Upgrading the SMA 600 GHz Receivers

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***Abstract*— We present the results of an ongoing effort to improve the sensitivity of the Submillimeter Array (SMA) 660 GHz receivers, including upgrades to the local oscillator (LO) units, improved telescope–receiver coupling optics, and upgraded 660 GHz mixers and receiver inserts. New tunerless varistor multiplier chains have resulted in increased local oscillator (LO) power across the frequency band (> 10 µW) and have enabled the upgrade of receiver coupling optics inserts, including the use of a fine (400 lines-per-inch) metal mesh as an RF/LO diplexer. This has resulted in a decrease in overall system complexity and an improvement of about 0.5 dB in signal beam transmission. This work has focused on improving the performance of the double sideband (DSB) SIS receivers designed for operation in the 630-700 GHz frequency range. In collaboration with University of Köln (KOSMA), a new batch of 660 GHz Nb/Al-AlOx/Nb SIS devices with end-loaded stub integrated tuning structures was designed and fabricated. We present an overview of this work and a summary of performance achieved both in a laboratory liquid helium cooled cryostat and in the SMA cryostat environment. First-light SMA observations with an upgraded 600 GHz receiver insert are shown.**

I. Introduction

The Submillimeter Array (SMA) is the world's first operational interoferometric telescope for submillimeter-wave astronomy. It is an eight-element array of 6 meter antennas with baselines ranging between 25 and 500 m resulting in high resolution observational capabilities (e.g., 5 to 0.25 arcseconds at 350 GHz). Each antenna contains a cryostat that houses heterodyne receivers covering four frequency bands including 180-250 GHz, 266-355 GHz, 320-420 GHz, and 600-700 GHz [1-2] (Fig.1). Polarization diplexing enables simultaneous observations with low and high frequency receiver pairs. An IF bandwidth of 4-6 GHz in dual frequency operation mode and 4-8 GHz with single frequency operation is now achievable with recent upgrades. The move to wider IF operation and the need for improvement in receiver sensitivity, especially for the high frequency bands where atmospheric transmission is comparatively poor, has prompted an ongoing effort to upgrade the 600 GHz SMA receivers.

We present results of the 600 GHz receiver upgrade work, including outfitting the 600 GHz LO units with new tunerless varistor multipliers capable of delivering more output power across the frequency band, upgrading the telescope – receiver coupling optics to eliminate the Martin-Puplett RF/LO diplexer and improve signal transmission, and the development and characterization of new SIS devices optimized for performance over the 630-700 GHz frequency range. Details of the main focal points of the upgrade work are presented in II. Measurement setup details and the results of laboratory characterization of new SIS mixers both in a liquid helium cooled test cryostat and in the SMA cryostat are provided in III and IV. A brief summary of this work is given in V.

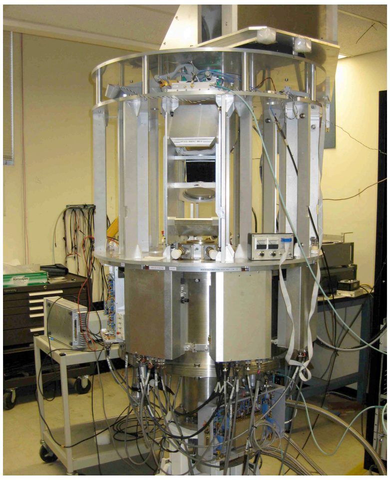

Fig. 1 SMA cryostat with upgraded 600 GHz receiver insert, LO unit, and coupling optics operating in the lab in Cambridge, MA.

II. 600 GHz Receiver Upgrade Project

We present a brief overview of the upgrade project including details of the SIS device design and fabrication work done in collaboration with KOSMA (*A.*) and upgrades to the 600 GHz LO units and optics inserts (*B*).

A. SIS Device Design and Fabrication

A new batch of 660 GHz Nb/Al-AlOx/Nb SIS devices with end-loaded stub integrated tuning structures were optimized and fabricated in collaboration with KOSMA. They are intended to serve as drop-in replacements for those currently in use at the telescope [3-4]. These devices incorporate the standard SMA waveguide probe optimized for performance over 600-720 GHz [5] and were designed to be used with existing mixer hardware.

