Band-1 Receiver Front-End Cartridges for Atacama Large Millimeter/submillimeter Array (ALMA): Design and Development toward Production

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ABSTRACT

The ALMA Band-1 receiver front-end prototype cold and warm cartridge assemblies, including the system and key components for ALMA Band-1 receivers have been developed and two sets of prototype cartridge were fully tested. The measured aperture efficiency for the cold receiver is above the 80% specification except for a few frequency points. Based on the cryogenically cooled broadband low-noise amplifiers provided by NRAO, the receiver noise temperature can be as low as 15 – 32K for pol-0 and 17 – 30K for pol-1. Other key testing items are also measured. The receiver beam pattern is measured, the results is well fit to the simulation and design. The pointing error extracted from the measured beam pattern indicates the error is 0.1 degree along azimuth and 0.15 degree along elevation, which is well fit to the specification (smaller than 0.4 degree). The equivalent hot load temperature for 5% gain compression is 492 - 4583K, which well fit to the specification of 5% with 373K input thermal load. The image band suppression is higher than 30 dB typically and the worst case is higher than 20 dB for 34GHz RF signal and 38GHz LO signal, which is all higher than 7 dB required specification. The cross talk between orthogonal polarization is smaller than -85 dB based on present prototype LO. The amplitude stability is below 2.0×10^{-7} , which is fit to the specification of 4.0×10^{-7} for timescales in the range of $0.05\ s \leq T \leq 100\ s$. The signal path phase stability measured is smaller than 5 fs, which is smaller than 22 fs for Long term (delay drift) $20\ s \leq T < 300$ sec. The IF output phase variation is smaller than 3.5° rms typically, and the specification is less than 4.5° rms. The measured IF output power level is -28 to -30.5 dBm with 300K input load. The measured IF output power flatness is less than 5.6 dB for 2GHz window, and 1.3dB for 31MHz window. The first batch of prototype cartridges will be installed on site for further commissioning on July of 2017.

Keywords: Atacama Large Millimeter Array, heterodyne receiver, cryogenically cooled low-noise amplifier, resistive transistor mixer, local oscillators.

1. INTRODUCTION

After commission by early 2013, Atacama Large Millimeter / submillimeter Array has been served for various astronomical observations. The receivers currently operated on-site cover the available atmospheric window with frequency range from 84GHz to 950GHz (band-3 to band-10) except band-5 (163 – 211 GHz). The development of the Band-1 receivers is aiming to extend the observing frequency down lower frequency side to 35 – 50 GHz. The scientific

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missions of ALMA thus can be extended to the following items which is suitable to be observed in the 6 – 9 mm wavelength: (1) detailing the evolution of grains in proto-planetary disks, as a complement to the gas kinematics, requires continuum observations out to 35 GHz (9 mm); and (2) detecting CO 3-2 line emission from galaxies like the Milky Way during the epoch of re-ionization, i.e., $6 < z < 10$, also requires Band 1 receiver coverage, (3) galaxy clusters (i.e., via the Sunyaev-Zel'dovich Effect), (4) very small dust grains in the ISM, the Galactic Center (i.e., Sgr A*), (5) pulsar wind nebulae, (6) radio supernovae, (7) X-ray binaries, (8) dense cloud cores, (9) complex carbon-chain molecules, ionized gas (e.g., in HII regions), (10) masers, (11) magnetic fields in the dense ISM, (12) jets and outflows from young stars, (13) the co-evolution of star formation with active galactic nuclei, and (14) the molecular mass in moderate redshift galaxies. The detail discussion of the science cases can be found in [1].

Earlier development of the ALMA Band-1 components and system has been presented in [2-4]. Based on the earlier development, the main items done for ALMA band-1 receiver development during 2014 – 2016 are (i) further optimization of the optics design, (ii) design improvement of the warm receiver chain, (iii) final selection of the mixer (iv) receiver configuration optimization and (v) receiver performance test.

2. SYSTEM CONFIGURATION

The ALMA Band-1 receiver is allocated in the lowest frequency window. Among all the receiver bands, Band-1 receiver is with the position at outer edge of the cryostat. Cryogenically cooled InP HEMT low-noise amplifiers operated in 15K environment with thermal noise as quiet as 5 - 8 times of quantum limit is used to amplified the RF signal, instead of the superconductor-insulator-superconductor (SIS) mixer which need 4K operating temperature. The receiver configuration is basically divided into cold cartridge assembly (CCA) and warm cartridge assembly (WCA). The configuration of the ALMA band-1 receiver is quite different to the band-3 to band-10 SIS-based receivers. In all ALMA bands, local oscillator fundamental source and active frequency multiplier chain (AMC) up to E-, W-, or F-band are located in WCA. For ALMA SIS-based receiver, most of the receiver components are located in CCA, except the last stage of IF isolators, filters, amplifiers, and attenuators. For ALMA Band-1, most of the receiver components are located in WCA, the major components inside cryogenic environment of CCA are feed horn antenna, orthomode transducer, and cryogenic low-noise amplifiers. The receiver block diagram is shown in Fig. 1.

