

# Progress Report FP6 – RadioNet – AMSTAR

From : SRON and TU Delft  
By: A. Baryshev, J. Gao, M. Kroug, W. Wild, H. Hoevers  
Period : January to December 2005

## W.P 2.1.3. Wide IF-band 0.5 mm Mixers

This work package concerns the development of a wide band IF SIS mixer for the frequency range 600-720 GHz.

### *At SRON*

By the end of 2004, a mixer block has been designed to support the wide IF bandwidth (1-13 GHz). A classical approach has been chosen for connection between mixer and LNA: a wide band (4-12 GHz) circulator was used. The test mixer has shown good IF band coverage and excellent noise temperatures (~100 K DSB in the 620-700 GHz region).

In the beginning of 2005 further optimizations were made for RF design of tuning structures of the mixer which will lead to a new mask design. More batches of devices have been produced and evaluated for technological process optimizations. Both DC and RF evaluation took place.

It was also found that the technology that is developed is very attractive to be used also in the 800-950 GHz range. The RF design of such a structure is under development. After feasibility study, that may lead to another mask set production and device run using normal metal tuning structures technology.

New technological process with NbTiN wire as a top electrode and Nb as a bottom electrode of a tuning structure has been evaluated. Additional study is required to find optimal tuner parameters and measure exact material parameters of Nb and NbTiN film.

The new batch of SIS mixers for 800-950 GHz was realized at TUDelft. New mixer blocks, adapted for higher frequency and wide IF bandwidth were produced. The junctions were DC evaluated and mounted in the mixer blocks. The heterodyne performance of new mixer was investigated and noise temperatures around 400 K were measured for 800-950 GHz band. The IF bandwidth up to 9 GHz was demonstrated. Still, there is a room for improvement for this design and we can propose to develop this bend for the future research.

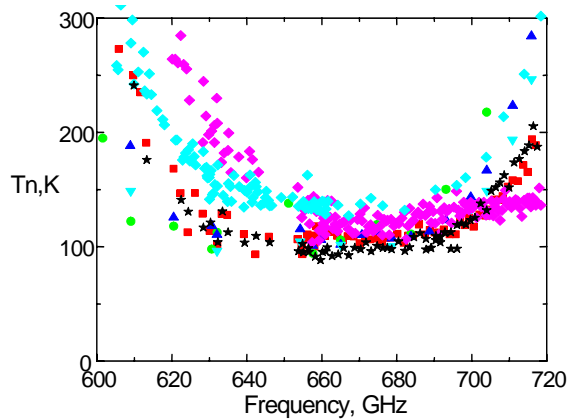
Finally, a new wide band cryogenic circulator was received from Pamtec (where the development takes place) was received showing good parameters starting from 4 GHz all the way until 12 GHz. This circulator as well as new amplifier covering the 4-12 GHz IF frequency were used to evaluate the trough IF performance 650 GHz mixer design. The IF bandwidth of 4-12 GHz was experimentally demonstrated with the good noise performance.

### *At TU Delft*

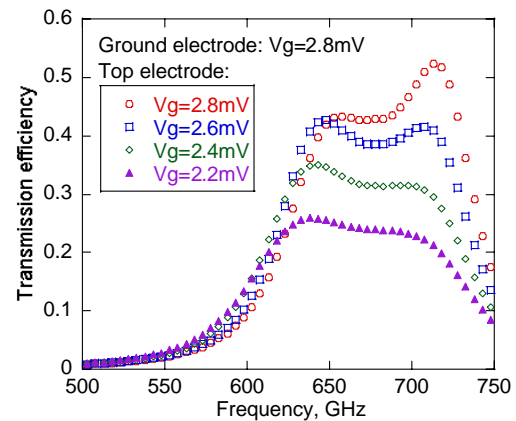
Several batches of 650 GHz mixer design has been produced to investigate process parameters variations. The main source of processing parameter uncertainties is being studied.

New production process involving Nb-AlOx-Nb Junction embedded into NbTiN-SiO<sub>2</sub>-Al stripline has been developed. Several batches of devices for 800-950 GHz has been produced with gradual improvement of junction quality.

