Low Noise Terahertz Receivers Based on Superconducting NbN Hot Electron Bolometers

J. Chen, *Senior Member, IEEE,* L. Kang, M. Liang, J. P. Wang, and P. H. Wu*, *Senior Member, IEEE*

***Abstract*—Low noise terahertz (THz) receivers based on superconducting niobium nitride (NbN) hot electron bolometer (HEB) mixers have been designed, fabricated and measured for applications in astronomy and cosmology. The NbN HEB mixer consists of a planar antenna and an NbN bridge connecting across the antenna's inner terminals on high-resistivity Si substrates. Double sideband (DSB) receiver noise temperatures of 698 K at 0.65 THz, 904 K at 1.6 THz, 1026 K at 2.5 THz and 1386 K at 3.1 THz have been obtained at 4.2 K without corrections and using changeable input local oscillation (LO) power to eliminate the affects of direct detection and instability of the LO power. The excess quantum noise factor β of about 4 has been estimated using a quantum noise model.**

***Index Terms*—hot electron bolometers (HEBs), quasi-optical superconducting heterodyne mixer, terahertz (THz), receiver noise temperature.**

I. Introduction

LOW noise receivers working at terahertz (THz) frequencies are very important for many applications and basic researches [1]. Due to the lack of high quality amplifiers at such high frequencies, the front end of a THz receiver is usually a mixer whose noise and conversion performances play the key role in determining the quality of the whole system. Below 1.4 THz, Superconductor-Insulator-Superconductor (SIS) mixers exhibit noise temperatures quite close to the quantum limit T_Q=hf/k$_B$ (where h is the Planck constant, k$_B$ is the Boltzmann constant and f is the operating frequency) [2, 3], while for operating frequencies higher than 1.4 THz, superconducting Hot Electron Bolometer (HEB) heterodyne mixers have higher sensitivity and require less local oscillation (LO) power [4-9]. Typically an HEB mixer consists of two parts, a bolometer for mixing the signal with the LO and a planar antenna for coupling both of them into it. It can be expected that superconducting HEB mixers will be used widely at THz waveband in the near future. Here, the fabrication and properties of low noise receivers based on niobium nitride (NbN) HEB mixers at THz frequency band are reported.

Manuscript received 20 April 2009. This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grants 10778602, 60721063, the National Basic Research Program of China (973 Program) under Grants 2006CB601006, 2007CB310404 and National High-tech R&D Programmer of China under Grant 2006AA12Z120.

J. Chen, L. Kang, M. Liang, J. P. Wang, P. H. Wu, are with the Research Institute of Superconductor Electronics (RISE), Department of Electronic Science & Engineering, and National Laboratory of Nanjing Microstructures, Nanjing University, Nanjing 210093, P. R. China (*corresponding author to provide phone: 86-25-83594540; fax: 86-25-83686680; e-mail: phwu@nju.edu.cn).

II. Experiments and Results

We use NbN films to make the devices. The films should be thin enough to increase the gain bandwidth of the receivers but remarkable suppression of Tc always accompanies reduction of film thickness when films are about or less than Bardeen-Cooper-Schrieffer (BCS) coherence length ξ_0。 Thus the fabrication of such films is crucial. Here the superconducting NbN film is deposited by DC magnetron sputtering on high-resistivity (> 5 kΩcm) Si substrate in Ar+N_2 gas mixture with the substrate kept at room temperature (RT) [10]. Fig. 1 shows an atomic force microscopy (AFM) image of a 4.5-nm thick NbN film sample on Si substrate. A root-mean-square (RMS) roughness of about 0.42 nm is obtained over an area of 5 μm squared, indicating that the film is of high quality with rather smooth surface. And the excellent interlayer growth between the film and the substrate can be confirmed by the transmission electron microscopy (TEM) observations. T_c of about 9 K and critical current density (J_c) of about 1.5×10^6 A/cm^2 at 4.2 K have been obtained for such ultra-thin films. When the small bridge made of the ultra-thin superconducting film is irradiated with THz photons, the electrons inside will be heated up (so called hot electrons) and the energy will subsequently relax to the substrate through the electron-phonon interaction [4,5].

