Performance of the first ALMA Band 5 production cartridge.

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***Abstract*—We present performance of the first ALMA Band 5 production cartridge, covering frequencies from 163 GHz to 211 GHz. ALMA Band 5 is a dual polarization, sideband separation (2SB) receiver based on all Niobium (Nb) Superconductor-Insulator-Superconductor (SIS) tunnel junction mixers, providing 16 GHz of instantaneous RF bandwidth for astronomy observations. The 2SB mixer for each polarization employs a quadrature configuration. The sideband separation occurs at the output of the IF hybrid that has integrated bias-T for biasing the mixers, and is produced using superconducting thin film technology.**

Experimental verification of the Band 5 cold cartridge performed together with warm cartridge assembly, confirms that the system noise temperature is below 45 K over most of the RF band, which is less than five photon noise (5 hf/k). This is to our knowledge, the best results reported at these frequencies. The measurement of the sideband rejection indicates that the sideband rejection better than 10 dB over 90% of the observational band.

***Index Terms*—Terahertz System, Astronomy instruments, ALMA, Superconducting devices, Millimeter wave mixers, Superconductor-insulator-superconductor mixers, Thin film circuits.**

I. Introduction

THE Atacama Large Millimeter/sub-millimeter Array (ALMA) is a radio interferometer under construction by an international consortium consisting of European countries (ESO), USA, Canada, Chile, Taiwan and Japan. ALMA is located at 5000 meters above sea level in the Atacama Desert in Chile, where the earth's atmosphere provide the most favorable conditions for radio astronomy observations at these frequencies. ALMA will cover the frequencies from 31 GHz to 950 GHz split into ten frequency bands. With its more than 60 antennas of 12 m diameter and a reconfigurable baseline ranging from 150 m to 18 Km, ALMA will offer unprecedented sensitivity and resolution.

The work presented here concerns the design and development of the ALMA Band 5 receiver. ALMA Band 5 is funded by the European Commission's sixth Framework Program (FP6), an infrastructure enhancement project. In this framework program, the project will supply 6 receiver cartridges to the ALMA project for integration into the ALMA frontend receiver. Similar to other ALMA bands, the Band 5 receiver is also divided into two separate units, a warm cartridge assembly (WCA) and a cold cartridge assembly (CCA).

The Group for Advanced Receiver Development at Chalmers University with Onsala Space Observatory is responsible for the design and development of the cold cartridge assembly (CCA) and the STFC Rutherford Appleton Laboratory, UK, is responsible for the design and development of the Band 5 warm cartridge assembly (WCA) and the local oscillator (LO) chain.

The CCA is a unit which is cryogenically cooled using a three stage cryo-cooler of the ALMA front end cryostat. Different components of the cartridge are thermally connected to different temperature stages of the cooler. The cold cartridge assembly hosts, receiver optics, orthomode transducer (OMT), SIS mixers, IF hybrid, IF low noise amplifiers, mixer bias and ESD protection circuitry and x6 multiplier which is delivered by RAL.

The warm cartridge assembly is a unit which resides outside the cryo-cooler and provides a blind mate interface to the cold cartridge assembly. The warm cartridge assembly hosts the local oscillator source operating from 14 GHz to 17 GHz, a x2 multiplier, phase lock loop for LO after the x2 multiplier stage, warm IF amplifiers and bias and control circuitry.

II. ALMA Band 5 cold Cartridge

The ALMA Band 5 receiver is a dual polarization, sideband separating, heterodyne receiver, covering frequencies from 163 GHz to 211 GHz, with 4-8 GHz down converted intermediate frequency (IF) for each channel. Band 5 receiver employs sideband separation quadrature configuration (2SB) based on all Niobium (Nb) Superconductor-Insulator-Superconductor (SIS) mixers [1]. The separation of two orthogonal polarizations is realized using a waveguide orthomode transducer [2]. For each polarization branch, the receiver will provide 8 GHz instantaneous RF band for observations. Among the other frequency bands of the ALMA project, Band 5 is the lowest frequency band that uses all cold optics. Consequently, the physical dimensions for all the optics components for Band 5 are largest compared to all other ALMA bands. The optics components packed inside a limited space of ∅ 170 mm, leave very little room for the other receiver components.

