Low-noise micromachined SIS mixers for millimeter-wave imaging arrays

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Heterodyne mixers with a micromachined horn antenna and a SIS tunnel junction as mixing element are tested in the 75-115 GHz and 180-220 GHz frequency range. The mixer performance is optimized by using a backing plane behind the dipole antenna to tune out the capacitance of the tunnel junction. For the W-band mixer a lowest DSB receiver noise temperature of 30 ± 3 K is measured at 106 GHz with a 3-dB bandwidth of 8 GHz. Preliminary measurements of the 180-220 GHz mixer yield a 109 K DSB noise temperature at 204 GHz. The design of a micromachined 190 GHz SIS focal plane array is described.

1 Introduction

Our recent progress in the development of micromachined horn antennas with superconducting (SIS) tunnel junctions as mixing elements has resulted in a heterodyne receiver for the W-band frequency range with a sensitivity comparable to the best waveguide and open-structure antenna receivers [1].

Micromachined horn antennas consist of a dipole antenna fabricated on a thin ($\sim 1 \ \mu$m) Si_3N_4 dielectric membrane inside a pyramidal cavity etched in silicon [2]. In the construction of this type of antenna, standard whole-wafer photolithography and well established anisotropic Si etching processes are used. The relative ease (and low cost) of fabrication of accurate millimeter- and submillimeter-wave components, the absence of substrate losses, and the possibilities of integrating a mixing element with super- or semi-conducting electronics (e.g. SQUID IF-amplifiers or Flux-Flow oscillators) make this type of antenna attractive in comparison with conventional waveguide and open structure antennas [3, 4].

A promising application of SIS micromachined horn antennas is in focal plane imaging arrays. Imaging arrays of SIS-receivers would be of great benefit for the observation of spatially extended sources in astronomy, but the high cost and mechanical difficulties of building an array of waveguide mixers and the poorer beam-quality of open-structure antennas have thus far limited the efforts of actually developing such arrays [5, 6, 7, 8, 9]. SIS-mixers made with micromachined horn antennas offer both a relatively easy, low cost fabrication and excellent Gaussian beam properties and are therefore well suited for the development of imaging arrays. To demonstrate the feasibility of micromachined horn antennas in imaging arrays we are currently fabricating a 3x3 focal plane SIS imaging array for the 180-220 GHz frequency range. In parallel we develop two room temperature imaging arrays with thin film Nb as bolometers for the 70-110 GHz and 180-220 GHz frequency range [10].
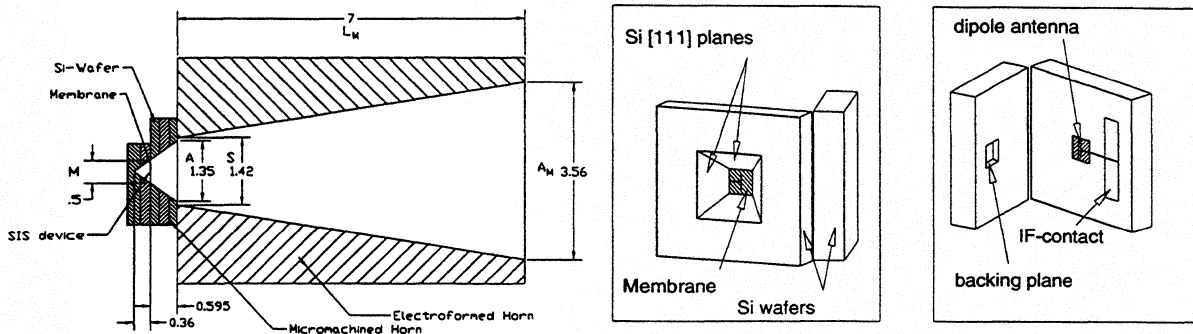
Figure 1: *(a) Geometry of the micromachined horn structure. Dimensions are given in units of wavelength at the designed frequency. (b) Details of a micromachined mixer before bonding the wafers together.*

This paper elaborates on the measurements of the micromachined SIS mixer for the 75-115 GHz frequency range presented in [1] and preliminary results of the 190 GHz mixer, and discusses some design aspects of the SIS focal plane imaging array.

