Development of a 1.9-THz Band Hot-Electron Bolometer Heterodyne Receiver with a Quantum Cascade Laser

H. Maezawa[1*], T. Yamakura[2],T. Koyama[1], S. Yamamoto[3], S. Shiba[3], T. Shiino[3], N. Sakai[3], N. Nakai[2], M. Seta[2], A. Mizuno[1], T. Nagahama[1], Y. Fukui[1], Y. Irimajiri[4], N. Sekine[4], I. Hosako[4]
[1] *Nagoya University, Furo-cho Chikusa-ku, Nagoya Aichi, Japan*
[2] *the University of Tsukuba, Department of Physics, Tsukuba ,Ibaragi Japan*
[3] *the University of Tokyo, Department of Physics, Hongo 7-3-1 Bunkyo-ku, Tokyo, Japan*
[4] *National Institute of Information and Communications Technology, Japan.*
*Contact: hiro@ stelab.nagoya-u.ac.jp, phone +81-52-747-6314

***Abstract*— We are developing a superconducting Hot-Electron Bolometer (HEB) mixer receiver for the 1.9 THz frequency band. The microbridge of the HEB mixer was made at room temperature from a 6 nm thick Niobium Titanium Nitride (NbTiN) film deposited on a 20 nm-thick AlN interface layer using a helicon sputtering technique. The mixer was cooled to 4.2 K by using a vibration-free closed-cycle mechanical 4 K pulse tube refrigerator. The stability of the HEB mixer receiver was studied in the 1.5 THz band by varying the local oscillator power of a multiplier chain solid-state source with the bias voltage of the mixer fixed. The output power of the intermediate frequency (IF) signal had a maximum peak as a function of the bias current of the HEB mixer. The receiver noise temperature was minimum at around the maximum peak. It was also found that the IF signal was most stable at around the maximum peak. For future use we have performed test fabrication of stacked GaAs/$Al_{0.1}Ga_{0.9}As$ active layers for the preparation of bound to continuum based quantum cascade lasers to be used as a 1.9 THz band local oscillator source. The result of X-ray diffraction measurements showed that the 120 repeated quantum well structures can be deposited with a molecular beam epitaxy (MBE) system within 0.78 % structural mismatch error.**

***Index Terms*—Terahertz, Hot-electron bolometer mixer, NbTiN film, Quantum cascade laser, Radio astronomy, Atmospheric research**

I. INTRODUCTION

Terahertz band heterodyne spectroscopy of ions, atoms, and molecules plays an important role in the study of the physical and chemical conditions in both astronomical targets and terrestrial and planetary atmospheres. In the millimeter/submillimeter wave bands, near quantum-noise limited superconductor-insulator-superconductor (SIS) receivers have enabled the development of highly sensitive ground-based, balloon-borne, and space-based astronomical and atmospheric research.

The Nagoya University Southern Observatory (NUSO) has employed mm/sub-mm SIS receives installed on instruments at Pampa la Bola in the Atacama desert, Chile (alt. 4860m), to carry out a broad range of work on both astronomical targets and terrestrial and planetary atmospheres. This work includes a large-scale survey of molecular clouds along the Galactic Plane, carried out with the NANTEN2 telescope (4m), as well as monitoring of millimeter wave band spectral lines of minor constituents in the stratosphere and mesosphere such as water vapor isotopes, ozone, NO_x species, etc [e.g. 1]. In addition, the National Institute of Information and Communications Technology (NICT) of Japan has succeeded in constructing a balloon-borne superconducting submillimeter-wave limb emission sounder (BSMILES) in the 600 GHz frequency band

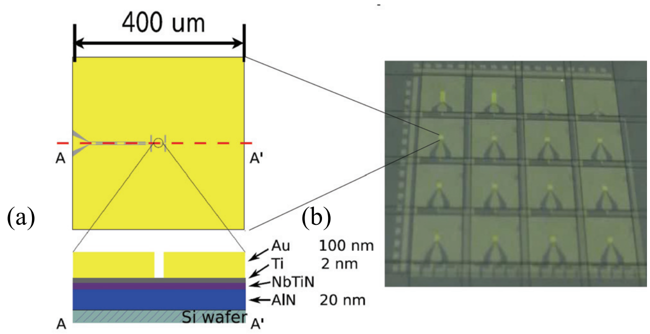

Fig. 1. (a) Cross section of the NbTiN HEB mixer. The 400um^2 field is patterned by an electron beam lithography system. (b) The photograph shows a 35mm-diameter FZ Si wafer on which 16 HEB mixer chips are prepared.

