Wideband Receiver Upgrade for the Submillimeter Array

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***Abstract*— The Submillimeter Array (SMA), a radio interferometer of eight 6-meter telescopes on Mauna Kea, Hawaii, has embarked on a wideband system upgrade, replacing its original SIS receivers with wideband receivers, which double the instantaneous bandwidth. The new SMA receivers are based on distributed superconducting tunnel junction arrays, comprising three SIS junctions connected in series. The use of a series junction array reduces the impact of the geometrical capacitance of the SIS junctions and increases the linearity range of the receiver, both of which are important for wide IF design. We here report on the design and performance of the upgraded SMA receivers. Wideband 200 and 300 GHz receivers have been installed in all eight antennas of the Array, and they are being used for routine astronomical observations.**

***Index Terms*—Distributed mixers, superconductor-insulator-superconductor (SIS) mixers, submillimeter receivers, ultra-wide-band receivers.**

I. INTRODUCTION

THE Submillimeter Array (SMA) is a radio interferometer comprising of eight 6-meter radio telescopes on Mauna Kea, Hawaii, operated by the Smithsonian Astrophysical Observatory (SAO) in partnership with the Institute of Astronomy and Astrophysics of Academia Sinica (ASIAA), Taiwan. Since its official dedication in 2003, the SMA has been making radio astronomical observations with high spatial and spectral resolution in the atmospheric windows between 200 and 420 GHz.

The instrument suite of the SMA was conceived in the early 1990s. It was based on Double-Side-Band (DSB) mixers, and the two sidebands are separated in the digital backend, using phase switching techniques. The total bandwidth capacity of the digital correlator is 4 GHz from each sideband. In an effort to improve the throughput of the array, we decided, a few years ago, to increase its instantaneous operating bandwidth. This system upgrade calls for front-end receivers with much wider bandwidth and a much faster digital correlator. The increased bandwidth improves the total power (or continuum) sensitivity of the instrument. Furthermore, it also increases the flexibility for spectral line observation.

The wideband instrumentation is to be supported by a wideband digital correlator, which is being developed in house, using open source FPGA boards designed by the Coalition for Astronomical Signal Processing and Electronics Research (CASPER) with inputs from a 5 GSample per second Analog-Digital Convertor. The new digital backend, the SMA Wideband Astronomical ROACH2 Machine (SWARM), will add multiple frequency slices, each of 2 GHz wide to provide full IF coverage from 4 – 12 GHz. The front-end receiver upgrade would involve the use of a new generation of superconducting receivers based on distributed superconducting tunnel junction arrays [1, 2]. In this report, we will present the design and performance of the upgraded SMA receivers.

II. SERIES-CONNECTED SIS MIXERS

The first generation of Superconductor-Insulator-Superconductor (SIS) mixer for the SMA employs a single SIS junction [3, 4]. The IF bandwidth of such a mixer is dictated by the resistor-capacitor (RC) network formed by the load resistance of the mixer and the total capacitance from the junction and parasitic capacitance introduced by the tuning network [5]. Since the load resistance is typically 50 ohm, reducing the mixer output capacitance is the key to increasing the IF bandwidth. By using N series connected junctions, the contribution of the junction capacitance is reduced by a factor of N. Furthermore, with more junctions in series, the impedance level of the mixer is also increased, reducing the need for lower impedance elements. This, in turn, reduces the parasitic capacitance of the tuning network. Therefore, although the IF bandwidth of a series-connected distributed SIS mixer does not rise linearly with N, it still offers significant improvement in bandwidth as more junctions are cascaded.

A second advantage for the series-connected mixer is the increased dynamic range. As the IF bandwidth is increased, the power output of the SIS mixer also rises. It is well known that saturation effect in SIS mixers is caused by output signal compression [6]. The wider IF bandwidth, therefore, should be accompanied by a higher power handling capacity of the mixer, which scales with N^2. Consider an SIS mixer terminated by an ambient load (T_{amb} ~ 300 K) and its DSB noise temperature, T_{DSB}, is ~ 100 K. Assume further that the

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DSB conversion gain, G_{DSB}, is 0 dB and the IF bandwidth, B_{IF}, is 20 GHz. Thus, the IF power output of the mixer is given by

$$P_{IF} = G_{DSB} * k(T_{amb} + T_{DSB})B_{IF} \quad (1)$$

Given that P_{IF} ~10 pW, the IF voltage swing around the bias point is ~70 μV rms across the 50-ohm load. Since we are dealing with noise like signal in radio astronomy, the peak-to-peak voltage swing is roughly 6 times the rms value, which represents ±3σ of the Gaussian distribution. At an LO frequency of 242 GHz, the width of the photon step in a single SIS junction is 1 mV, which is only ~2.5 times the peak-to-peak voltage swing. Clearly, mixer compression would not be negligible. That is why we have chosen to use a 3-junction array, which would improve the ratio of the photon step width to the peak-to-peak IF voltage swing to > 7 across the RF band.

