A low-noise, 9-element Micromachined SIS Imaging Array.

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Results from a 3×3 micromachined millimeter-wave focal-plane imaging array with superconducting tunnel junctions as mixing elements are presented. The array operates in the 170-210 GHz frequency range. The array uses 9 μm^2, low impedance ($3.5 - 4.5\ \Omega$) junctions, commercially available from Hypres Inc. Integrated tuning structures are implemented to match the devices to the antenna impedance. Noise measurements show a lowest DSB noise temperatures of 52 K (@190 GHz) (for the central element). Lowest noise temperatures from the off-axis elements are in the range of 60-100 K DSB, with a uniform bandwidth of 30 GHz. Antenna beam patterns with a high Gaussian profile have been measured for on- and off-axis elements.

1 Introduction

Imaging arrays of SIS-receivers are 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 [1, 2, 3, 4, 5]. SIS-mixers made with micromachined horn antennas offer a relatively easy, low cost fabrication, excellent Gaussian beam properties, and compactness, and are therefore well suited for the development of imaging arrays. Because of the specific structure of the micromachined horn antenna, interference of IF and DC-bias lines with RF antenna is avoided and also there is no limitation on the element spacing, which are problems of concern in waveguide and open structure antennas. Further advantages for the use of micromachined horn antennas in high frequency imaging arrays are 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) [6, 7, 8]. To demonstrate the feasibility of micromachined horn antennas in imaging arrays, we have developed a 3×3 focal plane SIS imaging array for the 170-210 GHz frequency range (the choice of the frequency range is mainly determined by the availability of the Local Oscillator and the dimensions of the cryostat). In parallel we have developed two room-temperature imaging arrays with thin-film Nb as bolometers for the 70-110 GHz and 170-210 GHz frequency range [9].

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 (see Fig. 1)[10, 11]. We previously developed a single-element micromachined SIS receiver for the W-band frequency range, which showed a sensitivity comparable to the best waveguide and quasi-optical open-structure receivers [12].

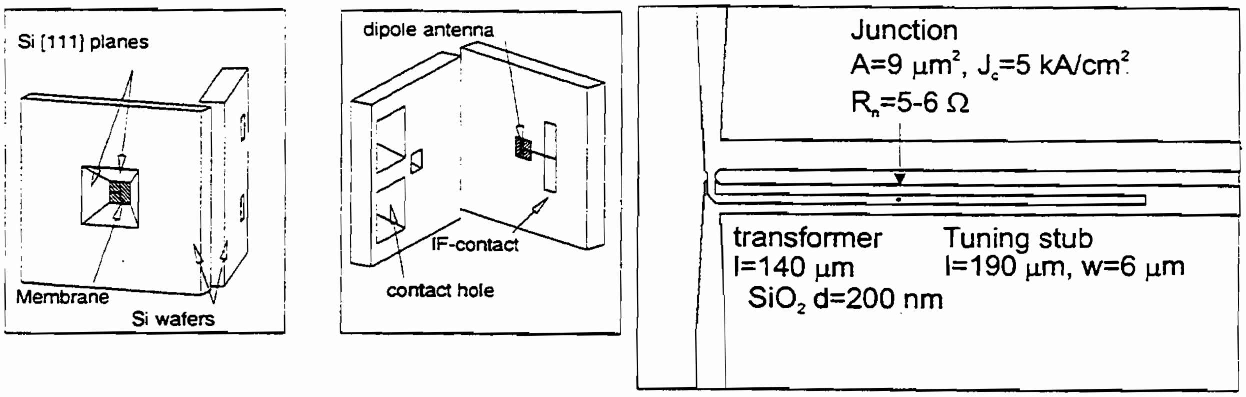


Figure 1: *(a) Details of a single element of the micromachined array, showing the pyramidal cavity, the membrane, the through holes for the IF/DC connections, and the dipole antenna. (b) Details of the central region of the dipole antenna. The junction and tuning structure are located on the DC/IF coplanar bias lines.*

This paper describes the design and fabrication of a 3×3 170-210 GHz imaging array receiver, and the DC and noise characterization of the array performance.

2 Receiver Design

An expanded view of the receiver and some details of the individual elements are shown in Figs. 1 and 2. A detailed description of the receiver is given in [13]

The micromachined array is made of a stack of 4 Si wafers with a total thickness of 1.7 mm. The dipole antenna on the membrane is 0.58 mm long (0.37 λ). In order to have access to the contact pads on the device wafer, through holes are etched in the two wafers forming the apex of the horn (see Fig. 1a). A detailed description of the individual micromachined antenna elements and the quasi-integrated horn antenna is given in [14, 15].

