Performance of SIS mixers for upgrade of CHAMP+ 7-pixel arrays

Andrey Khudchenko[1,*], Andrey M. Baryshev[1,2], Ronald Hesper[1], Marielle E. Bekema[1], Rob de Haan Stijkel[1], Jan Barkhof[1], Duc van Nguyen[2], Valery P. Koshelets[3], Pavel Dmitriev[3], Michael Fominsky[3], Kirill Rudakov[1,3,4], Stefan Heyminck[5] and Rolf Güsten[5]

[1]*NOVA/Kapteyn Astronomical Institute, University of Groningen, 9747 AD, Groningen, Netherlands*
[2]*Netherlands Institute for Space Research SRON, 9747 AD, Groningen, Netherlands*
[3]*Kotel'nikov Institute for Radio Engineering and Electronics, 125009, Moscow, Russia*
[4]*Moscow Institute of Physics and Technology, 141701, Dolgoprudny, Russia*
[5]*Max Planck Institute for Radio Astronomy, D-53121, Bonn, Germany*
*Contact: A.Khudchenko@sron.nl

Abstract— We present here the performance of SIS mixers for upgrade of CHAMP+ array instrument on APEX telescope. In total it includes 14 mixers: 7 for the low band (600-720 GHz) and 7 for the high band (790-950 GHz). The mixers are a replacement for the existing set, which was commissioned on APEX in 2006. The low band mixers are based on Nb/AlN/Nb single tunneling SIS junction and high band ones - on Nb/AlN/NbN SIS twin junctions. The corrected DSB noise temperature of the low band mixers is roughly between 60 K and 120 K for the entire frequency range, and the corrected DSB noise temperature of the high band mixers varies from about 200 K at low frequencies to 400 K at the high end.

INTRODUCTION

The CHAMP+ heterodyne array [1] was commissioned on the APEX (Atacama Pathfinder EXperiment) telescope [2] in 2006. The array consists of 14 pixels, divided into two sub-arrays of 7-pixels each, setup in a hexagonal configuration. The RF (radio frequency) tuning range is 600-720 GHz for the low band and 790-950 GHz for the high band sub-arrays, corresponding to atmospheric windows.

The low frequency array was based on the state of the art (at that time) superconductor-insulator-superconductor (SIS) mixers developed for the ALMA Band 9 receivers [3]. For the high band mixers, on the other hand, an one-off design was made, and the performance was not optimized as far as for the low band. Since then, the SIS mixer technology has been significantly improved and we have developed a new generation of detectors for both CHAMP+ bands. In this paper, we describe the performance of the new mixers installed in the CHAMP+ instrument in January this year (2017) and compare it with the old ones.

LOW BAND (600-720 GHZ) MIXERS

The original low band mixers installed in CHAMP+ instrument were fabricated using SIS junctions based on a Nb/AlO/Nb three-layer. The performance of these mixers is depicted in Fig. 1 by blue curves. Later, due to progress of SIS junction technology, it was found that SIS mixers with AlN barrier can have much higher current density providing significantly wider RF bandwidth and also better sensitivity [4]. This technology was successfully implemented to finalize production of the ALMA Band 9 receivers [3].

After the ALMA Band 9 cartridges were finished, additional mixers with AlN barrier were measured, and seven of them were selected to upgrade the CHAMP+ low band. The noise temperature of the new mixers is presented in Fig. 1 by red curves. One can see a significant improvement of performance in the entire RF range (from 30% in the middle of the band to several time at the edges). It should be mentioned, that the new mixers are operated in the first minimum of a critical current suppression curve.

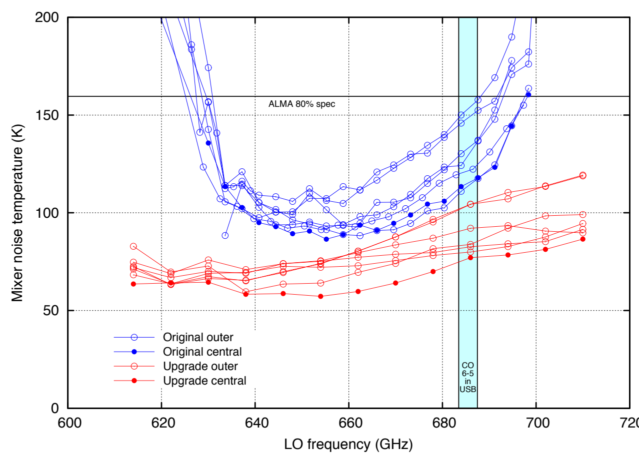

Fig. 1 DSB noise temperature of the new CHAMP+ low band mixers (red curves) compare to old ones (blue curves). Data is corrected for beam splitter insertion losses (5%). The curves with solid circles correspond to the central pixel of the array. The noise temperature in this figure is integrated over the entire 4–12 GHz IF band. Especially marked is the LO frequency range, where the CO j=6-5 line (one of the prime goals of the band) appears in upped sideband of 4-8 GHz IF band.