The disadvantage of using a series array is the increased LO power requirement, which also scales with N^2. At the same time, the output impedance level scales with *N*. As a result, devices with higher critical current density and of slightly bigger areas are desirable. A discussion of the properties of series connected SIS mixer is given in [7].

III. Distributed Tuning in Series SIS Array

The wideband SIS mixer chips are fabricated in the fabrication facility of ASIAA in Taipei [8]. A photo of the distributed mixer for the new SMA 300 GHz wideband receiver is given in Fig. 1. The junctions are shown in more details in the insert. The junctions are 1.5 μm in diameter and are spaced 8 μm apart. The first 2 junctions are located on an island, which forms the central conductor of a coplanar waveguide (CPW) with characteristic impedance of ~50-ohm. The inter-connecting CPW between the junctions add a considerable amount of inductance to the mixer circuit, such that no extra inductance is needed to tune the geometrical capacitance of the junction. In this sense, the tuning of the series-connected SIS junction array is distributed in nature.

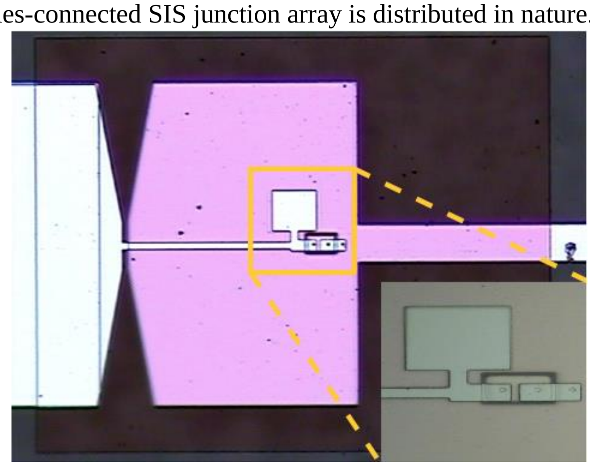

Fig. 1 Photo of a distributed mixer chip used in the upgraded SMA 300 GHz receiver. The insert shows the 3-junction series array in more details. The junctions are 1.5 μm in diameter. Note the absence of any external tuning inductance to the junction array. The inductance is distributed in the inter-connecting lines between the junctions.

We have also found evidence of extra spreading inductance in the junction array [9]. This spreading inductance is caused by a "current crowding effect" [10] as part of the RF current bends to enter the 1.5 μm diameter junction from the 6 - 8 μm wide CPW. The situation is depicted in Fig. 2. Since the extra current path is incurred in a CPW, which has higher characteristics impedance compared to that of microstrip, the added spreading inductance can be quite substantial. HFSS simulation shows that the spreading inductance is as much as 15% of the inductance introduced by the CPW lines connecting a pair of series junction array.

Referring to Fig. 1, a capacitance is put in parallel to the junction array to offset the higher total inductance in the distributed 3-junction array. Located between the junction array and the quarter wave microstrip transformer, which links it to the waveguide feed point of the mixer, this added capacitor helps to mitigate the effects of the extra circuit inductance.

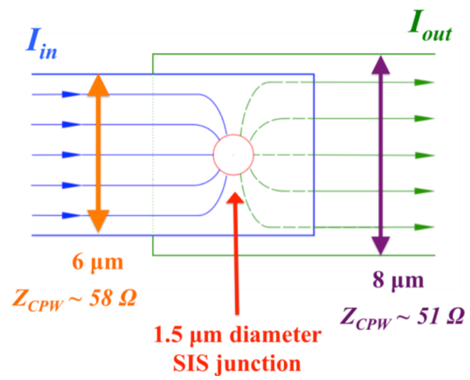

Fig. 2 Effect of "current crowding" in series connected SIS junction array. The additional RF current path introduces spreading inductance to both the input and output CPW lines to the junction.

