Development of a 385-500GHz SIS Mixer for ALMA Band 8

Wenlei Shan, Shinichiro Asayama, Mamoru Kamikura , Takashi Noguchi, Shengcai Shi and Yutaro Sekimoto

***Abstract*—In this paper, we report on the design and experimental results of a fix-tuned Superconductor-Insulator-Superconductor (SIS) mixer for Atacama Large Millimeter/submillimeter Array (ALMA) band 8 (385-500GHz) receivers. Nb-based SIS junctions of a current density of 10kA/cm^2 and one micrometer size (fabricated with a two-step lift-off process) are employed to accomplish the ALMA receiver specification, which requires wide frequency coverage as well as low noise temperature. Parallel-connected twin junctions (PCTJ) are designed to resonate at the band center to tune out the junction geometric capacitance. A waveguide-microstrip probe is optimized to have nearly frequency-independent impedance at the probe's feed point, thereby making it much easier to match the low-impedance PCTJ over a wide frequency band. The SIS mixer demonstrates a minimum double-sideband receiver noise temperature of 3 times of quantum limits for an intermediate-frequency range of 4-8GHz. The mixers were measured in band 8 cartridge with a sideband separation scheme. Single-sideband receiver noise below ALMA specification was achieved over the whole band.**

***Index Terms*—Atacama Large Millimeter/submillimeter Array, noise temperature, SIS Mixer, wideband performance.**

I. INTRODUCTION

THE Atacama Large Millimeter Array (ALMA) is a millimeter/sub-millimeter wave interferometer to be located at an altitude of about 5000 meters in Llano de Chajnantor, Chile. To be the most sensitive and highest spatial resolution radio interferometer in the world, ALMA is composed of 64 12-meter and 12 7-meter antennas equipped with the most sensitive receivers. The ALMA covers the frequency range of 31-950GHz, which is divided into 10 separate bands coinciding with those transparent atmospheric windows. This division also allows the optimization of both noise performance and optical coupling at all frequencies. The ALMA receivers from 84 GHz adopt superconducting SIS (superconductor-insulator- superconductor) mixers. The front end of an ALMA receiver includes SIS mixers, a LO (local oscillator) subsystem, IF amplifiers and all necessary optical components, all put inside a self-contained module known as cartridge. The SIS mixers are primarily responsible for the sensitivity of the total cartridge. The ALMA receiver specification requires the band 8 receiver's double-sideband (DSB) noise temperature to be below 4 times the quantum limit over 80% of the band, with an intermediate frequency (IF) bandwidth of 8GHz in total per polarization.

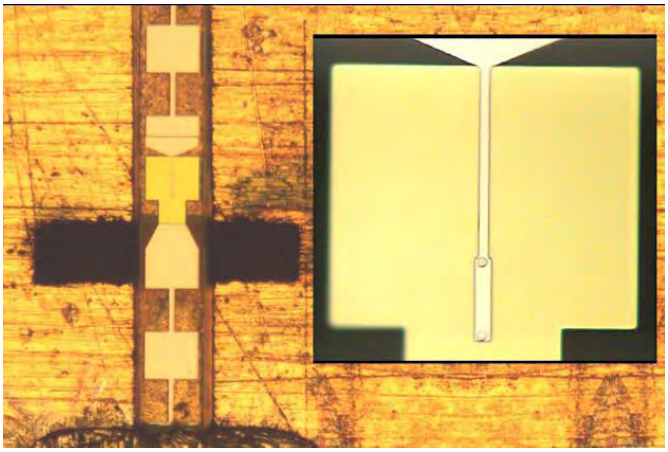

Fig. 1. A mounted mixer chip viewed from the mixer's backshort. Waveguide size is 508×127μm and chip size 120×60μm. Microstrip probe couples RF and LO signals from a half-reduced waveguide. The insect shows the detail of the PCTJ tuning structure.

To relax the ALMA requirement of having an 8GHz IF bandwidth, we designed the ALMA band 8 receiver on the basis of a sideband separation(2SB) scheme using a quadrature hybrid and two identical DSB SIS mixers. Similar design has been adopted for the ALMA band 4 mixers developed in NAOJ [1]. Since the RF bandwidth is of our most concern, great efforts have been made to achieve wideband response for each component of the SIS mixer including the SIS junctions, junction's tuning structure, impedance transformers and waveguide-microstrip probe. We also designed a compact fix-tuned mixer block unit incorporating with a superconducting magnet, which is easy to assemble and maintain in the band 8 cartridge.