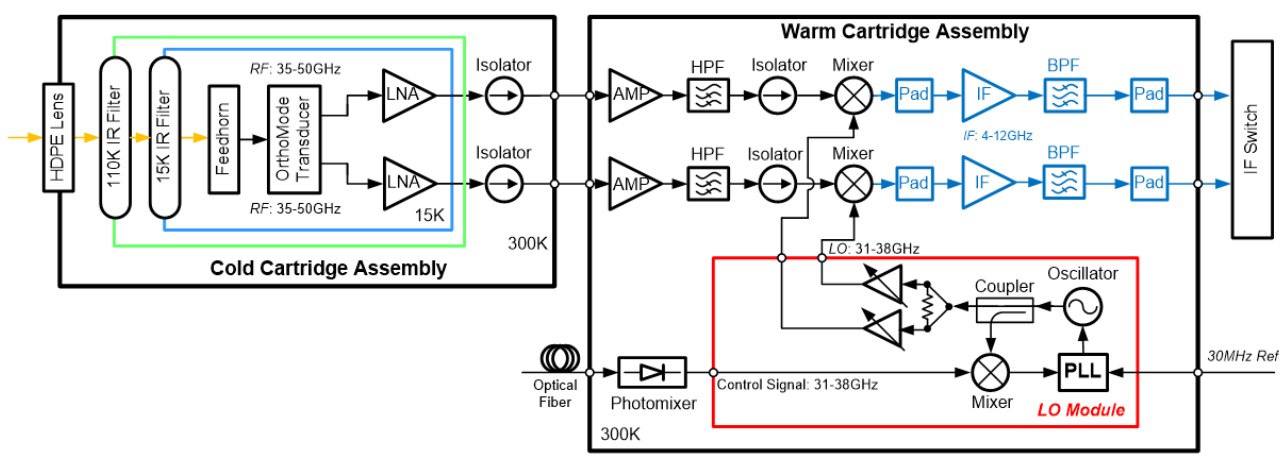


Figure 1. Block diagram of the ALMA band-1 receiver.

3. OPTICS DESIGN REVISION

Following the earlier optics design [5]-[8], further revision were developed and implemented to push the aperture efficiency higher than 80% over the whole RF frequency range. The major limitations of the optics design set by the ALMA receiver system are the following factors,

(1) The aperture of the IR blocking filters. The ALMA cryostat was design long time before the Band-1 receiver optics optimization. Based on the thermal load and space limitation, the aperture of the IR blocking filters for band-1 are limited in size of 60 mm diameter for 110K layer and 40 mm for 15K layer, as frequency band-3 to band-10 are

almost installed for observation now, we have proposed a optimized 110-K filter that permit achieve the ALMA specs. Nevertheless, replace the 110-K filter is difficult because the comprehensive mechanical disassembling and assembling, alignment, and calibration required.

(2) The location of the lens. Band-1 is with wavelength centered at 7mm, this means the optics components is with larger physical dimension compared to all the other higher frequency bands. The initial baseline design uses a dielectric lens to serve for both focusing the signal beam into the feed horn antenna and also as the vacuum window.

(3) Space restriction set by the optics relay arm for the water vapor radiometer (WVR) aside the band-1 cartridge position and the amplitude calibration device (ACD) system. The WVR optics relay arm is located aside the band-1 optics window, which restricts the available space for band-1 optics alternative solution only at the outmost edge of the receiver cryostat. The ACD is a set of load with different physical temperature to calibrate the amplitude response of receiver. However, the available space for band-1 optics alternative solution is beyond the coverage area of the ACD.

(4) Larger tilt angle due to the positions of the lowest frequency band. The design of the cryostat for the ALMA allocates the receivers the high frequency bands at innermost locations, and the lowest frequency bands at outermost edge of the cryostat.

Some initial design options have been proposed but the most of the proposals cannot overcome the above limitations. For example, the reflective optics design based on offset parabolic mirror is capable to reduce the optics noise contribution, which is significant at higher frequency edge by reduction of noise 4 – 6 K, due to the factor (3) mentioned above, thus this configuration is not feasible.

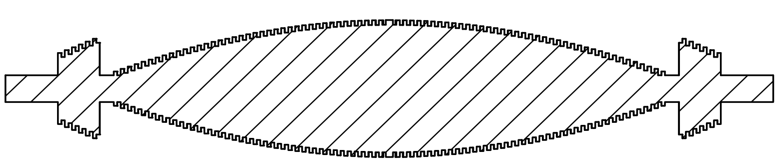
The design revision based on the room-temperature lens in these two years focus on the following items:

(1) Lens design further optimization: The HDPE bi-hyperbolic Fresnel zone lens is chosen to reduce the thickness of the lens. The final design is with central slab thickness of 8 mm and the maximum lens thickness of 40.8 mm. The focal lens of the lens is 180 mm and the distance between horn and lens central point is 175.4 mm. The antireflection layer fabricated as the corrugation groove surface is optimized to final thickness of 1mm, pitch of 2 mm, and the depth of the grooves changes with position on the lens with average value of 1.42mm.

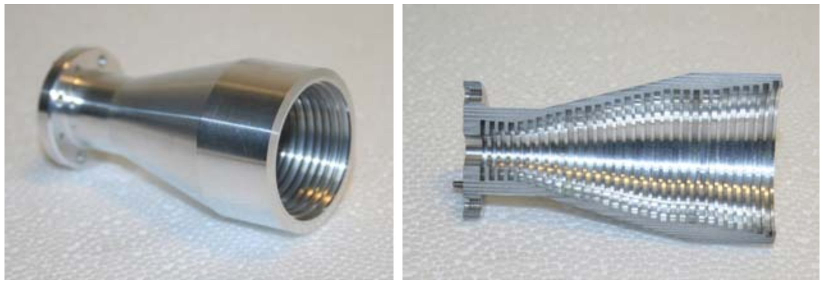
(2) Corrugated feed horn antenna profile design improvement: Horn antenna has been revised from the original standard canonical horn to the Spline-profile horn. The final mechanical parameter horn and the outline are shown in Table II and Figure 2, respectively. The aperture efficiency of the lens-horn configuration is shown in Figure 3.