2 Receiver design and device fabrication.

The geometry and main dimensions of the micromachined horn-antenna are shown in Fig 1, where the dimensions are expressed in units of wavelength of the design frequency. A detailed description of the receiver and the fabrication of the micromachined mixer and quasi-integrated horn antenna is given in [11, 12].

The dipole length and distance from the apex of the pyramidal horn as shown in Fig. 1a give a 35 Ω antenna impedance at the designed center frequency. This impedance gives a good match to the low capacitive GaAs Schottky diodes ($C \approx 10\ fF$) [13, 14] in the

original design, but causes a nearly 5 dB return loss with the highly capacitive ($C \approx 70\ fF$) superconducting tunnel junctions [12]. In order to reduce this impedance mismatch we fabricated and tested several horn antennas, where the backing wafers do not form a complete pyramidal cavity, but a reflecting backing plane located at various distances d_{bp} from the dipole antenna(see Fig. 1b). This backing plane can provide an inductive impedance at the antenna terminals, which resonates out the junction capacitance, thereby reducing the impedance mismatch.

The backing planes are fabricated by removing a wafer from the KOH-etchant before the wafer is completely etched through. In the resulting structure the surface of the (100) backing plane is slightly rough, but this roughness is on order of several microns and will therefore not influence the operation in the millimeter wave range. Backing planes at distances of 95, 240, and 345 μm have been fabricated, with etching times of (approximately) 1, 2, and 3 hours.

3 Results of the 90 GHz and 190 GHz mixers

3.1 FTS measurements

The frequency response of the micromachined horn antennas is measured with a Fourier Transform Spectrometer (FTS). Fig. 2a shows the result of the measured frequency dependent coupling of three 90GHz horn antennas with
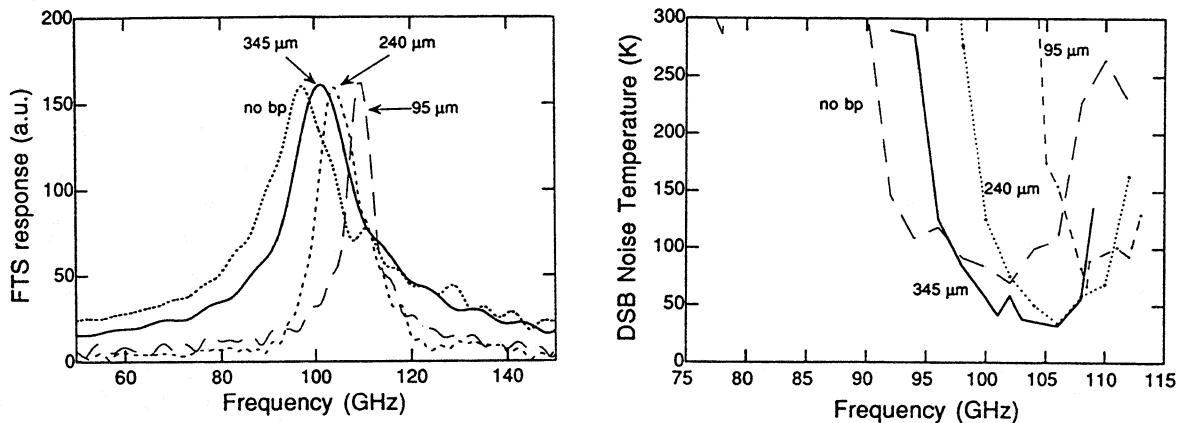
Figure 2: *(a) Frequency dependent coupling of a micromachined horn antenna with three different backing planes and a pyramidal backing cavity (no bp). The coupling is measured with a Fourier Transform Spectrometer. (b) Noise temperature of the micromachined SIS-mixer for three different backing planes and a pyramidal backing cavity, as a function of frequency.*

