A quasi-optical NbN HEB mixer with 800K DSB noise temperature at 2.5 THz

Y. Delorme[1], R. Lefèvre[1], W. Miao[1,3], A. Féret[1], W. Zhang[3], T. Vacelet[1],F. Dauplay[1], L. Pelay[1], J. Spatazza[1], M. Ba Trung[1], J-M. Krieg[1], Y.Jin[2], P. Khosropanah[4], J. R. Gao[4,5] and S. C. Shi[3]

1. *LERMA, Observatoire de Paris, UPMC, CNRS, 75014 Paris, France*
2. *LPN, Laboratoire de Photonique et de Nanostructures, 91460 Marcoussis, France*
3. *Purple Mountain Observatory, NAOC, CAS, Nanjing, Jiangsu 210008, China*
4. *SRON Netherlands Institute for Space Research, 9747 AD Groningen, The Netherlands*
5. *Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands*

* Contact: yan.delorme@obspm.fr, phone +33-1-4051 2042

***Abstract*— This paper presents the heterodyne measurement results of a quasi-optical NbN mixer at 2.5 THz. The HEB device was developed at LERMA in the frame of a CNES research project and the European programme Radionet FP7. It consists of a 2 µm wide, 0.2 µm long and about 3.5 nm thick NbN bridge on a silicon substrate. THz radiation is coupled to the HEB device through a quasi-optical circuit including an integrated spiral antenna and an anti-reflection coated hyper-hemispherical Si lens. The noise temperature measurement was performed at SRON using an optically pumped FIR gas laser as LO and a hot/cold load setup in vacuum to obtain the Y-factor. Two methods have been employed to measure the receiver noise temperature, either by adjusting the LO power at a fixed bias voltage between the hot and cold load to suppress the direct detection effect or by scanning the LO power when the bias voltage is kept constant to overcome the laser power fluctuations and the direct detection. The double sideband receiver noise temperatures obtained by both methods and without any corrections are as low as 800 K at 2.5 THz.**

I. Introduction

OBSERVING the fundamental transitions of HD and OH in the interstellar medium in the range of 2.5 to 2.7 THz has particular interest for astronomical research since it yields important information about the understanding of the star formation as well as the oxygen and nitrogen chemistries. However, detections of HD and OH so far performed by space missions have suffered from a lack of spectral resolution [1] [2]. The recent development on superconducting Hot Electron Bolometer (HEB) mixers [3] makes it possible to design highly sensitive spectrometers with enough spectral resolution. During the last decade, HEB mixers have been successfully used to detect spectral lines up to 2 THz on ground and space telescopes [4] [5].

We are developing quasi-optical phonon-cooled NbN HEB mixers operating at frequencies between 2-3 THz with the aim of building a heterodyne receiver for CIDRE (Campagne d'Identification du Deutérium par Détection hEtérodyne), a balloon experiment at an altitude of 40 km which will be carried out by CNES (Centre National d'Etudes Spatiales). It consists of carrying a heterodyne receiver mounted on a 80 cm telescope to observe from above most of the earth atmosphere the transitions of OH and HD in the interstellar molecular clouds.

For this mixer development, we have adopted a device fabrication process using direct Au-NbN contact. Excellent DSB noise temperature has been obtained with the realized HEB receiver. We will present in following sections the development and the measurement results of the receiver.

II. Devices design and fabrication

A quasi-optical design using an extended hemi-spherical silicon lens combined with a planar complementary logarithmic spiral antenna was chosen. The spiral antenna has an impedance nearly frequency independent in a broad frequency range which can be approximately determined by the outer and the inner diameter of the spiral [6]. For this quasi-optical design, we first used full wave electromagnetic solvers ANSYS-HFSS [7] and CST- Microwave Studio [8] to calculate the antenna's input impedance and its radiation pattern by replacing the lens by an infinite dielectric half space. At frequencies around 2.5 THz, the simulated input impedance obtained by both solvers is about 78 Ω with a reactance around 10 Ω. To include the lens effect, a hybrid approach combining geometrical and physical optics was used [9] to simulate and optimize the radiation characteristics of the whole integrated lens antenna configuration which still remains difficult to be simulated by full wave electromagnetic solvers.