Fig. 1 shows a CAD drawing of the cold cartridge, with the fiberglass supports removed for better visibility. It can be seen

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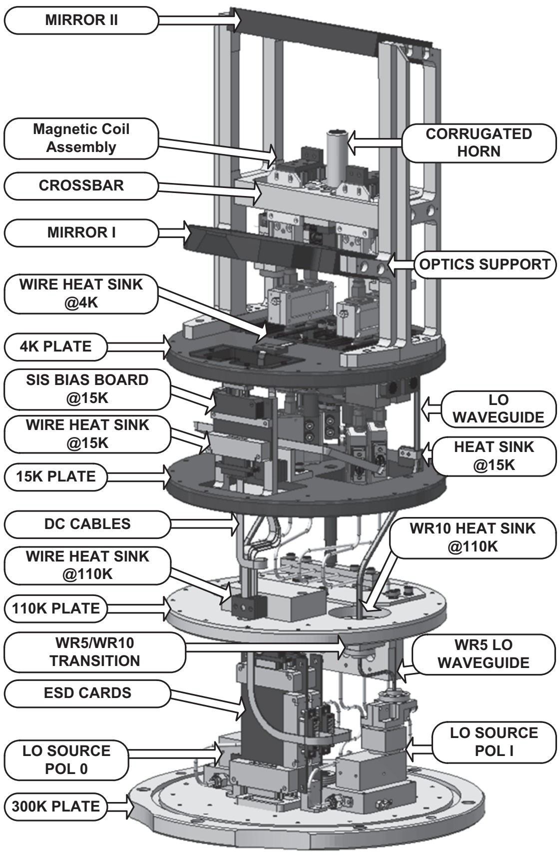


Fig. 1. A CAD drawing of the entire cold cartridge assembly (CCA), showing different temperature stages and arrangement of receiver components inside the cartridge envelop, the fiberglass supports separating different temperature stages are removed for visibility of components inside.

from the figure that the mirrors along with the optics supports occupy much of the space on the 4 K stage. The design parameters of Band 5 mirrors and corrugated horn are based on the design proposed by M. Carter et al., [3] and has been verified using physical optics simulation by M. Whale et al., [4]. The optics dimensions put strong constraints on the sizes of all the receiver components and demand a very compact design. A mixer block design with waveguide back piece layout [1], [5], [6] allows very compact design of the mixer block and also the IF output pointing in desirable direction. Furthermore, to avoid extra cables, all the components in the chain are directly attached to each other with SMA connectors. Keeping compactness of all the components in mind and in order to take advantage of cold temperature, we chose a custom made superconducting IF hybrid that fits the distance between the SMA connectors of the 2SB mixer IF outputs avoiding any unnecessary cabling. Apart from tight constraints on the size of all the receiver components, we have very limited cooling capacity at the 4 K stage, restricting the total power dissipation at the 4 K stage to merely 36 mW. These 36 mW are shared between the four SIS mixers, magnetic coils, low noise amplifiers and thermal load due to heat conduction. A lot of effort has been put to reduce the contribution from each of these components but still it does not allow us to integrate the DC bias circuit for the SIS mixers at the 4 K stage [7]. Therefore, in our design, as shown in Fig. 1, the DC biasing to the mixer is done using a bias circuitry placed at the 15 K plate and integrating a bias-T with the IF hybrid; the DC biasing is thus achieved through the output SMA connector of the mixers. The hybrid is followed by a 4-8 GHz isolator and a cryogenic HEMT low noise amplifier.