A single $Nb/Al_2O_3/Nb$ SIS junction is used as mixer element. The device has an area of 9 μm^2 and a current density of 5 kA/cm^2. The coupling of the relatively large-area and low impedance (3.5-4.5 Ω) junction to the 35 Ω antenna impedance is optimized by an on-chip tuning circuit, shown in Fig. 1b. The tuning circuit uses an inductive length of microstrip to tune out the junction capacitance, and a $\lambda/4$ microstrip impedance transformer to match the junction impedance to the antenna impedance. The microstrip is 6 μm wide and its characteristic impedance is 8.5 Ω. Devices with a microstrip length of 190 μm for the inductive stub and 140 μm for the impedance transformer show a maximum coupling around 190 GHz, which is the center frequency of the dipole antenna.

The geometry of the machined horn section is similar to the diagonal horn described in Ref [16]. Arrays of diagonal horns can be made with a high packing density and are relatively easy to fabricate on a milling machine with a split block technique. The array is formed by a stack of six gold plated tellurium copper blocks and fabricated at MIT Lincoln Laboratory

As shown in Fig. 2, the minimum spacing of the individual elements of the array is determined by the aperture dimensions of the machined diagonal horn section. For the 200 GHz array the element spacing is 6.5 mm, which is $\sim$ 3.5 beam waist (the $1/e^2$ 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 or reflector 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. A maximum sampling of the sky requires a 3 dB beam overlap and thus $\theta_r = 2\ \theta_{3dB}$ which gives an element separation of $d = 1.18\ w_{in}$. Our array

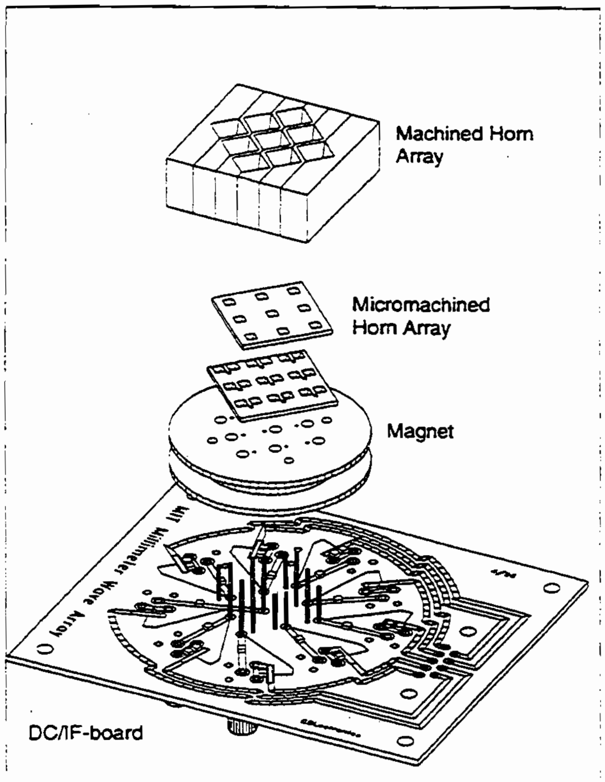


Figure 2: *Expanded view of the array receiver showing the machined horn array, the micromachined array, the magnet, and the DC/IF-board*

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 [2]. Quasi-integrated horn antennas can be used as a feed for reflector antennas without additonal lenses. Because of the limited diameter (5 cm) of the 77 K radiation filter (a 5 mm thick PTFE disk) and the dewar window (a 25 μm thick sheet of polypropylene) in the measurement set-up, a PTFE lens with a focal length of 37 mm is used in our set-up, to avoid truncation of the array beams. This lens is at 4.2 K.

