Enhanced sensitivity of THz NbN hot electron bolometer mixers

B. Mirzaei[1], J. R. G. Silva[2] W. J. Vreeling[2], W. Laauwen[2] and J. R. Gao[1,2]

***Abstract*—We present an unprecedented low noise temperature of a NbN hot electron bolometer (HEB) mixer at 1.63 THz, which demonstrated the best DSB receiver noise temperature (T_{rec}^{DSB}) of 530 K and DSB mixer noise temperature (T_{mixer}^{DSB}) of 240 K. The latter is 3 times quantum noise at this frequency (hν/k). The new mixer is developed for the proposed OASIS and SALTUS missions and was fabricated using contacts that have a cleaned interface between Au and NbN. The improvement of T_{mixer}^{DSB} is 30 % in comparison with NbN HEB mixers with a superconducting interlayer added to the contacts in our labs. The reduction in T_{mixer}^{DSB} can reduce the integration time of a heterodyne instrument roughly by a factor of 2. The performance is also evaluated at two higher frequencies of 2.52 and 5.25 THz, at which we also obtain better results than our previous devices.**

Keywords—terahertz, NbN HEB mixers, low noise

I. Introduction

NbN HEB mixers have been flown on Herschel [1], SOFIA [2], and STO2[3], and will be flown on GUSTO [4] and ASTHROS [5]. They are also the choice for the FIRSS (or LETO) [6], OASIS [7], and SALTUS [8] space missions, proposed (or to be proposed) to ESA and NASA, respectively. Due to limited lifetime for space missions, a low T_{mixer}^{DSB} is highly demanded to make optimal use of the observation time.

Many years of R&D at different research groups in the world have been devoted to realize low noise NbN HEBs, where the T_{rec}^{DSB} measured at 1.63 THz or extrapolated to this frequency are, for example, 750 K (for HIFI [1]), 690 K (STO2), and 760 K (GUSTO)[9]. Those values have not been reduced in the past decade. The HEBs for STO2 and GUSTO were fabricated at TU Delft using contacts that have a superconducting interlayer (either NbTiN or Nb) between the Au and thin NbN. This interlayer helps to overcome the proximity effect to maintain the NbN underneath the Au to be superconductive. However, this layer may introduce side effects e.g., on RF loss and RF current flow, which can affect T_{mixer}^{DSB}. Here we present the results of a new NbN HEB mixer using contacts that were cleaned and have a direct interface between thick Au and thin NbN. We show that the DSB mixer noise temperature improves by 30 % at 1.63 THz compared to the devices we have previously produced for GUSTO. We also find improvements at higher frequencies, but less significant, which will be briefly explained in section III.

II. HEB and Experimental Setup

HEBs with 400 nm in length and 4 µm in width imbedded in a spiral antenna were fabricated based on a standard thin NbN film [10]. We performed in-situ ion-cleaning of the NbN surface before deposition of thick Au but skipped the superconducting interlayer. Furthermore, we have also merged the two steps of making thin contact pads and thick antenna arms to only one. In this way 200 nm thick spiral arms end up right on both sides of the NbN bridge. This makes the current path from the Au antenna to the NbN bridge straightforward.

It should be mentioned that the spiral antenna of this device is a modified version of the one used in GUSTO [11] to be able to accommodate the two times wider bridge at its center.

The superconducting transition temperature (T_c) of an HEB from this batch is measured to be 8.8 K, which is lower than that of the original NbN film (≥ 9.5 K). This suggests that we indeed have a highly transmissive interface in the contacts [12]. Similar contact structures have been reported earlier by LERMA [13].

T_{rec}^{DSB} of a NbN HEB (OASIS BM2 7B) was measured at an IF of 1.7 GHz and a mixer operating temperature of 4.6 K in a standard setup in air using 1.63, 2.52 and 5.25 THz LOs. The IF chain consists of a circulator between the bias-tee and a low noise SiGe amplifier, which has a noise temperature of 6.5 K. A Si lens with an anti-reflection coating optimized at 1.6 THz was used to couple the radiation to the HEB for all the frequencies.

III. Results

The (un)pumped IV curves at 1.63 THz are shown in Fig. 1, where the optimum operating region, in which the best performance found is indicated.