Part of the local oscillator chain resides inside the cold cartridge assembly and is placed on the 300 K plate of the cartridge. The LO chain placed at 300 K stage includes a x3 active multiplier from QuinStar, followed by an amplifier and isolator both produced by RPG GmbH and a x2 doubler developed by RAL [8], [9]. The LO signal is then guided from the 300 K stage to 4 K stage to the mixers using overmoded (WR10) waveguide. In order to reduce the thermal coupling between the different temperature stages, we use stainless steel waveguide with heat sinks at all the temperature stages.

III. Band 5 cold cartridge key components

A. Mixer assembly

The 2SB mixer employs a modular design approach to facilitate characterization of each component separately. Fig. 2 shows an assembly comprising of a corrugated horn, orthomode transducer (OMT) and the mixer assembly. The 90^0 waveguide twist after the OMT is used so that both polarizations have the same orientation.

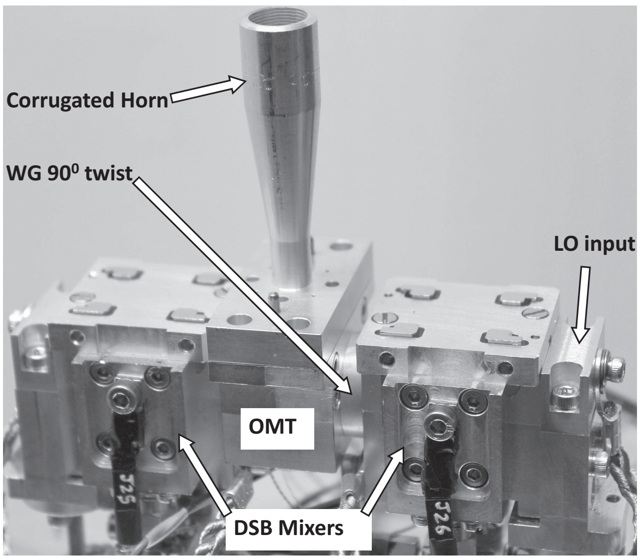


Fig. 2. A picture of the cartridge showing, the horn, OMT, 2SB mixers and the 90^0 waveguide twist. Coils, mirrors and optical support structures are removed for better visibility.

The sideband separation mixer [1] uses end piece configuration, with identical back pieces for both DSB mixers while the mixer chips in the two DSB back pieces are mirrored copy of each other. Fig. 3 shows the picture of the 2SB mixer. The middle piece houses an in-phase LO splitter [10] and 90^0 RF hybrid. All the mechanical components of the 2SB mixer are machined in tellurium copper and electroplated with gold.

The RF hybrid is an 8-section waveguide branch line coupler designed to achieve broadband performance [11],

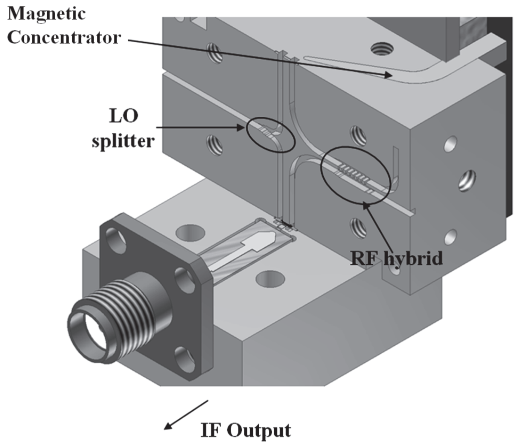


Fig. 3. Picture of middle piece, with RF hybrid and LO splitter.

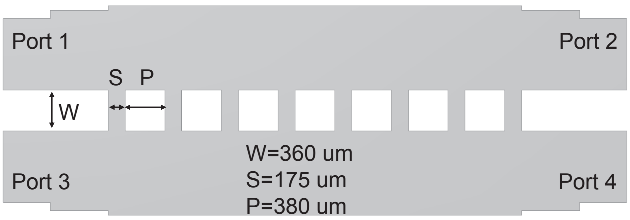


Fig. 4. Layout of the RF Hybrid, the waveguide dimensions are 1260 µm 630 µm.