The key element of a HEB mixer is a microbridge made from an ultra-thin superconductor film. The niobium nitride film used in this work was provided by the Russian company SCONTEL [10]. The film is deposited by magnetron DC reactive sputtering on a high purity silicon substrate. The details of the NbN film deposition are presented in [11]. The device fabrication process was performed by using the facilities in the clean room of LPN [12]. Previous to this work, excellent receiver noise temperature of 950 K at 2.5 THz has been reported with NbN phonon-cooled HEB mixers processed by adding an additional superconducting interlayer to the Au contact pad [13]. In our process (Fig. 1), the direct Au–NbN contact structure without additional superconducting layer was adopted. The Au layer is deposited on the NbN film

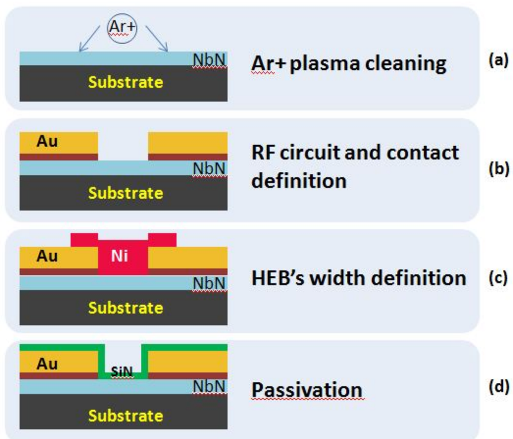

Fig. 1. Flowchart of the NbN HEB fabrication process.

after an in situ cleaning by the argon plasma. A 5 nm titanium layer is used as an adhesion layer. Then a lift-off process is performed on the Au layer to form the HEB's electrodes, the antenna, the transmission lines and the contact pads. The width of the microbridge is determined by reactive ion etching through a mask made of nickel. Finally a dielectric SiN layer

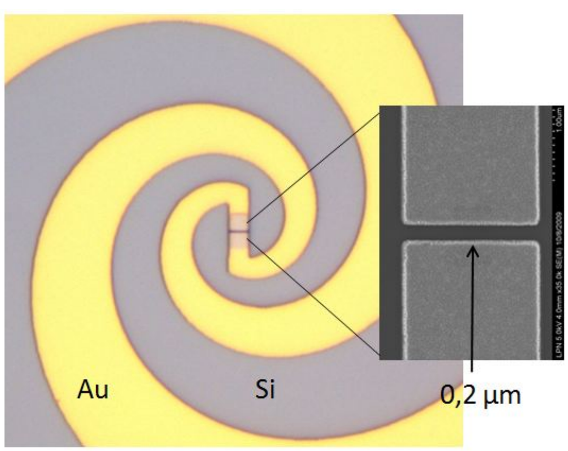

Fig. 2. Scanning electron microscope (SEM) image of a HEB device including the spiral antenna and the NbN bridge. The inset is a close-up of the NbN bridge with a length of 200 nm.

was deposited on the whole substrate for protection.

Fig. 2 shows the fabricated device consisting of a 2 µm wide, 0.2 µm long and 3.5 nm thick NbN bridge which is connected to the spiral antenna's inner terminals made of Au.

The device is then glued on the flat side of a hyper-hemispherical Silicon lens which is mounted into a copper mixer block to be fixed in the cold plate of a 4.2K liquid helium cryostat. The extended hemispherical lens is coated with a 18 µm thick parylene layer as an antireflection coating which is optimal for 2.5 THz.

The HEB device has a critical current of 260 µA at 4.2K. The critical temperature Tc is around 9.2 K with a ΔTc about 1.2 K. The DC resistance at room temperature is 74 Ω which is close to the simulated impedance of the log-spiral antenna (about 78 Ω).

III. Experiments at 2.5 THz

The mixer's characterization at 2.5 THz was performed at SRON using the Y factor measurement method during a joint measurement campaign carried out in the frame of the European programme FP7 Radionet-Amstar+. Fig. 3 illustrates the measurement setup at SRON. The LO source is an optically pumped far infrared laser adjusted at 2.5 THz. The LO power received by the HEB mixer is regulated by a rotating wire grid. The hot / cold blackbody load set used for the Y factor measurement was built in a vacuum box and attached to the cryostat. Between the mixer block and the hot / cold load there is no window but only a heat filter with 5 THz upper cutoff frequency. The LO and RF (from hot and cold loads) signals are combined by a beamsplitter made of a 3 µm thick Mylar film inside the vacuum box. The use of the vacuum box attached to the cryostat allows to avoid the

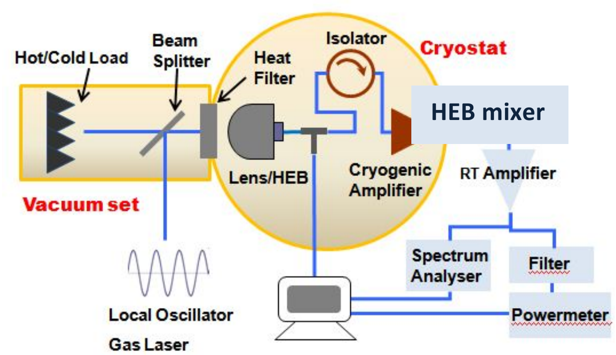

Fig. 3. Illustration of the measurement setup at SRON. The hot/cold loads used for the Y factor measurement and the beam splitter are built in a vacuum unit which is directly attached to the HEB cryostat.

atmospheric absorptions which are significant at 2.5 THz [14]. The HEB mixer's IF output signal is directed, through a bias-T and an isolator, to the input of a Berkshire cryogenic HEMT amplifier with a center frequency at 1.5GHz and followed by two room temperature amplifiers. The IF output power is recorded by a powermeter through a 200 MHz filter and a fast Agilent power head.