To describe other characteristics of the installed SIS mixers, we show as example the mixer installed in the central pixel. In Fig. 2 one can find the IV-characteristics, showing gap voltage of about 2.7 mV and normal resistance close to 10 Ohm. The IF power versus bias measurement, corresponding to the pumped IV-curve, is presented in Fig. 3. It includes classical hot/cold (300K/77K) curves and derived noise temperature dependence, showing a wide and stable area around 2 mV, which is fully suitable as mixer operating point.

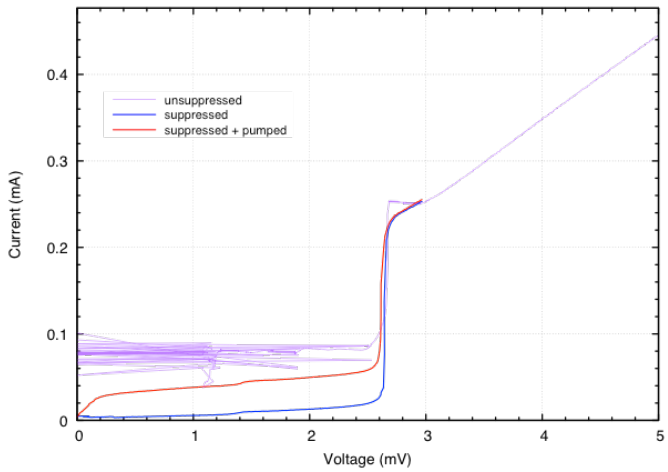

Fig. 2 IV-curves of the central pixel SIS mixer: unsuppressed (violet), with suppressed critical current (blue), with suppressed critical current and pumped by LO signal of 650 GHz (red).

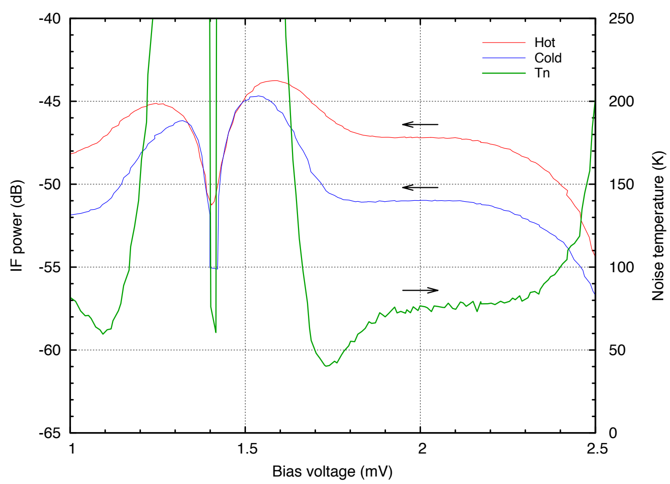

Fig. 3 Measured IF output power versus mixer bias voltage for hot (300K) and cold (77K) load – red and blue curves correspondingly. Using them, the noise temperature curve (green line) was calculated. Operating point is chosen close to 2 mV. The LO frequency is 650 GHz.

The flatness of the mixer sensitivity within the 4-12 GHz IF band is demonstrated by the curves in Fig. 4. Two LO points were chosen as an example.

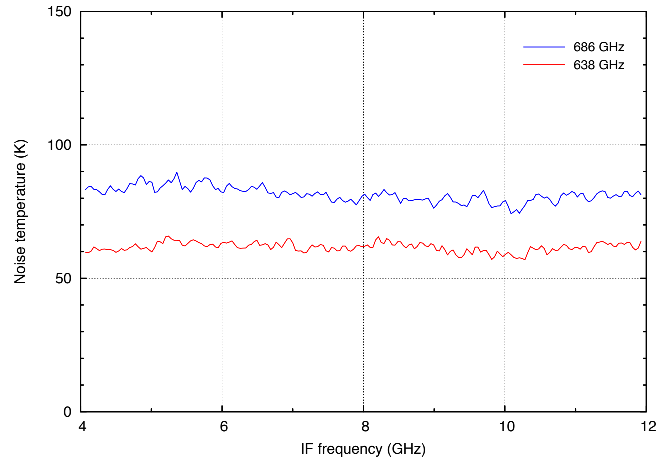

Fig. 4 IF noise temperature vs. frequency, measured for LO frequencies of 686 GHz (blue curve) and 638 GHz (red curve).