[2]. Currently the University of Tsukuba is planning a project for a THz radio telescope at Dome Fuji in Antarctica. For such projects, the establishment of 1.8-2.0 THz band heterodyne sensing technology is a common thread, which will enable us to observe plasma gases such as ionized carbon and various highly excited transition lines in the interstellar medium, as well as key species involved in photochemistry, such as OH radicals in planetary atmospheres.

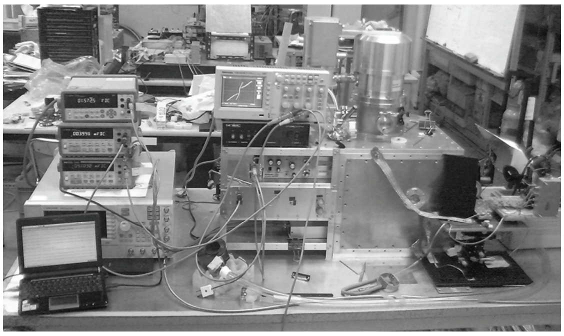

Fig. 2. Laboratory HEB mixer receiver system employing a vibration-free pulse-tube (PT) 4 K closed-cycle mechanical refrigerator.

In THz frequency band, however, SIS mixers do not function since the energy of the incident radiation is sufficient to completely break the superconducting cooper pair electrons[3] (for niobium the energy gap is ~ 700 GHz, for instance). Therefore, superconducting hot electron bolometer (HEB) mixers have been actively studied as an alternative sensitive heterodyne detector for THz band astronomy and atmospheric applications. In principle these superconducting HEB mixers can work from millimeter frequencies to far infrared wavelength without being limited to RF frequencies.

The most widely developed THz band heterodyne detectors to date have been niobium nitride (NbN) phonon-cooled HEB mixers. An alternative is niobium titanium nitride (NbTiN) HEB mixers [4-10]. In contrast to NbN films, the hot-electron cooling mechanism of NbTiN HEB mixers is not completely understood. NbTiN HEB mixers can be easily fabricated on quartz substrate, whose low dielectric constant and toughness is useful for microfabrication processes such as the lapping of THz band waveguide mixer chips. The combination of waveguide and horn antenna provides a well-defined beam pattern. Both diffusion- and phonon-cooling mechanisms may be able to function in the microbridge of NbTiN HEB mixers made by *in-situ* deposition processes [9,11]. Further study now promises to expand the potential performance of NbTiN HEB mixers.

We are developing a 1.9 THz band NbTiN HEB mixer. Since our micromachining process for the 1.9 THz band waveguide structure is not completely established, at present we have employed a quasi-optical antenna for the experimental development of our mixers. In addition we are now ordering a 1.9 THz band solid state multiple chain local oscillator (LO) source (Virginia Diodes Inc.). Until the delivery we are investigating the performance of our NbTiN HEB mixer by using an existing 1.5 THz band multiple chain LO source.

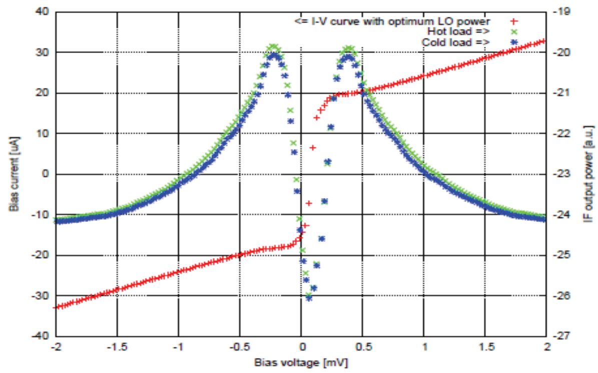

Fig. 3. I-V characteristic of HEB mixer at optimum LO power and the dependence of bias voltage on IF output power.