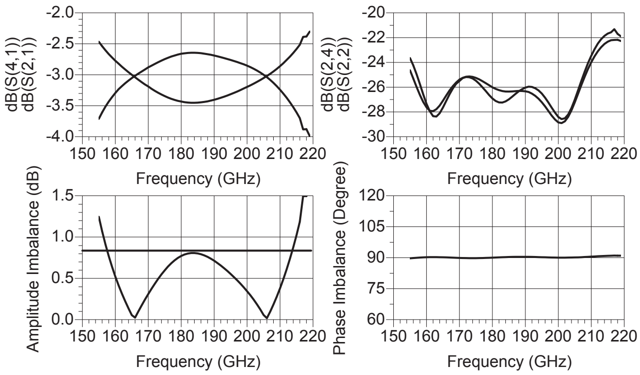


Fig. 5. Simulation of the RF hybrid, top left plot shows the output at through and coupled port, bottom left plot shows the amplitude imbalance, and the dotted line represents 0.85 dB. Top right plot shows the isolated port and reflection at one of the port (reflection at other three ports not shown but similar), bottom right plot shows the phase imbalance.

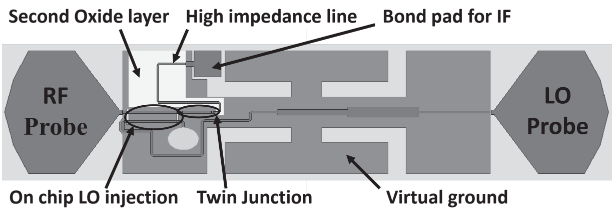


Fig. 6. ALMA Band 5 mixer chip layout showing the RF choke structure, RF and LO probe, LO coupler, RF and LO matching circuitry, on chip resistive termination and SIS junctions.

[12]. The RF hybrid is designed and simulated using CST microwave studio and Agilent EMDS. Fig. 4 shows the layout of the RF hybrid. The simulation results in Fig. 5 indicate that the maximum amplitude imbalance of $0.8\,dB$ can be achieved across the whole RF band, with negligible phase imbalance.

For the SIS mixer, we employ a MMIC-like approach where most of the DSB mixer components along with the LO coupler are integrated on the same z-cut crystal quartz substrate. The dimensions of the on-chip LO coupler are defined by photolithography, providing greater precision over the definition of coupler geometry and thus allowing accurate control over the LO coupling.

As shown in Fig. 6 an E-plane probe is used for the waveguide to microstrip transition for both RF and LO signal, a RF choke structure provides virtual RF ground for the RF and LO signals in microstrip mode. The choke is also DC/IF grounded to the chassis using bond wires. The LO circuitry includes a probe and an impedance transformer to bring the probe impedance to a desirable value. LO injection is implemented using a microstrip line coupler with slots in the ground plane. The isolated port of the coupler is terminated using a wideband elliptical floating load [13]. The down converted signal at intermediate frequency (IF) is extracted between the RF and LO waveguide.