The NbN HEB mixer consists of a complementary logarithmic-spiral antenna made of gold and an NbN film (bridge) connecting across the antenna's inner terminals. The outer diameter of the antenna should be larger than λ_{0max}/4 and inner diameter be smaller than λ_{0min}/20, where λ_{0max} and λ_{0min} are the maximum and minimum wavelengths in the free space respectively [11]. During the fabrication, NbN thin film is first deposited. It is then covered by photoresist. Two square

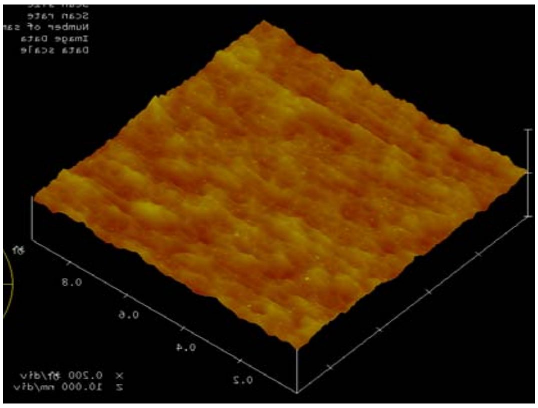


Fig. 1. AFM imaging of a 4.5-nm thick NbN film on Si substrate.

openings are positioned on the photoresist through which an additional NbN layer about 10 nm thick is deposited after a 10 s argon ion etching. Finally gold is deposited. The two square openings, with a preset distance between each other, are used to help maintain the desirable length of the bridge while the additional NbN is used as a buffer so that the superconductivity of the bridge underneath will not be seriously degraded by the gold contact [8]. The superconducting NbN HEB bridge is fabricated by electron-beam (EB) lithography, while the gold antenna defined by photolithography on Si substrate.

The NbN HEB mixer used in the experiments to be reported here is 3.5-4 nm thick, 3-4 μm wide and 0.4 μm long. Its T_c is about 8 K and ΔT_c is about 1.3 K. The normal resistance at RT R_{300} (about 150 Ω) is 2 times higher than the calculated impedance of the log-spiral antenna (about 75 Ω). In general, the RF impedance of the HEB mixer is approximately equal to R_{300}, which is frequency independent. Thus there is some mismatch between the quasi-optical superconducting HEB mixer and the log-spiral antenna, leaving much room for further improvements of our receivers.

With the quasi-optical NbN HEB as its mixer and operating at THz waveband, the receiver's double sideband (DSB) noise temperature (T_N) is measured by the Y-factor method using the equivalent temperatures of the blackbody loads at 300 and 77 K according to the Callen-Welton definition [12]. The loads are placed about 30 cm from the cryostat As shown in Fig. 2, an optically pumped far-infrared gas laser (FIRL100 from Edinburgh Instruments Ltd., with output power of about several milliwatts and linear polarization at 1.6, 2.5 and 3.1 THz) or a Gunn oscillator with its multipliers at 0.65 THz is used as the LO source. Although a THz band-pass (BP) filter at 4.2 K with about 10% bandwidth, made by Virginia Diodes, Inc. (VDI), is tried to eliminate the direct detection effect, it looks not enough for this purpose. So a wire grid is used to change the LO power for noise temperature measurements, which is not influence by the direct detection effect and instability of LO power [9]. To reduce the environment noise in our lab, an RF shielding room houses all the equipments except the laser which is too big to go into it.