A single magnet coil (made of copper) with approximately 2500 turns of superconducting 100-μm thick Nb wire (Supercon T48B) is used to suppress unwanted Josephson effects. The geometry of the micromachined array allows the magnet to be in very close proximity of the junction ($\sim$ 1.5 mm). Although the positioning of the magnet (with the magnetic field lines perpendicular to the junction surface) is not preferable, a magnet current of 200-300 mA is sufficient to suppress the Josephson effects

In order to have local access to the array elements, through holes are etched in the backing wafers. This avoids the use of long coplanar lines on the device wafer (to bring the signals to the border of the wafer) and thereby increases the available space for mixer elements, reduces possible cross-talk between different elements, and increases the flexibility of the receiver design. Contact between the array elements and the DC/IF board is made by Servometer bellow contacts (type 2510), mounted on top of a miniature screw. The screws are mounted either directly in the core of the magnet (for the ground contact) or as the center conductor of a short section of semi-rigid cable which is also mounted in the core of the magnet. This allows individual adjustment of all contacts

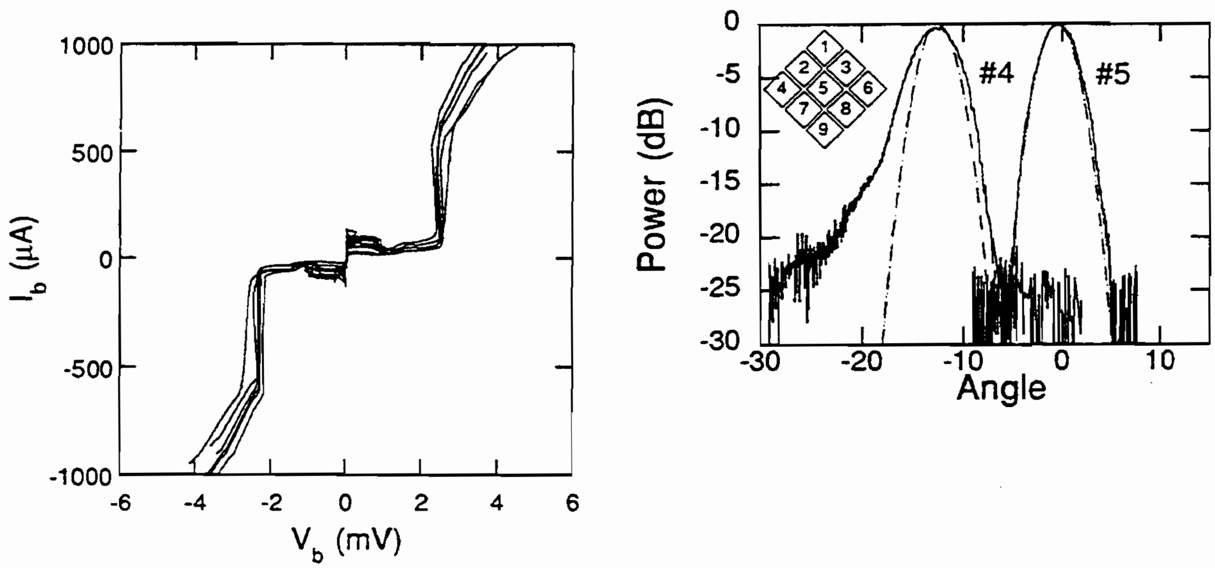


Figure 3: *(a) DC I-V curve of 5 SIS devices of the 9 element array. (b) Measured antenna beam patterns for two elements on the diagonal of the imaging array. The inset shows the device numbering.*

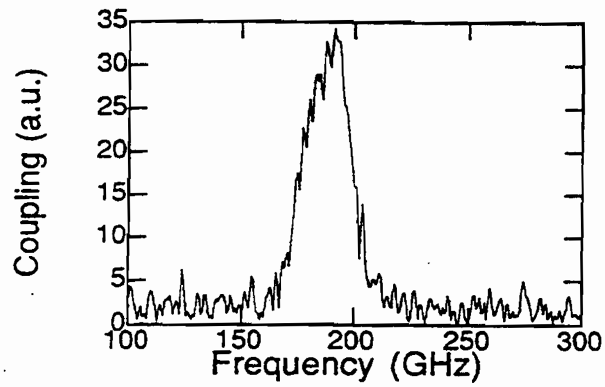
and has proven to be a reliable contact at cryogenic temperatures.

The IF/DC-board is made of Duroid 6010 material and contains a T-bias circuit for each array element. Contact between the contact screws and the IF board is made by using tight fitting sockets, soldered on the IF-board.

The array operates with a single IF-amplification stage. Noise measurements on different elements of the array are done by connecting the IF-amplifier to the different IF-ports on the DC/IF Board. The cold stage of the IF-chain consists of a Pamtech LTE 1268K isolator, and a Berkshire Technologies L-1.5-30HI IF-amplifier (40 dB). A further amplification of 60 dB is provided by room-temperature amplifiers outside the dewar. The IF-power is measured in a 35 MHz bandwidth with an HP-436A power sensor at a center frequency of 1.5 GHz (set by a tunable bandpass filter).