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II. SIS Mixer Design

A. Design of Waveguide-microstrip Probe

The SIS mixer design was divided into two independent sub-sections corresponding to different transmission media, namely waveguide-microstrip probe based on a 60μm-thick quartz substrate and superconducting microstrip circuit based on a 300nm-thick SiO_2 thin film. These two sub-sections are independently optimized to be wideband with different simulation tools.

As an antenna inside waveguide, the waveguide-microstrip probe couples the LO and RF signals into a quasi-TEM-mode microstrip line. In general there are three types of designs for such a probe, which have been adequately discussed by several authors [2]-[4]. The most commonly used one is a bow-tie probe with its feed point at the center of waveguide. Although this type of probe can reach 30% bandwidth, its feed-point impedance is rather high (about 100Ω) even if the waveguide height is largely reduced to suppress high-order modes. This disadvantage results in difficulty of wideband matching to low-impedance SIS junctions. Single-side probe [2] is found to be of low impedance and wideband with full-height waveguide. However this type of probe requires close location of the DC/IF ground to the mixer's IF port, which may bring uncertainty to the IF-circuit design and difficulty of DC/IF grounding especially for small mixer chips. Here we adopted a probe design proposed by S.C. Shi et al.[4] for the ALMA band 8 mixers. With the feed point moving outside waveguide and adding one section of impedance transformer, the feed-point impedance can be reduced to below 30Ω. Note that the waveguide height is half reduced to extend the matching bandwidth. The photograph of a mounted mixer chip is shown in Fig. 1. The junction's tuning structure (i.e., parallel-connected twin junctions, PCTJ) is also shown.

The probe was optimized together with the mixer's IF chock filter by a 3D electromagnetic field simulator (Ansoft HFSS).

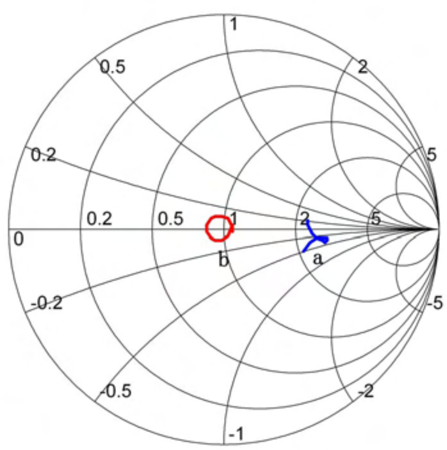

Fig. 2. Impedance seen at the feed point (curve a) and embedding impedance seen by the PCTJ (curve b). The smith chart is normalized to 13Ω(PCTJ's normal resistance) and the frequency range is 385-500GHz.

The goal is to achieve uniform RF impedance at the probe's feed point and low leakage of RF signal to the mixer's IF port within the frequency range of 385-500GHz. The optimized feed-point impedance and the impedance seen by twin SIS junctions (i.e., tuning circuit adopted here) are shown in Fig. 2.

B. Design of SIS Junction and Tuning Structure

The feed point impedance obtained by the preceding method acts as source impedance in this design process. To make good matching between this source impedance and the SIS junction circuit, we have to tune out the junction's geometric capacitance and make use of an impedance transformer.

Parallel connected twin junctions (PCTJ) [5], between which an inductive tuning microstrip line is situated (shown in Fig. 1), were employed to tune out the junction's geometric capacitance. This tuning scheme is favored because of its simple structure and relatively high input impedance. The bandwidth of the PCTJ tuning structure is limited by its quality factor Q=ωRC. Here ω is the center frequency, R is the RF resistance of individual SIS junction that is close to the junction's normal-state resistance at 500GHz band, and C is the junction's capacitance. Since the RC product is inversely proportional to the junction's current density (Jc), high Jc is preferred to have a wideband RF response (corresponding to a low Q). On the other hand, a large R is desirable to reduce the impedance-transform ratio so as to achieve a wideband performance. Based on the above considerations as well as limitations of junction fabrication, we adopted SIS junctions of a current density of $10kA/cm^2$ (ωRC =5) and measuring 1μm in diameter. The normal-state resistance of each SIS junction is about 26Ω and the junction's specific capacitance is estimated to be $90fF/\mu m^2$.

