# Investigation of the Performance of an SIS Mixer with Nb-AlN-NbN Tunnel Junctions in the 780–950 GHz Frequency Band

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***Abstract*—In this paper, we present preliminary measured performance of an SIS mixer employing a Nb/AIN/NbN tunnel junction in the frequency range of 780–950 GHz range. The mixer design is an upgrade of the Carbon Heterodyne Array of the Max-Planck-Institute Plus (CHAMP+) mixer, coupled with an easy to fabricate smooth-walled horn. The noise temperature of the mixer is measured using the standard Y-factor method, but all the RF optics is enclosed in the cryostat. We use a rotating mirror in the cryostat to switch between a room temperature load and a 4 K blackbody load. With this method, we have measured a noise temperature of 330 K around 850 GHz, corrected for a mismatch between a reduced height rectangular waveguide at the input of the mixer block and a full height waveguide at the output of the horn. To remove this mismatch we now plan to redesign a new mixer chip with a full-height waveguide back-piece. The expected performance of the new mixer chip is also reported.**

## I. Introduction

The Carbon Heterodyne Array of the Max-Planck Institute Plus (CHAMP+) installed in the Atacama Pathfinder EX-periment (APEX) telescope consists of two 7-pixel arrays: the low frequency band array operating from 620–720 GHz and the high frequency band array from 790–950 GHz [1]. The low frequency band array have shown state-of-the-art sensitivity, but the high frequency band array has struggled to achieve the similar quantum-limited performance [2], [3]. We have therefore designed and fabricated a new set of high-gap superconductor-insulator-superconductor (SIS) mixers to investigate the performance of the CHAMP+ high band array devices [4], [5]. In order to allow for the potential fabrication of a larger heterodyne array on APEX at such high frequencies, we have replaced the original corrugated horn with the Oxford-pioneered easy-to-fabricate smooth-walled horn designed to operate in the same frequency region. The integration of the smooth-walled horn with the high-gap SIS mixer also allows us to investigate the feasibility of constructing a large focal plane SIS mixer array near terahertz (THz) frequencies for future astronomical projects such as the Origin Space Telescope (OST) [6] and the Millimetron [7] project. Another key component of our project is the inclusion of the optics and the RF loads inside the cryostat. This will hopefully reduce the optical losses, allows more accurate measurement of the Y-factor by enclosing the RF loads in the vacuum environment, and utilise the full power of the local oscillator (LO) by reducing the optical path of the pumping signal.

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## II. SIS Mixer & Experimental Setup

The design of the high-gap SIS mixer used here has been reported before in [4], hence will only be briefly summarised here. We used two high current density (30 kA/cm$^2$) 0.5 $\mu$m$^2$ SIS junctions separated by a quarter-wavelength microstrip [8], [9] to tune out the parasitic junction capacitances for broadband performance. The tunnel junctions comprise of Niobium (Nb) ground and Niobium Nitride (NbN) top electrode, both 100 nm thick, sandwiching a thin Aluminium Nitride (AlN) insulation layer. The junctions are fabricated on top of a 300 nm thick Niobium Titanium Nitride (NbTiN) ground plane, with a 250 nm Silicon Dioxide ($SiO_2$) dielectric layer and a 500 nm thick Aluminium (Al) overlaid on top to form the microstrip transmission line, connecting the junctions to the rest of the superconducting circuits. The whole structure is

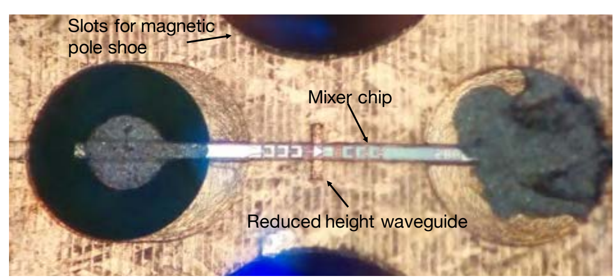



Fig. 1. An image of the mixer block's back-piece with the SIS mixer chip mounted on a 60 $\mu$m deep groove milled into the surface of the back-piece, with the triangular probe antenna positioned along the E-plane of a reduced height rectangular waveguide to couple the RF signal to the mixer.