Images of the 600 GHz mixer blocks and the SIS device integrated tuning structure are shown in Fig. 2. The mixer blocks sandwich the SIS device between a copper bottom piece containing a shorted waveguide cavity and a top block incorporating a corrugated feedhorn for coupling incident radiation to the device. Overall device dimensions are 160 µm x 2 mm x 40 µm and contact to the device is achieved mechanically with two spring wires installed in the top block. Junctions were designed with an area of 0.95 μm^2 and a critical current density of 12 kA/cm^2. The devices were fabricated on 200 µm thick crystalline quartz substrates (for improved device cooling) using e-beam lithography for the junction definition at KOSMA. Wafer runs were carried out in 2008 and 2009 and bulk wafer liquid helium diptesting performed in Köln reveals overall device-to-device uniformity (Fig. 3) with typical characteristics of R_{subgap} / R_N = 14.9, V_{gap} = 2.83 mV, and R_N = 22.8 Ω. Wafer post-processing (e.g., thinning of quartz substrates to 40 µm and device dicing) was carried out in Cambridge, MA. Subsequent diptest measurements agree well with the KOSMA bulk wafer characterization and do not reveal performance degradation.

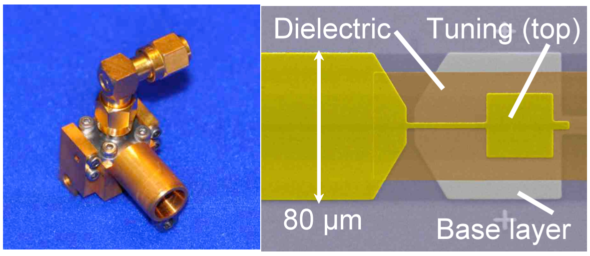

Fig. 2 *Left*: Assembled 600 GHz SMA mixer block. *Right:* SEM image of a 660 GHz SIS device fabricated at Univ. of Köln.

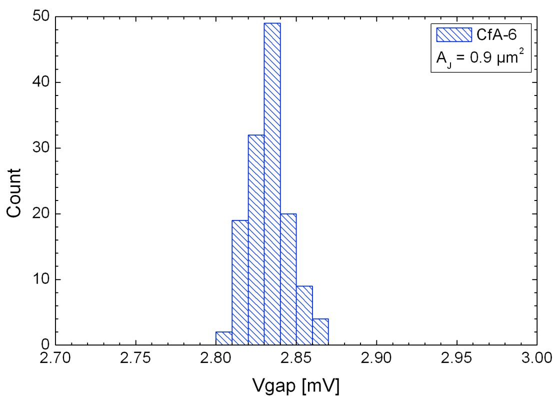

Fig. 3 Histogram of the spread in Vgap values measured for CfA-6 batch of 660 GHz SIS devices. The mode Vgap value is 2.83 mV.

B. 600 GHz LO and Optics Insert Upgrades

The original 660 GHz LO modules incorporated Gunn-oscillator driven, mechanically tuned multiplier chains with a thick Teflon lens at the output. Because of their particular topology and loss incurred by a waveguide isolator, these units were capable of delivering only about ≤ 5 µW of power across the frequency band of interest. Upgrading to a more tightly integrated Gunn-driven (~100 GHz, 25-35 mW output power) tunerless varistor x2 x3 multiplier chain and reflective LO optics has resulted in decreased system complexity and increased available LO power (at least 10 µW across the 640-700 GHz band) [6]. Because the signal coupling optics configuration was previously limited by the amount of available LO power (especially for high frequency operation), the original 660 GHz receiver optics inserts used a Martin-Puplett Interferometer (MPI) as an RF-LO diplexer. Drawbacks of this optics configuration include additional motorized actuators required to tune the MPI moveable roof mirror and increased RF transmission loss due to the insertion loss. Additionally, the instantaneous bandwidth limitation of the MPI is incompatible with the SMA's upgrade toward wide IF operation (e.g., 4-8 GHz current capability). Increased output power availability of the upgraded 660 GHz LO units has permitted a revision of the RF-LO coupling optics. A fine metal mesh (400 lines-per-inch, 20 µm wire thickness) is used to couple the incoming signals to the receiver insert, resulting in ~5% LO and ~95% RF coupling. The new coupling optics improves the signal beam transmission by about 0.5 dB.

III. Laboratory Measurement Setup

We present an overview of the measurement setups used to characterize the sensitivity of the upgraded 660 GHz mixers both in a laboratory liquid helium cooled test cryostat (*A*) and in the SMA cryostat environment (*B*).