HIGH BAND (790-950 GHZ) MIXERS

For the original CHAMP+ high band mixers, a Nb/AlO/Nb SIS technology was used, the same as for the low band ones. However, the high band mixers were based on twin SIS junctions, in contrast to the single junction design for the low band, and the embedded circuit of the junctions consisted of a microstrip line with a NbTiN bottom and aluminum top wire [1], similar to the HIFI band 3 mixers [5]. A one-off design was made without further iterations. Because of this, the mixers performance was not optimized, leaving room for improvement. The corrected noise temperature of the original mixers, measured before the installation in the instrument, is shown in Fig. 5 by blue curves. The data is not covering the full band due to limited range of the lab LO available at the time (a BWO source). This performance was confirmed by a recent lab-measurement of the original central-pixel mixer after it was removed form the telescope (green curve). Roughly, the mixers noise temperature varies form 300..400 K at low frequencies to twice this number at the high end.

To upgrade the high band receivers, we have developed an SIS mixer based on high critical current density Nb/AlN/NbN tunnel junctions incorporated in a microstrip line consisting of a 300 nm thick bottom electrode made of NbTiN and a 500 nm thick top electrode made of Al. The microstrip electrodes are separated by a 250 nm SiO_2 isolator. The Nb layer of the SIS junction is deposited on the NbTiN film, while the NbN layer is contacting the Al top electrode. The nominal critical temperature of NbTiN film is about 14.5 K. More details of the design and fabrication were presented earlier in our paper [6]. This technology allows to reach a junction current density of about 30 kA/cm^2 keeping the quality (ratio of sub-gap resistance to a normal one) as high as 25-30. Using a twin junction design, we have reached a wideband response providing a good noise temperature in the required frequency range (see Fig. 5 red curves).

From the data on the Fig. 5 one can conclude that the upgrade of the mixers should improve CHAMP+ high band sensitivity by a factor of 1.3-1.5, roughly doubling the mapping speed.

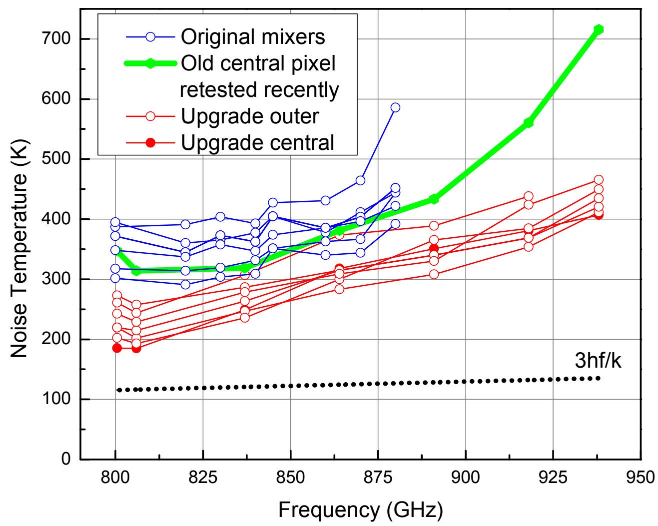

Fig. 5 DSB mixer noise temperature for the entire 4-12 GHz IF band vs. LO frequency. The noise temperature is corrected for about 10% insertion loss of a beamsplitter and for the hot LO (300K) contribution. The old mixers performances (blue curves), including additional recent verification for the central pixel (green curve), are compared here to results for the new mixers (red curves). For all the upgrade mixers the second minimum of the critical current suppression was used.

In addition to the integrated IF data in Fig. 5, we have measured the IF spectra for all LO points (see Fig. 6). Unfortunately, for some frequencies we had strong LO noise contribution, deteriorating IF sensitivity mainly around 4-6 GHz and of course influencing the results on Fig. 5.

