Improved design for low noise Nb SIS devices for Band 9 of ALMA (600 - 720 GHz)

C. F. J. Lodewijk, M. Kroug and T. M. Klapwijk
Kavli Institute of Nanoscience, Faculty of Applied Sciences,
Delft University of Technology,
Lorentzweg 1, 2628 CJ Delft, The Netherlands

F. P. Mena, A. M. Baryshev and W. Wild
Space Research Organisation of the Netherlands,
Kapteyn Astronomical Institute,
Landleven 12, 9747 AD Groningen, The Netherlands

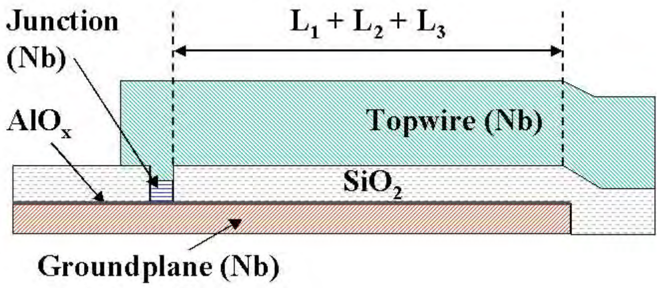
***Abstract*— Superconducting-insulating-superconducting mixers incorporating a novel design were fabricated and evaluated for heterodyne detection in the frequency range of 600 to 720 GHz (ALMA Band 9). The improved design consists in tapering the corners of the RF transformer and a careful optimization of the dimensions to obtain a flat response over the full band. We demonstrate that this new design together with state-of-the-art technology lead to an improved noise temperature of T_N=100K. Since the working frequency of our devices crosses the superconducting gap frequency, we had to include the Mattis-Bardeen theory to simulate the response of this particular design. The results of the simulation are in excellent agreement with the experimental data.**

I. Introduction

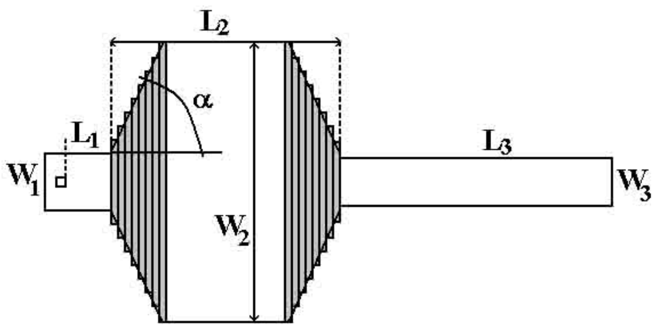
Since their introduction, almost 30 years ago [1], [2], superconducting-insulating-superconducting (SIS) junctions have become the dominant mixing elements for heterodyne detection for space research in which the highest sensitivity is needed. Currently, two instruments are being developed[4], spanning the frequency range of 600 to 720 GHz. The most straightforward state-of-the-art technology uses niobium with a gap-frequency of about 700 GHz, which means that losses in the tuning structure must be taken into account in the design. Most designs [3] use some kind of lumped circuit to model the various pieces of the tuning structure. In practice they do not provide a proper prediction of the bandwidth and leave room for further improvement in noise temperature. In this article we present results obtained with SIS mixers for Band 9 of the Atacama Large Millimeter Array (ALMA), fabricated with state-of-the-art technology and which have been incorporated in a tuning structure using a new design, with 75 degree tapered edges, permitting to achieve an improvement of the noise temperature. Up to now the best noise temperature was about 150 K at 640 GHz [6]. We now report a double sideband uncorrected noise temperature of 100 K over 60% of the band, with a minimum of 93 K at 654 GHz and a slight increase towards ∼175K.

II. Devices

The mixers incorporate a SIS junction and a stripline that tunes out the capacitance of the junction. This structure consists of a superconducting ground plane with a thickness of 200 nm Nb, at the junction an about 7 nm thick Al layer covered with AlO_x as the tunnel barrier and a 500 nm Nb top wire. Between ground plane and top wire a 250 nm layer of SiO_2 serves as dielectric. Contact pads are made of 50 nm thick Au. A schematic cross section along the tuning stripline is shown in Fig. 1(a).