II. Fabrication Processes and Design of NbTiN HEB Mixers

A non-doped high resistivity floating zone (FZ) silicon wafer is first cleaned in deionized water with an ultrasound bath. Within a 400μm×400μm field a microbridge, RF choke filter, and twin-slot antenna are patterned with an electron-beam lithography system. An AlN interface layer is deposited by DC reactive sputtering [12], after which a NbTiN superconducting thin film is accurately deposited using a helicon sputtering technique with an NbTi (weight ratio of Nb:Ti = 4:1) alloy target in a mixture of Ar and N_2 gas at room temperature. This sputtering system was designed and purpose-built on the basis of a process simulation [13] and the field pattern is formed by a lift off process with a positive photo resist mask.

In our multi-deposition system, the sputtering room and electron-beam evaporation room are connected through a load lock room. Without breaking the vacuum, a bilayer consisting of a 2 nm-thick Ti interface layer and a 100 nm-thick Au contact/electrode layer is deposited on the NbTiN layer. This is an *in situ* technique, which minimizes the impeditive deterioration of the NbTiN film surface. The critical temperature (T_c) of a bilayer consisting of a 6 nm thick NbTiN film and a 20 nm interface AlN layer on Si wafer was found to be 3.0 K higher than the T_c of a 6 nm thick NbTiN film alone. However, in our current fabrication process the T_c of the HEB mixer is less than 10 K due to the superconducting proximity effect induced by the remnant 2 nm thick Ti interface layer.

Ground plane and IF read out coplanar patterns are determined by a photo mask aligner, and 350 nm Al layers are

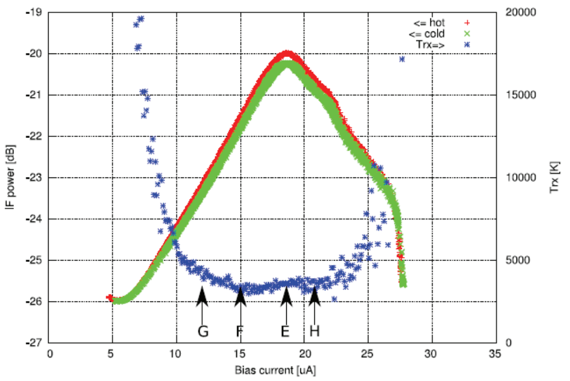

Fig. 4. Uncorrected receiver noise temperature of HEB mixer receiver and IF output power corresponding to input blackbody temperatures of hot (295 K) and cold loads (77 K) at 1.47 THz as a function of bias current with bias voltage fixed. The bias current is varied by changing the LO power. Position E shows the bias current point corresponding to the maximum peak of the IF output power, where the receiver noise temperature was minimum and insensitive to bias current levels.

deposited. Finally the length of the microbridge is defined by the electron-beam lithography system and subsequent inductively coupled plasma (ICP) etching with Ar gas. The Ti interface layer remaining on the NbTiN microbridge plays the role of the etching stopper. A cross sectional view of the HEB structures is shown in Fig. 1 (a), and a scanning electron microscope (SEM) photograph of sixteen 4mm×4mm HEB mixer chips is shown in Fig. 1 (b). In this 1.5 THz band experiment an HEB mixer employing an NbTiN microbridge of 0.3 μm in length and 0.5 μm in width was studied. The bridge size, including the thickness, was adjusted for the insufficient pumping power of our 1.5 THz band LO source and the cooling operation temperature of the mixer mount (4.2 K). Therefore this bridge size was not fully optimized for the sensitivity and the IF bandwidth of the HEB mixer.

