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 RF 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 mixer, providing 16 GHz of instantaneous RF bandwidth for the astronomy observations. The 2SB mixer for each polarization employs a quadrature layout. 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 the system noise temperature below 45 K, less than five quantum noise (5 hf/k) over most of the RF band, which is to our knowledge, the best results 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 Millimetre/sub-millimeter Array (ALMA) is a radio interferometer under construction by an international consortia consisting of European countries (ESO), USA, Canada, Chile 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 up into ten different 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, one of the 10 frequency bands of the ALMA project. ALMA Band 5 is funded by European Commission's Framework Program 6 (FP6), an infrastructure enhancement project. In this framework program, the project considers to 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 local oscillator stage. The x6 (times six) local oscillator stage 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 in the frequency range from 14 GHz to 17 GHz, a x2 (times two) multiplier, phase lock loop for LO after the x2 (times two) 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 the RF 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 layout (2SB) based on all Niobium (Nb) superconducting tunnel junction (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. All these relatively big optics components packed inside a limited space

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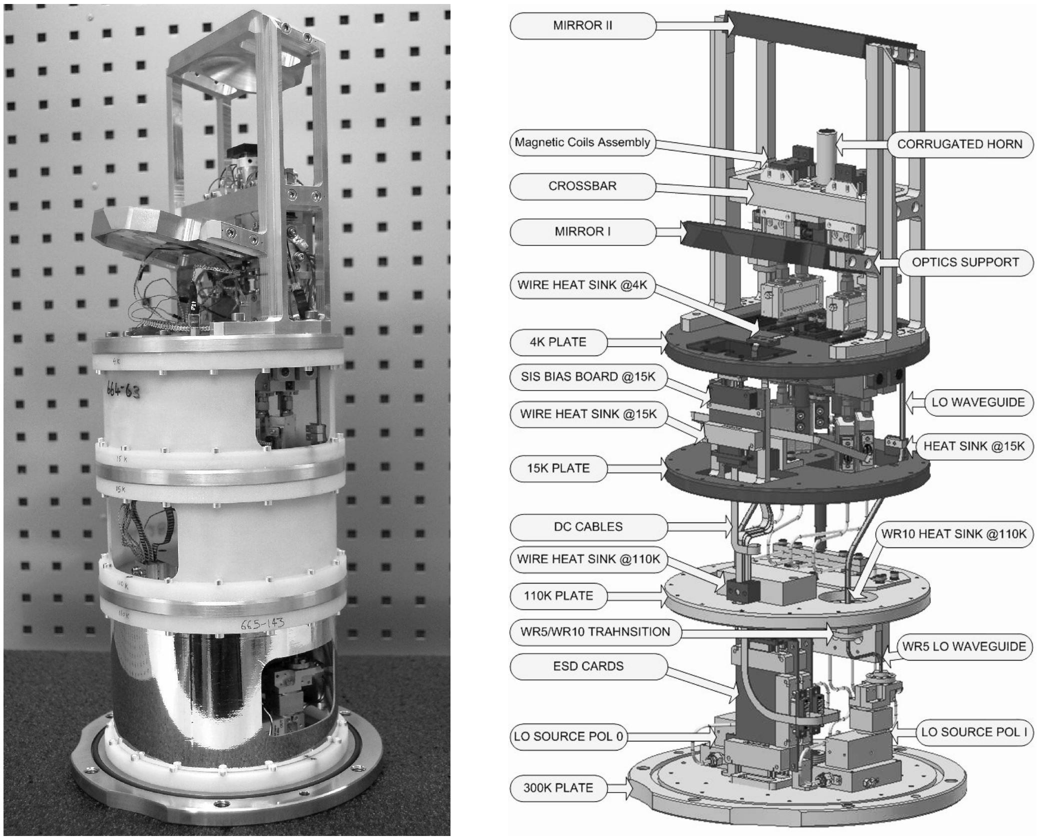

(a) (b)

Fig. 1. Band 5 CCA 01 (a) Picture of the first Band 5 cold cartridge assembly (b) a CAD drawing of the CCA, showing different temperature stages and arrangement of receiver components inside the cartridge envelop, the fiber glass supports separating different temperature stages are removed for visibility of components inside.

of ∅ 170 mm, which leaves very little space for the other receiver components.