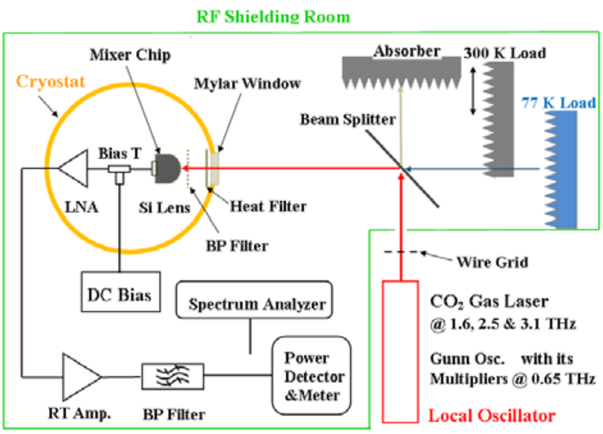


Fig. 2. Schematics of the measurement system. 36-μm and 15-μm thick Mylar films are used as the window and beam splitter. A wire grid is used to change LO power for noise temperature measurements, which is not influence by the direct detection effect and instability of LO power.

The distance between the laser and the cryostat is about 70 cm, and thus only about 2% of the laser's output power can reach the window of the cryostat at 2.5 THz and a humidity of 30%. The radiation is focused onto the antenna-coupled HEB mixer using a Si hyper-hemispherical lens (12 mm in diameter) which has no anti-reflection (AR) coating or an AR coating layer on its surface (see Fig. 2). A cryogenic low noise amplifier (LNA; noise temperature ~ 12 K, gain ~ 30 dB, frequency range of 1.3-1.7 GHz) working at ~ 15 K together with two other ordinary RT amplifiers are used to amplify the intermediate frequency (IF) signal of the mixers. No additional isolator is used between the mixer and the LNA, but a bias tee is used there. An IF filter with the center frequency of 1.5 GHz and bandwidth of 100 MHz is used between the IF amplifier and the microwave power meter or RF detector. The beam splitter and the cryostat window are Mylar films, a thickness of 15-μm for the former and 36-μm for the latter from the considerations that the losses of the LO power caused by them should be as little as possible and that mechanically they should be robust enough. With the beam splitter at 45 degrees to the incidence and the window normal to the incidence, the optical losses at 2.5 THz are calculated to be about 0.05 dB for the window and 1.2 dB for the beam splitter.

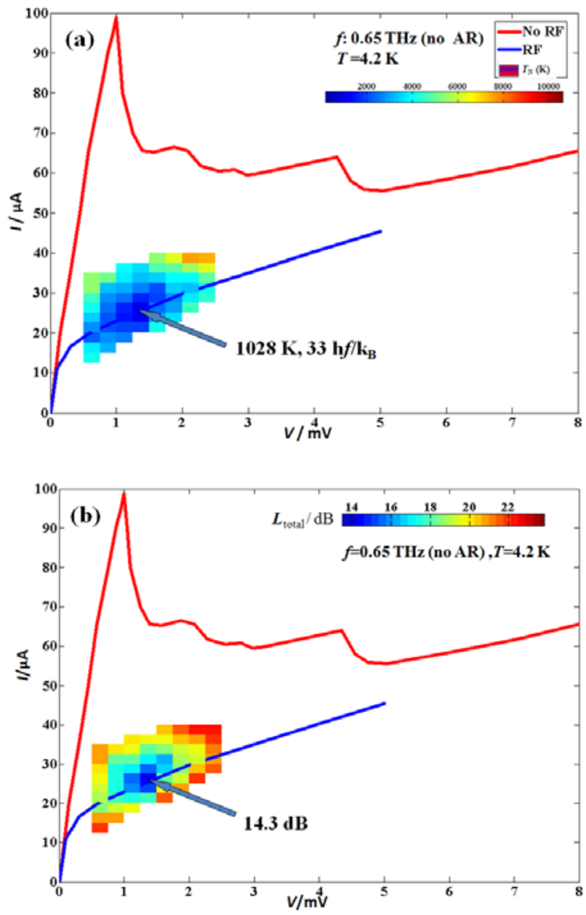
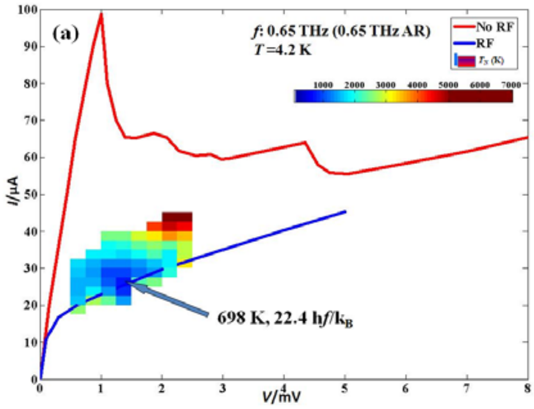