IV. Performance of the Receiver

The design and performance of the upgraded 200 GHz receivers for the SMA has been reported previously [7, 11]. We here focus on the performance of the 300 GHz receivers.

As stated above, the diameter of the individual SIS junction in the array is 1.5 μm. The critical current density of the device is about 7 kA/cm^2. For the 3-junction array, the normal state resistance is in the range of 55 – 60 Ω, such that the ωCR product is ~ 4.5. The total IF output capacitance, including capacitances from both the junction and the tuning circuit, is ~ 0.18 pF. The expected IF bandwidth is 17 GHz, for a 50-Ω IF load impedance [5].

The mixer is connected to a wideband isolator that provides isolation between 4 and 14 GHz [12]. Its insertion loss is < 1.2 dB, with the highest value found at the top end of the band. The isolator is followed by a low noise cryogenic amplifier, which has a typical noise temperature of 4 – 8 K over the frequency range of 4 – 16 GHz [13].

The current – voltage (I -V) characteristics of the junction array in the presence of optimal magnetic field is plotted in Fig. 3. The sub-gap leakage resistance is ~ 500 Ω, yielding a leakage resistance ratio of only 8.5. When compensated for the series resistance from the 2-point measurement setup, the gap voltage is found to be 8.1 mV with no magnetic field and 7.9 mV when operated with optimal magnetic field around the second null. The photon step, induced by a Local Oscillator (LO) at 300 GHz, is observed to be quite flat, indicating very high output impedance. The isolator is, therefore, indispensable. The receiver power outputs at an IF of 10 GHz in response to both ambient and cold input loads are also plotted in Fig. 3. At a bias voltage of about 6.5 mV, a Y-factor of 2.51 was recorded, corresponding to a DSB receiver noise temperature of 65 K. The estimated DSB conversion loss at this setting is around 0 dB.

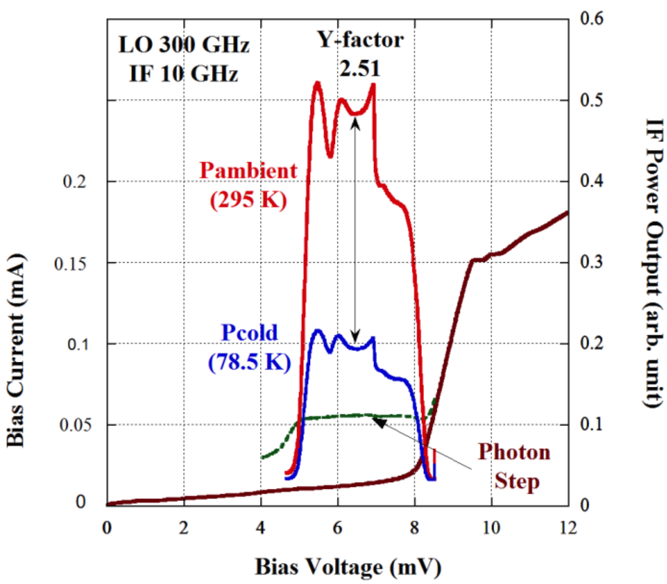

Fig. 3 Current-Voltage (I-V) and Power-Voltage (P-V) curves of SMA 300 GHz mixer (Batch SAO300-2-2 #F1-29). The I-V curve was measured with a 2-point setup, and the added series resistance to the bias circuitry is 3.2 Ω. This device exhibits a sub-gap leakage resistance to normal state resistance ratio of 8.5. When driven by an LO at 300 GHz, flat photon step was observed. A Y-factor of 2.51 was recorded at a bias voltage of around 6.5 mV at an IF of 10 GHz.

The receiver noise temperature as a function of IF for a number of LO frequencies is displayed in Fig. 4. The sensitivity is quite flat for IF between 4 – 12 GHz, rising slightly above 12 GHz. This is mostly due to the higher insertion loss and poorer insertion loss of the wideband isolator. In spite of this, significant degradation of noise temperature does not set in until the IF rises close to 16 GHz. This demonstrates that the receiver presents a wide IF bandwidth as designed. The best noise temperature is obtained with LO frequencies of 300 and 324 GHz, around the center of the SMA band of 255 – 350 GHz. Sensitivity roll-off is observed towards the RF band edges but noise temperature remains below 100 K over the IF of 4 – 12 GHz IF. Note that the RF bandwidth would improve if devices with lower sub-gap leakage resistance were available, as this would improves the conversion loss at the band edges. Alternatively, a higher critical current density of the SIS array would also help. At the present current density, the expected percentage RF bandwidth is ~ $1/\omega CR$ or about 22 % [13].

