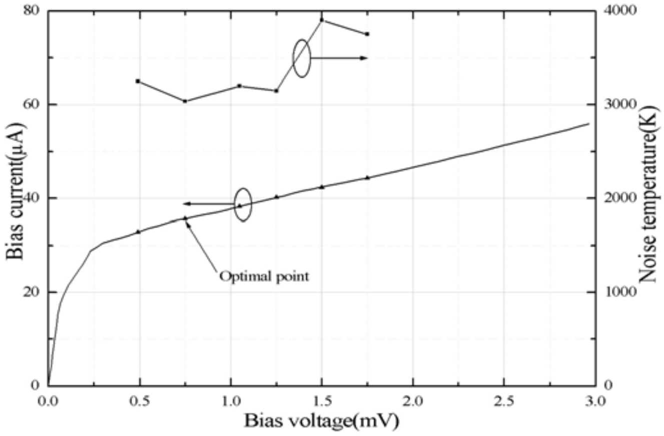


Fig.3 Measured receiver noise temperature along the optimal I-V curve at 850GHz

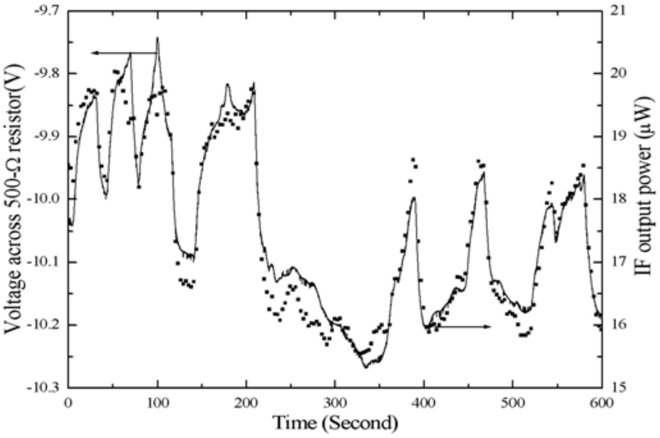


Fig.4 Dependence of IF output power on the voltage cross the 500Ω resistor in series with BWO.

Then we measured the receiver noise temperature at 500GHz with solid-state source (gun oscillator plus 6x multiplier) as LO source. The measured DSB receiver noise temperature T_{rec} at 500 GHz for different wire angles at the same bias point (V_{bias} =0.87 mV and I_{bias}= 38 μA) is exhibited in Fig. 5. The lowest receiver noise temperature of 2700K was obtained when the wire angle was tuned to -50 degree (i.e., counterclockwise from the vertical direction), and T_{rec} deteriorated drastically with the increment of the wire angle. It had been demonstrated that the log-spiral antenna integrated with hyper-hemispherical lens was elliptical polarization. There was an angle of about 25 degree between the line along the tapered section of the antenna and the long axis of the elliptical polarization, and the axis ratio was 1.3 and 3 at 1.4 and 2.5 THz, respectively [6]. Given the fact that the position of our HEB mixer was clockwise tilted about 15 degree from vertical direction due to not so good alignment, measured results were consistent with polarization of log-spiral antenna. Assumed that the axis ratio of elliptical polarization of log-spiral antenna is 1.25 at 500GHz and the long axis is 40 degree clockwise from the vertical direction, we theoretically calculated the receiver noise temperature. The Y factor is given by the following formula

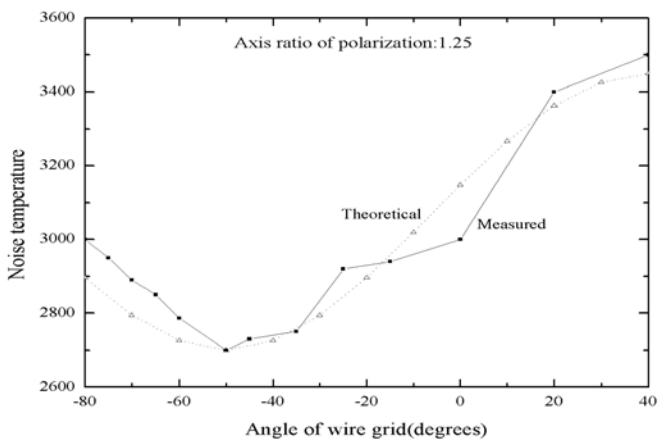


Fig. 5 Measured and theoretical receiver noise temperature

$$Y=\frac{(300+T_m)*S*A+300*R*B}{(77+T_m)*S*A+300*R*B}=\frac{300+T_m+300*R/S*B/A}{77+T_m+300*R/S*B/A} \qquad (1)$$

