BROADBAND ARRAY SIS MIXERS FOR 780–880 GHz WITH ALUMINUM TUNING CIRCUITS

Sybille Haas, Stephan Wulff, Dirk Hottgenroth, Netty Honingh, Karl Jacobs

KOSMA, I. Physikalisches Institut, Universität zu Köln,
Zülpicher Str. 77, D–50937 Köln, Germany

Abstract—As a building block for an 8-pixel 800 GHz array receiver at KOSMA we developed a low noise SIS mixer. The mixerblock is tunerless and similar to the "stamped waveguide cavity" mixers we have used from 345 GHz to 800 GHz before [1]. We embedded the SIS junction into a standard broadband tuning circuit, commonly used at lower frequencies. The circuit consists of a short end-loaded stub in series with two impedance transforming sections.

For the 780-880 GHz band, we fabricated the electrodes of the tuning circuit as a combination of niobium and aluminum layers in different sequences. First heterodyne tests were performed on devices with a tuning microstrip circuit ground plane consisting of 40nm Nb with 200nm of Al on top and a top conductor consisting of a 70 nm thick Nb layer with a 280 nm thick Al layer on top.

The Nb-Al_2O_3-Nb junction has an area of about 0.5 μm^2 and is fabricated with optical lithography. For anisotropic Nb etching, we use a RIE gas mixture of CCl_2F_2 and NF_3. The Al_2O_3 barrier is removed with Ar sputter etching. Fabrication yield improved considerably when we introduced a light CMP-step after self-aligned SiO dielectric liftoff. For a SIS junction with R_nA equal to 14 $\Omega\mu m^2$, the R_{Subgap}/R_n value of 15.4 is remarkably good.

We measured uncorrected receiver noise temperatures around 400 K over the whole band from 780 to 880 GHz, with a best noise temperature of 370 K at 804 GHz.

1 Introduction

Our aim was to build an 800 GHz prototype mixer for a 2x8-pixel dual frequency array receiver [2] for the atmospheric windows around 800 GHz and 490 GHz to be installed at the KOSMA telescope on Gornergrat (Switzerland) for the next winter observation period (2000/2001).

To take full advantage of a multibeam receiver, array mixers should be just as sensitive as the best available single pixel mixer. For optimum sensitivity around 800 GHz the best noise temperatures are reported for mixers using superconducting NbTiN integrated tuning circuits [3]. Although we are developing mixers with NbTiN integrated tuning circuits for our contribution to HIFI (Band 2: 640 – 800 GHz) on the FIRST satellite, this development is not yet advanced enough to implement it for a practical array receiver under observatory conditions.

We have, however, long time experience in fabricating devices and mixers with Nb-Al_2O_3-Nb junctions embedded in Nb tuning structures [1], [4], [5]. For the mixer described here we designed a type of tuning circuit that was successfully used in Nb at frequencies below its gap frequency, with aluminum electrodes for the 780-880 GHz band. We integrated this device in a fixed tuned waveguide mount.

2 Mixer Block Design and Assembly

Our fixed tuned waveguide mixerblock design [1] meets the requirements concerning stacking of individual blocks close together to form an array (size: 20x20x10 mm^3, all connectors for DC and IF at the backside of the mixer). The magnetic field to suppress the Josephson current is concentrated close to the junction by two iron pole pieces integrated into the mixerblock. The magnet coil itself, with superconducting NbTi wire, connects the two pole pieces at the backside of the mixer. The minimum distance between the junction and the tip of the pole pieces is 0.8 mm. Figure 1 shows a photograph of the mixer without the horn antenna. The waveguide of dimensions 330x90 μm^2 is stamped into a copper block with an appropriate steel tool. The bottom of the stamped guide yields a perfect short circuit at a fixed position behind the junction (50 μm). The mixerblocks are made in house with a mechanical precision of ± 5 μm on a CNC lathe. A Potter horn is flanged to the mixerblock for coupling to the receiver optics.