With a new design we have successfully achieved a very low noise temperature over the main part of the 600 to 720 GHz band (Fig. 1; black stars). SIS devices based on niobium technology pose the challenging task of matching the junction to the incoming radiation at frequencies below and above the superconducting gap frequency (680 GHz). By choosing an optimized geometry of the LC circuit to tune out the capacitance and by smoothening of the discontinuity between the different widths very encouraging results have been obtained. They suggest that improved noise temperature and bandwidth can be realized by a more accurate design that properly deals with the discontinuities in the superconducting matching circuit. Since we find also for nominally identical devices scatter in the bandwidth and the noise temperatures we aim for a more accurate modeling in relation to fabrication tolerances in geometry and materials properties. We find a high sensitivity for some geometrical factors and material parameters. The geometry factors consist of precision of the lithography alignment and variation in the junction area. The difference in the superconducting gap voltages for top and ground electrodes due to different Nb quality has significant influence on the calculated transmission efficiency of the circuit (Fig. 2). The results obtained imply that further improvement in modeling in relation to the fabrication-variations (and possibly mounting variations) is needed to achieve identical response curves in a multi-disk array.



**Figure. 1**  
Measured Noise temperatures of several SIS Mixers



**Figure 2**  
Direct response of 660 GHz SIS with different gap of Nb in the tuning circuit.

## Publications

Jackson, BD, Lange, G de, Zijlstra, T, Kroug, M, Klapwijk, TM, & Stern, JA (2005). Niobium titanium nitride-based superconductor-insulator-superconductor mixers for low-noise terahertz receivers. *Journal of applied physics*, 11(113904).

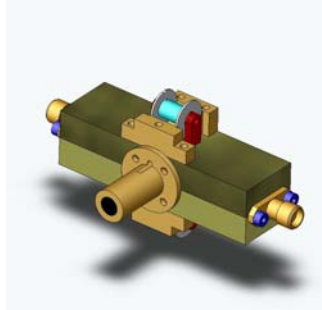
Zijlstra, T, Kroug, M, Rong, B, & Klapwijk, TM (2005). Nanoscaled niobium trilayer technology, using temperature controlled pattern transfer. *Microelectronic engineering*, 78-79, 369-373.

## W.P 2.2.2. 600-720 GHz 2-SB Mixer

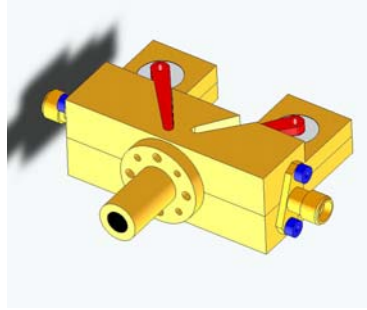
Work is carried out towards the design of a sideband separation (2SB) mixer in the 600-720 GHz band. The development of this mixer will allow a significant improvement of the system noise temperature at ground based telescopes due to the suppression of the relatively high atmospheric noise in the 650 GHz image sideband.

### *At SRON*

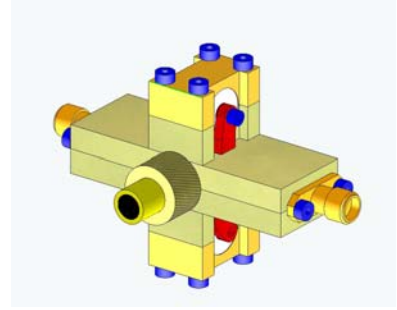
As at the end of 2004 the electromagnetical design of inner waveguide structure with LO splitters, hybrids and junction mounts was finished. The design work on the 2SB block is progressing. The conceptual design is almost finished. Three design concepts were made. A visit to a fine mechanics company on April 12th 05 was made to discuss the feasibility of them:



Design 1



Design 2



Design 3

Investigation on which load material is most suitable is ongoing. Preliminary, RT testing of the load material will be done with the FTS spectrometer at SRON-G. But testing also at cryogenic temperatures has to be done at the University of Geneva. In April discussions with Delft will start to discuss the production of junctions. A memo including the design and a simulation of the load performance for the 2SB mixer was published in the ALMA memo series ([www.alma.nrao.edu/memos](http://www.alma.nrao.edu/memos)). An abstract about the complete design of the 2SB mixer was submitted to the International Symposium on Space Terahertz Technology (ISSTT) to be held in Gothenburg, Sweden, from 2 to 4 May. A visit to Delft was made to discuss new mask sets for junction fabrication.

The new mask set was designed at SRON for 2SB junctions. This mask set was produced at TUDelft and one batch of devices has been delivered and dc tested. A few suitable junctions have been found.