3 Device fabrication

The micromachined SIS arrays are made partially at Hypres and partially at MIT Lincoln Lab. The SIS devices are fabricated on 0.38 mm thick (100)-oriented silicon wafers, covered on both sides with a 1-μm thick, low-stress Si_3N_4 layer. The junctions and antennas are defined with the standard Hypres fabrication procedure. The freestanding membrane is formed by etching the silicon in a solution which contains 20% KOH by weight at 80 ^{0}C for 4-5 hours and another hour at 60 ^{0}C. The last step is used to create smooth sidewalls of the aperture. The final fabrication step is the deposition by E-beam evaporation of a 400-nm Ti/Au layer on the sidewalls of the aperture through a ceramic shadow mask.



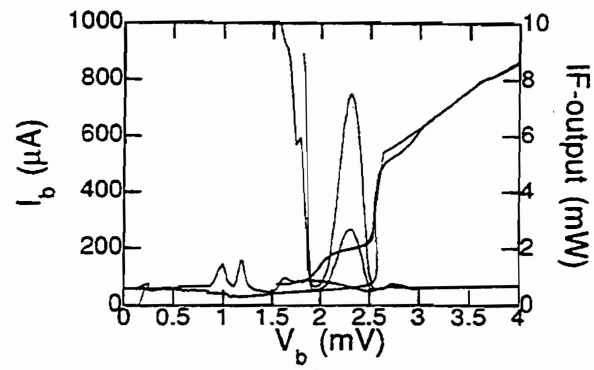


Figure 4: *(a) FTS Measurement of an array element with a tuning structure as shown in Fig. 1b. (b) Pumped I-V characteristics of element #5 at a LO frequency of 190 GHz and the measured IF-output power with a 295 and 77 K input load.*

4 Results

4.1 DC measurements

Results of typical DC I-V measurements of 5 SIS devices in the array are shown in Fig. 3a. The measurements are performed with the mixerblock mounted in the vacuum dewar (at a bath temperature of 4.2 K). As shown in Fig. 3a the I-V characteristics show 'back bending' at voltages above the 2.5 mV gap voltage. This is not observed if the devices are measured on a dip-stick submerged in liquid helium and therefore it indicates heating of the devices due to the poor thermal conductance of the membrane. Previous measurements with smaller (2.5 μm^2, $R = 40\ \Omega$) devices did not show this heating effect. Although the back bending does not severely deteriorate the mixer performance, future designs can have an improved cooling by extending the tuning structure (with an extra length of $\lambda/2$), which will locate the devices on the solid silicon region. The device resistance ranges from 3.5 to 4.5 Ω. A drawback of SIS arrays fabricated on one single chip is the possible failure of one of the elements, which then cannot be replaced. We have measured the I-V characteristics of several arrays and always found all 9 elements operating.

4.2 Antenna Pattern Measurement

As a preliminary test of the antenna patterns of different array elements, we previously measured the 45-degree antenna patterns of two elements at a frequency of 182 GHz. The 45-degree plane antenna are obtained by measuring the video response of the elements while rotating the dewar with a rotation stage. Due to the 45 degree angle of the array with respect to the optical table, a combined co- and cross- polarisation is measured. The two elements are at the center and outermost postion on the diagonal of the array, with the antenna beams parallel to the optical table. This measurement includes the cold lens inside the dewar. The measured antenna patterns are shown in Fig. 3b, together with a Gaussian beam profile. The measured radial separation of the beams is 12.5°, and the 10 dB beamwidth of the central beam is 6.8°. Calculated values (using a thin lens approximation) for the beam separation and beam width are 14.4° and 5.2°, respectively. with The off-axis element has a wider beam and it has an assymmetric shoulder at -17 dB, which we attribute to abberations caused by the lens. Previous measurements of single element quasi-integrated horn antennas [11] and single element [17] and arrays of diagonal horns with waveguide feeds [16] have shown excellent Gaussian antenna beam profiles at frequencies close to 1 THz. Recent