The fused quartz substrate with the junction and tuning circuit is mounted in a substrate channel across the waveguide. Ground and IF-connections are ultrasonically bonded with 25 μm diameter aluminum wires.

Mounting these thin substrates (2740x80x30 μm^3) usually is a tedious job with the risk of breaking them in this final step of assembly. We applied an innovative method for mounting the substrates with the help of a Nanomotor^{TM}-driven [7] micro-gripper station as shown in Figure 2. The waveguide mixer and the Fluoroware^{TM} junction storage box are both mounted on a Nanomotor^{TM}-driven x-y stage and can be positioned with a smallest step size of only 1 nm under computer control. The storage box is moved under the gripper which is lowered with the z-axis Nanomotor and then opened and carefully closed under computer control to grab the selected substrate. A sliding clutch in the Nanomotor prevents the gripper and the substrate from breaking. The gripper can also be rotated to catch the selected substrate at any given angle. The substrate can then be positioned in the substrate channel under microscope control. A small hypodermic needle attached to the side of the gripper holder is used to distribute tiny amounts of glue in the 100 μm wide substrate channel of the mixer block. We use a thermoplastic glue which softens at 90 °C. This microassembly station provides a reliable and reproducible device mounting procedure which is essential for fabricating a larger number of mixers and for space qualification of the waveguide mixer assembly.

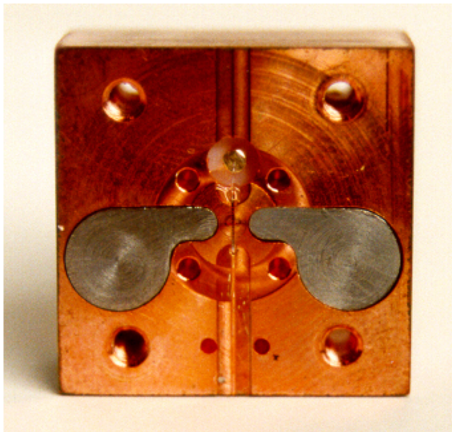

Fig. 1: Photo of the KOSMA fixed tuned mixerblock (without horn antenna) showing the magnetic pole pieces.

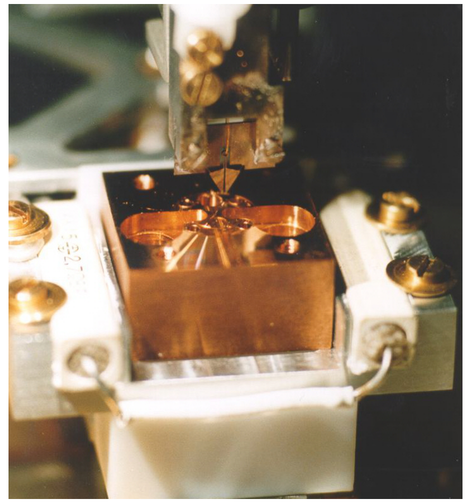

Fig. 2: Photo of the KOSMA microassembly station.

3 Junction RF Design

We use the standard materials Nb and Al for the integrated tuning. Even when we use NbTiN tuning circuits in the future, we can probably only replace one of the tuning electrodes by NbTiN as long as we are using Nb-Al_2O_3-Nb junctions. Heat trapping in Nb junction electrodes fully embedded in a higher gap superconductor may severely degrade the mixer performance [8]. In order to find an alternative to an NbTiN tuning top conductor, we took the opportunity to investigate which material (Nb or Al) or a combination of both materials could be useful. The crossover point in performance between Nb and Al tuning is somewhere in the frequency range between 760 and 820 GHz, depending on the exact quality of the different layers.