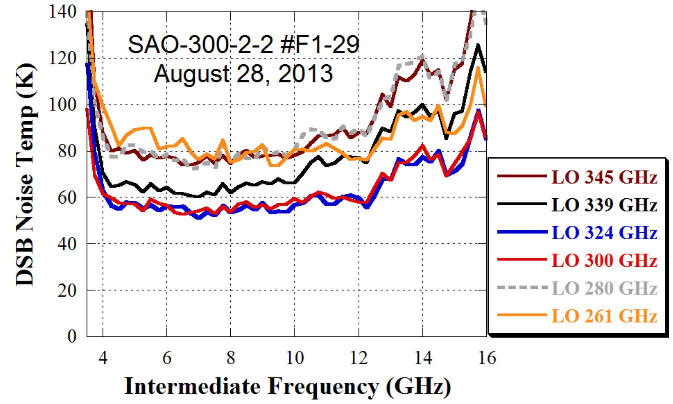

Fig. 4 Double-side-band (DSB) receiver noise temperature as a function of IF for different LO frequencies measured in the laboratory in Cambridge.

All 300 GHz SMA receivers have been upgraded with this new generation of wideband receiver in 2013, following the upgrade of the 200 GHz receivers in 2012. Both the 200 and 300 GHz receivers are being used for routine astronomical observations. Although the full capability of these new wideband receivers will not be available before the operation of the new digital backend, SWARM, SMA users can now access the higher IF using the Bandwidth Doubler feature of the SMA. Fig. 5 shows a 10 GHz wide spectrum obtained with the new receivers. In this observation, the Local Oscillator of the receiver was fixed at 337 GHz. The Bandwidth Doubler mode was used to map a 2 GHz wide spectrum from the 4-12 GHz IF to the SMA correlator in a sequential manner. Since both sidebands are recovered in the SMA correlator, one can use the new receivers to observe a pair of spectral lines that are separated by up to 27 GHz in the 300 GHz band.

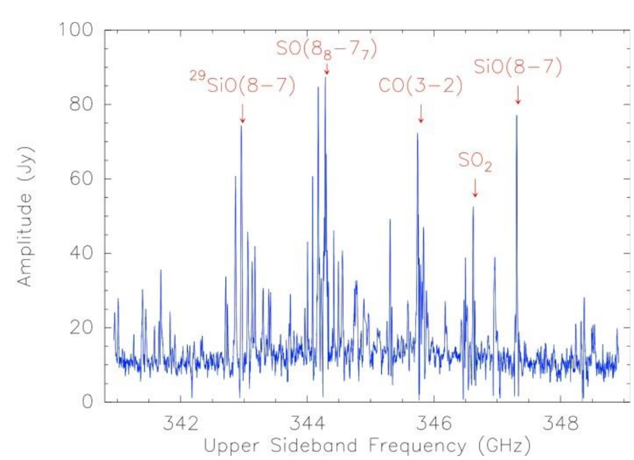

Fig. 5 Upper sideband spectrum of Orion BN/KL for a single baseline taken in a test observation in Dec. 2013. With a local oscillator frequency of 337 GHz, the 4-12 GHz portion of the receiver IF is stepped in frequency, 2 GHz at one time for processing by the SMA correlator. The four spectra are merged to produce this figure. During this observation, the weather was quite poor (~4 mm PWV) and the source was not very high in the sky. Integration time per 2 GHz spectrum is about 20 minutes).

V. Conclusion

A second generation of wideband receivers for the SMA has been commissioned. These receivers are based on a series-connected 3-junction SIS array which offers wide IF bandwidth of up to 16 GHz, and higher dynamic range to ensure good linearity for both observation and calibration. These receivers offer competitive sensitivities and they are being used in routine astronomical observations. Once the new SMA digital backend is in full operation by late 2014, these receivers will provide 4 – 12 GHz IF coverage in double-side-band operation. Future expansion of the digital backend would extend its coverage to 16 GHz.

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