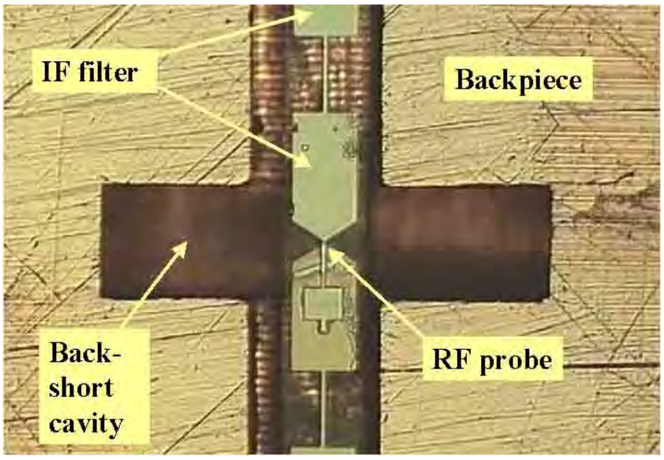
(a) Schematic cross section of SIS junction, wiring and dielectric, along the stripline. The indicated length L_1+L_2+L_3 is the total length of the stripline, L_i referring to the different sections shown in the figure on the right.



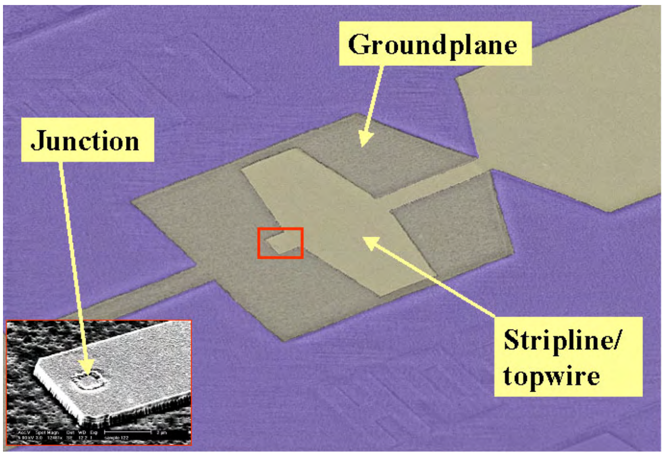
(b) Schematic picture of the tuning structure. The design has tapered edges of the middle section with an angle α of 75 degrees. The tapered part has been modeled by dividing the middle section into small segments, each characterized by an impedance and a propagation constant. The stripline is defined by the widths W_i and lengths L_i of its sections.

Fig. 1. Schematic representations of a tuning stripline.

The devices are fabricated on a quartz substrate. First, a Nb monitor layer is deposited, after which an optically defined ground plane pattern of Nb/Al/AlO_x/Nb is lifted off. Junctions



(a) Photograph of a SIS device with low-pass IF filter, mounted across the backshort cavity. The electromagnetic radiation of the waveguide is coupled into the center of the bowtie (RF probe). The stripline has a design with rectangular middle section.



(b) Scanning electron micrograph of SIS wiring system, with the tapered tuning stripline. Inset shows SIS junction.

Fig. 2. Images of superconducting tuning structures and their surroundings.

are defined by e-beam lithography in a negative e-beam resist layer and etched out with a SF_6/O_2 reactive ion etch (RIE) using AlO_x as a stopping layer. The junction resist pattern is subsequently used as a lift off mask for a dielectric layer of SiO_2. A Nb/Au top layer is deposited and Au is etched with a wet etch in a KI/I_2 solution using an optically defined mask. Finally, using an e-beam defined top wire mask pattern, the layer of Nb is etched with a SF_6/O_2 RIE, finishing the fabrication process.

Part of the top wire is the tuning structure to tune out the capacitance of the SIS junction. In previous designs a narrow strip attached to the junction is connected to a wide section of a certain length followed again by a narrow section. Each section is described by a series and parallel impedance.