A. Liquid Helium Cryostat

A series of receiver noise measurements made in the laboratory in a liquid helium cooled IR Labs test cryostat were used to assess the sensitivity of upgraded 660 GHz mixers. Receiver Y-factor measurements were made using room-temperature (295 K) and liquid nitrogen cooled (77K) absorber loads. These measurements were made across the 630-700 GHz frequency band with a 600 GHz LO unit incorporating a Gunn oscillator driven, tuneable x2 x3 multiplier chain from RPG. A curved mirror was used to couple the incident signal to a wire grid diplexer oriented at a 7° angle for minimal RF signal loss (e.g., 7° corresponds to a 1.5% loss or 4.5 K at room temperature). A removable sheet metal hood was used to change between ambient and cooled absorber loads for Y-factor measurements.

A photograph of the cryostat interior is shown in Fig. 4. The vacuum window of the cryostat was a 0.1" thick crystalline quartz window with an 80 µm thick polyethylene anti-reflection (AR) coating. Three layers of 8 mil thick Zitex attached to the 77 K radiation shield and to the 4 K cold plate were used as infrared blocking filters and a cold mirror was used to couple incident RF and LO signals to the mixer feedhorn. The mixer and mirror share the same OFHC mount to ensure optimal signal coupling at cryogenic temperatures. A coil of Nb wire was used to generate a magnetic field used to suppress the Josephson noise of the SIS device and a 4-6 GHz cryoisolator was used both to inject the device DC bias and to curb reflections between the low noise amplifier (LNA) and the mixer. The LNA is a multi-stage InP HEMT amplifier providing ~25 dB of gain and 3.5 K noise across the 4-6 GHz IF. A room temperature IF chain consisting of a MITEQ 4-6 GHz amplifier and a 5 GHz bandpass filter were used along with an HP power meter to measure receiver total output power for Y-factor characterization.

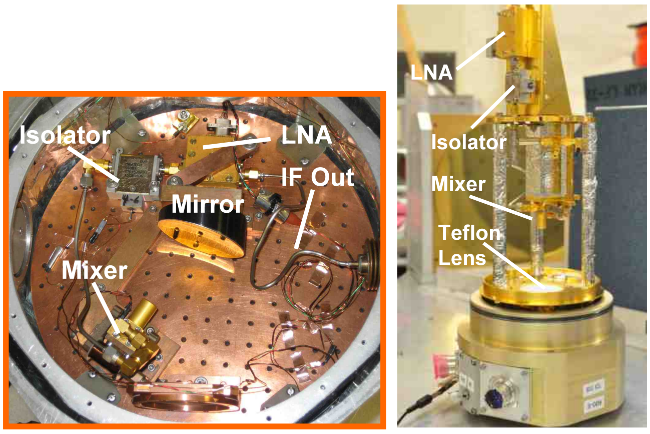

Fig. 4 *Left:* Photograph of interior of IR Labs liquid helium cryostat (4K cold plate). *Right:* Photo of upgraded 600 GHz SMA receiver insert cartridge. Vacuum window is located on the bottom along with feed-through connections. The radial o-ring vacuum seal on the cartridge is also visible.

B. Laboratory SMA Cryostat

Fig. 4 shows a photograph of an upgraded SMA 600 GHz receiver insert. The RF and LO signal (provided by the Gunn-driven solid state multiplier chain) are combined optically prior to entering the insert (see II *B* and Fig. 1). The RF/LO signals enter the insert through an AR-coated crystalline quartz vacuum window and pass through several layers of Zitex IR-blocking filters mounted to the 70 K radiation shield. A cooled Teflon lens (~100 K at the lens center) mounted to the 70 K shield is used to couple the incident signals to the mixer feedhorn. The SIS mixer sits at the heart of the receiver insert and during operation, the mixer mount is connected to the cold head of a closed-cycle Joule-Thomson mechanical cryocooler with multi-layered high-purity copper heat straps to minimize thermal losses. The mixer is connected via a 6” stainless steel semirigid cable to a 4-8 GHz Pamtech cryoisolator used to mitigate reflections between the mixer and a 4-8 GHz HEMT LNA, providing ~30 dB of gain and 9 K noise. Y factor measurements were accomplished by removing the central turning mirror used to couple the incident sky signal to the receiver optics insert during normal telescope operations and directing the beam across the optics cage (Fig. 1) to room temperature and liquid nitrogen cooled absorber loads.

Y-factor measurements across the IF passband were made using a sweepable, programmable Hittite 10 MHz-20 GHz signal generator to supply a 2^{nd} LO for a room temperature mixer. A 2-18 GHz Krytar power splitter was used to supply the 4-8 GHz receiver IF to the RF input of the 2^{nd} mixer. The signal generator was swept from 3-9 GHz in steps of 0.1 GHz and the resulting signal (2^{nd} IF = 650 MHz) total power was detected with an HP power meter. Measurements were recorded for the receiver looking at room temperature and cooled absorber loads.