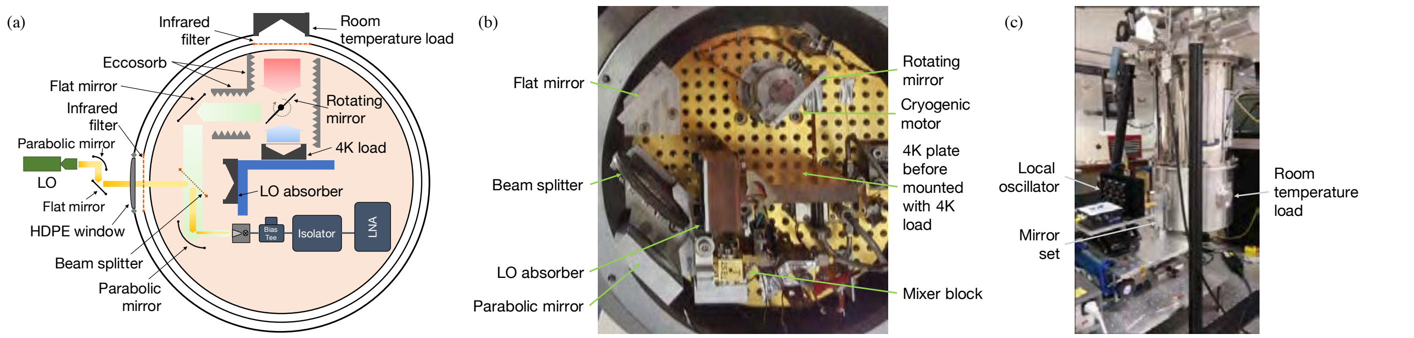


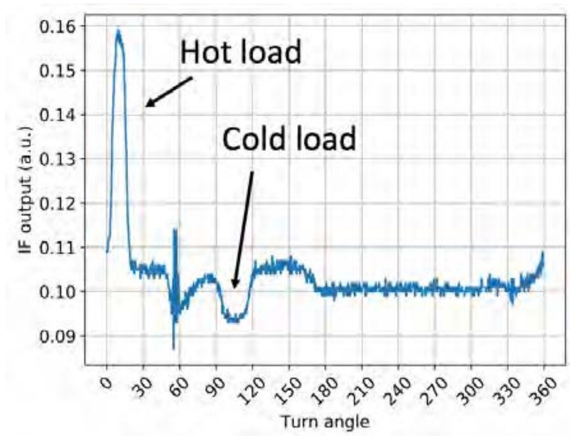

Fig. 2. (a) Schematic layout of the internal optics of the cryostat. (b) Image showing the actual optical setup. (c) A photo showing the external LO setup along with the PTC cryostat.

supported by a 40 $\mu$m thick Quartz substrate, positioned along the E-plane axis of a reduced height rectangular waveguide fabricated on the back-piece of the mixer block, with the normal vector to the chip aligned to the direction of the propagation of the incoming RF wave along the waveguide, as shown in Fig. 1.

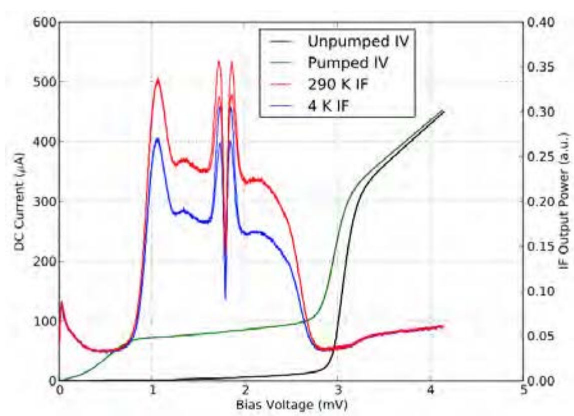
The back-piece carrying the mixer chip was aligned to the rectangular waveguide output of the feed horn and held in place using a threaded centring ring. The whole assembly (horn + mixer) is then slotted into an Atacama Large Millimetre/Sub-Millimetre Array (ALMA)-style mixer block, which contains a temperature sensor, magnetic coils and the DC/IF SMA connector. This assembly was designed such that a separate back-piece could be bolted to the same mixer block for quick turn-around testing. The SIS device-loaded back-piece and part of the mixer block were supplied by the Kapteyn Astronomical Institute (RUG) group to Oxford, where the rest of the mixer block including the feed-horn was fabricated.