(3) Investigation of the truncation due to small IF blocking filter apertures and very small distance to horn antenna: the layout of the optics configuration is as shown in Figure 4, the distance between the feed horn antenna aperture to the 15K IR blocking filter is only several mm and the impedance coupling is significant. These effects lead to the following results: (i) directivity degraded, which leads to widening of the beam, (ii) cross-polarization degraded, (iii) aperture efficiency frequency-dependent degradation, which turn to ripple of the aperture efficiency frequency response, (iv) increament of the receiver noise temperature. Figure 5 shows the analysis results.

The overall optics performance measurement is done by using phasor network analyzer (PNA) with scanner, the results is as shown in Figure 6. More detail of the ALMA Band-1 optics design revision is presented in [9] and [10].



(a)



(b)

Figure 2. Mechanical outline of the ALMA Band-1 optics key components: (a) outline and fabricated HDPE Zone Lens, (b) Spline corrugated horn antenna.

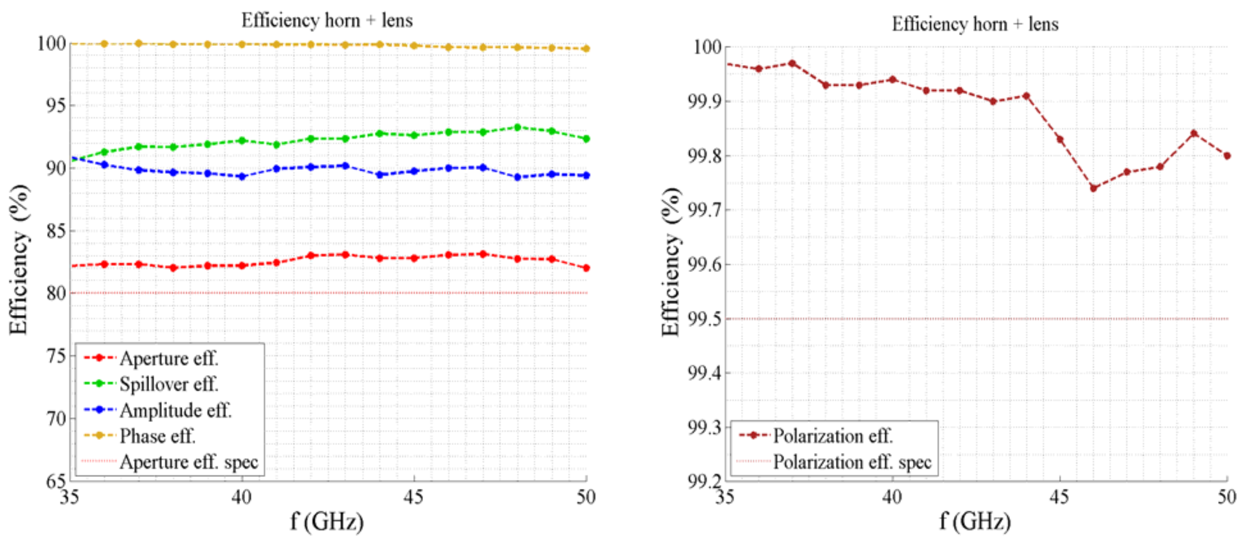


Figure 3. Simulated results of (left) aperture efficiency, spillover efficiency, amplitude efficiency and phase efficiency of the ALMA Band-1 optics lens-horn configuration, and (right) polarization efficiency. Please note the effects of the 110 and 15K IR blocking filters are not included in this simulation.

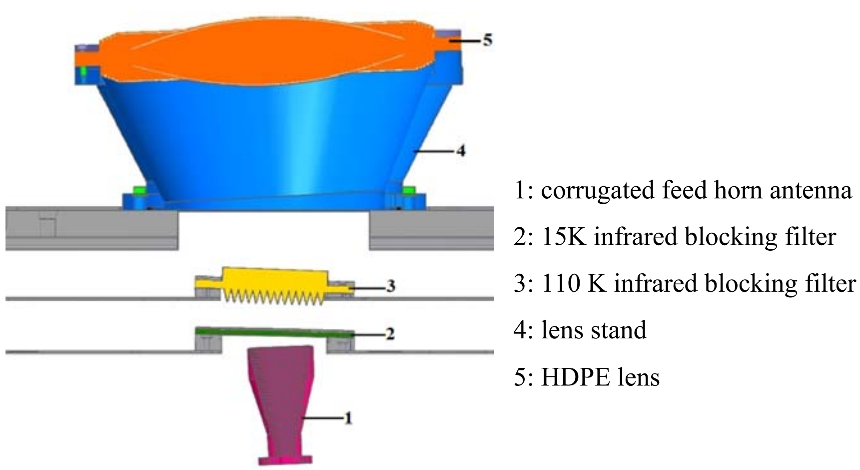


Figure 4. Layout of the ALMA Band-1 optics configuration.