IV. RESULTS

We present the results of receiver characterization in the liquid helium cooled cryostat (*A*) and in the SMA cryostat environment (*B*).

A. Liquid Helium Cryostat Performance

A comparison of SIS DC-IV characteristics between diptest data and measurements made in the liquid helium cooled cryostat reveal that the device is operating near 4.2 K with V_{gap} = 2.83 mV, R_{subgap} / R_N = 20, and R_N = 26 Ω. Using the measurement setup described in III *A*, a series of Y-factor measurements were made for the upgraded 660 GHz mixer in the lab test cryostat over the 630-700 GHz frequency range. These measurements resulted in Y factors spanning 1.94-2.22 (with best performance ~ 670 GHz). This corresponds to double-sideband (DSB) receiver noise temperatures of T_{rec}= ~100-150 K. Mixer conversion loss was calculated over this frequency range and resulted in ~2-5 dB conversion loss. A comparison was made with Y-factor measurements obtained using a 600 GHz SIS device from an older batch with characteristics typical of the devices currently being used at the telescope. We observed good improvement in sensitivity; T_{rec} spanned ~160-220 K for the older device in the same test cryostat measurement setup.

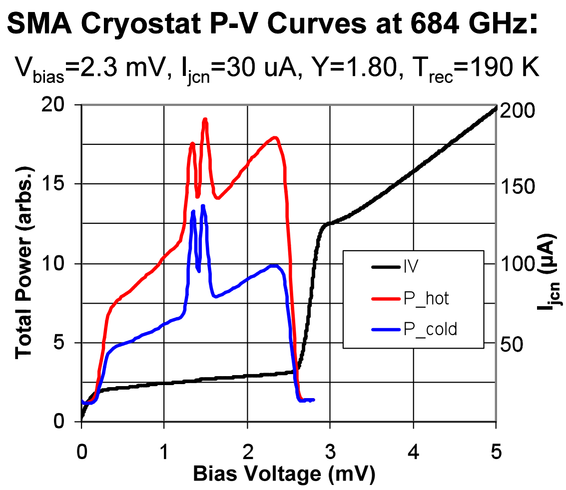

Fig. 5 Typical DC-IV curves and total power (PV) measurements made for the upgraded 660 GHz receiver insert in the lab SMA cryostat. Device bias parameters and Y-factor results are shown.

B. SMA Cryostat Performance

After characterization in the liquid helium cryostat, the same 660 GHz mixer was incorporated into an SMA receiver insert and its performance was measured in a laboratory SMA cryostat (see III *B* for a description of the setup). DC-IV curves taken in the SMA cryostat reveal that the device was operating at a warmer temperature (~4.8 K) than in the liquid helium cooled cryostat, with V_{gap} = 2.80 mV, R_{subgap}/R_N = 16, and R_N = 25 Ω. Typical SIS device DC-IV curves and swept total power curves at 684 GHz are shown in Fig. 5. Y-factor measurements over the frequency band of interest reveal elevated noise temperatures compared with results in the liquid helium cryostat, with T_{rec} = ~190-280 K over 630-700 GHz (Fig. 6). The observed difference in sensitivity is likely attributable to multiple factors, including warmer device operating temperatures and increased IR loading in the SMA cryostat environment (e.g., ~100 K Teflon lens in SMA insert vs. 4 K mirror in the test cryostat). As described in IV *B*, Y factor measurements were made over the 4-8 GHz IF passband for the receiver operating at 632 GHz. The results are shown in Fig. 7 and reveal that the upgraded receivers provided a wider IF coverage of up to > 7 GHz which fits into the recent IF bandwidth upgrade of the SMA. These measurements were limited by resonance effects observed at ~7.5 GHz with the bias tee supplying the SIS DC. The bias tee will be replaced in the future.

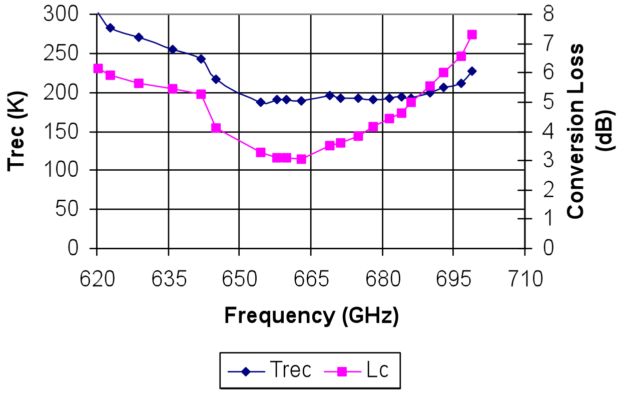

Fig. 6 Measured T_{rec} *(left, blue)* and mixer conversion loss *(right, pink)* over the 620-696 GHz frequency range for a receiver insert with an upgraded 660 GHz mixer operating in the laboratory SMA cryostat.