In the original CHAMP+ mixer assembly, the feed horn block was electro-formed with the corrugated horn and the circular-to-rectangular waveguide fabricated in a single piece. However, to avoid the need for the complex electro-forming, we fabricated a smooth-walled horn by direct drilling with a circular to full-height rectangular waveguide transition. The performance of the smooth-walled horn has been reported previously [10], and has shown to have comparable high quality as the corrugated horn in the frequency range.

Fig 2 shows the optical arrangement of the experimental setup. The mixer test was performed in a Janis pulse-tube cooler (PTC) system at Oxford, with the optics that bring the RF signal to the mixer mounted inside the cryostat, including the hot and cold loads for Y-factor measurements. This should reduce the optical path of the LO signal in air and eliminate losses from the cryostat window. The room temperature load was mounted on the outer wall of the cryostat (via a window socket), while the 4 K load was attached to a 4 K plate anchor mounted on the cold plate. We used a rotating mirror mounted on top of a cryogenic motor to sweep the mirror between the hot and cold load for Y-factor measurements. LO power was coupled from outside the cryostat to the mixer using a Gaussian telescope arrangement via another optical window. This arrangement ensures that the effect of the water absorption at high frequencies is minimised, thus allowing us to access the actual performance of the mixer near THz frequencies.




(a)




(b)

Fig. 3. (a) The measured IF response of the mixer when the mirror is swept along its rotational axis, pointing the mixer beam towards different surfaces within the cryostat, including the room temperature hot and 4 K cold load. The mixer was optimally biased at 2.4 mV and the LO set at 850 GHz. (b) The measured pumped and unpumped IV curves, along with the hot and cold IF responses, at 850 GHz. All plots are corrected for a 3.1Ω series resistance in the device.

## III. Preliminary Measured Results

Fig. 3 (a) shows the intermediate frequencies (IF) response of the SIS mixer when the rotating mirror was swept around in a full rotation cycle. We can clearly see the difference in the IF responses when the mixer is illuminated by a hot (room temperature) or a cold load (4 K) loads. Fig 3 (b) shows the pumped and unpumped current-voltage (IV) curves, along with the IF responses when the mirror was fixed to face either the hot or the cold blackbody loads. When the LO was set at 850 GHz, we measured an uncorrected noise temperature of about 600 K (double side-bands, DSB), and the noise temperature remains at a similar level from about 820 to 880 GHz, as shown in Fig 4. The sensitivity has then started to deteriorate and the cause of this increase in noise temperature at the high frequency end is still under investigation.

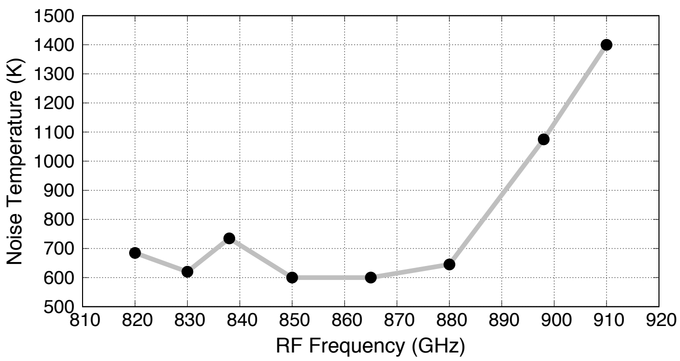



Fig. 4. The measured uncorrected noise temperature from 820–910 GHz.