where T_m is the equivalent input noise temperature, S and R are the transmission and reflection coefficient of wire grid (S=R=0.5), while A and B are the coupling coefficient of transmitted (E field vertical to wire) and reflected (E field parallel to wire) load signal due to elliptical polarization of log-spiral antenna. So the measured receiver noise temperature T_{rec} is given by

$$T_{rec}=\frac{300-77*Y}{Y-1}=T_m+300*R/S*B/A=T_m+300*B/A \qquad (2)$$

The contribution of LO chain to the total receiver noise temperature (300*B/A) is between 240 and 375K while the wire grid was rotated, which cannot be neglected as thin Mylar film as beamsplitter (~30K) [7].

The noise temperature after correcting the loss of wire grid and polarization influence of log-spiral antenna can be given

$$T_{mr}=T_m*0.5*A \qquad (3)$$

The lowest noise temperature after such correction is 1230K at the direction when transmitted E field signal can be optimally coupled to HEB mixer (i.e. wire vertical to the long axis of elliptical polarization), which should be constant. The theoretical receiver noise temperature is also shown in Fig. 5, which is consistent with measured one.

3.3 Noise temperature at 500GHz with 15-μm thick Mylar film as beamsplitter

In order to improve the transmission coefficient of beamsplitter and reduce the contribution of LO chain to the total receiver noise temperature, we replaced the wire grid with 15-μm thick Mylar film to measure the receiver noise temperature (DSB, T_{rec}) of the quasi-optical NbN superconducting HEB mixer for different LO pumping levels and dc biases. The measurement results (with no corrections) are plotted in Fig. 6a. Obviously, the lowest receiver noise temperature in the stable region appears 1200 K at 500 GHz (biased at 0.7 mV and 25 μA) and the area giving similar noise performance is quite large. The LO power absorbed by the HEB device was estimated to be 366 nW by an isothermal

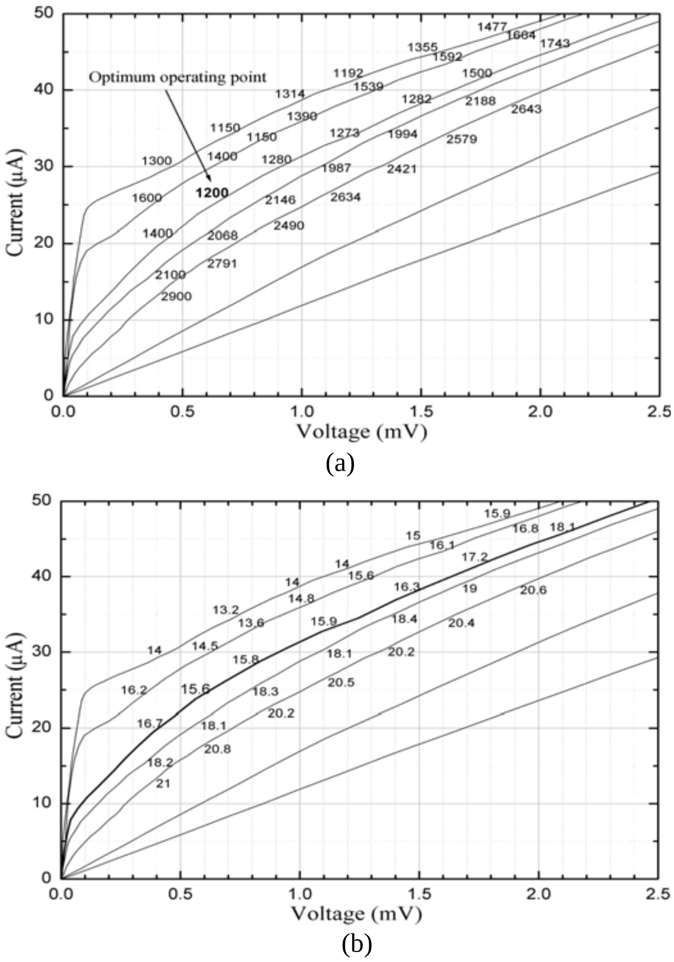


Fig. 6 Uncorrected receiver noise temperature (a) and conversion loss (b) for different LO pumping levels and dc biases.