The mechanical and IF design of the mixer block has been finalized. Final production drawings have been produced and the mixer block has been ordered at mechanical company. The estimated delivery date of the first demonstration prototype will be by the end of 2005. The final version of the block will be delivered in the beginning of 2006.

A preparation work has been started to make an experimental setup available. That includes the design of optics and purchase of the dewar.

Evaluating first prototype

Make an advanced junction design, implement measurement feedback

The first measurements expected in the beginning of 2006.

### *At TU Delft*

Striplines suitable for 2SB mixer designed. Process-discussions have been finished. First generation maskset has been produced and first batch of devices yielding good quality junctions at dc test was made. Few more batches of this devices will be produced due to an additional requirement of greater similarity.

## Publications

F. P. Mena, A. M. Baryshev, C. F. J. Lodewijk, M. Kroug and T. M. Klapwijk, and W. Wild, Improved design for low noise Nb SIS devices for Band 9 of ALMA (600 - 720 GHz), 15 STT symposium, Gothenborg 2005

F. P. Mena, J. Kooi, A. M. Baryshev, C. F. J. Lodewijk, and W. Wild, Design of a side-band-separating heterodyne mixer for band 9 of ALMA, Proceedings of 15th STT symposium, Gothenborg 2005

### W.P 2.3.1. Phonon cooled HEB mixers (TU Delft/SRON)

At TuDelft : M. Hajenius, R. Barends, B. de Lange, T. Klapwijk, J.R. Gao;  
At SRON: Z. Yang, J. Baselmans, A. Baryshev, J.R. Gao, P. de Korte

The progress in NbN hot electron bolometer (HEB) mixers carried out at TuD and SRON during 2005 can be highlighted by three major results, all of which have been published or to be published in Applied Physics Letters. These are:

a) Demonstration of a THz quantum cascade laser (QCL) as a local oscillator.

We report the first demonstration of an all solid-state heterodyne receiver that can be used for high-resolution spectroscopy above 2 THz. The receiver uses a NbN HEB as mixer and a QCL operating at 2.8 THz as LO. We measure a double sideband receiver noise temperature of 1400 K at 2.8 THz and 4.2 K (see figure 2.3.1(left)) and find that the free-running QCL has sufficient power stability for a practical receiver, demonstrating an unprecedented combination of sensitivity and stability.

b) Direct detection effect of a NbN mixer due to broadband radiation.

We measure the direct detection effect in a small area ( $0.15 \times 1 \mu\text{m}^2$ ) quasioptical NbN HEB mixer at 1.6 THz. We find that the small signal sensitivity of the receiver is underestimated by 35% due to the direct detection effect and that the optimal operating point is shifted to higher bias voltages when using calibration loads of 300 K and 77 K. Using a 200 GHz bandpass filter at 4.2 K the direct detection effect virtually disappears. This has important implications for the calibration procedure of these receivers in real telescope systems.

c) Modeling pumped current-voltage (IV) characteristics of a NbN mixer.

We present a description of the IV characteristics of HEBs in terms of the current-dependent intrinsic resistive transition of NbN films. We find that by including this current dependence we can correctly predict the complete IV characteristics, showing excellent agreement with measurements for both low and high bias and for small as well as large devices (see figure 2.3.1(right)). It is assumed that the current dependence is due to vortex-antivortex unbinding as described in the Berezinskii-Kosterlitz-Thouless theory. The presented approach will be useful in guiding device optimization for noise and bandwidth. Noise issue remains to be explored.