We would like to emphasise that the relatively high value of 600 K noise temperature was caused by the rectangular waveguide mismatch between the output of the feed horn and the back-piece where the mixer is mounted. As shown in detail in Fig. 5, the rectangular waveguide port of the feed horn is a full-height waveguide with the narrow wall of 150 $\mu$m, in comparison to the reduced height back-piece waveguide that is half the size. We estimated that this costs about 16–20% losses of RF power coupling to the SIS mixer, and the situation is probably more severe when they are compounded by the conversion loss of the mixer itself. Furthermore, the dielectric beam splitter we used in our setup has a reflection coefficient of about 30% across the band, which was necessary due to the low output power of the LO source at these frequencies. By taking into account these two effects and other optical losses such as the infrared filter and the dielectric window, we estimated that the noise temperature measured is in the range of 250–400 K, which is similar to the values reported by [4].

## IV. Improved Mixer Chip Design

In order to improve the performance of the SIS receiver, we have since started to modify the SIS mixer design such that it can be used along with a full-height waveguide back-piece, eliminating the waveguide mismatch effect. Furthermore, as shown in Fig. 3, the current SIS mixer suffers from the junction heating effect. This is probably caused by the resistive properties of the mixer, and partly due to the fact that the bottom electrode of the tunnel junction, which was made out of Nb is being sandwiched between the high gap NbTiN ground plane and the NbN top electrode. Although the junction heating may not be critical for the mixer operation, we aim to resolve this problem in the new mixer design, by replacing the NbTiN ground plane with an aluminium (Al) layer, so that the hot electrons can escape via the normal metal. We will also replace the top wiring layer with NbN, so that it has the same superconducting material as the top electrode of the tunnel junction. The tunnel junctions are expected to be 1 $\mu m^2$ in area, with an $AlO_x$ insulation layer.

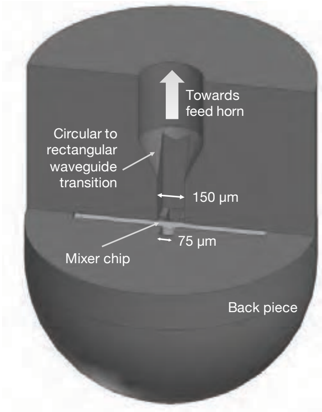
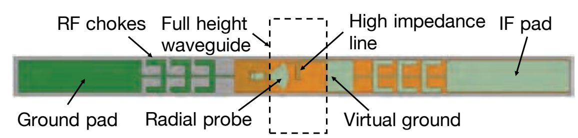
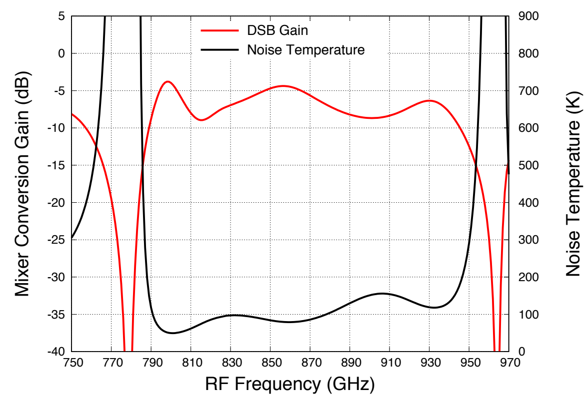



Fig. 5. Illustration showing the rectangular waveguide mismatch between the reduced-height waveguide back-piece with the full-height circular-to-rectangular waveguide transition.




(a)




(b)

Fig. 6. (a) Preliminary design of an SIS mixer chip with radial probe coupled to a full-height rectangular waveguide. (b) Simulated noise temperature performance of the SIS mixer chip using High Frequency Structure Simulator (HFSS) and SuperMix [11] software package.