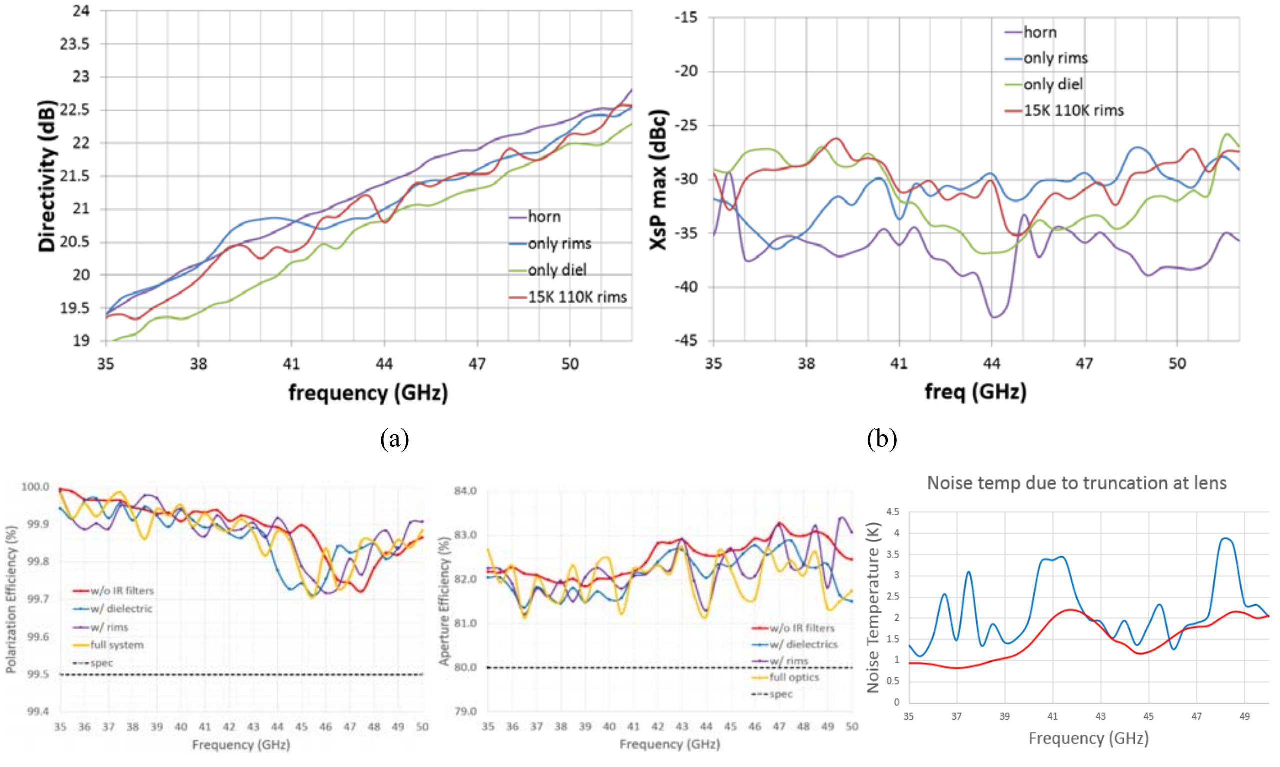
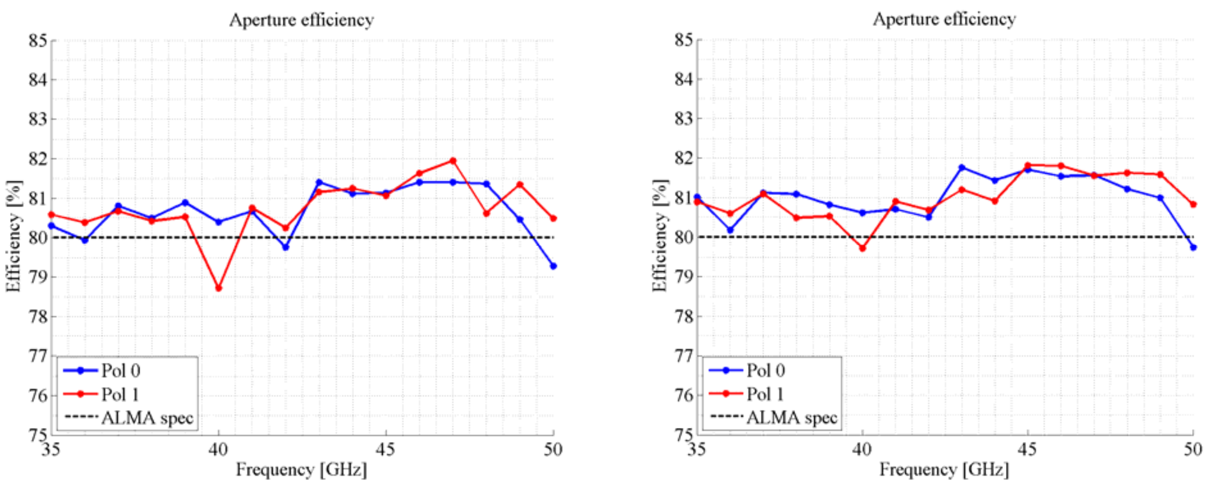


Figure 5. the simulated effects of the truncation and impedance coupling effect due to small IF blocking filter apertures and very small distance to horn antenna, (a) directivity, (b) cross-polarization, (c) polarization efficiency, (d) aperture efficiency, (e) increment of the receiver noise temperature.