Twin-slot antennae prepared for various frequency bands including the 0.2, 0.6, 0.8, 1.5, 1.9 and 2.5 THz bands are patterned on the basis of the design reported in [14,15]. The structure of the coplanar slot and choke filter are slightly re-designed with a high frequency structure simulator (HFSS, Ansoft inc.). The frequency responses of the HEB mixers measured by a Fourier transform spectrometer (FTS) system were in accordance with those predicted by the designs. In the FTS system a signal beam emitted from an Hg lump is collimated to the mixers by a parabolic reflector. The polarizations of the mixers were checked by tilting an inner wire grid polarizer set in the evacuated FTS chamber. The ratio of co- to cross-polarization was greater than 10dB at 1.9 THz.

IF output coplanar lines formed on Si wafer are connected to an IF Duroid microstrip circuit by bonding wires. The reflection and transmission coefficient at this connection was designed based on the HFSS simulation. The mixer chip is attached to the bottom surface of a hyper hemisphere made of a non-doped high resistivity Si lens. This lens should be coated by anti-reflection (AR) coating in order to match the impedance

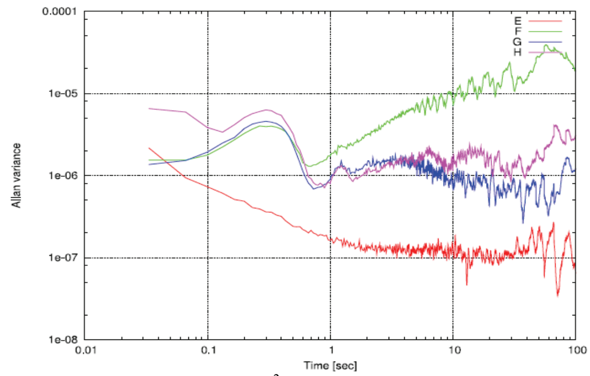

Fig. 5. Allan variance $(\sigma_A/<v(t)>)^2$ of the 1.5 THz band NbTiN HEB mixer receiver system measured for the four bias current positions labeled in Fig.4. Except for bias current position E, corresponding to the IF maximum peak, the influence of mechanical vibration on the Allan variance can be seen below 1 second.

between the atmosphere and the lens. On Si lenses prepared for the 1.9 THz band we employ a 27 um thick layer of Parylene-C, which is widely used for printed circuit boards (PCBs) and medical and space industry devices. However, for this experiment at 1.5 THz, we used a Si lens without AR coating.

III. Measurement Setup

The HEB mixer chip was cooled to 4.2 K with a vibration-free pulse-tube (PT) 4 K close-cycled refrigerator (Sumitomo heavy industries, Ltd.) for which the cooling capacity and amplitude of the mechanical vibration are 0.5 W and less than 3 μm, respectively. The temperature fluctuation synchronized to inner He gas circulation is 300 mk with a period of about 1.2 seconds, which is greater than that of a Gifford McMahon 4 K close-cycled refrigerator with same cooling capacity. We inserted various interface metal materials between the mount block of the HEB mixer and the 4 K cold head, so that the temperature fluctuation at the mixer mount block was reduced to less than 2 mK.

In this measurement the beam of a 1.5 THz band multiplier chain LO source is collimated with a parabolic mirror, and is coupled with the blackbody RF signal from slabs of Eccosorb at 295 K (hot load) and 77 K (cold load) by using a polarized wire grid. Because of the insufficient power of the LO source, the RF/LO coupling efficiency is reduced to 67 % by the wire grid. The vacuum window is 25μm-think Kapton film. The infrared filter attached to 50 K shield panel is a Zitex G106.

In front of the HEB mixer, a band pass mesh filter is inserted to transmit only 1.5 THz band signal with a band width of 10 %. Broad band incident thermal emission ranging from millimeter to infrared wavelengths makes it difficult to evaluate the performance of HEB mixers accurately because it induces the well-known cumbersome bolometric phenomenon known as the direct detection effect. This direct detection effect drifts the operation bias voltage and bias current, which complicates the intensity calibration of observed spectra.