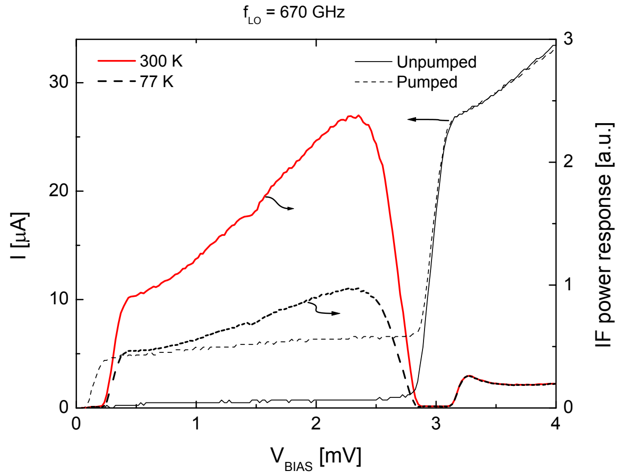


Fig. 3. I-V characteristics and IF response for the SIS mixer pumped at a frequency of 670 GHz.

As usual a periodic RF choke structure is connected to both the groundplane and the top wire to act as a low-pass filter for the intermediate frequency (IF). The complete device is mounted on a backpiece, perpendicular to a waveguide. This waveguide is connected to the feed horn of the astronomical signal. The waveguide ends in a backshort cavity. A photograph of a mixer device mounted across the backshort cavity can be found in Fig. 2(a).

Fig. 3 shows the IV characteristics in the pumped and unpumped situation. Notice that in the pumped situation the first photon assisted tunneling step covers almost the full gap ($\hbar\omega \simeq 2\Delta$).

III. Rectangular Tuning Structure

The input impedance at the RF probe point of the SIS mixer, the center point of the bowtie structure, as can be seen in Fig. 2(a), has been calculated with Microwave Studio™. The input impedance is connected to the SIS junction via the multi-section stripline. The stripline serves as a tuning structure to match the input impedance with the SIS impedance. In this paper, we focuss on improvements of this tuning structure. Its design has been modeled with the software package Mathematica™.

Since we are working close to or above the gap-frequency of the superconductor (Fig. 3), we have to use the complex conductivity, defined as $\sigma = \sigma_1 - i\sigma_2$, and derived from the microscopic theory by Mattis and Bardeen [7]. The surface impedance of a superconductor, in the local limit since we are using Nb[3], is given by

$$Z_s = \sqrt{\frac{i\omega\mu_0}{\sigma}}\mathtt{coth}(\sqrt{i\omega\mu_0\sigma}t) \tag{1}$$

for a strip of thickness t at an angular frequency ω; μ_0 represents the permeability of free space. The series impedance of a part of the strip line is now the sum of the geometrical inductance and the surface impedance of the superconductor, the parallel impedance is formed by the capacitance of the

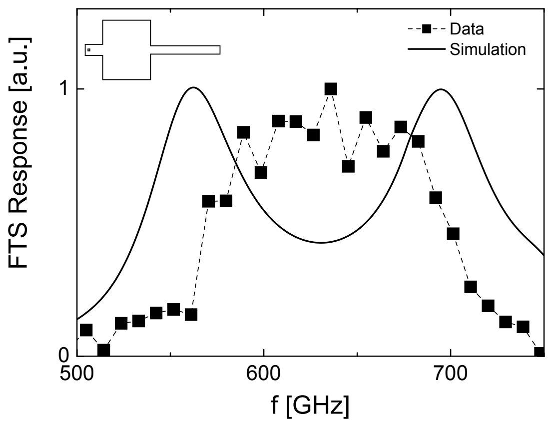


Fig. 4. Frequency response of the mixer with old stripline design: experimental data (solid squares) and simulation with design parameters (full line).

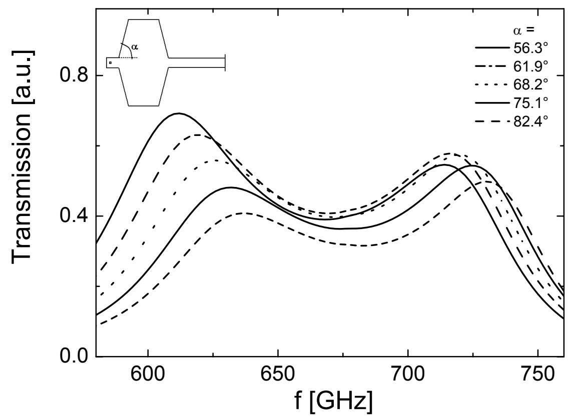


Fig. 5. Calculated transmission as a function of frequency for striplines with tapered middle section. Different lines represent different tapering angles α, while maintaining the same length L_2 (see Fig. 1(b)).

dielectric layer. Following *e.g.* Pozar [8], for each part of the strip line a propagation constant γ and a characteristic impedance Z_0 can be derived; using these two parameters a transmission (or ABCD) matrix is defined.