technique [8]. At the optimal point we also measured noise temperature with wire grid as beamsplitter (as shown in Tab.1), the corrected noise temperature with wire grid is the same as that with Mylar film after correction the contribution (300*R/S) of LO chain and the influence of transmission coefficient (S) of beamsplitter, where we ignored the effect of elliptical polarization of log-spiral antenna since it's too small.

We also evaluated the total conversion loss (L_{total}) of the quasi-optical NbN superconducting HEB mixer using a U-factor technique [9]. This U-factor technique assumes that HEB devices in the superconducting state have a zero IF impedance at zero dc bias. With this assumption, the U-factor, defined as a ratio between the IF output powers at its operating point (P_{295}) and zero dc bias (P_{sc}), is written as

$$U=\frac{P_{295}}{P_{sc}}=\frac{T_{295}+T_{rec}}{T_{bath}+T_{if}}\frac{2}{L_{total}} \qquad (4)$$

where T_{295} and T_{bath} are effective radiation temperatures derived from Callen-Welton formula for the physical temperatures of 295 K and 4.2 K at the measurement frequency, respectively, and T_{if} is the equivalent input noise temperature of the IF chain (assumed to be 20 K here). The total conversion loss is therefore given by

$$L_{total} = \frac{2(T_{295} + T_{rec})}{U(T_{bath} + T_{if})} \quad (5)$$

Fig. 6b shows the calculated mixer conversion losses (with no corrections) of the quasi-optical NbN superconducting HEB mixer corresponding to different LO pumping levels and dc biases.

Tab.1 Comparison of noise temperature with wire grid and Mylar film

Beam Splitter	Trans. &Ref.	T_{rec}	Contribution of LO chain	T_m	Corrected T_m
Wire grid	0.5,0.5	2500	300	2200	1100
Mylar	0.96,0.04	1200	12.5	1187.5	1140

Tab. 2 Loss and equivalent noise temperature of the quasi optical components.

Component	Loss (dB)	Physical Temp. (K)	Noise Temp. (K)
Beam splitter	0.2	295	14.5
Vacuum window	1.25	295	102.4
Zitex filter	0.2	40	2
Si lens, reflection	1.55	4	7.7
Si lens, absorption	0.1	4	
Lens antenna	0.5	4	

To understand how good the intrinsic performance of the quasi-optical NbN superconducting HEB mixer is, we calculated or estimated the losses and noise contributions of individual quasi-optical components. The results are summarized in Tab. 2. Clearly the vacuum window has considerable loss and noise contribution. We indeed found that after correcting the losses and noise contributions of individual components before the quasi-optical NbN

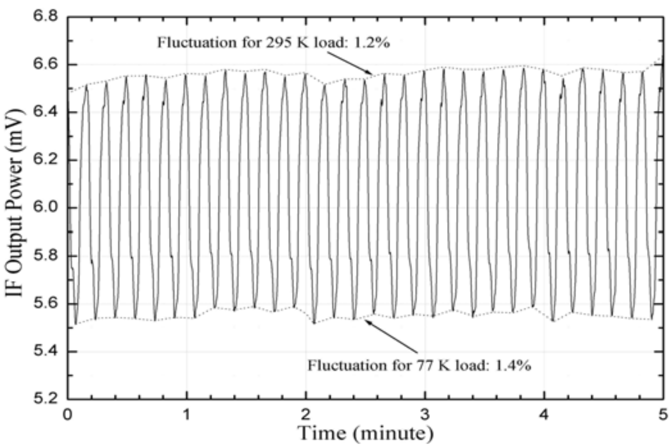


Fig. 7 Measured IF output power for a 295-K and 77-K load chopped at 0.1 Hz.

superconducting HEB mixer, the lowest receiver noise temperature was only 445 K.