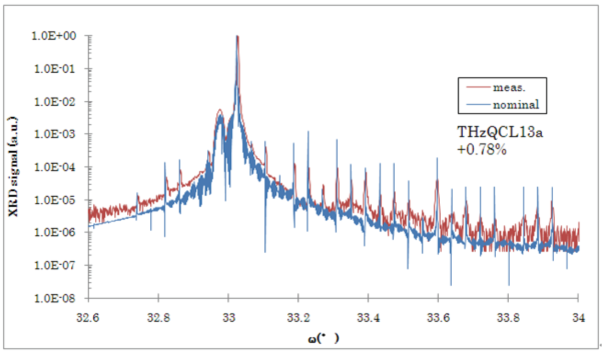

Fig. 6. X-ray diffraction measurement of the stacked GaAs/$Al_{0.1}Ga_{0.9}As$ active layers prepared for a bound to continuum based quantum cascade laser.

For the stable bias control of the HEB mixer, we improved the Nitsuki 8842 bias control unit used for the operation of SIS mixers. The intermediate frequency (IF) signal output from the HEB mixer is connected via a bias-tee to a 1.3-1.8 GHz band isolator and a low noise HEMT amplifier made in Russia, and then amplified by two low noise HEMT amplifiers at room temperature. The equivalent noise temperature of this cryogenic LNA cooled to 4.2 K is less than 3 K. The linearity of the system is checked by variable attenuators. The frequency characteristics of the IF signal are evaluated with a spectrum analyzer. When the Allan variance of the HEB mixer receiver is measured, the IF output signal is narrowed by a frequency tunable band pass filter with 15 % bandwidth, and then monitored by a square law direct detector.

IV. Measurement Results

A. Receiver noise temperature

The receiver noise temperature of the NbTiN HEB mixer was measured at 1.47 THz by using the Y-factor method on the basis of a Callen and Welton radiation law [16]. Fig. 3 shows the bias current and IF output power corresponding to the input blackbody temperatures of the hot and cold loads measured as a function of the bias voltages at the optimum LO pumping level. The maximum Y-factor is 0.3 dB at a bias voltage of 0.4 mV and a current of 20 μA. The lowest uncorrected receiver noise temperature was 3400 K. Taking into account only our low RF/LO coupling efficiency at the wire grid splitter and the reflection loss at the surface of the Si-lens without AR coating, this receiver noise temperature is partially corrected to be about 1600 K for the 1.3-1.8 GHz IF band, which is comparable to those of other NbTiN HEB mixers reported previously [6,7]. By optimizing the microbridge dimension of the NbTiN HEB mixer using an LO source with sufficient power the noise performance will be further improved.

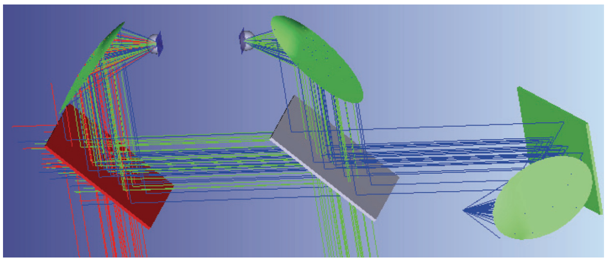

Fig. 7. Schematic optical design of NbTiN HEB mixer receiver with a THz band CW QCL LO source, where an additional superconducting HEB mixer is prepared exclusively for the phase locked loop system. The HEB mixers and the QCL are assembled on the 2nd stage (4K) and 1st stage (50 K) of our PT cryostat, respectively

B. Stability

Generally the Allan variance, $(\sigma_A/<v(t)>)^2$, is measured to study the stability performance of the HEB mixer receiver system [e.g. 17-19]. Here $v(t)$ and σ_A present the instantaneous output voltage of a direct detector and the standard deviation (rms voltage), respectively. Firstly in this measurement the receiver noise temperature and IF output power as a function of the HEB mixer bias current were investigated by varying the LO power at 1.47 THz around the bias voltage giving the lowest receiver noise temperature. As shown in Fig. 4 we found that the maximum peak of the IF output power is a function of the bias current. The receiver noise temperature was not strongly influenced by bias current at around the IF maximum peak.