For the complete strip line, the transmission matrix can be calculated by matrix multiplication. For a strip line consisting of three parts, this yields $A_{tot} = A_1.A_2.A_3$, where the A_i's are the individual ABCD matrices.

The total transmission of electromagnetic radiation from the RF probe to the SIS junction is found as follows. A matrix $A_{j,i}$ is calculated for the imaginary part of the junction impedance and a matrix $A_{a,i}$ for the imaginary part of the antenna impedance [8]. From this, a final transmission matrix X is calculated: $X = A_{j,i}.A_{tot}.A_{a,i}$. Using the real part of the junction impedance, R_j, and the real part of the antenna impedance, R_a, the total transmission coefficient T reads

$$T = \frac{4R_j}{R_a \left| \frac{R_a X_{1,1} + X_{1,2} + R_j R_a X_{2,1} + R_j X_{2,2}}{R_a} \right|^2} \qquad (2)$$

where the $X_{i,j}$'s are the matrix elements of the final transmission matrix X.

We have fabricated devices with a rectangular tuning stripline. The frequency response has been determined using a home-made Fourier Transform spectrometer by measuring the changes produced by the incoming light in the bias current at a particular chosen bias voltage which is selected to be close to the gap.

For these devices, the measured FTS response was flat, but it covered mostly the lower part of the 600 - 720 GHz band. To get a better hold of what was going on, the transmission of these devices has been calculated. As can be seen in Fig. 4, experiment and calculations clearly do not match. Changing the parameters that may have varied due to fabrication uncertainties were not successful to make the correspondence better. As a result, we were unable to improve the performance of these rectangular devices, experimentally nor theoretically.

IV. Tapered tuning structure

If the middle strip is much wider than the two outer parts, the simple way of calculating the transmission matrix as described in the previous section is inaccurate, because there is expected to be a gradual change in current density. This means there are parts of the wide sections where no current flows, which will add extra capacitance.

In using normal metal striplines, extra capacitors should be added to the model to compensate for the step in width [8]. For superconducting striplines the right method of compensation is unclear. As an alternative, we introduce in the design itself a gradual change, by tapering the corners of the wide section. This has been modeled by artificially dividing the middle strip into small segments with increasing and decreasing widths, as can be seen in Fig. 1(b). The total transmission matrix is now

$$A_{tot} = A_1.A_{21}.A_{22}.(...).A_{2n}.A_3 \qquad (3)$$

where A_{2i} are the partial ABCD matrices of the n parts the middle strip was divided into.

We have calculated the transmission for striplines with different tapering angles, plotted in Fig. 5. It can be seen that for smaller tapering angles, corresponding to a smoother transition to and from the middle section, the high end cutoff frequency remains more or less the same, determined by the frequency-dependence of the surface resistance of the superconductor, but the lower side of the band shifts downwards.

It was decided to design and fabricate mixers with a 75^o tapered stripline. For a top view of such a device, a scanning electron microscope (SEM) picture is shown in Fig. 2(b). The simulation was changed accordingly and when the measured FTS data are compared with the calculated transmission, as shown in Fig. 6, it is clear that there is a much better correspondence between the two. The FTS data show a flat response and a frequency coverage beyond 700 GHz. The difference in size of the bandwidth can be attributed to uncertainties in

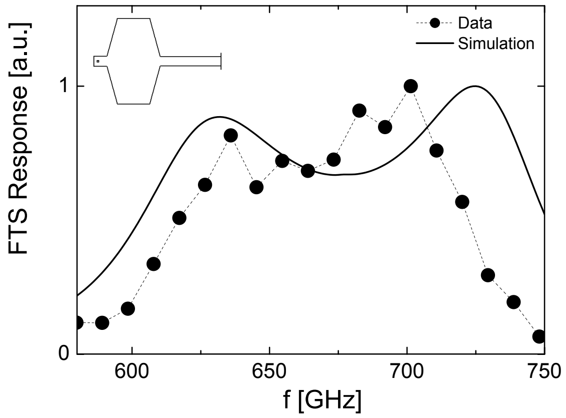


Fig. 6. Frequency response of the mixer with tapered stripline design: experimental data (solid dots) and simulation with design parameters (full line).