Fig. 3. *I-V* curves without and with optimized LO power, as well as DSB noise temperature (a) and conversion loss (b) as a function of bias voltage for the receiver with a Si lens without AR coating at 0.65 THz. 36-μm and 15-μm thick Mylar films are used as the window and beam splitter, respectively.



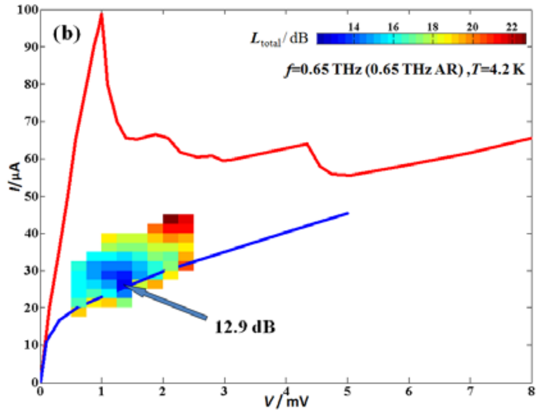


Fig. 4. *I-V* curves without and with optimized LO power, as well as noise temperatures (a) and conversion loss (b) as a function of bias voltage for the receiver with a Si lens with 70-μm thick AR coating layer at 0.65 THz. 36-μm and 15-μm thick Mylar films are used as the window and beam splitter, respectively.

The unpumped (without LO) and optimally pumped (with LO at 0.65 THz) current-voltage (*I-V*) curves of an NbN HEB mixer working at 4.2 K and without the AR coating on Si lens are shown in Fig. 3 (a), together with the DSB receiver noise temperatures (T_N) measured as a function of the dc bias voltages along the pumped *I-V* curve. As the *I-V* curves are measured using two-probe method, a contact resistance of about 10 Ω is evident in the *I-V* curve, which should be improved in near future by the *in-situ* method [13]. The uncorrected T_N reaches a lowest value of 1026 K. As the operating frequency is 0.65 THz, this value is about 33 times of the quantum limit T_Q. T_N increases considerably while the dc bias is shifted away from the optimum bias point. Using the isothermal method [14], the absorbed LO power of about 130 nW is estimated. The conversion loss L_{total} of the HEB mixer was characterized using U-factor method [15]. The calculated L_{total} for different bias voltages and LO pumping levels around optimized condition are shown in Fig. 5 (b). A lowest value of 14.3 dB has been obtained.

When there is no AR coating on the lens, the loss incurred by it is approximately 30% of the total loss. To reduce the loss and thus improve the noise performance of the receiver at some frequencies, Parylene C has been chosen as the material for AR coating on the Si lens [16, 17]. A refractive index *n* of 1.65 is determined at RT using a femtosecond (fs) laser driven THz time-domain spectroscopy (TDS) system [18]. The thicknesses of the AR coating layers are 18.5 μm at 2.5 THz and 70 μm at 0.65 THz. The results are shown in Fig. 4 for a receiver with AR coating at 0.65 THz. The lowest T_N is about 698 K, which is about $22.4T_Q$ and 32% improvement over the case without coating. Also, lowest L_{total} becomes to be 12.9 dB.