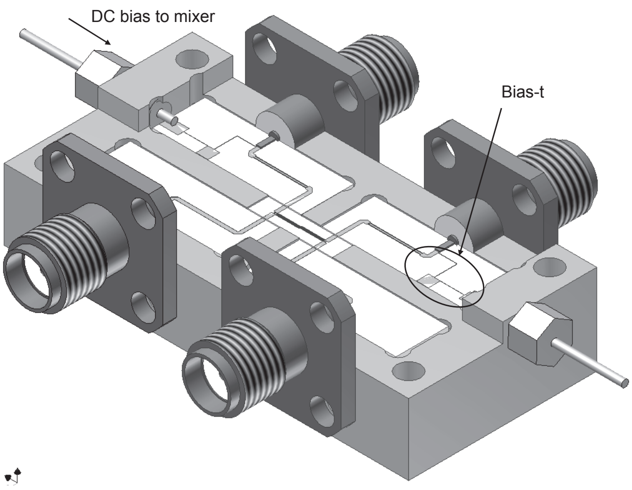
At intermediate frequencies, the RF and LO matching components, including the transmission lines and the LO coupler structure appears as a capacitor and hence affect the mixer IF performance, especially at the higher end of the IF band. It is therefore necessary that the whole RF and LO circuitry represents as low capacitance as possible at the IF frequencies. At the same time it is very important that the LO coupler has minimal losses at RF frequencies. Therefore, the LO coupler has been designed to have very low coupling of $-18\,dB$, this ensures that the LO circuitry does not introduce any losses at RF frequencies, and we chose a coupler design with slots in the ground plane, which ensures that the coupler contribute very little to the overall IF capacitance of the chip.

B. IF Hybrid

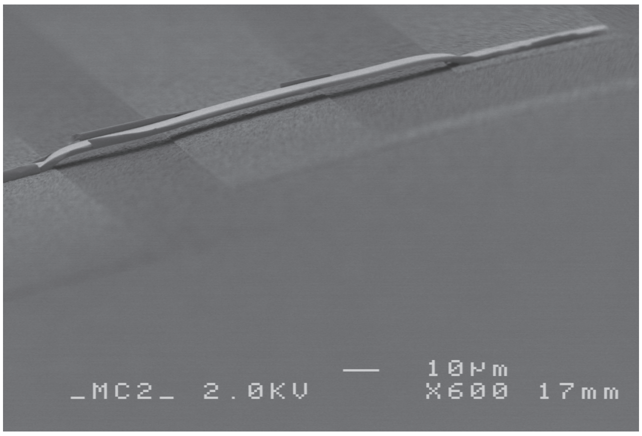
In order to avoid unnecessary IF cabling inside the Band 5 cartridge, all the components are directly connected to each other via SMA connectors. For this reason, any commercially available IF hybrid cannot be used, and hence the IF hybrid was specially designed and built. The pitch between the two SMA connectors of 2SB mixer defines the distance between the two input SMA connectors of the hybrid. The IF hybrid is fabricated on 500 micron thick Alumina substrate and glued to the gold plated copper housing using a silver conductive epoxy.

The IF hybrid is designed for frequency 4-8 GHz using Lange coupler layout, and to take advantage of the cryogenic temperatures the IF hybrid is fabricated with superconducting Nb lines to eliminate conductive losses. A thin Palladium layer is deposited onto the Niobium to allow bonding where it is necessary.

In order to avoid substrate modes, which could compromise the hybrid performance, the complete IF hybrid is divided into



(a)



(b)

Fig. 7. IF hybrid with integrated bias-T (a) Layout of the hybrid with capacitive feed-through for DC bias, (b) SEM image of the air bridge fabricated along with the Lange coupler.

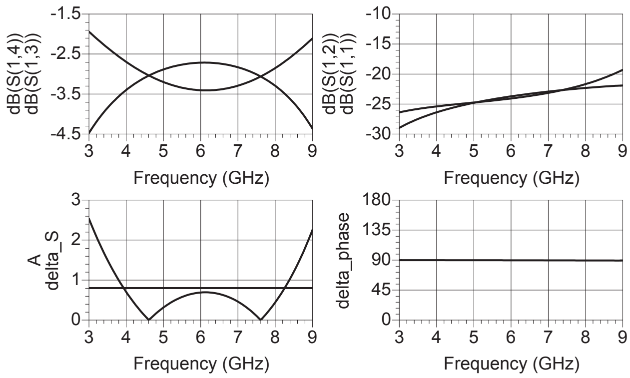


Fig. 8. Simulation result of the IF hybrid, top left plot shows the output at through and coupled port, bottom left plot shows the amplitude imbalance, and the dotted line represents 0.6 dB. Top right plot shows the isolated port and reflection at one of the port (reflection at other three ports not shown but similar), bottom right plot shows the phase imbalance.