Based on the quantum mixing theory [6] with a 5-port approximation and a calculating model for thin-film superconducting microstrip lines [7], we developed a simulation tool to optimize the tuning inductive microstrip line and impedance transformer in order to minimize the receiver noise temperature while keeping good RF coupling and avoiding instability due to oscillations in RF and IF passes over the whole frequency band.

The length of the inductive tuning microstrip line was finally reduced by 15% taking account of the current spreading around the two SIS junctions. In fact, this spreading inductance was simulated numerically by calculating the phase of reflection coefficient of a thin-film microstrip line short-circuited by a conductive pole, which has the same transaction profile as the SIS junction. This modification is important to achieve a correct center frequency for PCTJs that employ a short tuning microstrip line at sub-millimeter wavelengths.

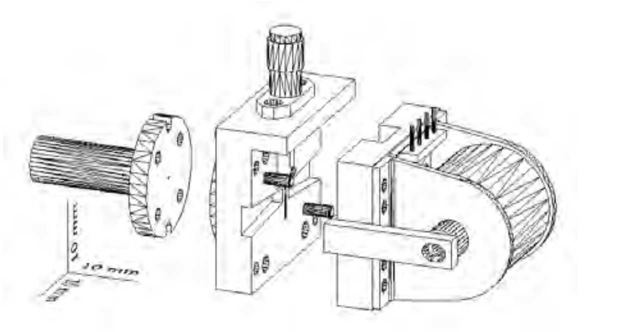

Fig. 3. Mechanical design of the mixer block. Superconducting magnet is fixed onto the backshort part by screws to form a single unit and biased through a 4-pin connector.

C. Mixer Block Design

We aimed to design a mixer block of compactness and assembling simplicity as well as good performance. The DSB mixer block shown in Fig. 3 consists of a diagonal horn, a taper part, a centering ring which aligns the horn with the taper part (not shown), a backshort piece and a superconducting magnet. Since sufficient magnetic field is necessary to suppress the Josephson effect at the 500GHz band, the two arms of the superconducting magnet yoke were designed to locate 1mm away from the mixer's junction chip for a good coupling of magnetic-field flux from the coil to the SIS junctions. The magnetic field at the junctions was designed to be larger than 300 Gauss, which produces approximately two flux quanta in a 1µm-diameter junction. The total number of winding is about 3500 to 4000 with a 0.125mm-diameter Cu-cladding NbTi wire. Experimental results show that a current as small as 30mA was sufficient to suppress the Josephson current of a 1µm SIS junction. The superconducting magnet frame was fixed onto the backshort piece to form a single unit and biased through a 4-pin connector.

The 2SB scheme can be readily assembled with two DSB mixer blocks and a RF hybrid (Fig. 4). Except for the disadvantages of its bulk in size and associated transmission loss in the waveguide as well as the loss at waveguide flanges, this configuration provides great convenience to evaluate the performance of each part in the 2SB unit especially when the measurement result is not as good as expected.

D. RF Hybrid Design

A RF hybrid shown in Fig. 5, which includes a quadrature branch line coupler and two branch line in-phase LO dividers, is a scaled version of RF hybrid of Band 4 2SB mixer developed in NAOJ. The quadrature coupler employs a six-branch line structure with branch width 67µm and spacing 163µm (Fig. 6). The measured S-parameters plotted in Fig.7 were found to be in good agreement with those simulated ones. Two 2-slot branch line couplers with a coupling coefficient -17dB were employed to feed the two DSB mixers of equivalent power of same phase.

III. SIS Junction Fabrication

The 500-GHz Nb SIS junctions were fabricated by incorporating SNEP (Selective Niobium Etching Process) with the anodization technique on crystalline quartz substrates [8]. The barrier was formed by the oxidation of a 7nm-thick Al film with 3.3 Pa Ar+10%O_2 for 30 minutes to achieve a critical current density of around 10kA/cm^2. The quality measured by the ratio of sub-gap resistance to normal-state resistance was typically 15.