different backing planes, together with the coupling of the original pyramidal shaped cavity. The results shown in the figure are scaled to each other, to give the same maximum coupling. As can be seen in the figure, the frequency of maximum coupling increases with decreasing distance between the dipole antenna and the backing plane, while the bandwidth of the coupling decreases. This can be understood qualitatively if we assume a simple waveguide model of the hornstructure, where the impedance of the backing plane is given by $Z_{bp} = jZ_0 \tan(2\pi d_{bp}/\lambda_g)$, which should resonate out the junction reactance $1/(j2\pi fC)$. For small values of d_{bp}, this gives a resonance frequency of $f_{res} = 1/(2\pi)\sqrt{(/\mu_0 C d_{bp})}$, which increases with decreasing d. With the same model it can also be shown that the bandwidth decreases with decreasing backing plane distance.

In the inset of fig. 4b the measured frequency dependent coupling of the 190 GHz mixer is shown. In this measurement the backing plane is located at 95 μm. The maximum coupling occurs at 202 GHz, which is slightly higher than the design frequency of 190 GHz for a horn with a pyramidal backing cavity.

3.2 Noise measurements

Results of heterodyne measurements with the 90 GHz and 190 GHz mixers are shown in Figs. 2b, 3a, and 4a. Both mixers use an array of two Nb junctions The arrays have a normal state resistance of $R_N = 37\ \Omega$ (90 GHz) and $R_N = 42\ \Omega$ (190 GHz) The junction area is 2.6 μm^2 (the critical current density is $J_c \sim 5$ kA/cm^2). The signal and LO-power are combined by a 97% transmission beam splitter and the IF-power is measured in a 35 MHz bandwidth at a center frequency of 1.5 GHz.

Fig. 3a shows the pumped DC I-V curve and IF-output power of the 90 GHz mixer measured at a 106 GHz LO frequency (at a mixer mount temperature of 3.1 K) and the backing plane located at 345 μm. The maximum Y-factor (measured at the first photonstep below the gap voltage) is 4.8 dB, which results in a 30 $\pm$ 3 K DSB receiver noise temperature (without any correction). Analysis of the receiver noise temperature shows that the
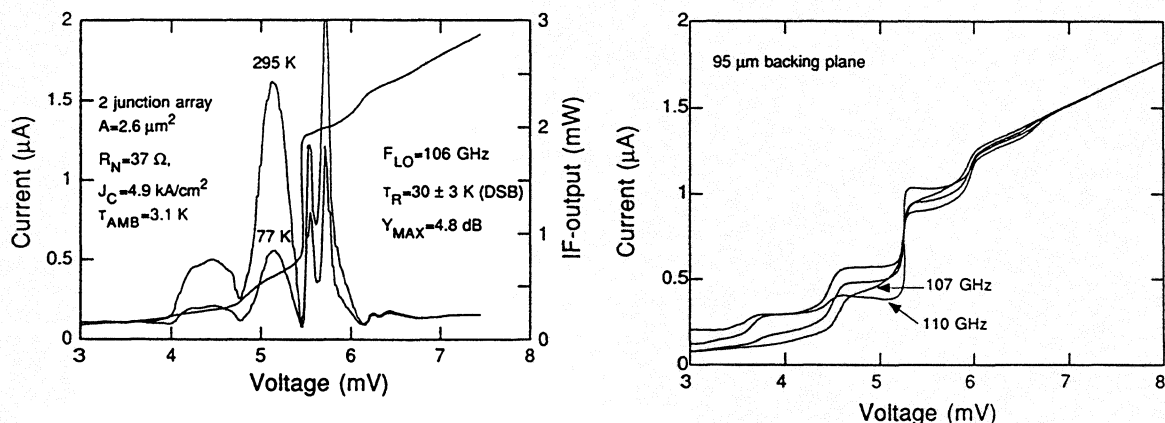
Figure 3: *(a) Pumped I-V characteristics of device HEN52 at a LO frequency of 106 GHz and the measured IF-output power with a 295 and 77 K input load. (b) Pumped I-V curves with 107-110 GHz LO frequencies for the 90 GHz mixer with a 95 μm backing plane. The changes in the dynamic resistance of the I-V curve on the photon steps indicate that the geometric capacitance of the junction is tuned out.*