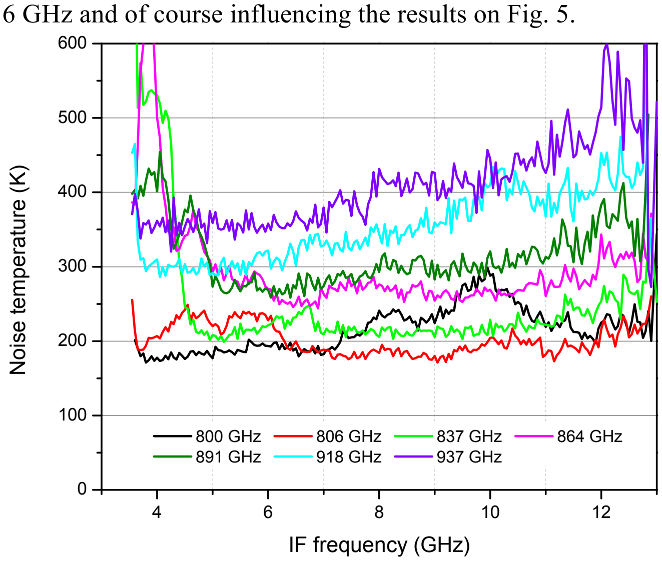

Fig. 6 Corrected noise temperature over the IF band for different LO points. Peaks are caused by LO noise and resonances in the testing horn. The presented lab data corresponds to one of the upgrade mixers installed later in an outer pixel of the array.

To estimate the mixers performance without this extra noise contribution we have plotted the best IF noise temperature within the 4-12 GHz band versus LO frequency (see Fig. 7). As expected, it is lower than the integrated results, but the sequence of curves does not change – the mixer with the lowest noise temperature in Fig. 5 stays the best in Fig. 7 as well. About the data in Fig. 7 one can say that it shows a performance for typical spectral lines observations.

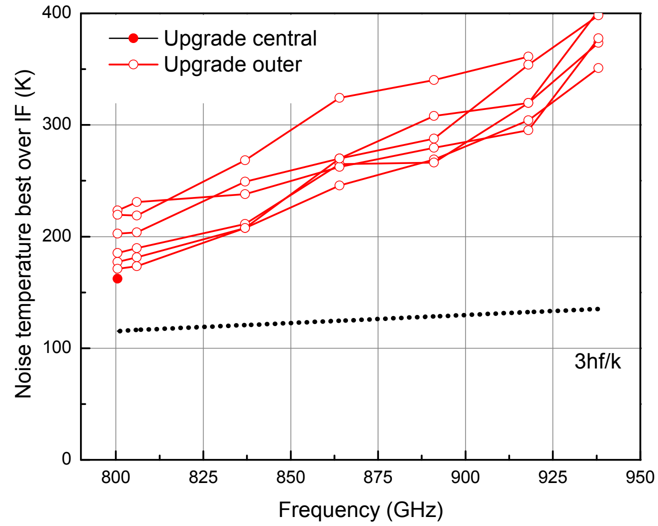

Fig. 7 Noise temperature at the best point in the IF band vs. for different LO frequencies. The data is corrected for the beam splitter as on Fig. 5. For the central pixel (solid dot) only the lowest frequency point was measured.

On Fig. 8 is shown an IV-curve of the central pixel mixer. One can see 1 Ohm serial resistance in a contact introduced by a silver epoxy paste and clearly exposed by unsuppressed IV-curve critical current. The pumped IV-curve shown by red curve corresponds to an optimal LO power and has a pumping level of about 16% (ratio of photon-assisted current to a gap current). The related Y-factor measurement is depicted by a dotted curve on the same figure, demonstrating a wide possible biasing range.

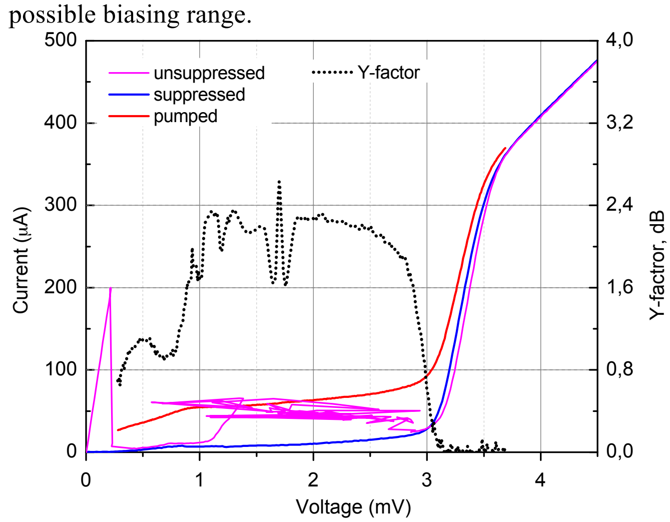

Fig. 8 IV-curves of one of the high band SIS junctions: autonomous unsuppressed (violet line), with suppressed critical current (blue line), pumped by LO signal providing an optimal noise temperature (red curve). The uncorrected Y-factor measured using 77 K/300 K loads is shown by dotted curve. The LO frequency is 800 GHz.