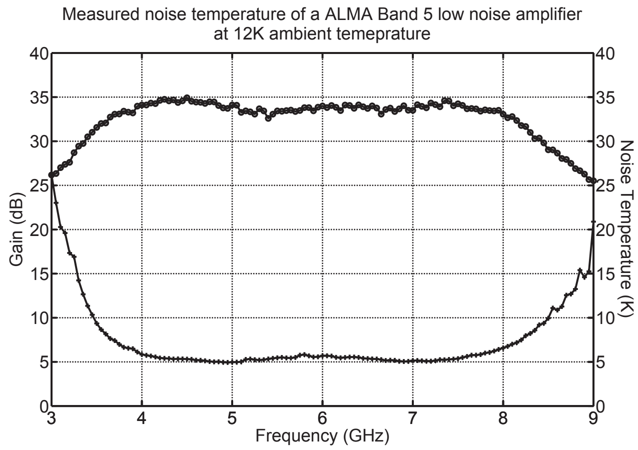


Fig. 9. Measurement of one of the ALMA Band 5 low noise amplifiers performed at 12 K ambient temperature, showing 35 dB gain and noise temperature below 6 K. Measurements of all other amplifiers shows consistent performance.

five separate sections, one for the Lange coupler, two for $50\ \Omega$ connecting line and two for the bias-T. The lines, bias-T and the Lange coupler are connected using paired bond wires to reduce parasitic inductance of the inter-connection.

Fig. 7 (a) shows the layout of the IF hybrid. The width of the coupled lines of the Lange coupler is 45 µm with spacing between the lines 34 µm. The Lange coupler uses air bridges fabricated together with the hybrid using thin film technology. Fig. 7 (b) shows the scanning electron microscope image of the air bridge that connects the fingers of the Lange coupler, the measured height of the air bridge is 3 µm.

Fig. 8 shows the simulation result with 3 micron height of the air-bridge, the maximum amplitude variation is 0.7 dB and phase variation is negligible.

C. IF Amplifiers

The cold IF amplifier used for ALMA Band 5 is based on previously developed 3-stage HEMT amplifier for the Swedish Heterodyne Facility Instrument for the APEX telescope [14]. In contrast to the earlier design, the amplifier uses HRL InP transistors for the first stage (provided by ESO for the ALMA Band 5 project) and for the subsequent two stages uses Mitsubishi MGFC4419G InGaAs pseudomorphic HEMT. Fig. 9 shows the measured performance for one of the Band 5 low noise amplifier. The amplifier has 35 dB gain over the 4-8 GHz band with noise temperature less than 6 K over the entire band, while consuming merely 6 mW of power.

IV. Measurement results

A. Noise temperature measurement

The performance verification of the Band 5 cold cartridge was carried out together with the warm cartridge assembly delivered by the Rutherford Appleton Laboratory, UK. To perform these tests we used the NAOJ cartridge test cryostat [15]. Most of the measurements are done using an automated system, built around the test cryostat [16].

The noise specifications for the ALMA Band 5 project requires the system noise temperature to be below 65 K over 80% of the band and less than 108 K at any frequency. Fig. 10 shows the measured noise performance of the first Band 5 production cartridge. The noise was measured over the 4-8