We use Nb-Al_2O_3-Nb tunnel junctions embedded in an Nb/Al tuning circuit with a junction area of about 0.5 μm^2 and R_nA of about 14 $\Omega\mu$m^2. This rather small area junction with high current density facilitates a broadband coupling to the impedance of the waveguide mount. The impedance of this waveguide mount has been determined by reflection measurements on a scaled model of the mixer to be 40–50 Ω. Optimum coupling is accomplished by an end-loaded stub tuning structure with two quarter wavelength transformer sections as was successfully used at lower frequencies [1]. Figure 3 shows a sketch of the junction with its tuning structure on the photolithography mask. The actual layer sequence is given schematically in Figure 4.

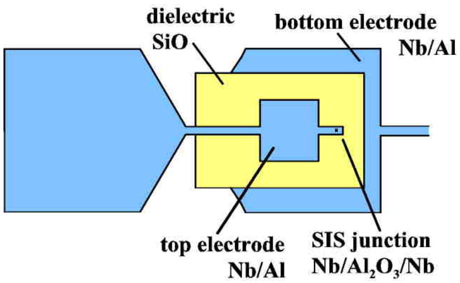

Fig. 3: Sketch of junction and integrated tuning circuit.

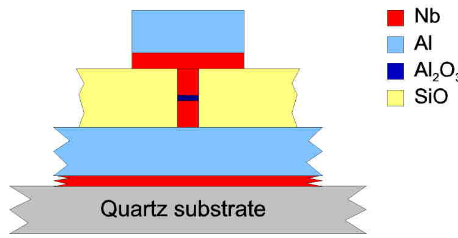

Fig. 4: Sketch of the layer sequence of junction and tuning.

4 Device Fabrication

The initial stack of five layers for this type of SIS detectors consists of a 40 nm niobium layer, 200 nm aluminum as the ground plane, 100 nm niobium tunnel junction base layer, 8 nm aluminum for the tunneling barrier followed by 100 nm niobium for the junction top layer. All five layers are sputter-deposited in-situ onto INFRASIL fused quartz substrates into UV lithographically patterned bilayer AZ 7212 (Clariant) photoresist windows. The bilayer technique [9] with its large undercut profile is well suited for a liftoff process with more than 400 nm layer thickness. The base pressure of the sputter chamber is in the $5 \cdot 10^{-9}$ mbar range. Before depositing the aluminum layer for the barrier, the wafer is cooled to -10 °C. The barrier oxidation is performed in the load lock chamber in a static pure oxygen atmosphere at a pressure of 1.7 Pa for 5.5 minutes, which results in an R_nA product of about 14 $\Omega\mu m^2$. Even with this rather high current density for an Al_2O_3 barrier, the subgap to normal resistance ratio is still about 15.

After standard UV-lithography with AZ 7212 to define the $(0.8\ \mu m)^2$ - $(0.7\ \mu m)^2$ junction top electrodes, a mixture of 6 sccm CCl_2F_2 and 1.2 sccm NF_3 is used for reactive ion etching of the niobium top electrodes. This is a variation of the recipe introduced in [10] which replaces the usual CF_4+O_2 with nitrogen trifluoride. Pure NF_3 has high etch rates in Nb (>280 nm/min at 4 Pa, 0.13 W/cm^2 RF power, self-bias voltage of -55 V) and does not need an oxygen component, as the lack of carbon apparently prevents polymer formation. The disadvantage is that NF_3 etches almost isotropic. The CCl_2F_2/NF_3 mixture is used at 4 Pa, 0.17 W/cm^2 and -105 V self-bias with an etch rate of 80 nm/min and results in an aspect ratio of at least 4:1. The etch times are influenced by a latency time of approximately 13 seconds which is probably caused by a thin niobium oxide layer which has a low etch rate. Also, the etch rate is very dependent on the heat sinking (i.e. temperature) of the wafer. To achieve the given etch rate, a 2 mm thick Teflon disk essentially decouples the wafer from the water-cooled stainless steel RIE cathode.