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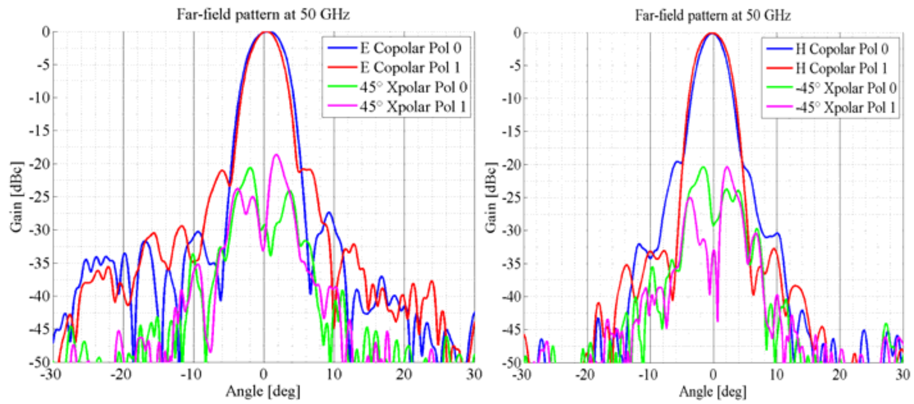


(b)

Figure 6. measured results of the ALMA Band-1 overall optics performance, (a) extracted aperture efficiency for 12-meter antenna (left) and 7-meter antenna (right), (b) far field co-polar and cross-polar pattern at 50GHz.

4. COLD CARTRIDGE ASSEMBLY

In cold cartridge assembly (CCA) of the ALMA band-1 receiver systems, major front-end key components are the corrugated feed horn antenna, orthomode transducer (OMT), and the hetero-junction field effect transistor (HFET) cryogenic low noise amplifiers (CLNA). The output ports of the CLNAs are then connected with waveguide section with temperature gradient from 15K to room-temperature base plate. The layout of the CCA is shown in Figure 7.

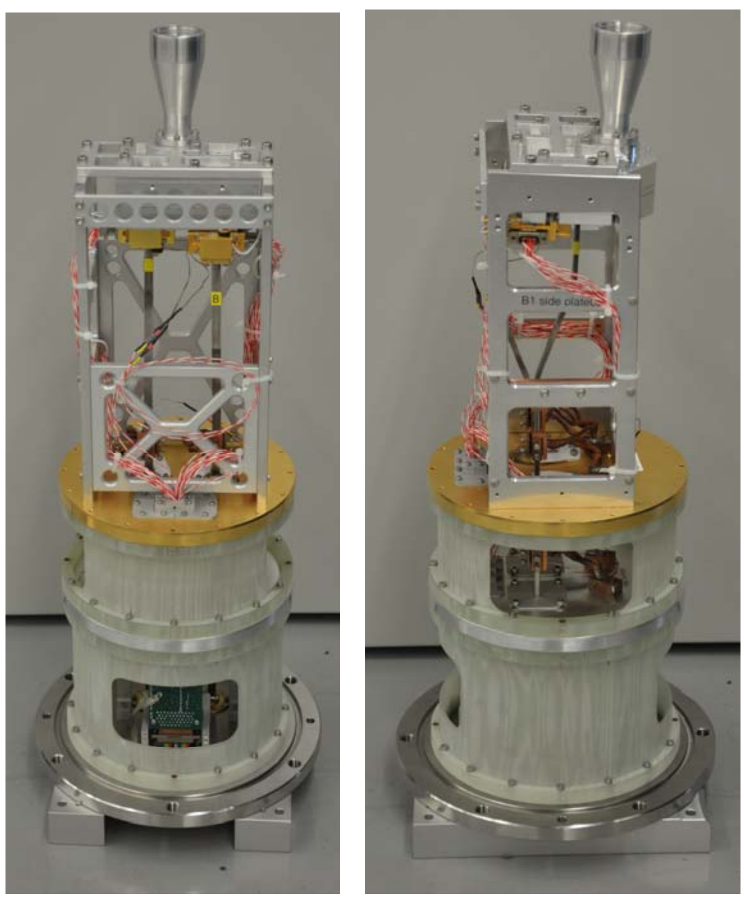
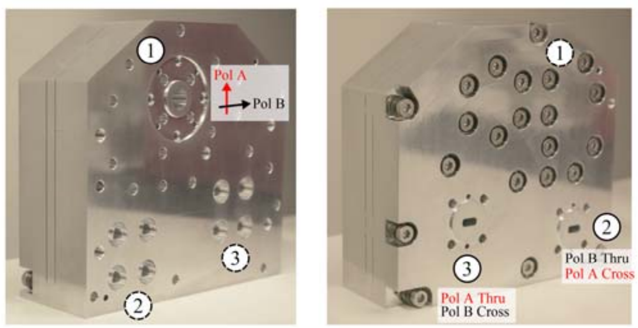


Figure 7. Prototype Cold Cartridge Assembly for ALMA Band-1 receiver

The orthomode transducer is with circular waveguide input and two WR-22 waveguide output. One of the challenges of the design is to suppress the trapped mode among the very wide bandwidth [11], and keep good and reliable performance in cryogenic environment, which mat be degraded by thermal coefficient difference of the materials. Detail of the OMT design can be found in [12]. The performance measured results of the OMT are shown in Figure 8.

The design of the 32 – 52 GHz 5-stage 80-nm InP HEMT hybrid cryogenic low-noise amplifier is revised from [13] and now it is ready for preproduction with lower noise temperature and better gain flatness. 8 pieces of the cryogenic LNA were produced and delivered, the typical noise temperature is around 10 – 15 K and at the band edge is around 18 K, as shown in Figure 9. The gain of the amplifier is typically higher than 35 dB and gain flatness is around 4 dB peak to peak. For such wide bandwidth in millimeter-wave frequency, it is very difficult to keep both input and output matching very well, in the first few batches, the input matching can be -2 dB at lower frequency edge (< 38GHz) and -7 dB at higher frequency edge, the output matching is below -4dB typically. Please note that due to the mechanical layout and stress introduced by the flange screws, the interface with the CLNA is specially design as UG-599/U which is typically used for WR-28, not the standard UG-383/U flange.