An essential advantage of the new SIS mixers is the higher gap voltage compared to the old ones with Nb electrodes: 3.15 mV against 2.8 mV. This plays a significant role for our band, because a frequency of 950 GHz gives a photon step of 3.9 mV [7], which exceeds the gap voltage. As a result, the voltage range available for SIS mixer biasing is wider by about 0.7 mV for the upgrade mixers, compared to the original ones, which is a big advantage for the mixers operation due to the presence of problematic Shapiro feature right in the middle of the photon step (see Fig. 8).

Conclusions

Upgrading the SIS mixers for the CHAMP+ instrument improved the high band sensitivity by about a factor of 1.4 and the low band sensitivity from 30% in the middle of the band to a few times at the edges. Moreover, the low band frequency coverage was significantly extended.

The low band mixers we can characterize as demonstrating state of the art performance. The high band ones can still be improved, as demonstrated by other groups [8][9].

Acknowledgment

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References

[1] C. Kasemann, R. Güsten, S. Heyminck, B. Klein, T. Klein, S. D. Philipp, A. Korn, G. Schneider, A. Henseler, A. Baryshev, T. M. Klapwijk, “CHAMP+: a powerful array receiver for APEX”, *Proc. of SPIE*, vol. 6275, 62750N, 2006.

[2] R. Güsten, R. Booth, C. Cesarsky, K. Menten, et al., “Ground-based and Airborne Telescopes”, *Proc. of SPIE*, vol. 6267, 626714-1, 2006.

[3] A. M. Baryshev, R. Hesper, F. P. Mena, T. M. Klapwijk, T. A. van Kempen, M. R. Hogerheijde, B. D. Jackson, J. Adema, G. J. Gerlofsma, M. E. Bekema, J. Barkhof, L. H. R. de Haan-Stijkel, M. van den Bemt, A. Koops, K. Keizer, C. Pieters, J. Koops van het Jagt, H. H. A. Schaeffer, T. Zijlstra, M. Kroug, C. F. J. Lodewijk, K. Wielinga, W. Boland, M. W. M. de Graauw, E. F. van Dishoeck, H. Jager and W. Wild, “The ALMA Band 9 receiver. Design, construction, characterization, and first light”, *A&A* 577, A129, 2015.

[4] T. Zijlstra, C. F. J. Lodewijk, N. Vercruyssen, F. D. Tichelaar, D. N. Loudkov, and T. M. Klapwijk, “Epitaxial aluminum nitride tunnel barriers grown by nitridation with a plasma source”, 2007, Appl. Phys. Lett., 91, 233102.

[5] B. D. Jackson, G. de Lange, T. Zijlstra, M. Kroug, T. M. Klapwijk, J. A. Stern, “Niobium titanium nitride-based superconductor-insulator-superconductor mixers for low-noise terahertz receivers”, *J. Appl. Phys*., vol. 97, 113904, 2005.

[6] A. Khudchenko, A.M. Baryshev, K.I. Rudakov, P.M. Dmitriev, R. Hesper, L. de Jong, V.P. Koshelets, "High-Gap Nb-AlN-NbN SIS Junctions for Frequency Band 790–950 GHz," in IEEE Transactions on Terahertz Science and Technology, 2016. vol. 6. no. 1. pp. 127-132.

[7] J. R. Tucker, M. J., Feldman, ”Quantum detection at millimeter wavelength”, *Rev. Mod. Phys*., vol. 57, no. 4, pp. 1055-1113, 1985.

[8] Y. Uzawa, Y. Fujii, A. Gonzalez, K. Kaneko, M. Kroug, T. Kojima, A. Miyachi, K. Makise, S. Saito, H. Terai, and Z. Wang, “Tuning Circuit Material for Mass-Produced Terahertz SIS Receivers”, *IEEE Trans. on Appl. Supercond*., vol. 25, no. 3, 2401005, 2015

[9] G. de Lange, B. D. Jackson, M. Jochemsen, W. M. Laauwen, L. De Jong, M. Kroug, T. Zijlstra, T. M. Klapwijk, “Performance of the flight model HIFI band 3 and 4 mixer units”, *Proc. of SPIE*, vol. 6275, id. 627517, 2006.