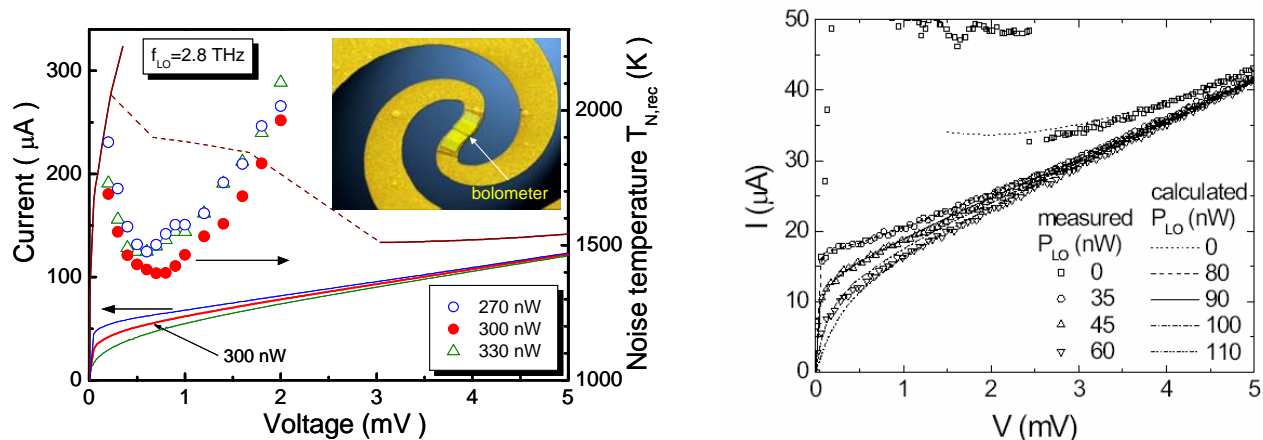


FIG. 2.3.1. Measured receiver noise temperature  $T_{N,rec}$  versus the bias voltage for different LO power levels at the HEB mixer without and with radiation from the QCL at 2.814 THz (left figure); Calculated current-voltage characteristics are compared to those of a small ( $1 \times 0.15 \mu\text{m}^2$ ) NbN HEB mixer measured at 1.6 THz and 4.2 K (right figure).

### Publications:

M. Hajenius, R. Barends, J. R. Gao, T. M. Klapwijk, J. J. A. Baselmans, A. Baryshev, B. Voronov, and G. Gol'tsman, "Local Resistivity and the Current-Voltage Characteristics of Hot Electron Bolometer Mixers", *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY*, **15**, 495(2005).

J. J. A. Baselmans, M. Hajenius, J. R. Gao, A. Baryshev, J. Kooi, T. M. Klapwijk, B. Voronov, P. de Korte, and G. Gol'tsman, "NbN Hot Electron Bolometer Mixers: Sensitivity, LO Power, Direct Detection and Stability", *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY*, **15**, 484(2005).

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J. J. A. Baselmans, A. Baryshev, S. F. Reker, M. Hajenius, J. R. Gao, T. M. Klapwijk, Yu. Vachtomin, S. Maslennikov, S. Antipov, B. Voronov, and G. Gol'tsman, "Direct

detection effect in small volume hot electron bolometer mixers", *Appl. Phys. Lett.* **86**, 163503 (2005).

R. Barends, M. Hajenius, J. R. Gao, and T. M. Klapwijk "Current-induced vortex unbinding in bolometer mixers", *Appl. Phys. Lett.* **87**, 263506 (2005).

Evaluation of a Quantum Cascade Laser as Local Oscillator for Heterodyne Detection of THz Radiation. A.J.L. Adam, J. N. Hovenier, T.O. Klaassen, M. Hajenius, J.R. Gao, B. S. Williams, S. Kumar, Q. Hu and J. L. Reno, Proceedings of the 1st Conference on Optical Terahertz Science and Technology, Topical Meeting, March 14-16, 2005, Orlando FL, U.S.A. On CD-ROM (The Optical Society of America, Washington, DC, 2005), presentation number TuA4 I SBN: 1-55752-786-5, 3 pp.

Microantennas based on quantum cascade lasers, E.E.Orlova, E.F.Orlov, A.M. Belyantsev, T.O. Klaassen, J.N. Hovenier, A.J. Adam, I.Kasalynas, J.R.Gao, B.S. Williams, S.Kumar, J.L. Reno, Proceedings of "Nanophysics and Nanoelectronics" Symposium 25-29 March 2005, N.Novgorod, Russia, p. 445.

T.O. Klaassen, A.J.L. Adam, N. Hovenier, I. Kasalynas, J-R. Gao, B.S. Williams, S. Kumar, Q. Hu, E. E. Orlova, and J. L. Reno, "Optical beam profiles of Terahertz Quantum Cascade Lasers with a metal-metal waveguide", in IRMMW-THz2005, Williamsburg, Virginia, USA, Sep. 19-23, 2005, page 152-153.

## **W.P 2.4.2. Detectors for bolometer array (SRON/TU Delft)**

In this work package we develop superconducting Kinetic Inductance Detectors (KIDs), which have, potentially, a high sensitivity and offer the possibility to produce large-format arrays. We have decided to start with superconducting Ta (4 K) and Nb (9K), in contrast to Al (1 K) used at California Institute of Technology (US). We will start with a Coplanar Waveguide Transmission (CPW) resonator because of its simplicity and the possibility to produce high-Q (up to  $10^6$ ) resonators.