After etching the top niobium layer, the Al_2O_3-Al barrier is etched with Argon at 1 Pa, 1.1 W/cm^2 RF power, -605 V self-bias for 9 minutes. To avoid excessive heating of the photoresist, this etch is performed in 1 min intervals with 1 min cooling time between the etching steps. The base niobium layer is again etched in CCl_2F_2/NF_3 with the bottom aluminum layer acting as an etch stop. The CCl_2F_2/NF_3 etch leaves a residue on the aluminum layer which is removed with a 2 minute etch with 10 Pa O_2 at 0.45 W/cm^2.

The dielectric layer for junction insulation and for the tuning microstrip consists of 250 nm silicon monoxide, defined in the usual self-aligned liftoff procedure. After liftoff, a 1 minute CMP (Chemical Mechanical Polishing) step [11] was introduced to clean the top niobium electrodes from residues of the photoresist, which is hard baked by the long RIE times and hard to remove. The introduction of this step increased the yield to more than 90 %. After lithography for the wiring layer including the tuning circuit, the wiring electrode layers are sputtered with a subsequent liftoff. After DC-testing of the junctions, the wafer is diced and thinned to 30 μm thickness.

5 Measurement and Analysis

In the course of the experiments with different top layer metallisations, one batch was fabricated with 70 nm Nb followed by 280 nm Al. These devices showed good quality I/V-curves and self induced current steps at bias voltages corresponding to a Josephson oscillation frequency in resonance with the tuning circuit within the designed RF band.

We investigated the RF-coupling of one of these devices with a resonance at 830 GHz in a direct detection Fourier transform spectroscopy measurement as well as its heterodyne response in the frequency range from 780 to 880 GHz.

The direct detection measurement was performed with a commercial Fourier Transform Spectrometer [12] with a maximum resolution of 3.5 GHz. The SIS receiver is used as an external detector of the FTS monitoring the DC current at a proper bias voltage as a function of the displacement of the moving mirror of the interferometer. A broadband Hg arc serves as radiation source.

Figure 5 shows the the measured spectral response. The prominent dips around 753 GHz and 990 GHz are due to absorption of water vapor in the non-evacuated spectrometer. The maximum response occurs at the same frequency as the DC resonances in the I-V curves. The response is very broadband: at least 180 GHz. For a more accurate determination of the bandwidth we will have to repeat the measurement with an evacuated spectrometer.

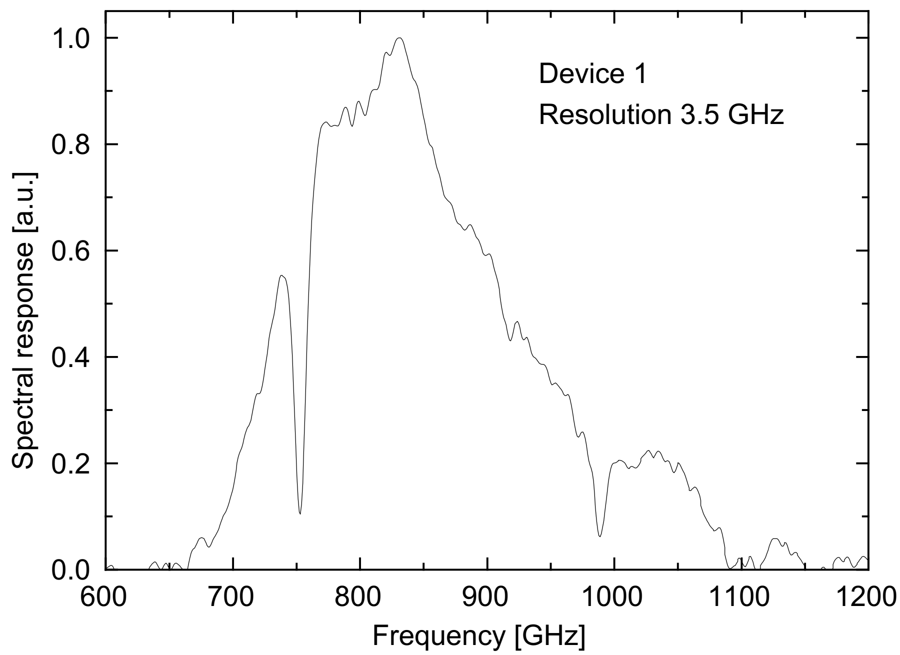

Fig. 5: Spectral response of the device measured with FTS in direct detection.