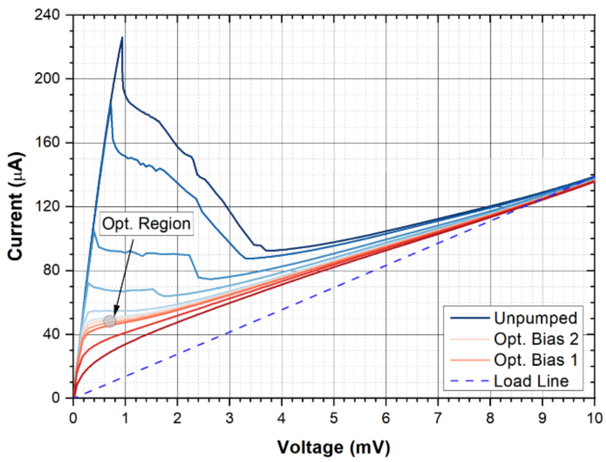

Fig. 1. Pumped IV curves of a NbN HEB at 1.6 THz

Measured T_{rec}^{DSB} together with T_{mixer}^{DSB} (including the contribution of a Si lens ideally antireflection coated for the specific frequency), in unit of hν/k (quantum noise, QN), and DSB mixer conversion gain G_{mixer}^{DSB} are summarized in Table I for all three frequencies. The T_{rec}^{DSB} includes the contributions from the air, a beam splitter, window, heat filter, and the Si lens. The T_{mixer}^{DSB} is about 30 % better than the best device out of 16 GUSTO HEBs at 1.63 THz, which was measured in the exact same setup and has an T_{mixer}^{DSB} of 350 K. We also find a 3-4 dB higher G_{mixer}^{DSB}, which may suggest a lower RF loss due to the contacts.

---

[1]Department of Imaging Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands; [2]SRON Netherlands Institute for Space Research, Leiden/Groningen, The Netherlands.

At 5.25 THz we also observe an improvement, but it is less significant. This can be partly attributed to the non-optimized spiral antenna used for the higher frequencies since the coupling degraded because of the antenna modification explained in the previous section, and can be partly to the quantum noise, which plays a more role at the higher frequency [14].

Table I: Measured receiver noise temperature T_{rec}^{DSB}, derived mixer noise temperature T_{mixer}^{DSB} (including the contribution of a Si lens ideally antireflection coated for the specific frequency), T_{mixer}^{DSB} in unit of hv/k (QN), and DSB mixer conversion gain (G_{mixer}^{DSB}). All are obtained at an IF of 1.7 GHz and an operating temperature of 4.6 K

LO frequency (THz)	T_{Rec}^{DSB}(K)	T_{mixer}^{DSB}(K)	T_{mixer}^{DSB} in units of hv/k (QN)	G_{mixer}^{DSB}
1.63	530 K	240 K	3.1	-4.35 dB
2.52	640 K	290 K	2.4	-5.45 dB
5.25	2180 K	620 K	2.5	-7.39 dB

In Fig. 2 we show the receiver output power in responding to hot/cold loads as well as the DSB noise temperature at 1.63 THz LO around the optimum bias point. As shown, the low noise performance is present in a relatively wide current range, which gives some freedom in tuning the LO power.

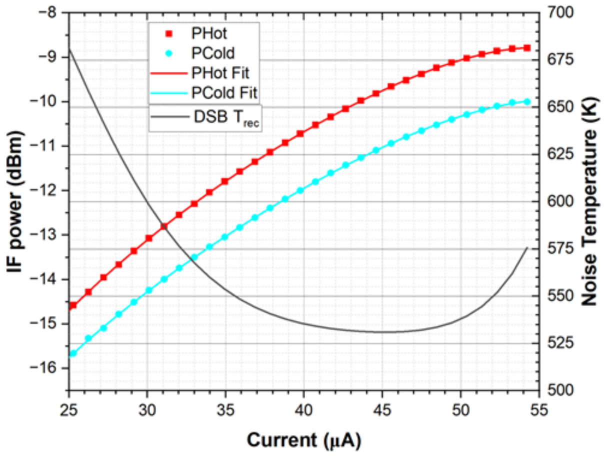

Fig. 2. Measured output power responding to hot and cold loads (left) and resulting DSB receiver noise temperature (right) measured at 1.6 THz and 0.6 mV bias.

This device requires an LO power of ~240 nW at all 3 frequencies, which is a good compromise between availability of the LO source and stability of the receiver.

We acknowledge that this work was supported by NWO (a project number of 614.061.609).

REFERENCES

[1] S. Cherednichenko, V. Drakinskiy, T. Berg, P. Khosropanah and E. Kollberg, “Hot-electron bolometer terahertz mixers for the Herschel Space Observatory”, Review of Sci. Instruments, vol. 79, pp. 034501, 2008.