mixer gain is 1.2 ±0.8 dB and the mixer noise temperature is 7.6 ± 5 K.

The measured noise temperature as a function of frequency of this device is shown in Fig. 2b. The 3 dB bandwidth of the mixer is ≈ 8 GHz. Fig. 2b also shows results of a measurement with the same array of junctions but used in a horn with the pyramidal shaped backing cavity. The best results obtained then are a DSB noise temperature of 70 K and a 3-dB bandwidth of 15 GHz [12], which shows the effectiveness of the backing plane in reducing the RF-mismatch. Results of the measurements with two other backing planes are also shown in Fig. 2b. Similar to the FTS measurement, a decreasing bandwidth and a shift in frequency response towards higher frequencies is observed when the distance between the dipole antenna and the backing plane is decreased. The lowest DSB noise temperatures measured with the 240 μm and 95 μm backing plane is 35 K and 66 K, respectively.

In measurements with the backing plane located at 95 μm, shown in Fig. 3b, the pumped I-V curve exhibits regions of negative dynamic resistance. This is a consequence of the reactive part of the tunnel current, and indicates that the geometrical capacitance of the junction is completely tuned out, again showing the effectiveness of the backing plane.

The current state-of-the-art waveguide and quasi-optical receivers for the 90-115 frequency range have DSB noise temperatures of 19 K and 38 K, respectively [15, 16, 17, 18, 19]. Our current results show therefore that the sensitivity of micromachined SIS-mixers is comparable to the best waveguide and quasi-optical mixers. The bandwidth of the mixer is now limited by the tuning range of the backing plane tuning. In a future design we will use on-chip integrated tuning elements to tune out the junction capacitance, which will likely increase the bandwidth to 15%, the bandwidth of the dipole antenna in the micromachined horn.

Preliminary results of the 190 GHz mixer with a 95 μm backing plane and a 204 GHz LO frequency are shown in Fig. 4a. The best result obtained thus far is a 109 K DSB receiver noise temperature at 204 GHz. The gold on the sidewalls of the device wafer used in this measurement was partly delaminated, which gives rise to increased
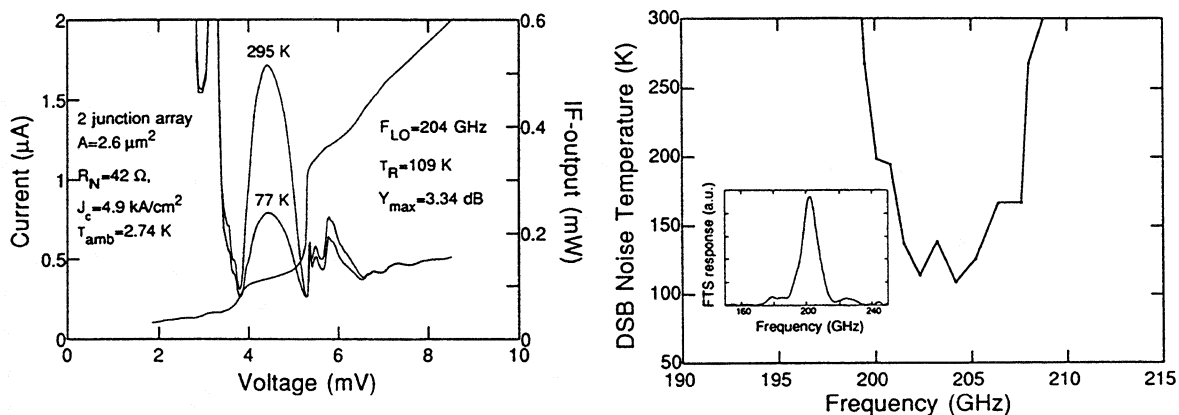
Figure 4: *(a) Pumped I-V characteristics of the 190 GHz mixer at a LO frequency of 204 GHz and the measured IF-output power with a 295 and 77 K input load. (b) Instantaneous bandwidth of the 190 GHz mixer. The inset shows the frequency dependent coupling of the horn antenna measured with an FTS.*