The one of the major revision of the ALMA Band-1 CCA during past two years are the waveguide section from 15K environment to the base plate. The waveguide section is composed by oxygen-free high-purity copper (OFHC) section with slightly bends for CLNA output port to 15K plate, then straight stainless-steel waveguide sections with low thermal conduction for temperature gradient from 15K to somewhere between 115K plate and 300K base plate. Due to the thermal load consideration, the waveguide bends from bottom of the straight sections to the 300K side are fabricated by stainless steel also. The fabrication of the stainless steel waveguide bends is quite challenging on the mechanical accuracy. The RF component in front of the waveguide vacuum geedthru on the base plate is full waveguide band isolator, which is to prevent strong multiple reflections and gain flatness degradation between cold and warm amplifiers.



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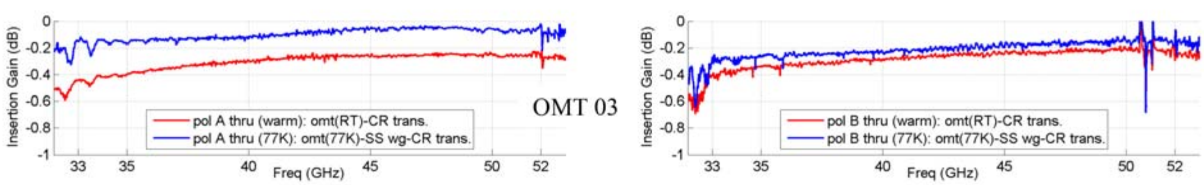

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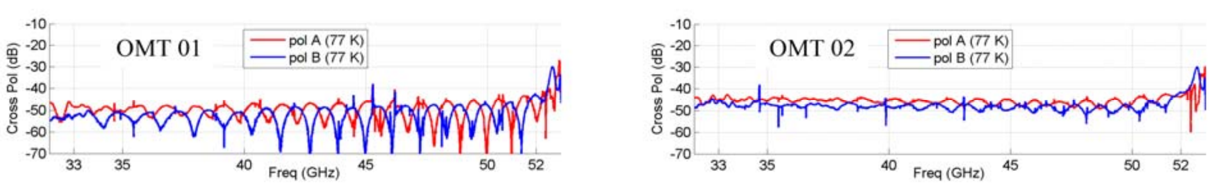
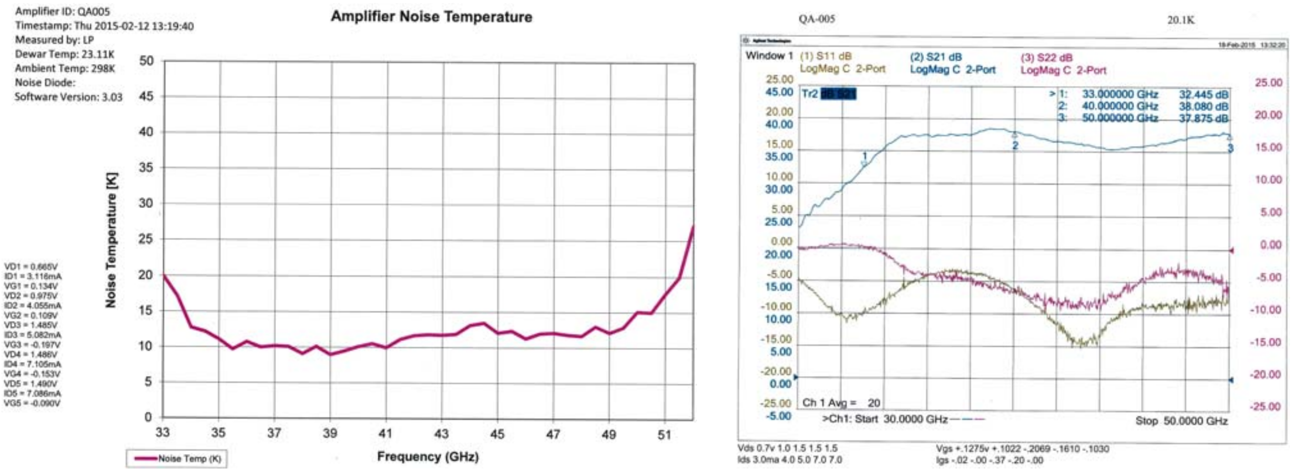


(c)

Figure 8. The orthomode transducer for ALMA Band-1, (a) layout of the OMT, (b) measured performance of insertion gain at 300K and 77K, (c) measured performance of cross-polarization at 77K.



(a) (b)

Figure 9. measured results of the 32 – 52 GHz 5-stage InP HEMT hybrid cryogenic low-noise amplifier (CLNA) for preproduction, (a) the noise temperature, (b) the scattering parameters.

5. WARM CARTRIDGE ASSEMBLY

Warm cartridge assembly (Figure 10) incorporates two major modules, warm receiver chain and LO module. The warm receiver chain includes the warm RF amplifier, isolator, RF high-pass filter, mixer, IF section (IF bandpass filter, IF isolator, and IF amplifier, if gain compensation is required) and the attenuators for matching and flatness adjustment. The local oscillator incorporates a YIG-tuned oscillator with phase locked loop (directional coupler, diode mixer, and phase-lock circuit), power divider and variable gain amplifiers, the coaxial isolators will be added if the matching improvement to the LO port of the mixer is required.

The major revisions of the warm cartridge assembly compared to the earlier prototype version are the following items:

(a) Warm RF amplifier revision for power linearity / gain compression consideration. Since the ALMA band-1 is with gain compression specification set to 5% compression higher than 373K input thermal load, the estimated output 1dB compression for warm RF amplifier should be higher than +10 dBm. The amplifiers originally designed for cold stage is optimized to lowest noise performance with higher gain, which could not fit the power performance.