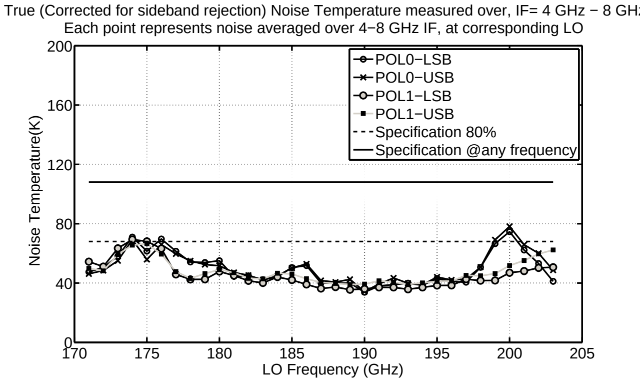


Fig. 10. Measurement of noise temperature for ALMA Band 5 CCA 01, for both sidebands and polarization, measured over the 4 -8 GHz IF band.

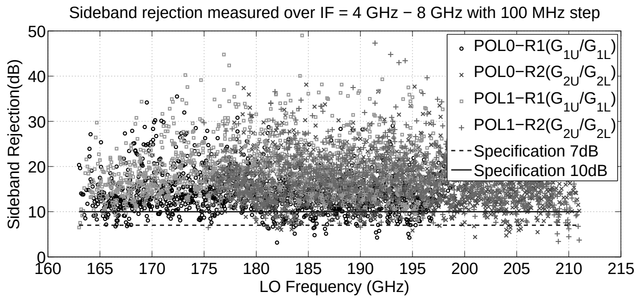
GHz IF band for both sidebands and polarizations and includes the contribution from the dewar windows, IR filters and takes into account all the noise contributions up to the IF output ports of warm cartridge assembly. The noise measurements were carried out using standard Y-factor method with liquid nitrogen and room temperature loads. The presented noise temperature also takes into account the correction for the sideband rejection [17]. Our measurements confirm that the receiver performance meets all the noise specification for the Band 5 project and is in most cases better than the specifications with a good margin.

B. Sideband rejection measurement

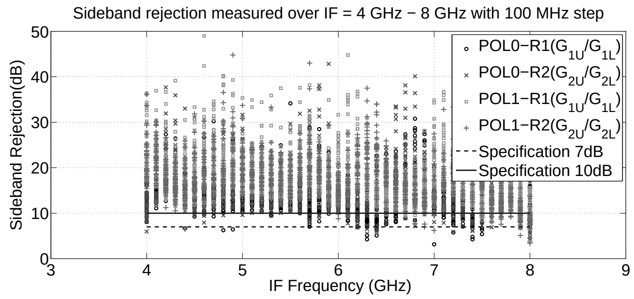
In sideband separation millimeter wave receiver, knowledge of image rejection is very important. Unless the image rejection is very high, a correction term is required for the estimation of the system noise temperature. We use the technique proposed by A. Kerr [17] to estimate the sideband rejection. Fig. 11 (a) shows the sideband rejection measurement results, performed at RF frequencies from 163 to 211 GHz with 100 MHz frequency steps and Fig. 11 (b) shows the same measurements plotted across the IF band for all RF frequencies. The measurements confirm that the sideband rejection is better than 10 dB over 90% of the band and better than 7 dB over 99%.

C. Receiver stability

1) Amplitude stability: One of the most important design parameter for a modern radio telescope is the stability of the instrument. The stability of the receiver is generally described in terms of its Allan variance time (T_A). The Allan variance time describes the integration time for a receiver beyond which the observing efficiency is reduced. Fig. 12 shows the receiver stability measurements using the Allan variance method. Measurements were performed at 3 different LO frequencies and total output power over 4-8 GHz IF band is used to calculate the Alan variance. It is evident from the Fig. 12 that the receiver meets the specification with margin for all the measured frequencies.



(a)



(b)

Fig. 11. Measurement of sideband rejection/image rejection for ALMA Band 5 CCA 01, for both polarization, (a) Sideband rejection vs. RF (b) Sideband rejection vs. IF.