Next, we measured the IF output power at bias current levels close to those resulting in the IF maximum peak in order to calculate the Allan variance of the HEB mixer receiver. Direct detection of an IF signal with a center frequency of 1.5 GHz and a band width of 150 MHz was measured for 15 minutes with a 20 ms sampling speed by using a high speed digital multi-meter. As can be seen in Fig.5 we found that the most stable condition, where the Allan variance and time are of the order of 10^{-7} and about 10 seconds, respectively, is obtained at the bias current level marked E, which gives a moderate receiver noise temperature. This mainly seems to be because the IF output power is relatively insensitive to the bias current, that is to say, the LO power at the IF maximum peak.

The Allan variance and time obtained for bias current level E are better than those measured with a 4 K GM refrigerator as previously reported in [10,20]. In other bias current positions such as G, F, and H, the Allan variance value and time are worse than those for position E. The convex features seen in F, G, and H data at shorter than 1 sec are due to the LO power fluctuation induced by the imperceptible mechanical vibration of the PT refrigerator. The power of LO source also drifts with the change of ambient room temperature. If the temperature of the HEB mixer bias unit, IF amplifier chain, and multiplier chain LO source were stabilized, the Allan variance and time would be further improved.

V. Quantum Cascade Laser

Quantum cascade lasers (QCL) promise a continuous-wave (CW) solid-state LO source providing sufficient power for THz band heterodyne receivers. Several successful demonstrations of stabilization in the CW THz band frequency of QCLs have been reported by using electronic phase lock loop (PLL) systems employing heterodyne mixing techniques [e.g.21-23]. We are also planning to integrate a 1.8-2 THz band tunable CW QCL as a LO source in our HEB mixer receiver system, where the frequency of the QCL should be stabilized by a PLL system with a superconducting HEB mixer. In order to prepare such a QCL we have attempted the fabrication of quantum well structures by using a molecular beam epitaxy technique at the photonic device laboratory of NICT. In this fabrication the same active layer structure consisting of GaAs-wells, $Al_{0.1}Ga_{0.9}As$-barriers, and an Si doped layer, as reported in [24], was deposited 120 times on a semi-insulating GaAs substrate. In X-ray diffraction measurements (Fig.6) the sample showed good property where the uniformity of the active layer thickness was within 0.78 %. With this grown active layer, bound to continuum based QCLs will be fabricated experimentally, and then the performance such as power, frequency, current density and operational temperature will be studied.

VI. Conclusion and Future Work

In this study HEB mixers employing a 6 nm thick superconducting NbTiN microbridge with an 20 nm thick AlN interface layer and Ti/Au bilayer by an *in situ* fabrication process were prepared. The best Allan variance was obtained at the maximum peak of IF output power where the receiver noise temperature is optimum.

As shown in our previous paper both phonon- and diffusion-cooling mechanisms may function potentially in our NbTiN HEB mixers due to this *in situ* process. Based on these results, the basic characteristics and potential performance of the NbTiN HEB mixer receiver in the 1.9 THz frequency band will be investigated by optimizing the dimensions of the NbTiN microbridge and by improving the RF/LO coupling efficiency and reflection at the lens surface.

In addition we will develop a 1.9 THz band HEB mixer receiver employing a continuous-wave QCL LO source with stacked GaAs/AlGaAs layers (Fig.7).

Acknowledgments

We are grateful to Dr. H. Matsuo of the advanced technology center of the National Astronomical Observatory of Japan for cooperative FTS measurements. We also extend our thanks to the technical staff at Nagoya University, K. Kobayashi and T. Kawai for the fabrication of the cryostat and wire grids. This work is supported by Grant-in-Aid for Scientific Research (B) of the Japan Society for the Promotion of Science (JSPS). This development of the NbTiN HEB mixer was carried out as a part of the doctoral thesis of T. Yamakura.