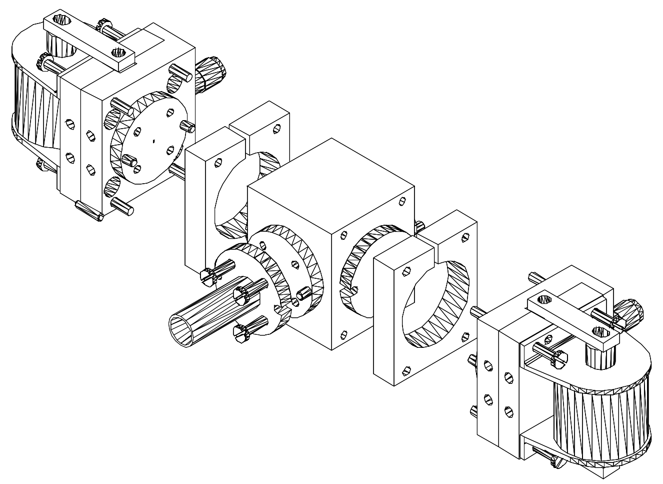

Fig. 4. Mechanical drawing of 2SB mixer assembly. It includes two DSB mixer blocks, a RF hybrid, two centering rings and a feed horn.

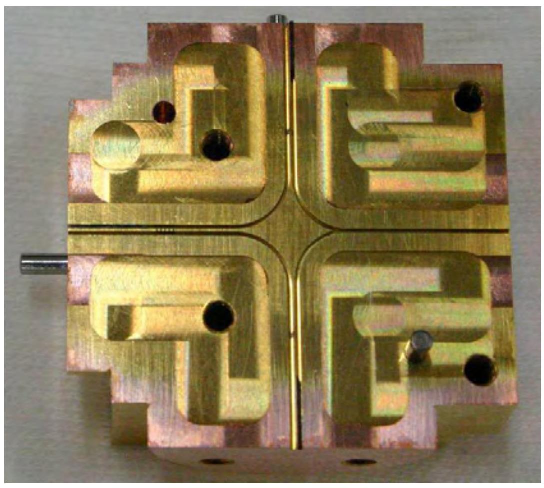

Fig. 5. Photograph of a RF hybrid, which includes a quadrature coupler and two LO dividers.

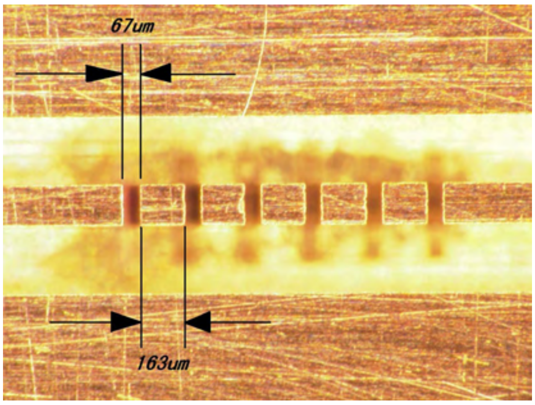

Fig. 6. Photograph of a 6-branch line quadrature coupler with branch width 67µm and spacing 163µm

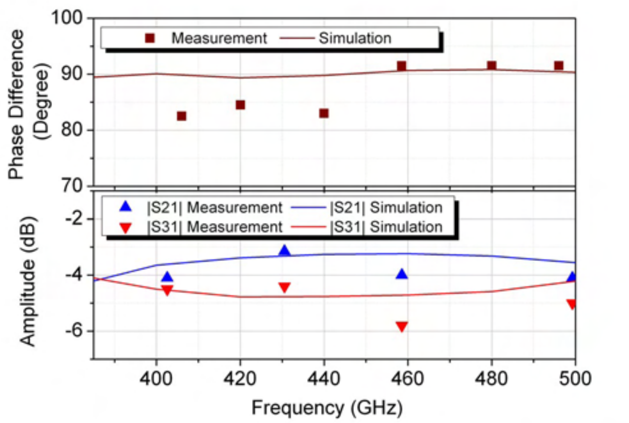

Fig. 7. Measured S parameters and simulated ones of a 6-branch line quadrature coupler.

To achieve good yield and uniformity, two photo masks with circular patterns of 1µm and 3µm in diameter, respectively, were employed to form the junction's contact hole. The 1µm pattern was defined by a g-line (635nm) stepper with high dimensional accuracy. The junction area was then isolated by reactive ion etching (RIE) combined with anodization. Then the whole wafer was covered by an 80nm SiO_2 and a 20nm Al_2O_3 protection layer. After a lift-off process, the 3 µm photoresist pattern was coaxially overlapped to the contact hole by a ultra-violet mask aligner with the second mask. Remaining 250nm of SiO_2 is deposited and a second lift-off process exposed the contact hole for wiring layer connection. The thickness of insulator deposition was adjusted according to subsequent etching consumption to form 300nm SiO_2 in total.