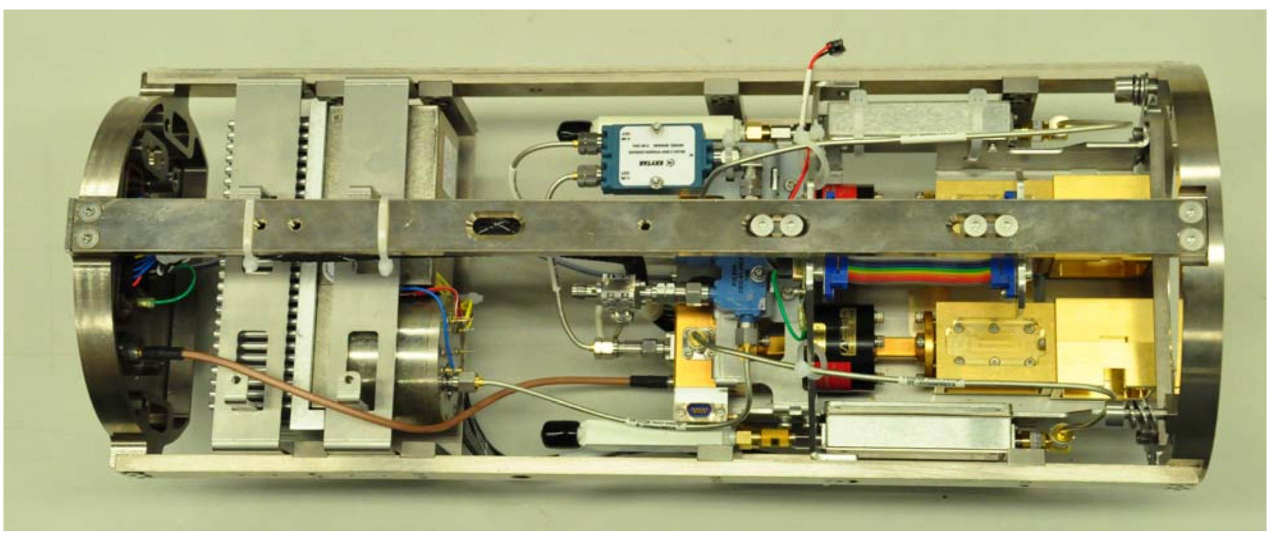


Figure 10. The layout of warm cartridge assembly for ALMA Band-1 receiver.

(b) Mixer revision for power flatness. The original cascode mixer is with trouble on the conversion gain flatness after packing into module.

(c) Waveguide high-pass filter is revised to 11-th order with sharper out-of-band roll-off to provide better image rejection.

(d) Adjustment of the warm receiver chain configuration to ensure the best impedance matching and power flatness. To fulfill the best power flatness and the stability of the solar observation [18], the warm receiver chain is setting down to with high pass filter allocated at the output of the warm amplifier.

(d) Optimization of the IF section configuration to provide sufficient output power level, gain flatness, and also the LO-IF isolation. For this purpose, the shortage of the receiver gain is fulfill by the IF amplifier with attenuators at the input and output ports.

The iteration of the warm receiver configuration is to integrate the WCA with CCA and tested as the standard procedure of an ALMA receiver front-end. Beside the system level optimization, the most recent key components developed results are (i) revision of the waveguide high-pass filter, and (ii) mixer development and selection, (iii) warm RF amplifier selection.

Following the prototype mixer covering 30 – 48 GHz using a cascode transistor pair [3] [14], revisions with better flatness were designed, fabricated and measured. The iteration include the further enhancement of the LO-RF isolation by additional cascode stage as triple cascode mixer [15] [16], and the design with even advanced 70-nm MHEMT process. The major challenges are not just the high conversion gain and good flatness of the microwave integrated circuit, but also keep good performance after packing into the mixer block. The measured results of the cascode mixers are summarized in Table I. The conversion gain is shown in Figure 11. Besides, the mixer developed in house also has to compete to the commercially available diode mixers.

TABLE I. SUMMARY OF THE 33 – 52 GHZ CASCODE MIXERS FOR ALMA BAND-1 RECEIVERS

Foundry and stages	***Measured Conversion Gain, chip***	***Measured Conversion Gain, module***
WIN 0.15μm GaAs power PHEMT [14] dual cascode mixer	-2 to +4 dB	-4 to -1 dB
WIN 0.15μm GaAs low-noise PHEMT [15], triple cascode mixer	+4 – +8 dB	-4 to +2 dB
WIN 0.15μm GaAs low-noise PHEMT [16], triple cascode mixer	-8 to -5 dB	-11 to -5 dB
OMMIC 70nm MHEMT	-4 to -3 dB	-8 to -7 dB