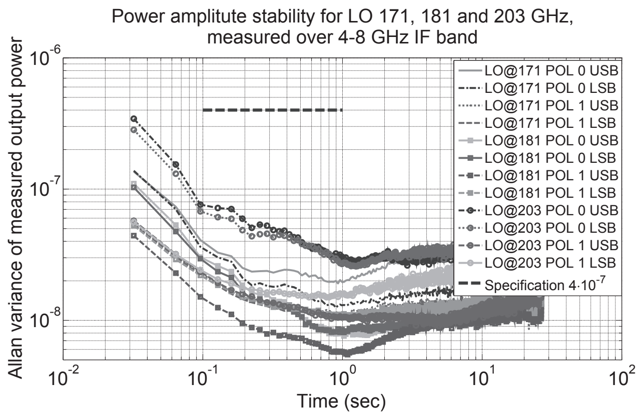


Fig. 12. Measurement of receiver stability using the Allan variance method, the total IF power is measured over the 4-8 GHz bandwidth.

2) Signal path phase stability: Along with signal amplitude stability, for a radio interferometer it is equally important to have very good phase stability of the signal path. To ensure a stable baseline, ALMA Band 5 project specification requires that for all frequencies within the IF pass-band the signal path transfer function should maintain phase stability better than 0.9 degrees on timescales up to 300 seconds. The phase being the average value measured in 16 msec. The signal path includes all components between the RF window and the IF outputs of the warm cartridge assembly that houses the second-stage amplifier and the local oscillator chain. The required phase stability excludes any contribution from the local oscillator chain residing in the WCA but takes into account contributions from the LO components inside the CCA. Fig. 13 shows the measured phase stability of the signal

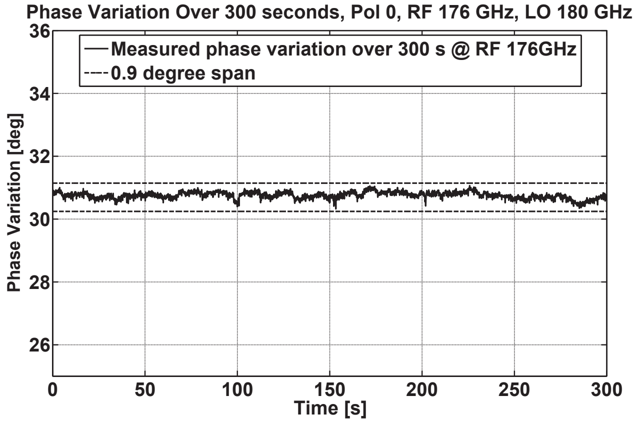


Fig. 13. Measurement of signal path phase stability, measured at 180 GHz LO frequency and 176 GHz RF frequency. Plot shows 300 s measurement data of the phase of 4 GHz down converted IF at the lower sideband. The two dotted lines shows 0.9 degree span.

path. For the measurement of phase stability, a LO signal at 180 GHz and a RF signal at 176 GHz were used and the phase of the down-converted IF was measured at 4 GHz IF at the lower sideband. Fig. 13 shows the measurement results of the phase stability confirming signal path phase stability less than 0.9 degrees over time period of 300 s.

V. Conclusion

We have designed and built the first ALMA Band 5 production cartridge and fully characterized it. The characterization of the cold cartridge was performed with integrated warm cartridge assembly. Performance verification of the entire system including cryostat window, IF filters and all IF components, confirms that the first Band 5 production cartridge meets all ALMA project specifications.

The measurement of 2SB configuration confirms that the system noise temperature less than 45 K over most of the RF band, which is less than five quantum noise (5 hf/K) and less than 65 K (7 hf/K) over the entire RF band. This is to our knowledge the best results so far at these frequencies. The sideband separation for both polarizations is better than 10 dB over 90% of the band and better than 7 dB over 99% of the RF band.

The first ALMA Band 5 cartridge has been delivered to the European ALMA Integration Center at RAL in UK and is expected to be in operation at the ALMA cite in Chile during year 2012.

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