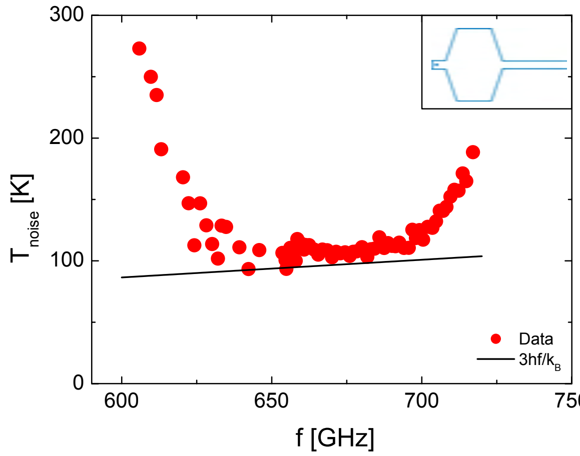


Fig. 7. Uncorrected DSB noise temperature realized with improved tuning structure. Inset shows the tuning stripline with the tapered middle section. The full line shows a noise level of 3hf/k$_B$.

fabrication parameters, such as thickness of the SiO_2 and the area (i.e. capacitance) of the junction.

V. Noise Temperature

The noise temperature of the mixer, the accompanying optics and IF chain [5] has been measured using the standard Y-factor method. The hot and cold loads were kept at 295 and 77 K, respectively, and their radiation was mixed with the local oscillator (LO) signal using a 10 μm mylar beam splitter. The SIS mixer is kept in a cryostat which has a quartz window coated with an antireflection layer. As an example, in Fig. 3, we show the IV curve when the mixer is pumped with an LO frequency of 670 GHz. The same figure also shows the IF power levels at the same frequency. The resulting uncorrected DSB noise temperatures at different LO frequencies are presented in Fig. 7. The noise temperature is as low as 93 K at 654 GHz and is about 100 K for 60% of the 600 - 720 GHz band. The results presented here correspond to the mixer exhibiting the best noise temperature. However, the reproducibility between mixers is excellent, the maximum achieved noise temperature being no more than 30% higher than the one presented in Fig. 7.

VI. Conclusions and Discussion

SIS mixers with a new design have been fabricated and evaluated for heterodyne detection in the frequency range of 600 to 720 GHz (ALMA band 9). We have shown that the combination of this design with state-of-the-art technology results in the lowest noise temperature ever achieved in this frequency band. The improved design consists in tapering the corners of the RF transformer which traditionally is rectangular. As a result, the frequency response is flatter in the desired band and the noise temperature is lower, compared to previous devices.

Acknowledgements

The authors would like to thank NanoImpuls, the Dutch Research School for Astronomy (NOVA), the Dutch Organisation for Scientific Research (NWO) and the European Southern Observatory (ESO) for funding this project.

References

[1] G. J. Dolan, T. G. Phillips, and D. P. Woody, Appl. Phys. Lett. **34**, 347 (1979)

[2] P. L. Richards, T. M. Shen, R. E. Harris and F. L. Lloyd, Appl. Phys. Lett. **34**, 345 (1979)

[3] G. de Lange, J. J. Kuipers, T. M. Klapwijk, R. A. Panhuyzen, H. van de Stadt, and M. W. M. de Graauw, J. Appl. Phys. **77**, 1795 (1995).

[4] For example, two main astronomical large projects that are demanding such applications are ALMA (http://www.eso.org/projects/alma/) and its precursor CHAMP (http://www.mpifr-bonn.mpg.de/div/mm/apex/).

[5] A. Baryshev, E. Lauria, R. Hesper, T. Zijlstra, and W. Wild, ALMA memo 429.

[6] C. M. Gaidis, H. LeDuc, M. Bin, D. Miller, J. A. Stern, and J. Zmuidzinas, IEEE Transactions on Microwave Theory and Techniques **44**, 1130 (1996).

[7] D. C. Mattis and J. Bardeen, Phys. Rev. **111**, 412 (1958).

[8] D. M. Pozar, *Microwave Engineering*, John Wiley and Sons (1998).