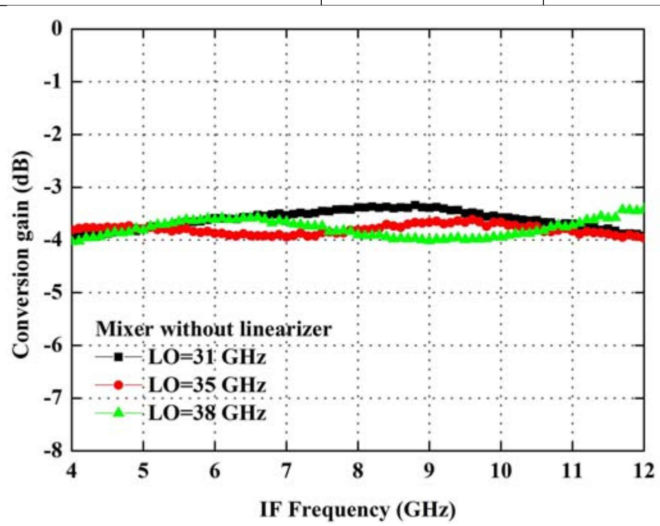


Figure 11. Conversion gain of the 70-nm MHEMT cascode mixers

The major disadvantage of the cascode mixer is the requirement of external bias, the advantage is the much lower required LO power level (~ 0 to 3 dBm). The commercially available diode mixers usually do not need external bias, but the drawback is higher optimal LO power (~ 13 dBm). Due to the consideration of the production, simplicity, and long-term reliability, the critical design review panel recommend using commercially available diode mixer, and the most recent released product [17] is with gain flatness compete with the in-house developed mixer.

The warm RF amplifier development is aiming to fix the problem of the lower gain compression. For this part both in-house and contracted development are prepared in parallel. The final selection of the warm RF amplifier will be made by July 2016.

6. MEASURED OVERALL PERFORMANCE

Following the previous estimation of the receiver performance shown in [4], the components and cartridge assembly development progress were finally integrated to measure various performance items. The RF performance items of the first cartridge assembly equipped with fully functional receiver components S/N 003 were measured and tested. In this section, the following measured performances are presented, (1) noise performance, (2) image rejection ratio, (3) spurious response, total IF output power, and IF power variation (flatness), (4) gain compression, (5) output power (amplitude) stability, (6) phase stability, and IF phase variation, (7) crosstalk, (8) beam-pattern measurement, (9) cross polarization.

So far two fully functional cold cartridges are assembled; one is configured as baseline design and the other is equipped with experimental cold low noise amplifiers. The measurement was done in the test line originally for East Asia Front-End Integration Center (EA-FEIC) equipped with a single cartridge test cryostat instead of the 10-band receiver cryostat. The purpose of the first-set cartridge integration test is to find out the optimized warm receiver chain configuration as described in previous section. The measured performance and specifications are summarized in Table II and Table III. Please note that the noise performance is set to 13 – 15 times of quantum limit, which is higher than the original specification set by scientists. The specification is modified by constrain of the input optics loss, and the input optics loss is limited by the mechanical size of the window and the available space for optics components. Detail measured results are described in [19].

TABLE II. ALMA BAND-1 RECEIVER SPECIFICATIONS AND MEASURE PERFORMANCE: RF PART

Item	Specification	Measured Results
RF Frequency	35 – 50 GHz	
LO Frequency	31 – 38 GHz	
IF Frequency	4 -12 GHz	
Receiver Noise Temperature	25K for 80 % bandwidth, 32K full band	< 25K for all LO frequency, averaged over full IF band
Image band suppression	> 10 dB over 90% of IF frequency range, > 7 dB over 100% IF frequency range	> 20 dB for worst case ~ 30 dB typically
Spurious response	10 dB below nominal noise power in 2 GHz bandwidth	No spurious signal found at the IF output spectrum
IF output power	-32 to -22 dBm (load temperature 10 to 800K) in IF frequency range	> -31.33 dBm in-band with 300K input load, > -30.6 dBm total
IF power variation	6.0 dB peak-to-peak, whole IF band 4.0 dB peak-to-peak, any 2 GHz range 1.35 dB peak-to-peak, any 31 MHz range	2.6 – 5.6 dB typically whole IF band <5.2 dB p-p any 2GHz < 1.3 dB p-p any 31MHz
Gain compression	< 5 % when load temperature change from 77 to 373K	Equivalent load temperature with 5% gain compression > 492K
Amplitude stability	$<4 \times 10^{-7}$ at 0.05 sec < T < 100 sec $<3.0 \times 10^{-6}$ at T = 300 sec	$< 1.0 \times 10^{-7}$ at 0.05 sec < T < 100 sec $< 3.0 \times 10^{-8}$ at T = 300 sec
Signal path phase stability	Long-term delay drift < 22fs for 20 sec < T < 300 sec	< 5 fs for 10 sec < T < 300sec
IF phase variation	Deviation of the average IF phase < 4.5 degree RMS for any 31 MHz	< 3.5 degree for LO = 35, 38 GHz, < 4 degree for LO = 31 GHz, except IF = 4 GHz.

TABLE III. ALMA BAND-1 RECEIVER SPECIFICATIONS AND MEASURE PERFORMANCE: OPTICS PART

Item	Specification	Measured Results
Aperture efficiency	> 80.0 %	> 80% typically, except 79.6% for 50GHz
Polarization efficiency	> 99.5 %	> 99.5% all frequency points
Focus efficiency	> 98.0 %	> 98.3%
Illumination Error	< 5.0 mrad (0.287 degree)	0.01 – 0.05 degree
Polarization alignment	Within + - 2 degree	-1.22 degree to + 1.47 degree
Cross Talk	-63 dB	< -85 dB

7. UPCOMING PLAN AND SUMMARY

On May 25, 2016, ALMA Board approved the production of the Band-1 receivers, Based on this approval, the production plan will be organized. The development of the ALMA band-1 receiver front end cartridge will be finalized by July 2016. Before October 2016, three preproduction cartridges will be assembled and tested and one of them will be integrated to the receiver cryostat in laboratory. Manufacture readiness review (MRR) will be held at by November 2016. another nine cartridges will be produced before June 2017. The first one-site acceptance test is schedule on July 2017. Full production will be finished by December 2019.

8. ACKNOWLEDGEMENT

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