Finally, we studied the stability of IF output power of the quasi-optical NbN superconducting HEB mixer cooled by a 4-K close-cycled refrigerator. We recorded the IF output power when doing the Y-factor measurement. As displayed in Fig. 7 (for 5 minutes), it is rather stable, giving fluctuation of 1.2% for the 295-K load and 1.4% for the 77-K load.

IV. Conclusion

We have investigated the performance of a quasi-optical NbN superconducting HEB mixer at 500 and 850GHz, when it is cooled by a 4-K close-cycled refrigerator. The lowest receiver noise temperature was 3000K with wire grid as beamsplitter at 850GHz. The theoretical total receiver noise temperature was in good agreement with measured one at 500GHz for different wire grid angles. The lowest receiver noise temperature is about 1200 K and 2500K with no correction corresponding to Mylar film and wire grid as beamsplitter at 500GHz, while they are coincident after correcting the contribution of LO chain and the influence of transmission coefficient of beamsplitter. This HEB mixer demonstrates a fairly large range of good mixer performance for both LO pumping and dc bias. The corrected receiver noise temperature was reduced to 445 K after correcting the losses and noise contributions of individual components before the HEB mixer. Furthermore, this HEB mixer exhibits fairly good stability even working with a close-cycled cryocooler. It will be very beneficial to real applications.

V. Acknowledgement

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References

[1] J. J. A. Baselmans, M. Hajenius, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov and G. Gol'tsman, "Doubling of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers," *Applied Physics Letts.*, Vol. 84, No. 11, pp. 1958-1960, 2004.

[2] K.S. Yngvesson, C. F. Musante, M. Ji, F. Rodriguez, Y. Zhuang, E. Gerecht, M. Coulombe, J. Dickinson, T. Goyette, J. Waldman, C. K. Walker, A. Stark, and A. Lane, "Terahertz receiver with NbN HEB device (TREND)-A low-noise receiver user instrument for AST/RO at the south pole," *Proc. of 12th International Symposium on Space Terahertz Technology*, San Diego, pp. 262-285, 2001.

[3] H.-W. Huebers, A. Semenov, J. Schtibert, G. Gol'tsman, B. Vornov, E. Gershenzon, A. Krabbe, and H. P. Roser, "NbN hot electron bolometer as THz mixer for SOFIA," *Proc. SPIE vol. 4014 (Airborne Telescope Systems)*, pp. 195-202, March 2000.

[4] Th. de Graauw and F. P. Helmich, “Herschel-hifi: the heterodyne instrument for the far-infrared,” *Proc. of Symposium “The Promise of the Herschel Space Observatory,”* Toledo, Spain, December 2000.
[5] L. Jiang, J. Li, W. Zhang, Q. J. Yao, Z. L. Lin, S. C. Shi, Y. B. Vachtomin, S.V. Antipov, S. I. Svechnikov, B. M. Voronov and G. N. Goltsman, “Characterization of NbN HEB mixers cooled by a close-cycled 4 Kelvin refrigerator,” *IEEE Trans. Appl. Supercond.,* June 2005, in press.
[6] P. Yagoubov, W. –J. Vreeling, and P. de Korte, “Characterization of an integrated lens antenna at terahertz frequencies,” *Proceedings of 12th International Symposium on Space Terahertz Technology*, San Diego, pp. 193-204, 2001.
[7] Goutam Chattopadhyay, Frank Rice, David Miller, Henry G. LeDuc and Jonas Zmuidzinas, “A 530-GHz balanced mixer,” IEEE microwave and guide wave letters, vol.9, No. 11, pp.467-469, Nov. 1999.
[8] G.N. Gol’tsman et al, “NbN hot electron superconducting mixers for 100 GHz operation,” *IEEE Trans. Appl. Supercond.*, vol. 5, March 1995.
[9] S. Cherednichenko et al, “1.6 THz heterodyne receiver for the far infrared space telescope,” *Physica C: Superconductivity and its Applications*, 372-376:427-431, 2002.