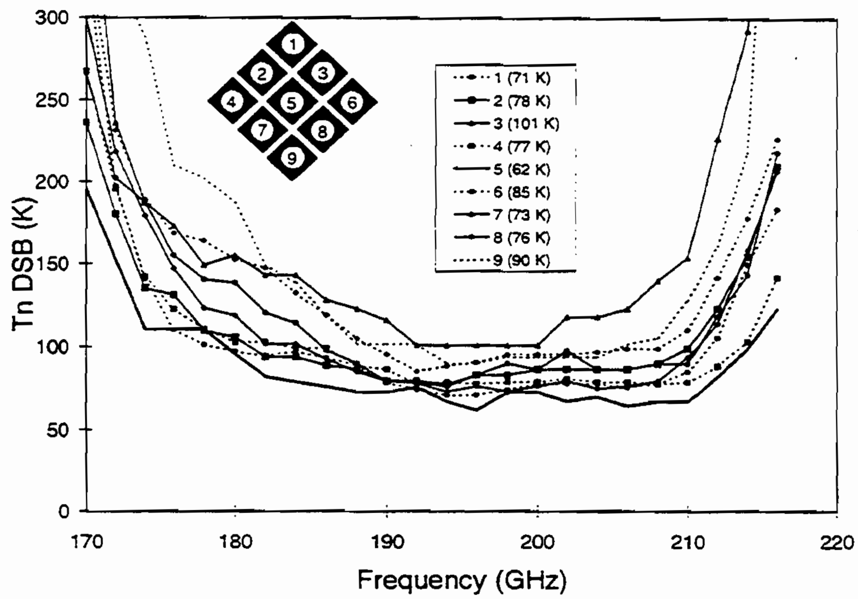


Figure 5: *Measured DSB noise temperatures of the different elements in the array. The inset shows the minimum noise temperature for the individual elements.*

measurements on our 95 GHz room-temperature bolometer also show excellent beam properties [18].

4.3 FTS measurements

The frequency response of the integrated tuning structures is measured with a Fourier Transform Spectrometer (FTS). The FTS uses a Hg-arc lamp as a broadband millimeter wave source, and is operated in the step-and-integrate mode. In these measurements the devices are biased at a voltage just below the gap voltage and used as a video detector. Fig. 4a shows the result of a measured frequency dependent coupling of a device with a tuning stub length of 190 μm and a transformer length of 140 μm. The calculated bandwidth for this tuning structure (assuming a frequency independent antenna impedance) is about 60 GHz. The measured bandwidth of 30 GHz is therefore limited by the 15 % bandwidth of the dipole antenna.

4.4 Noise measurements

Results of a heterodyne measurement on the central element (device # 5, see inset of Fig. 3b) of the array are shown in Fig. 4b. 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. 4b shows the pumped DC I-V curve and IF-output power measured at a 190 GHz LO frequency. The minimum uncorrected receiver noise temperature is 52 K DSB, measured at a bath temperature of 2.7 K. Although the device shows some heating effects above the gap-voltage, this noise temperature is still comparable to the best results obtained in tunable waveguide mixers [19, 20, 21].

The measured noise temperatures as functions of frequency for 9 elements of another array are shown in Fig. 5. In this array the minimum noise temperature of the central element is 62 K (see the inset). The measured noise temperature of the different elements is fairly uniform, with minimum noise temperatures for 8 elements ranging from 62 to 90 K and one element with a somewhat elevated noise temperature of 101 K. The 3-dB noise bandwidth of the elements has a uniform value of around 30 GHz across the array. We contribute the differences in the noise temperature across the array partly to the effect of the limited size of our dewar window and the need of using a rather thick lens inside the dewar. Measurements of different arrays always showed a lowest noise temperature for the central element. As shown in Fig. 4b, the lens deteriorates the off-axis beam pattern and because the 9 beams enter the dewar under different angles, it complicates the coupling of the LO and the Hot/Cold source. The LO and signal coupling is now optimized by tilting and rotating the beam splitter or the dewar. Further optimization of the optical coupling will most likely make the noise temperature across the array more uniform.

Our measurements therefore indicate the feasibility of compact, low-cost micromachined SIS focal plane imaging arrays, with competetive noise temperatures. Furthermore, the scalability of the machined and micromachined sections show the promising prospect for the use of micromachined focal plane imaging arrays for frequencies up to 1 THz.

5 Summary

We have described the design, fabrication, and testing of a SIS micromachined 3 × 3 focal-plane imaging array for the 170-210 GHz frequency range. Heterodyne noise measurements on the array elements showed a lowest DSB noise temperature of 52 K for a central element, with a 3-dB bandwidth of 30 GHz. The noise temperature of the off-axis elements ranges from 71 to 101 K, with a uniform bandwidth of 30 GHz.

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