(At TU Delft: R.Barends, N.Hovenier, J.R.Gao, and T.M.Klapwijk)

Two batches of Kinetic Inductance Detectors (KIDs) based on superconducting Nb on Si have been fabricated. The design contains single resonators or multi-frequency resonators with slightly different frequencies on one detector chip. We developed a fabrication process in combination with e-beam lithography and RIE etching. An example of such a device is illustrated in the figure (the part of the CPW resonator). As described in the next paragraph, microwave tests show that those KIDs work and show the resonance frequency closed to the designed ones. An evaluation test set up based on a two stage  $^3\text{He}$  cooler and a vector network analyzer is ready at Delft and we succeeded in getting the first resonance data.

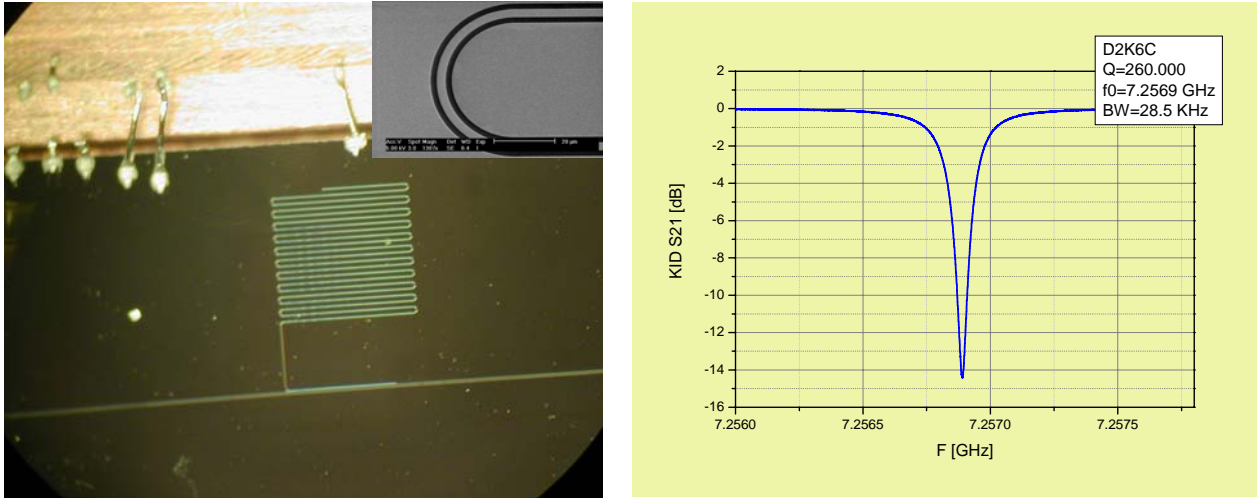


FIG. 2.4.2: a typical CPW resonator structure and a zoom of the part of a Nb resonator. The measured resonance at 7.2 GHz and around 300 mK.

(At SRON: J.J.A.Baselmans, M.P.Bruijn, H.Hoevers, P. de Korte, J.R. Gao)

We have successfully evaluated Nb resonators on Si substrates at temperatures ranging from 300 mK to 6K. The setup has been upgraded with computer controlled measurements of the KID resonance dips using the vector network analyzer. As a consequence we can now semi-automatically measure the resonances as a function of temperature. We find Q factors up to 100.000 at temperatures below 1 K. However, the depths of the resonance dips are shallow, indicating that the intrinsic Q factor of our Nb resonators is limited to values up to 200.000. We found that this is probably due to a combination of losses in the metal and the substrate. As a consequence we have initiated contact with Cambridge Microfab who have delivered us high quality Ta films on Si. Furthermore we have designed and made a mask which enables KID fabrication at SRON on 2" and 4" wafers. Fabrication of Ta KID's on Si at SRON using this mask and the Cambridge films has been initiated. In the near future Ta on Sapphire KID's can be made using the same process, a metal/substrate combination that would enable very high Q's at 300 mK.

With respect to the measurement setup we are in the process of ordering an ADR cooler with cryoperm magnetic shielding, which would enable us to measure Al on Sapphire KID's.