References

[1] Kuwahara, T., Mizuno, A., Nagahama, T., Maezawa, H., Morihira, A., Toriyama, N., Murayama, S., Matsuura, M., Sugimoto, T., Asayama, S., Mizuno, N., Onishi, T., Fukui, Y.,"Ground-based Millimeter-wave Observations of Water Vapor Emission (183 GHz) at **Atacama**, Chile", Advances in Space Research, Volume 42, Issue 7, p. 1167-1171,2008

[2] Y. Irimajiri,T. Manabe,S. Ochiai, H. Masuko, T. Yamagami, Y. Saito, N. Izuka, T. Kawasaki, M. Namiki, and I. Murata, "BSMILES –A Baloon-Borne Superconducting Submillimetere-Wave Limb-Emission Sounder for Stratosphere Measurements",IEEE Geoscience and Remote Sensing Letteres, vol.3,no.1,pp.88-92,2006

[3] D. C Mattis and J. Bardeen, "Theory of the Anomalous Skin Effect in Normal and Superconducting Metals", Phys. Rev., Vol. 111, no. 2, pp. 412-417, Jul.,(1958).

[4] C.E. Tong, J. Stern, K. Megerian, H. LeDuc, TK Sridharan, H. Gibson, and R. Blundell. A low-noise NbTiN hot electron bolometer mixer. In Proc. 12th Int. Symp. Space Terahertz Technology, pp. 253–261, 2001

[5] D. Loudkov, C.Y.E. Tong, R. Blundell, KG Megerian, and JA Stern. Performance of the NbTiN hot electron bolometer mixer with AlN buffer layer at terahertz frequency range. IEEE Transactions on Applied Superconductivity, Vol. 15, No. 2 Part 1, pp. 476–479, 2005.

[6] PP Munoz, S. Bedorf, M. Brandt, T. Tils, N. Honingh, and K. Jacobs. THz Waveguide Mixers With NbTiN HEBs on Silicon Nitride Membranes.IEEE Microwave and Wireless Components Letters, Vol. 16, No. 11, pp. 606–608, 2006.

[7] M. C. Wiedner, G. Wieching, F. Bielau, K. Rettenbacher, N. H. Volgenau,M. Emprechtinger, U. U. Graf, C. E. Honingh, K. Jacobs, B. Vowinkel, K. M. Menten, L.-A. Nyman, R. Gusten, S. Philipp, D. Rabanus,J. Stutzki, and F.Wyrowski, "First observations with CONDOR, a 1.5 THz heterodyne receiver," Astronomy and Astrophysics, vol. 454, pp. L33–L36, 2006.

[8] Pedro Pablo Muñoz, Sven Bedorf, Michael Brandt, Thomas Tils, Netty Honingh, and Karl. Jacobs, "THz waveguide mixers with NbTiN HEBs on silicon Nitride membranes," *IEEE Microwave and Wireless Components Lett.*, vol. 16, no. 11, 2006.

[9] L. Jiang, S. Shiba, K. Shimbo, M. Sugimura, P. G. Ananthasubramanian, H. Maezawa, Y. Irimajiri, S. C. Shi, and S. Yamamoto, "Development of 0.8 THz and 1.5 THz Waveguide NbTiN HEB Mixers," *Proc. of 19th Int. Symposium on Space Terahertz Tech.*, pp. 409-412, 2008.

[10] L. Jiang, S. Shiba, K. Shimbo, N. Sakai, T. Yamakura, M. Sugimura, P. G. Ananthasubramanian, H. Maezawa, Y. Irimajiri, and S. Yamamoto, "Development of THz Waveguide NbTiN HEB Mixers," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3,pp.301-304,2009

[11] S. A. Ryabchun, I. V. Tretyakov, M. I. Finkel, S. N. Maslennikov, N. S. Kaurova, V. A. Seleznev, B. M. Voronov, and G. N. Goltsman, "Fabrication and characterization of NbN HEB mixers with in situ gold

contacts," Proc. of 19th Int. Symposium on Space Terahertz Tech., pp. 62-67, 2008.