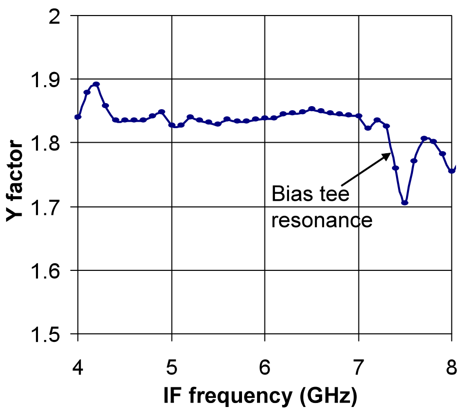

Fig. 7 Y-factor measurements made at 632 GHz over the 4-8 GHz IF passband for an upgraded 660 GHz receiver in the SMA cryostat. Measurements made from 3-9 GHz in steps of 0.1 GHz looking at a room temperature and liquid nitrogen cooled loads. Resonance effects with the bias tee used to provide SIS device bias are apparent at ~7.5 GHz.

C. First Results at the Telescope

New 660 GHz devices have been incorporated into several receiver inserts now at the SMA. One of these upgraded inserts has been operating at the telescope since the beginning of the 2009 fall-winter observing semester and the other was shipped for installation last week. Observations were recently made at 658 GHz toward the evolved star VX Sgr, the brightest submillimeter water maser, as part of recent 600 GHz receiver testing. The resulting spectrum representing the vector-average of all baselines with the antenna containing a new 660 GHz receiver is shown in Fig 8. Observations were made with the SMA operating in "very extended" configuration, corresponding to a maximum baseline of 500 m and a synthesized beam of < 0.25 arcseconds during very good weather conditions (atmospheric opacity at 225 GHz ~ 0.05). The frequency resolution of the spectrum is ~ 1 MHz.

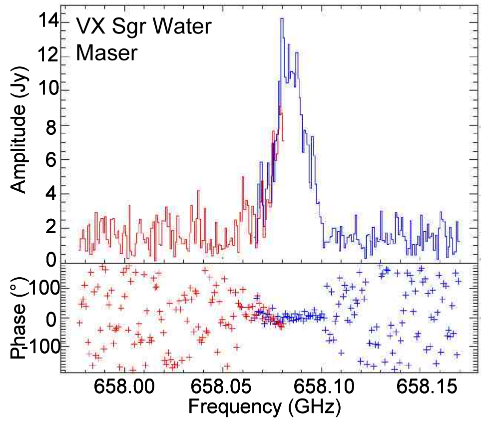

Fig. 8 Spectrum at ~658 GHz toward VX Sgr made with the SMA. Spectrum is vector average of all baselines containing Antenna 2 (with upgraded 660 GHz receiver insert).

V. SUMMARY

We report on the status of an ongoing project to upgrade the performance and sensitivity of the 600 GHz SMA receivers. The LO units have been upgraded with new tunerless varistor x2 x3 multiplier chains, resulting in increased LO output power (>~10 μW) across the 640-700 GHz frequency range. This has enabled the receiver coupling optics to be upgraded. A fine metal mesh is used as an RF/LO diplexer instead of a MPI, resulting in less overall complexity and has improved signal beam transmission by ~0.5 dB. New SIS mixers were designed, fabricated, and characterized in collaboration with Univ. of Köln for operation in the 630-700 GHz frequency range. Results of laboratory Y-factor measurements are presented for operation in both a liquid helium test cryostat and in the lab SMA cryostat. DSB T_{rec} of 100-150 K were achieved over the design frequency range in the liquid helium cooled cryostat. This shows good improvement compared with the sensitivity of typical SIS devices currently in use at the SMA measured under the same laboratory operating conditions. Y-factor measurements made across the IF passband indicate that the upgraded receivers provide wider IF coverage, up to > 7 GHz, which fits into the recent IF bandwidth upgrade of the SMA. First-light observations with an upgraded 660 GHz SMA receiver insert are presented.

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