losses. We therefore expect a reduction in noise temperature in future measurements. The noise temperature as a function of frequency for the 190 GHz mixer is shown in Fig. 4a. The 3 dB bandwidth of the mixer is $\approx$ 6 GHz. Although there is room for improvement of the 190 GHz receiver sensitivity, these results do indicate that the micromachined SIS-mixer work well in the 180-220 GHz frequency range.

4 190 GHz SIS Focal Plane Array

Based on the excellent performance of the single element mixers, we are currently fabricating a 3 x 3 SIS focal plane imaging array for 190 GHz. The choice for a 190 GHz center frequency is mainly determined by the availability of an LO-source and the dimensions of the cryostat. The array will first operate with a single IF-amplifier, where separate elements can be selected by voltage controlled IF-switches. For simultaneous measurements of the elements the array has to operate in a direct detection mode.

The design of the array of machined horn sections is shown in Fig. 5a. Arrays of diagonal horns can be made with a high packing density and are relatively easy to fabricate on a milling machine [20].

In front of the horn array we use two TPX lenses (with a focal length of 43 and 50 mm) separated in distance by their focal lengths (see Fig. 6 This combination of lenses adequately avoids truncation of the antenna beams at the dewar window and forms a slightly magnified image of the array elements at a 15 cm distance in front of the dewar. This lens set-up is convenient for our test receiver, since we can use a small hot/cold load for the heterodyne measurement and the array is reasonably uniform illuminated if we use a beam splitter between the two lenses to couple the LO. In a set-up for measurements at a telescope the second lens can be used to adapt for the required f-number of the telescope optics.

The spacing of the individual elements of the array is determined by the aperture dimensions of the machined horn section. For the 190 GHz array the element spacing is 6.5 mm, which is $\sim$ 3.5 beam waist (the
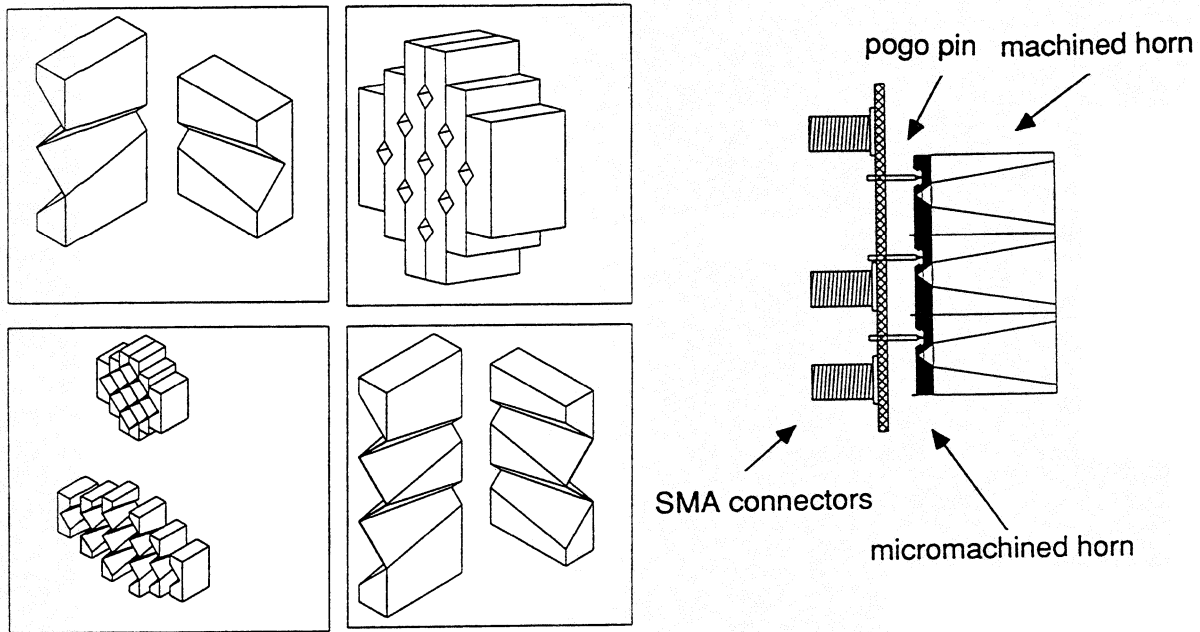
Figure 5: *(a) Design of the machined section of the 190 GHz SIS imaging array (b) Design for the IF/DC connections for the seperate elements of the array.*