Fig. 6 (a) shows the preliminary design of a new mixer chip. The design is similar to the existing mixer chip, except that we replaced the triangular probe with a radial probe to cover broader bandwidth. The probe was also extended to about 35% of the waveguide height to achieve maximum coupling. A high impedance line is used to connect the radial probe to the virtual ground pad, along with the RF chokes and the IF bonding pads, forming an integrated bias-tee arrangement [12]. We expect a good noise temperature performance from 790–940 GHz, as shown in Fig. 6 (b). However, the simulated double sideband (DSB) gain is not ideal yet, at the level of about –5 to –10 dB level across the band. Hence, we are currently in the process of optimising the mixer chip design, to cover the full 780–950 GHz, and to improve the conversion gain performance as well.

## V. Conclusion

We have presented preliminary measured performance of an SIS mixer operating in the ALMA Band 10 frequency range. The mixer was coupled with an easy to fabricate smooth-walled horn operating in the same frequency region. The hot and cold load for performing the noise temperature measurement, along with other optical components, are enclosed within the vacuum environment of the test cryostat to reduce the water vapour contaminations. Using this arrangement, we measured a preliminary noise temperatures of about 330 K, corrected for the waveguide mismatch and the loss from a thick beam splitter. To overcome this mismatch and to include other design improvements, we are currently in the process of designing a new mixer chip to further improve the performance of our THz SIS receiver.

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# Superconducting Parametric Amplifiers: the Next Big Thing in (Sub)Millimeter-wave Receivers

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***Abstract***—Superconducting paramps developed for quantum computing have narrow bandwidths, low dynamic range, and operate at sub-Kelvin temperatures. Our collaborators at JPL/Caltech recently demonstrated a microwave Travelling-Wave Kinetic Inductance Parametric (TKIP) amplifier with several GHz of bandwidth, and orders of magnitude larger dynamic range with near quantum-limited noise performance up to an operating temperature of 3K. Similar amplifiers but at higher frequencies up to 1 THz could be designed since the operation principle and physics remain largely unchanged. These qualities make TKIPs suitable candidates for ground-based astronomy with instruments such as ALMA.

In a 2-year study at NRAO we are looking into the feasibility of a high-frequency TKIP demonstration prototype as a front-end replacement for the ALMA band-3 SIS mixer receivers. Our collaborators at Caltech have designed and fabricated a TKIP chip that covers a very wide bandwidth of 55-175 GHz, and we are preparing to test this device at NRAO-CDL. We believe that ultimately the main challenge will be in further optimizing the superconducting thin-film materials to retain their desired properties such as ultra-low loss at temperatures close to 4K.

The enhanced observational capabilities that would be enabled by a RF TKIP amplifier front-end would benefit ALMA science across all bands. For example the Band-3 improved signal-to-noise would be a factor of ~ 5 measured at the receiver input. Including the loss of atmosphere this translates to a doubling of system sensitivity and a factor of ~ 4 increase in array efficiency (speed) enabling the detection of weaker spectral lines and continuum sources and mapping larger fields. The increased sensitivity from the RF front-end relaxes the requirements on IF amplifiers and allows for tradeoff with bandwidth to increase the instantaneous IF bandwidth from the current 4 GHz per sideband per polarization to ~ 10 GHz. For continuum observations, this provides a greater than factor of two increase in efficiency (speed), which combined with the increased RF efficiency would result in a factor of ~ 8 increase in observation efficiency (speed). For spectral observations such a wide bandwidth also enables the detection of various spectral lines simultaneously, removing the need of multiple observations at different LO frequencies to cover the whole band.

These amplifiers are not only interesting for ALMA, but are also very useful for direct detection astronomy (e.g. MKID detectors, TES detectors) for amplifying or multiplexing signals from large focal-plane arrays of photon detectors for space telescopes such as NASA's Origins Space Telescope and X-ray telescopes. Therefore, this development activity is highly synergistic with development of future generations of direct detectors on space and ground platforms.