The Y factor is given by $Y = P_{IF(hot)} / P_{IF(cold)}$. The double sideband (DSB) receiver noise temperature is calculated from: $T_R = (T_{Hot} - T_{Cold}*Y)/(Y-1)$, where T_{Hot} and T_{Cold} are respectively the temperatures of the blackbody at 293 K and 77 K with the effective radiation temperature of 297 K and

92 K at 2.5 THz according to the Callen-Welton definition [15].

We first measured the Y factor in the commonly used way by measuring the receiver's IF output power as a function of the HEB's bias voltage. The noise temperature is then derived from the Y factor. During the tests, we noticed a direct detection effect on the IV curves. The pumped IV curve is

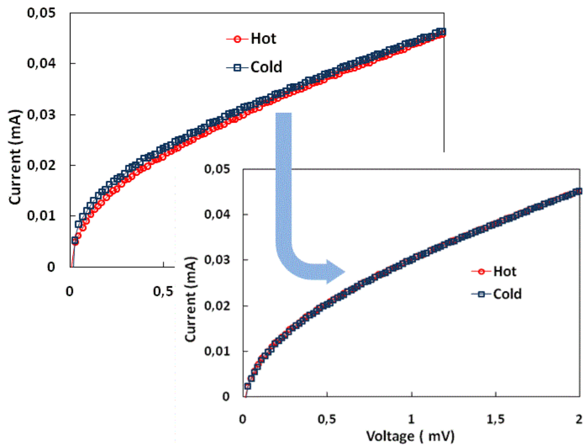

Fig. 4. Current-voltage characteristics of the HEB device responding to the hot and cold load. The direct detection effect (left) was disappeared by adjusting the LO power (right).

slightly changed between hot and cold load (Fig. 4. left). To compensate this effect, the LO power was adjusted to make the IV curves unchanged between hot and cold load measurements (as shown in Fig. 4. right). The degradation of the measured receiver noise temperature caused by the direct detection effect was estimated about 9 % in this experiment.

Fig. 5 shows the measurement results at the optimum LO power. The measured DSB receiver noise temperature presents a relatively broad region of optimal response in its voltage dependence around 0.6 mV, where the lowest noise without correction is as low as 790 K. The LO power absorbed by the HEB and calculated by the isothermal technique is about 280 nW.

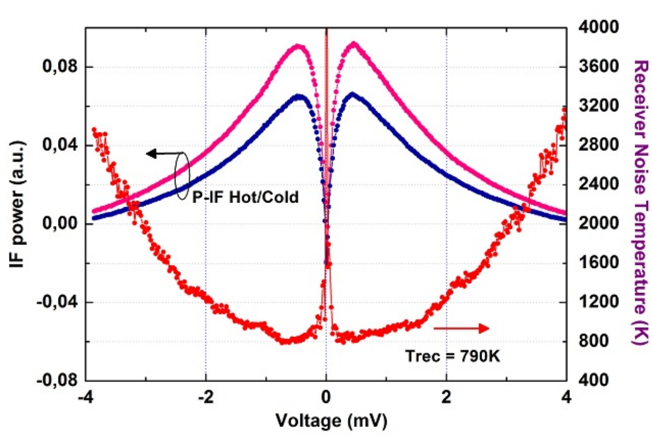

Fig. 5. Measured receiver IF output power (left axis) responding to the hot and cold load at optimal LO power together with the DSB receiver noise temperature (right axis) as a function of bias voltage.

The second measurement method was introduced in order to overcome the influence of the fluctuation of HEB's current on the mixer's sensitivity. This current fluctuation may be caused by the direct detection effect or by the change of LO power due to the laser instability or the air vibrations. This method has been proposed in [16] and consists of measuring, at one fixed bias voltage, the HEB's current and the IF output power for the hot and cold load while the LO power level was changed, from very low to almost fully pumped level. The Y factor is deduced from the fitted curves, i.e. from each pair of fitted lines of hot and cold IF output power. Since the Y factor is calculated for each pair of points $P_{IF(hot)}$ and $P_{IF(cold)}$ at exactly the same bias voltage and current, the noise temperature obtained in such a way is then not influenced by either the LO power fluctuations or the direct detection.