We used our usual receiver test setup as described in [1] with two solid state local oscillators [6] ranging from 780 to 820 GHz and from 800 to 880 GHz, respectively. The LO power was combined with the hot/cold signal via a 36 μm Mylar beamsplitter. Table 1 gives the measured transmission of the optical components in front of the mixer, measured with a Fourier transform spectrometer together with the calculated noise contribution T_{noise} referred to its input.

component	material	T_{phys} [K]	d [μm]	gain [dB]	T_{noise} [K]
beamsplitter	mylar	295	36	-0.22	14.5
dewar window	teflon	295	500	-0.46	30.6
IR filter	teflon	77	300	-0.36	5.1

Table 1: Loss of optical components at 830 GHz measured with FT spectrometer and deduced noise contributions.

The IF output of the mixer is fed via a 50 Ω coaxial cable to a HEMT amplifier (1-2 GHz) located on the 4 K–plate. An amplifier chain outside the cryostat amplifies the signal by about 70 dB. A bandpass filter restricts the IF bandwidth to 100 MHz around 1.4 GHz.

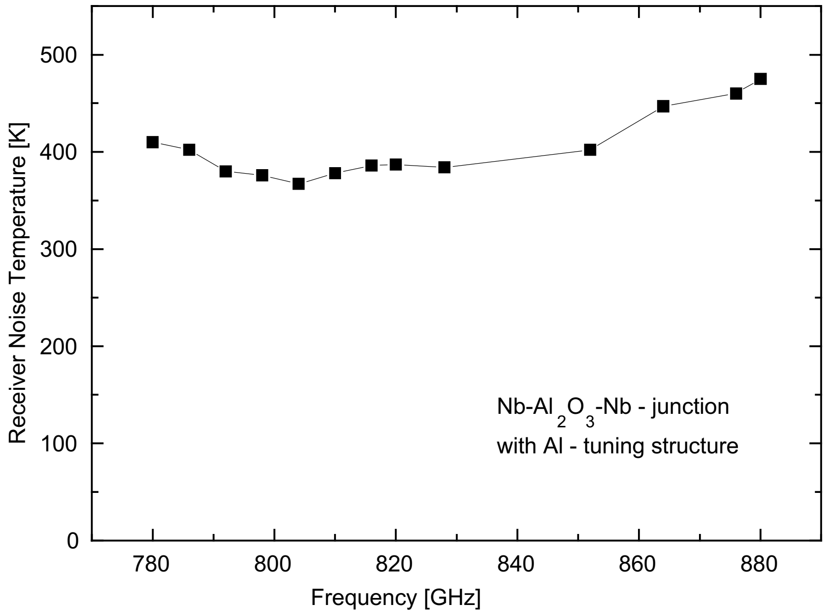

Fig. 6: Measured DSB receiver noise temperatures from 780 to 880 GHz at 4.2K operating temperature.