IV. Measurement Setup

The ALMA band 8 DSB mixers were measured in a 4-K Gifford-McMahon/Joule-Thomson mechanical cryocooler. An isolator with a built-in bias-T, inserted between the SIS mixer and a 4-8GHz low noise amplifier, was cooled to 4K to reduce the thermal noise injection from its terminated port. An off-axis ellipsoidal mirror with an edge-taper of 30dB was put on the 4K stage to refocus the beam from the diagonal horn onto an external hot (300K) /cold (liquid nitrogen) load. A 100µm-thick polyimide film was used as the vacuum window, while a 150µm-thick Zitex sheet cooled at the 70K stage blocked the infrared radiation. A 12.5µm-thick polyimide film was used as a beam splitter, coupling the LO signal generated by a Gunn oscillator followed by two Schottky-diode doublers with a factor of -15dB.

V. Measurement Results And Discussion

A. DSB Receiver Noise

Typical I-V and IF responses with hot and cold loads are shown in Fig. 8. With a magnet driving current of 30mA, no additional noise induced by the Josephson current was found. We used a standard Y-factor measurement technique to determine the receiver noise temperature. All presented noise temperatures were uncorrected for the optics loss, and a Callen/Welton formula [9] was used to obtain the black-body radiation temperatures. A noise temperature of 60K at the band center and 120K at the band edges are demonstrated in Fig. 9.

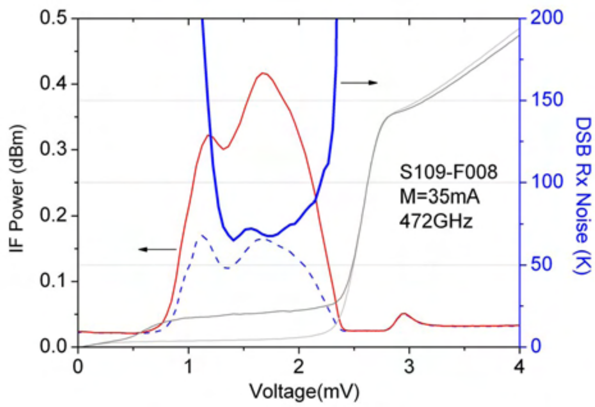

Fig. 8. Typical I-V curve and IF output power (left) at 472GHz with magnet driving current 30mA. The noise temperature is also plotted as a function of bias voltage.

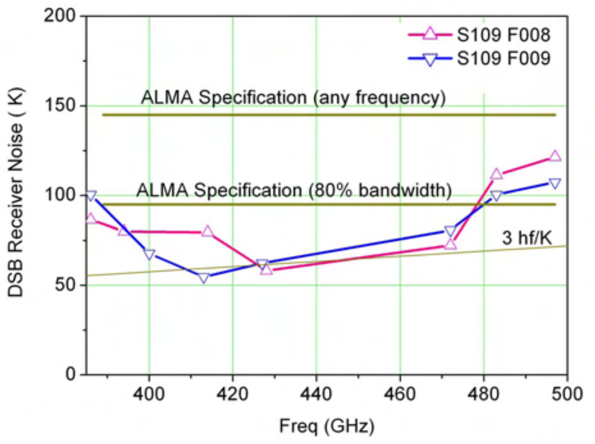

Fig. 9. DSB receiver noise of two typical band 8 mixers. In a wide frequency range, the receiver noise is as low as 3 times of quantum limits.

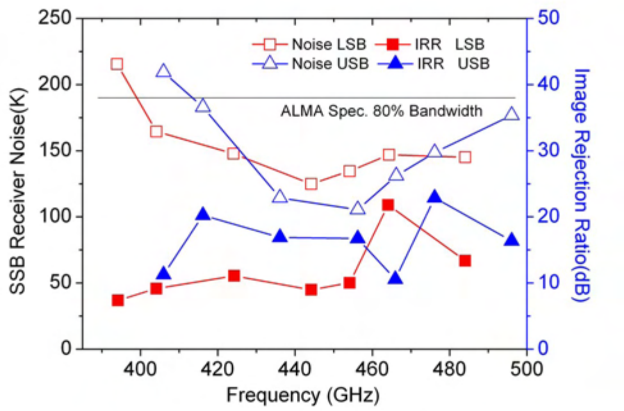

Fig. 11. SSB receiver noise and image rejection ratio of Band 8 cartridge

The measurement results demonstrate a wide bandwidth, which benefits from employing high current density, small-sized SIS junctions and wideband design of the mixer chip. The best performance is well located at the band center, indicating an accurate design of the PCTJ's tuning inductance. The intermediate frequency (IF) noise, calculated to be 15K, is mainly contributed by a 2-stage GaAs based HEMT low noise amplifier (LNA) and the isolator before it. We expect that the IF noise contribution can be further reduced by adopting InP based LNA, which can ordinarily reaches 5K noise temperature at 4-8GHz band.