[12] T. Shiino, S. Shiba, N. Sakai, T. Yamakura, L. Jiang , Y. Uzawa , H. Maezawa, and S. Yamamoto," Improvement of the critical temperature of superconducting NbTiN and NbN thin films using the AlN buffer layer", Supercond. Sci. Technol. 23, 045004,2010

[13] H. Maezawa, T. Sato, and T. Noguchi, "Process simulation of reactive DC magnetron sputtering for thin film deposition of niobium-titanium nitride", IEEE Trans. *Appl. Supercond.*, vol.15, no. 2, pp. 3520-3523, 2005

[14] RA Wyss, A. Neto, WR McGrath, B. Bumble, and H. LeDuc."Submillimeter-wave spectral response of twin-slot antennas coupled to hot electron bolometers". proceedings of 11th Int. Symp. on Space, THz Tech. ,JackEast Editor, pp.379–388.

[15] P. Focardi, A. Neto, and W. R. McGrath,"Coplanar-Waveguide-Based Terahertz Hot-Electron-Bolometer Mixers Improved Embedding Circuit Description", *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 10, pp2374-2383,2006

[16] Anthony R. Kerr, "Suggestions for revised definitions of noise quantities, including quantum effects," *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 3, pp. 325-329, 1999.

[17] D. W. Allan, "Statistics of Atomic Frequency Standards", *Proc. of the IEEE*, vol. 54, no. 2, pp. 221-230, 1966.

[18] J.W.Kooi,J.J.A.Baselmans,A.Baryshev,R. Schieder, M. Hajenius, J.R. Gao, T.M.Klapwijk,B.Voronov,G.Gol'tsman,"Stability of heterodyne terahertz receiver", Journal of Appl.Phys.100,064904,2006

[19] T. Berg, S. Cherednichenko, V. Drakinskiy, P. Khosropanah, H. Merkel, E. Kollberg, and J. W. Kooi,"Stability of HEB receivers at THz frequencies", Proc. SPIE,21-25 Jun., Glasgow, Scotland, United Kingdom, (2004).

[20] Ling Jiang, Wei Miao, Wen Zhang, Ning Li, Zhen Hui Lin, Qi Jun Yao, Sheng-Cai Shi, Sergey I. Svechnikov, Yury B. Vakhtomin, Sergey V. Antipov, Boris M. Voronov, Natalia S. Kaurova, and Gregory N. Gol'tsman, "Characterization of a quasi-optical NbN superconducting HEB mixer," *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 7, 2006.

[21] .D. Rabanus, U.U. Graf, M. Philipp, O. Ricken, J. Stutzki, B. Vowinkel, M.C. Wiedner, C. Walther, M. Fischer, J. Faist, "Phase locking of a 1.5 Terahertz quantum cascade laser and use as a local oscillator in a heterodyne HEB receiver", Optics Express, Vol. 17, No.3, pp.1159–1168,2009.

[22] J. R. Gao, J. N. Hovenier, Z. Q. Yang, J. J. A. Baselmans, A. Baryshev, M. Hajenius, T. M. Klapwijk, A. J. L. Adam, T. O.Klaassen. B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Terahertz heterodyne receiver based on a quantum cascade laser and a superconducting bolometer",Appl. Phys. Lett,86,244104, 2005

[23] H.-W. Hübers, S. G. Pavlov,A. D. Semenov,R. Köhler, L. Mahler, A. Tredicucci,H. E. Beere, D. A. Ritchie, and E. H. Linfield,"Terahertz quantum cascade laser as local oscillator in a heterodyne receiver",OPTICS EXPRESS, Vol. 13, no. 15, 5890-5896,2005

[24] C. Walther, G. Scalari, J. Faist, H. Beere, and D. Ritchie, "Low frequency terahrtz qyantum cascade laser operating from 1.6 to 1.8 THz", Applied Phys. Lett, 89, 231121,2006.