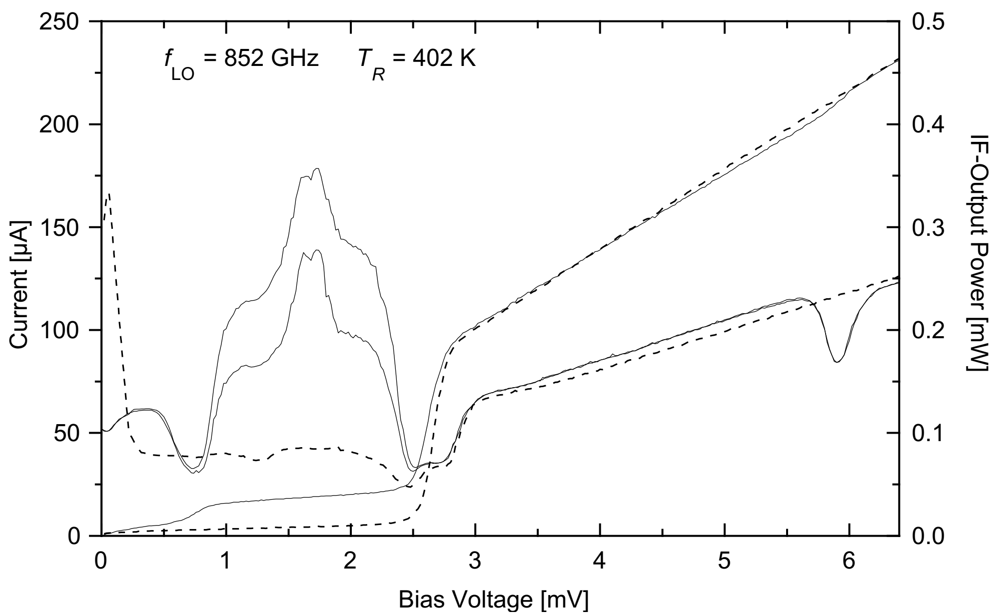

Fig. 7: IF output power as function of bias voltage for a hot (295 K) and a cold (77 K) load input at an LO frequency of 852 GHz.

Figure 6 shows the measured DSB receiver noise temperatures at 4.2 K operating temperature determined from a standard Y-factor measurement calculated with the

Callen-Welton formula. These values are not corrected for any loss. The noise temperature is almost constant over the whole frequency range with a lowest value of 370 K at 804 GHz and increases to only 480 K at 880 GHz. To our knowledge these are the best receiver noise temperatures achieved with Nb-Al_2O_3-Nb junctions and Al tuning circuits from 780 to 880 GHz. It is remarkable that there is only a very slow increase in noise temperature at higher frequencies, despite of the rather thick Nb layer under the Al top layer.

Figure 7 gives the IF output power as a function of bias voltage for a hot (295 K) and a cold (77 K) load input at an LO frequency of 852 GHz.

A noise breakdown was calculated at an LO frequency of 828 GHz. The noise contributions of the optics in front of the mixer add up to $T_{opt} = 55$ K with a (measured) total gain of $G_{opt} = -1.1$ dB. The shot noise technique [13] was used to determine the noise of the IF system. The noise temperature T_{if} of the HEMT amplifier has been determined to be 3 K, while the total IF gain is 97.1 dB. The effect of the reflection loss at the mixer output due to mismatch between HEMT amplifier and mixer is described by a term $T_{mis}|\Gamma_{mis}|^2$, with $|\Gamma_{mis}|^2$ being the reflection coefficient between the load impedance (taken as 50Ω) and the differential resistance of the unpumped IV-curve. T_{mis} is fitted to be 8 K.

From the measured heterodyne response to a hot and a cold load the following parameters T_{mix} and G_{mix} – noise temperature and gain of the mixer (including the contribution from the tuning stripline) – can be determined:

$$T_{rec} = T_{opt} + \frac{T_{mix}}{G_{opt}} + \frac{T_{IF}}{G_{opt}G_{mix}} + \frac{T_{mis}|\Gamma_{mis}|^2}{G_{opt}G_{mix}} \qquad (1)$$

Values at 828 GHz are $T_{mix} = 200$ K and $G_{mix} = -10.2$ dB.

The mixer proved to be very stable during testing. Measurements could be carried out for several hours without readjusting magnet current and bias voltage despite the electrically noisy lab environment.