Receiver noise was also measured as a function of IF as shown in Fig. 10. Due to standing waves between SIS mixer and isolator the receiver noise varies about 10% around the average value over the whole IF band.

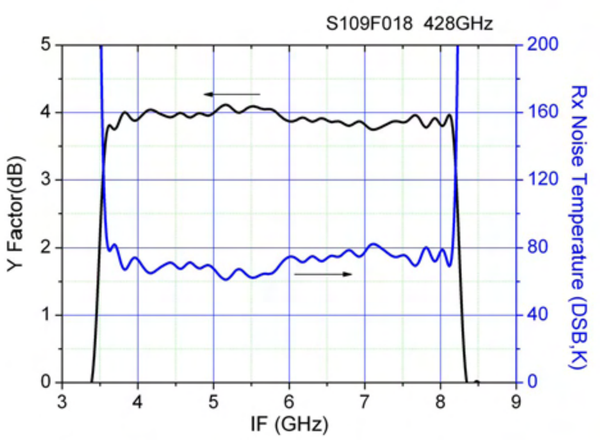

Fig. 10. Receiver noise as a function of intermediate frequency. Ripples are due to standing waves between SIS mixer and isolator.

B. Sideband Separation Receiver Noise and Image Rejection Ratio (IRR)

A 2SB assembly was measured to evaluate the mixer performance in the qualification model of Band 8 cartridge. The SSB noise temperature and image rejection ratio are plotted in Fig.11. Noise temperatures below ALMA specification was achieved over the whole band from 385GHz to 500GHz. The loss of RF hybrid, which was thought to contribute a lot to overall receiver noise, turns out to be much smaller than estimated. The IRR of 10dB~20dB was achieved. The large difference between IRR measured at lower sideband and higher sideband is possibly caused by unbalanced conversion gain of the two mixers , which were individually measured beforehand.

C. Determining the Embedding Impedance of SIS Mixers

The embedding impedance seen by PCTJ was determined experimentally with the "RF voltage match" method [10]. We improved the method so that it can treat PCTJ structure. Fitting process was performed with pumped IV curves at several frequencies. At each frequency three IV curves at different pumping levels were fitted respectively and the average value was adopted. The embedding impedances for three mixers are plotted in a Smith chart (Fig. 12), which is normalized by PCTJ normal resistance. Good matching between PCTJ and signal source can be found though the three curves do not agree well, which is due to the combination of mixer mounting misalignments, mixer block fabrication errors, uncertainty of PCTJ parameters as well as the fitting errors of this method itself .

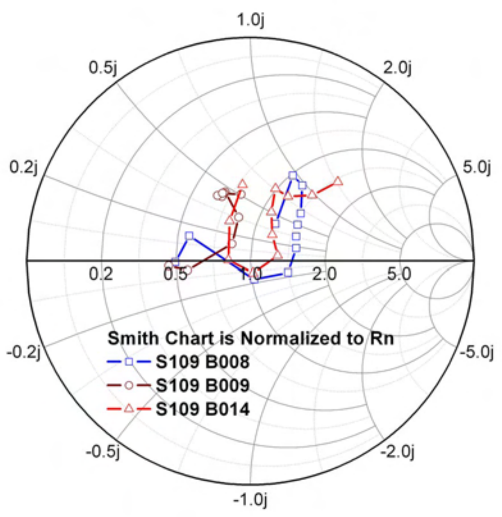

Fig. 12. Fitted embedding impedance of three mixers. Results indicate good matching between PCTJ and signal source.

VI. Conclusion

We have designed a wide-band, low noise SIS mixer for ALMA Band 8. DSB receiver noise as low as 3 time quantum limits has been demonstrated. The SSB receiver noise measured in a Band 8 cartridge is below the ALMA specification over the whole band. The good RF performance is attributed to accurate design of PCTJ embedding impedance and the tuning microstrip line as well as adopting high current density one micrometer size SIS junctions.

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