[2] C. Risacher, R. Güsten, J. Stutzki, H.-W. Hübers, R. Aladro, A. Bell, C. Buchbender, D. Büchel, T. Csengeri, C. Duran, U. U. Graf, R. D. Higgins, C. E. Honingh, K. Jacobs, M. Justen, B. Klein, M. Mertens, Y. Okada, A. Parikka, P. Pütz, N. Reyes, H. Richter, O. Ricken, D. Riquelme, N. Rothbart, N. Schneider, R. Simon, M. Wienold, H. Wiesemeyer, M. Ziebart, P. Fusco, S. Rosner and B. Wohler, “The upGREAT Dual Frequency Heterodyne Arrays for SOFIA”, Journal of Astronomical Instrumentation, vol. 7, no. 4, pp. 1840014, 2018.

[3] Y. M. Seo, P. F. Goldsmith, C. Walker, D. J. Hollenbach, M. G. Wolfire, C. Kulesa, V. Tolls, P. N.Bernasconi, Ü. Kavak, F. F. S. van der Tak, R. Shipman, J. R. Gao, A. Tielens, M.G. Burton, H. York, E. Young, W. L. Peters, A. Young, C. Groppi, K. Davis, J. L. Pineda, W. D. Langer, J. H. Kawamura, A. Stark, G. Melnick, D. Rebolledo, G. F. Wong, S. Horiuchi and T. B. Kuiper, “Probing ISM Structure in Trumpler 14 and Carina I Using the Stratospheric Terahertz Observatory 2”, Astrophys. J., vol. 878, no. 2, 2019.

[4] C. Walker, C. Kulesa, A. Young, W. Verts, J. R. Gao, Q. Hu, J. Silva, B. Mirzaei, W. Laauwen, J. Hesler, C. Groppi, and A. Emrich, Gal/Xgal U/LDB Spectroscopic/ Stratospheric THz Observatory: GUSTO, Proc. SPIE, vol. 12190, 2022, Art. no. 121900E.

[5] Jose V. Siles, Jorge Pineda, Jonathan H. Kawamura, Paul F. Goldsmith, et al., “ASTHROS: The astrophysics stratospheric telescope for high spectral resolution observations at submillimeter-wavelengths,” Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 114453G (2020).

[6] D. Rigopoulou, C. Pearson, B. Ellison, M. Wiedner, V. Ossenkopf Okada, et al. “The far-infrared spectroscopic surveyor (FIRSS). Experimental Astronomy,” Springer Link, 2021, 51 (3), pp.699-728.

[7] C. K. Walker, G. Chin, S. Aalto, C. M. Anderson, J. W. Arenberg, C. Battersby, et al., “Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS): “Following Water from Galaxies, through Protostellar Systems, to Oceans”,” Proc. of SPIE 11820, 11820-26 (2021).

[8] https://live-azs-saltus.pantheonsite.io/sites/default/files/2023-03/SALTUS_Intro_5March23.pdf

[9] José R. G. Silva, Wouter M. Laauwen, Behnam Mirzaei, Nathan Vercruyssen, Matvey Finkel, Menno Westerveld, Nikhil More, Vitor Silva, Abram Young, Craig Kulesa, Christopher Walker, Floris van der Tak and Jian Rong Gao, 4×2 Hot electron bolometer mixer arrays for detection at 1.46, 1.9 and 4.7 THz for a balloon borne terahertz observatory, to be submitted to IEEE TST 2023 (special issue of ISSTT).

[10] The NbN film was provided by TERAHERTZ AND INFRARED PHOTONICS, Moscow, Russia

[11] J. R. G. Silva, M. Finkel, W. M. Laauwen, S. J. C. Yates, B. Mirzaei, N. Vercruyssen, A. Young, C. Kulesa, C. Walker, F. van der Tak and J. R. Gao, “Beam waist properties of spiral antenna coupled HEB mixers at Supra-THz frequencies”, IEEE Transactions on Terahertz Sci. and Tech., vol. 13, no. 2, pp. 167 – 177, 2023.

[12] T. M. Klapwijk and A. V. Semenov, “Engineering physics of superconducting hot-electron bolometer mixers”, IEEE Trans. Terahertz Sci. Technol. Vol. 7, pp. 627–648, 2017.

[13] R. Lefèvre, Y. Jin, A. Féret, T. Vacelet, W. Miao, L. Pelay, F. Dauplay, M. Ba-Trung, G. Gay, J.-C. Villégier, J. Spatazza, J.-M. Krieg, and Y. Delorme, “Terahertz NbN hot electron bolometer fabrication process with a reduced number of steps”, *in Proc. of 23rd ISSTT*, Tokyo, April 2012.

[14] W. Zhang, P. Khosropanah, J. R. Gao, E. L. Kollberg, K. S. Yngvesson, T. Bansal, R. Barends, and T. M. Klapwijk, “Quantum noise in a terahertz hot electron bolometer mixer,” Appl. Phys. Lett. 96, 111113 (2010).