In conclusion, we achieved a very good noise performance at 780-880 GHz with Nb-Al_2O_3-Nb junctions using a Nb-Al tuning circuit. These noise temperatures are only a factor of 2 worse than the best results reported up to now with NbTiN tuning circuits [3]. The excellent stability together with low noise temperatures over a large bandwidth make these mixers very suitable for the planned array application.

Acknowledgment

We thank Michael Schultz for dicing, thinning and mounting the devices, Marc Sahr for his contribution to the mask design and Michael Brandt for arranging the contact to Klocke Nanotechnik and for the electronic adaptation of the microassembly station. This work was supported by the Verbundforschung Astronomie through grant 05 AH9PK1, by the Ministerium für Wissenschaft und Forschung, Land Nordrhein-Westfalen, by DLR (Deutsches Zentrum für Luft- und Raumfahrt), Förderkennzeichen 50 OF 0001 2 and 50 OF 9902 4 and by DFG (Deutsche Forschungsgemeinschaft), Sonderforschungsbereich 494.

References

[1] S. Haas, C. E. Honingh, D. Hottgenroth, K. Jacobs, J. Stutzki, "Low noise broadband tunerless waveguide SIS receivers for 440–500 GHz and 630–690 GHz", *Int. J. of Infrared and Millimeter Waves*, vol. 17, no. 3, pp. 493–506, March 1996.

[2] U .U. Graf, S. Haas, C. E. Honingh, K. Jacobs, R. Schieder, J. Stutzki, "Array receiver development at KOSMA for the sub-mm and THz spectral range", *Proc. SPIE*, Kona, Hawaii, 1998.

[3] J. Kawamura, J. Chen, D. Miller, J. Kooi, J. Zmuidzinas, B. Bumble, H. LeDuc, J. Stern, "Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers", *Appl. Phys. Lett.*, vol. 75, no. 25, pp. 4013-4015, 1999.

[4] D. Hottgenroth, C. E. Honingh, S. Haas, K. Jacobs, J. Stutzki, "Design and analysis of a waveguide SIS mixer above the gap frequency of niobium", *Int. J. of IR and MM waves*, vol. 18, no. 3, March 1997.

[5] C. E. Honingh, S. Haas, D. Hottgenroth, K. Jacobs, J. Stutzki, "Low noise broadband fixed tuned SIS waveguide mixers at 660 and 800 GHz", *IEEE Transactions on Applied Superconductivity*, vol. 7, no. 2, pp. 2582–2586, 1997.

[6] Radiometer Physics GmbH, Meckenheim, Germany.

[7] Dr. Volker Klocke Nanotechnik, Aachen, Germany. For details including an animated sequence of the junction gripping see www.nanomotor.de/het

[8] B. Leone, B. D. Jackson, J. R. Gao, T. M. Klapwijk, "Geometric heat trapping in superconductor-insulator-superconductor mixers due to niobium titanium nitride leads", *Phys. Rev. Lett.*, vol. 76, pp. 780-782, 2000.

[9] G. J. Dolan, "Offset masks for lift-off photoprocessing", *Appl. Phys. Lett.*, vol. 31, no. 5, pp. 337-339, 1977.

[10] H. G. LeDuc, B. Bumble, S. R. Cypher, A. J. Judas, J. Stern, "Submicron Area Nb/AlOx/Nb Tunnel Junctions", *Proc. of the Third Int. Symp. on Space Terahertz Technology*, pp. 408–418, Ann Arbor, University of Michigan, March 1992.

[11] P. Puetz, K. Jacobs, "E-Beam SIS Junction Fabrication Using CMP and E-Beam Defined Wiring Layer", *Proc. of the Tenth Int. Symp. on Space Terahertz Technology*, pp. 118-129, Charlottesville, University of Virginia, March 1999.

[12] Bruker Optik GmbH, Rheinstetten, Germany.

[13] D. P. Woody, R. E. Miller, M. J. Wengler, "85-115 GHz Receivers for Radio Astronomy", *IEEE Trans. Microwave Theory Tech.*, vol. 33, pp. 90-95, 1985.