Fig. 1 shows a CAD drawing of the cold cartridge, the fiber glass support is removed for better visibility. It can be seen from the figure that the mirrors along with the optics supports occupy much of the space on the 4 K temperature 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 demands a very compact design. Furthermore, the arrangement of the components in the cartridge is such that we have to direct the IF output of the mixers pointing down along the cartridge axis. In such a configuration, the mixer design with a split block technique becomes too big to fit inside the cartridge. We have found that the only possible solution is to use a mixer block configuration with waveguide back piece [5], [6]. This layout 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 matched SMA connectors. Keeping compactness of all the components in mind and 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 4 K stage, restricting the total power dissipation at 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 efforts have been put to reduce contribution from each of these components but still it does not allow us to integrate the DC bias circuitry for the SIS mixers at 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 signal is then guided from the 300 K stage to 4 K stage to the mixers using WR10 (over-sized) waveguide. In order to reduce the thermal coupling between the different temperature stages, we use stainless steel waveguide with heat sinks at all the corresponding temperature stages.

III. ALMA BAND 5 WARM CARTRIDGE

Fig. 2 shows the picture of the Band 5 warm cartridge produced by the Band 5 WCA team at the Rutherford Appleton

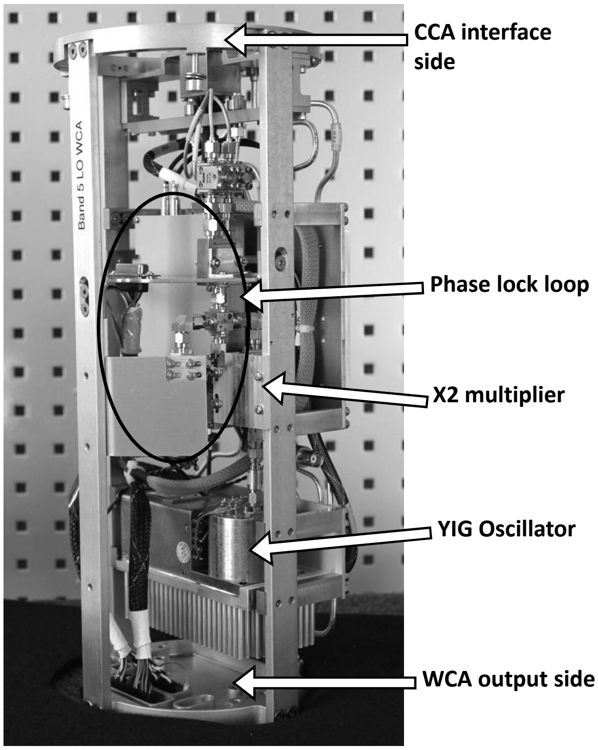

Fig. 2. A picture of the entire warm cartridge assembly (WCA), showing different components of the cartridge.

Laboratory in UK. Warm cartridge assembly consists of a YIG oscillator source in the frequency range of 14-17 GHz followed by a frequency doubler. The frequency doubler is then followed by a phase lock loop operating in the range of 28-34 GHz. In its final operational state, the reference signal for the phase locking will be provided by mixing two lasers in a photo-mixer producing a down converted reference in the frequency range of 28-34 GHz. In our measurement setup in the lab, we use a frequency synthesizer to obtain the required 28-34 GHz reference for the phase lock.

The warm cartridge assembly provides a blind mate interface to the cold cartridge. The blind mate interface consist of two input K-type connectors for the LO signals for both the polarizations, DC biasing for frequency doublers and multipliers for the LO stages inside CCA through Fisher connector, and biasing for the CCA through Glen-air connectors. The blind mate interface also includes four IF outputs from the CCA.

Fig. 3 shows the cold cartridge base plate, which hosts part of the LO multiplier chain and provides hermetically tight blind mate interface to the WCA. The part of the LO chain inside the CCA consists of a active frequency tripler (x3) followed by a frequency doubler (x2). The biasing to the tripler and doubler is provided through a fisher connector. Similar to all other ALMA bands, the DC biasing of different CCA components - the mixers, amplifiers, coils, and temperature sensors is done through a standard double 51 pin Glenair connector.