Table I Lowest receiver noise temperatures and conversion loss at different frequencies for different AR coating conditions.

AR conditions \ *f*	0.65 THz	1.6 THz	2.5 THz	3.1 THz
No AR	1028 K 33 $h f/k_B$ 14.3 dB	1165 K 15.2 $h f/k_B$ 14.3 dB	1396 K 11.6 $h f/k_B$ 14.7 dB	1734 K 11.7 $h f/k_B$ 16.4 dB
AR @ 2.5 THz	1278 K 41 $h f/k_B$ 17.7 dB	904 K 11.8 $h f/k_B$ 13 dB	1026 K 8.5 $h f/k_B$ 12 dB	1401 K 9.4 $h f/k_B$ 12.9 dB
AR @ 0.65 THz	698 K 22.4 $h f/k_B$ 12.9 dB	1057 K 13.8 $h f/k_B$ 13.5 dB	1462 K 12.2 $h f/k_B$ 15.2 dB	1386 K 9.3 $h f/k_B$ 12.8 dB

In order to quantify the effect of the quantum noise to the receiver noise, lowest T_N and L_{total} of different receivers with same HEB mixer chip and different AR coating conditions are characterized at different frequencies in details. The results are summarized in Table I. The lowest T_N of 698 K at 0.65 THz, 904 K at 1.6 THz, 1026 K at 2.5 THz and 1386 K at 3.1 THz have been measured at 4.2 K without corrections. Using a quantum noise theory [19] as well as the frequency dependences of the beam splitter, optical window and AR coating layers, the excess quantum noise factor β of about 4 can been estimated as shown in Fig. 5.

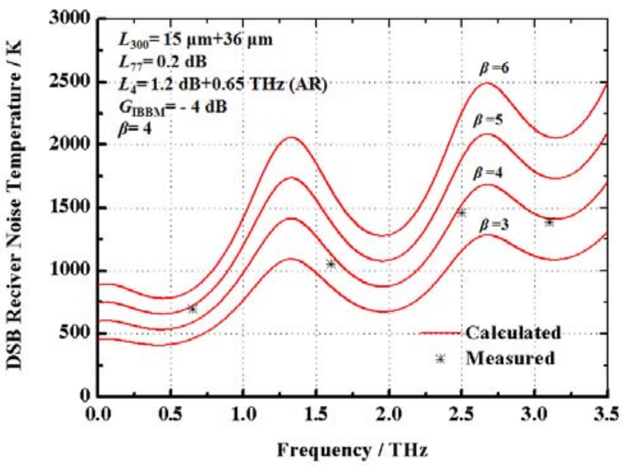


Fig. 5. Frequency dependence of lowest receiver noise temperatures for a Parylene C AR coating on Si lens with thickness of 70-μm (@ 0.65 THz). β=3,4,5,6 were assumed for calculations and best fit is obtained for β=4.

III. Conclusions

The receiver performances of the quasi-optical superconducting NbN HEB mixers have been investigated at frequencies from 0.65 THz to 3.1 THz. The lowest DSB receiver noise temperature measured at 2.5 THz is 1026 K, which is about 8.5 T_Q, without any corrections. Also, the excess quantum noise factor β of about 4 has been estimated using a quantum noise model.

Acknowledgment

We thank Drs. W. Zhang, L. Jiang, S. C. Shi, and Prof. G. N. Gol'tsman for their helpful discussions.

References

[1] P. H. Siegel, "Terahertz Technology", IEEE Trans. on Microwave Theory and Tech., **MTT-50**, 910-928, (2002)

[2] J. Kawamura, J. Chen, D. Miller, et al., "Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers", Appl. Phys. Lett., **75** (25), 4013-4015, (1999).

[3] A. Karpov, D. Miller, F. Rice, J. A. Stern, B. Bumble, H. G. LeDuc, and J. Zmuidzinas, "Low-noise 1THz -1.4 THz mixers using Nb/Al-AlN/NbTiN SIS junctions", IEEE Trans. on Appl. Supercond., **17**(2), 343-346, (2007).