Fig. 6 shows the measurement at the optimal bias voltage,

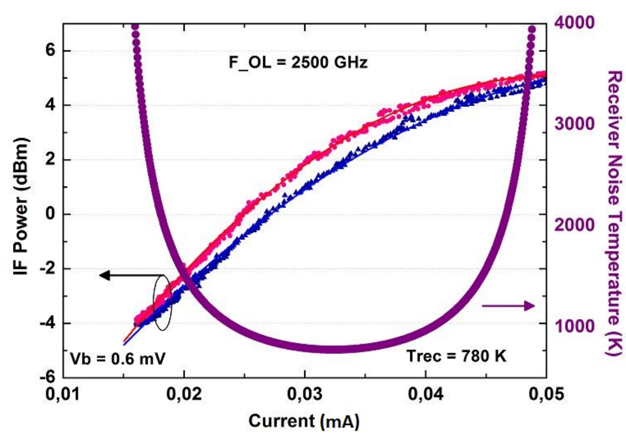

Fig. 6. Measured and fitted IF output power and the deduced noise temperature of the receiver as a function of the mixer's current when the bias voltage is 0.6mV. The lowest noise temperature is below 800K.

0.6 mV. By the calculation from the fitted curves, we determined the noise temperature corresponding to all LO pumping levels at this bias voltage. The lowest receiver noise is 780K, which is in good agreement with the one measured with the first method.

IV. Conclusion

We have presented the development of a quasi-optical phonon cooled NbN HEB mixer working at 2.5 THz for CIDRE, a stratospheric balloon experiment. The HEB device was fabricated with a recently developed process using a direct Au-NbN contact structure. With the excellent DSB receiver noise temperature of 800 K measured at 2.5 THz without any corrections, we have shown that HEB devices with a direct Au-NbN contact and processed without using in situ technology are able to offer state-of-the-art sensitivity at THz frequencies.

Multi-pixel configuration is currently under development and experiments with either multiplier chain or cascade quantum laser as THz local oscillator are planned.

ACKNOWLEDGMENT

This work has been funded by CNES - Centre National d'Etudes Spatiales and the European programme Radionet FP7 – Amstar+.

REFERENCES

[1] Caux, E., Ceccarelli, C., Pagani, L., et al, A&A, 383, L9, 2002,
[2] Cernicharo, J., Polehampton, E., and Goiocoechea, J.R., ApJ, 657, L21, 2007.
[3] Gerecht, E.; Musante, C.F.; Zhuang, Y.; Yngvesson, K.S.; Gol'tsman, G.N.; Voronov, B.M.; Gershenzon, E.M. "NbN hot electron bolometric mixers - a new technology for low-noise THz receivers" IEEE Trans. on Microwave Theory and Techniques, vol.47, pp.2519, 1999.
[4] C. Risacher, D. Meledin, V. Belitsky, and P. Bergman "First 1.3 THz Observations at the APEX Telescope", Proc. of 20th Symposium on Space Terahertz Technology, Charlottesville, April, 2009.
[5] T. de Graauw, F. P. Helmich, T. G. Phillips, J. Stutzki, E. Caux, N. D. Whyborn, P. Dieleman, P. R. Roelfsema et al. "The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)", Astronomy & Astrophysics, Vol. 518, July-August 2010.
[6] J. D. Dyson, "The equiangular spiral antenna", IRE Trans. Antennas Propag., AP-7, 181-187, 1959.
[7] High Frequency Structure Simulator, http://www.ansoft.com
[8] Computer Simulation Technology, http://www.cst.com
[9] A. D. Semenov, H. Richter, B. Gunther, H.W. Hubers, and J. Karamarkovic, "Integrated planar antennas at terahertz waves", Proc. Of 16th International Symposium on SpaceTerahertz Technology, Gothenburg, Sweden, pp. 324-328, 2005.
[10] www.scontel.ru
[11] G. N. Gol'tsman, K. Smirnov, P. Kouminov, B. Voronov, N. Kaurova, V. Drakinsky J. Zhang, A. Verevkin, and R. Sobolewski, "Fabrication of Nanostructured Superconducting Single-Photon Detectors", IEEE Transactions On Applied Superconductivity, Vol. 13, No. 2, June 2003.
[12] www.lpn.cnrs.fr
[13] 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", Appl. Phys. Lett. 84 (11), 2004.
[14] B. S. Karasik, M. C. Gaidis, W. R. McGrath, B. Bumble, and H. G. LeDuc, "Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz", Appl. Phys. Lett. 71 (11), 1997.
[15] A.R. Kerr, "Suggestions for revised definitions of noise quantities, including quantum effects", IEEE Trans. MTT. 47 (3), 1999.
[16] 12. P. Khosropanah, W. M. Laauwen, M. Hajenius, J.R. Gao, and T. M. Klapwijk, "Sensitivity of a hot electron bolometer heterodyne receiver at 4.3 THz", 19th International Symposium on Space Terahertz Technology, Groningen, 28-30 April 2008.