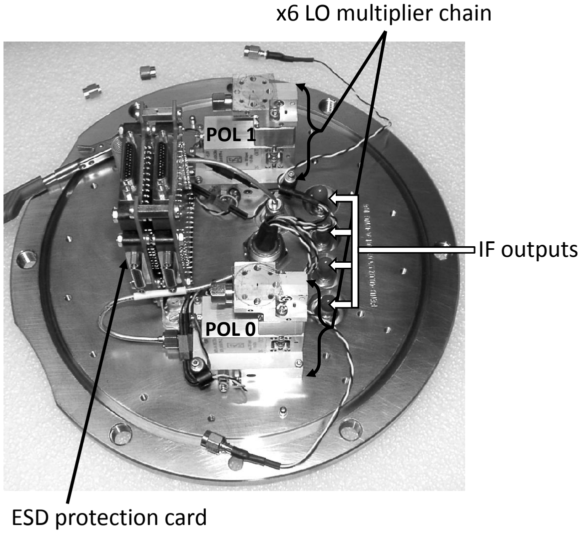

Fig. 3. A picture of 300 K CCA base plate showing, multiplier stages, ESD protection circuitry and IF outputs.

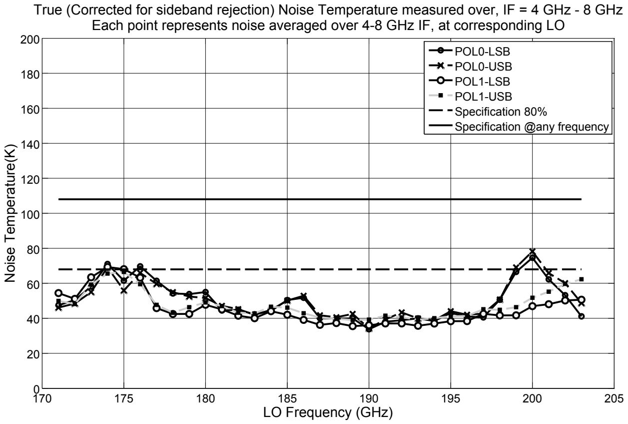

Fig. 4. Measurement of noise temperature for ALMA Band 5 CCA 01, for both sidebands and polarization, measured over the 4 -8 GHz IF band.

IV. MEASUREMENT RESULTS

A. *Noise temperature measurement*

The performance verification of the Band 5 cold cartridge was performed together with the warm cartridge assembly delivered by the Rutherford Appleton Laboratory, UK. To perform these tests we used NAOJ cartridge test cryostat [8]. Most of the measurements are done using an automated computerized system, built around the test cryostat [9].

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. 4 shows the measured noise performance of the first Band 5 production cartridge. The noise was measured over the 4-8 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. The presented noise temperature also takes into account the correction for the sideband rejection [10]. Our measurements confirm that the receiver performance meets all the noise specification for the Band 5 project, and in most cases better than the specifications with a good margin.

B. Sideband rejection measurement

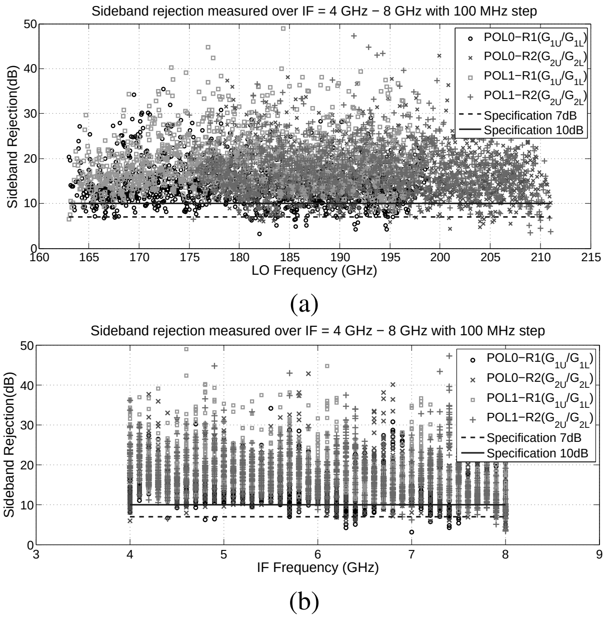

Fig. 5. Measurement of sideband rejection/image rejection for ALMA Band 5 CCA 01, for both polarization, (a) Sideband rejection vs. RF frequency (b) Sideband rejection vs. IF frequency.

In sideband separation millimeter wave receiver knowledge of image rejection is very important. Unless the image rejection is ideal, a correction term is required in estimation of the system noise temperature. We use the technique proposed by A. Kerr [10] to estimate the sideband rejection. Fig. 5 (a) shows the sideband rejection measurement results, performed at RF frequencies from 163 to 211 GHz with 100 MHz frequency steps and Fig. 5 (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%.

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 the 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 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 is 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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