$1/e^2$ beam angle of the horn is $16°$). The angular separation θ_r of the parallel beams from the array, separated by a distance d, in combination with a lens of focal length f is $\approx d/f$ whereas the 3dB beam angle θ_{3dB} of a beam with input beam waist w_{in} is $0.59\, w_{in}/f$. For a maximum sampling of the sky one requires a 3 dB beam overlap and thus $\theta_r = 2\, \theta_{3dB}$ which gives a element separation of $d = 1.18\, w_{in}$. Our array therefore undersamples the sky, as any horn array will do since the beam waist of the horn is always considerably smaller than the aperture dimensions of the horn [6].

Because of the specific structure of the micromachined horn antenna interference of IF and DC-bias lines with RF antenna is completely avoided and also poses no limitations on the element spacing, problems which are of concern in waveguide and open structure antennas. The design of the DC/IF connections is shown in Fig. 5. Holes are etched in the Si wafers forming the backing cavity to give access to the contact pads (see Fig. 1). The contact with the pads is made with spring-loaded (pogo) pins and these pogo pins are mounted in a Duroid substrate and connected via a microstrip line to SMA-connectors.

5 Summary

We have shown the operation of micromachined SIS mixer for the 75-115 GHz and 180-220 GHz range. Excellent noise temperatures are measures, comparable to state-of-the-art waveguide and open structure antennas. A SIS micromachined focal plane imaging array for 190 GHz is currently under construction.
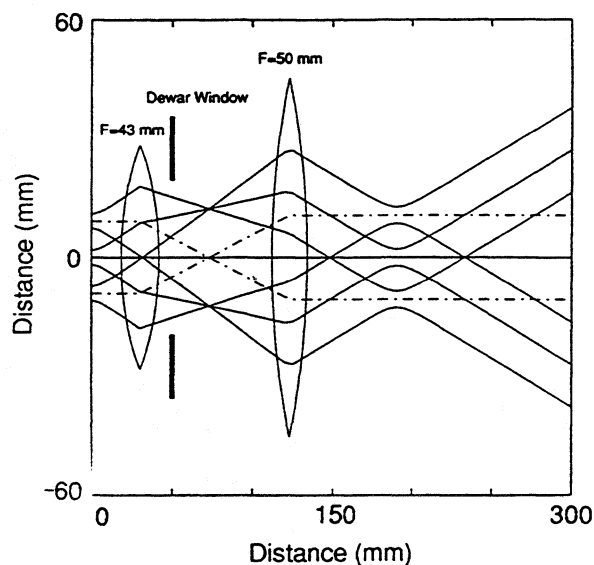
Figure 6: *Optics for the 190 GHz SIS imaging array.*

6 Acknowledgement

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