[4] A. D. Semenov, G. N. Gol'tsman, and R. Sobolewski, "Hot-electron effect in superconductors and its applications for radiation sensors", Supercond. Sci. Technol., **15**, R1-R16, (2002).

[5] A. D. Semenov, H. Richter, H. W. Hübers, et al., "Terahertz performance of integrated lens antennas with a hot-electron bolometer", IEEE Trans. on Microwave Theory and Tech., **55**, 239-247, (2007).

[6] H. Richter, A. D. Semenov, S. G. Pavlov, et al., "Terahertz heterodyne receiver with quantum cascade laser and hot electron bolometer mixer in a pulse tube cooler", Appl. Phys. Lett., **93**, 141108, (2008).

[7] S. Cherednichenko, V. Drakinskiy, T. Berg, P. Khosropanah and E. Kollberg, "Hot-electron bolometer terahertz mixers for the Herschel Space Observatory", Rev. Sci. Instruments, **79**, 034501, (2008).

[8] J. J. A. Baselmans, M. Hajenius, J. R. Gao, et al., "Double of sensitivity and bandwidth in phonon cooled hot electron bolometer mixers", Appl. Phys. Lett., **84** (11), 1958-1960, (2004).

[9] J. J. A. Baselmans, A. Baryshev, S. F. Reker, et al., "Direct detection effect in small volume hot electron bolometer mixers", Appl. Phys. Lett., **86**, 163503, (2005).

[10] P. H. Wu, L. Kang, Y. Chen, et al., "Fabrication and characterization of NbN/AlN/NbN junction on MgO(001) and AlN/NbN bilayer on MgO(111) substrates", IEEE Trans. on Appl. Supercond., **15** (2), 209-211, (2005)

[11] J. D. Dyson, "The equiangular spiral antenna", IRE Trans. Antennas Propag., **AP-7**, 181-187, (1959).

[12] A. R. Kerr, "Suggestions for Revised Definitions of Noise Quantities, Including Quantum Effects", IEEE Trans. on Microwave Theory and Tech., **47**, 325-329, (1999).

[13] S. A. Ryabchun, I. V. Tretyakov, M. I. Finkel, et al., "Fabrication and charaterisation of NbN HEB mixers with in situ gold contacts", Proc. of 19th International Symposium on Space Terahertz Technology, 62-67, (2008).

[14] H. Ekstrom, B. S. Karasik, E. L. Kollberg, and K. S. Yngvesson, " Coversion gain and noise of niobium superconducting hot-electron-mixers", IEEE Trans. on Microwave Theory and Tech., **43**, 938-947, (1995).

[15] S. Cherednichenko, M. Kroug, H. Merkel, et al., "1.6 THz heterodyne receiver for the far infrared space telescope", Physica C, **372-376**, 427-431, (2002).

[16] A. J. Gatesman, J. Waldman, M. Ji, C. Musante, and S. Yngvesson, "An anti-reflection coating for silicon optics at terahertz frequencies", IEEE Microwave and Guided Wave Lett., **10** (7), 264-266, (2000).

[17] H. W. Hubers, J. Schubert, A. Krabbe, et al., "Parylene anti-reflection coating of a quasi-optical hot-electron-bolometric mixer at terahertz frequencies", Infrared Phys. & Tech., **42**, 41-47, (2001).

[18] T. D. Dorney, R. G. Baraniuk and D. M. Mittleman, "Material parameter estimation with terahertz time-domain spectroscopy", J. Opt. Soc. Am. A, **18**, 1562-1570, (2001).

[19] E. L Kollberg and K. S. Yngvesson, "Quantum-noise theory for terahertz hot electron bolometer mixers", IEEE Trans. Microwave Theory & Tech., 54, 2077-2089, (2006).