The Band 7 Cartridge (275-373 GHz) for ALMA

S. Mahieu, B. Lazareff, D. Maier, M. Carter, AL. Fontana and S. Claude

***Abstract*—IRAM is responsible for designing the ALMA Band 7 cartridge covering the signal frequency range 275-373 GHz, and for building 8 pre-series units. The cartridge must meet a number of specifications, including SSB noise temperature less than 133K, but also total power stability, beam pattern, etc… We present in this paper some of the challenging issues met during the design and prototyping of the cartridge, and experimental results obtained so far.**

I. INTRODUCTION

THE Atacama Large Millimeter Array (ALMA) will be a radio telescope with 64 antennas. It is under construction in the Atacama desert in northern Chile. The front end for ALMA will consist of a 4-K cryostat with ten insertable receivers called cartridges covering the frequency range 31 to 950 GHz. Each cartridge will operate simultaneously in two linear polarizations. A block diagram of the Band 7 cartridge is given in Figure 1 and an overall view of the #1 cartridge is given in Figure 2.

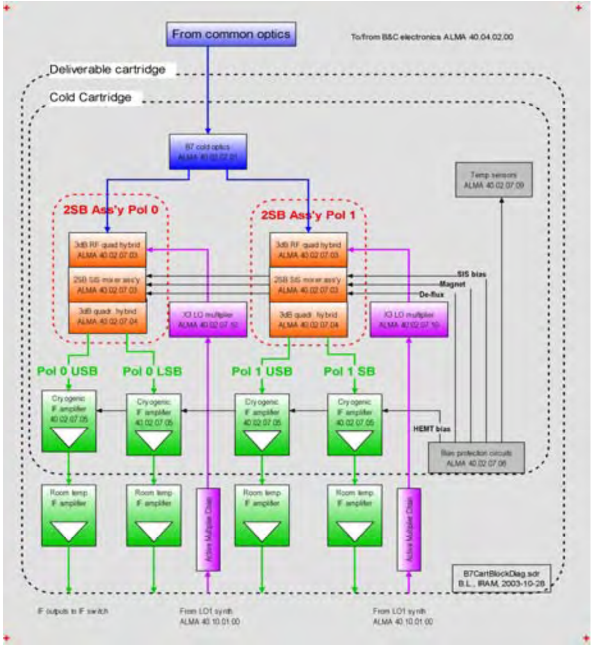

Figure 1: Band 7 cartridge block diagram

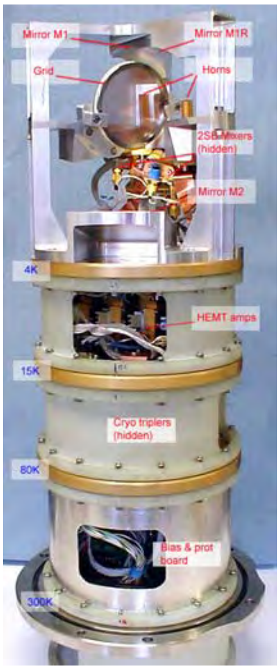

Figure 2: Complete Band 7 Cartridge #1

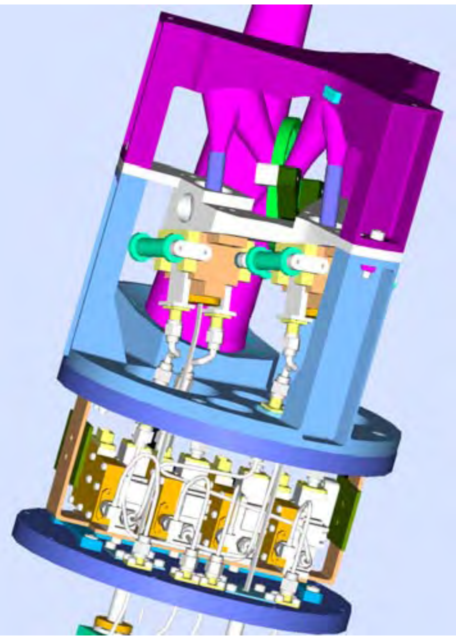

Figure 3. 4K stage: optics, 2x2SB mixer assemblies; 15K stage: 4x HEMT amplifiers (thermalized to 4K).

The cartridge consists in three cold stages with operating temperatures of 4K, 20K and 90K and a room temperature baseplate which is the interface between the vacuum and the air. The stages are supported by G10 glass fiber tube spacers. The four plates and GFRP tubes constitute the blank cartridge, designed and supplied within the ALMA project by Rutherford Appleton Laboratories (UK)

- The 4 K assembly comprises:
  - The cold optics, consisting of three off-axis elliptical mirrors and a polarization diplexing grid, designed to achieve near-optimum coupling of the cartridge to the telescope within prescribed tolerances;
  - The two dual-sideband (2SB) mixer assemblies (see Maier et al this conference);
  - A thermal sink for the four HEMT amplifiers;
  - Mechanical structures to support these elements in the adequate positions within tolerances.
- The 15 K stage only provides thermal shunts for wiring, IF coaxial cables, and LO waveguides, as well as mechanical (thermally insulated) support for the HEMT amplifiers.

- The 90K stage has the two LO triplers, wiring thermal shunts mounted on it.
- The 300 K baseplate supports the ESD protection board and the IF, DC and LO feedthroughs.

II. 4 K OPTICS AND SUPPORT ASSEMBLY

A. Requirements

The constraints for the design of the optical train were to: a) couple to the f/D=8 optics of the telescope with an edge taper of 10dB, independent of wavelength over the operating band; b) perform polarization diplexing; c) provide a clear aperture of 5w (fundamental Gaussian mode) at each optical element (mirrors, grid); d) last but not least, fit within a cylinder of ∅170mm×H475mm (from 300K baseplate).

Furthermore, the cartridge beam should point to the center of the subreflector, with a global tolerance of 6mrad, which corresponds to 1.2% loss of spillover efficiency. Out of that global budget, 4mrad are allocated to the cartridge optics.

B. Optical train.

To minimize risk and development effort, the decision was made to realize the polarization diplexing using a grid rather than an orthomode transducer. The space limitations led to a design where each mixer horn is coupled to the Cassegrain focal plane by two off-axis elliptical mirrors, labeled M1 and M2 (counting from the horn towards the sky), and the polarization-separating grid is placed between M1 and M2; accordingly, there are actually two identical mirrors M1 and M1R (see Figure 2 and Figure 3). The two 2SB mixers have parallel orientations, while being coupled to orthogonal polarizations on-sky. A first design was made based on fundamental Gaussian mode analysis, with a goal of 12dB edge taper; further multimode analysis performed by Tham and Withington (Cambridge University) showed that, as expected, the actual edge taper was very close to 10dB, and led to small adjustments of the parameters.

	Diam.	***L (axial)***		***d-to-next***
Horn	6.0	45.68		38.0
	R_{source}	***$2\times\theta$***	***R_{image}***	***d-to-next***
M1	44.58	40°	61.01	157.0
M2	108.12	25°	268.38	

The fact that these optical elements are cooled to 4K prompts the question of the impact of contraction on performance. The answer is: nil, and can be best explained by a thought experiment. Stage 1: cool down the optics, and adjust the wavelength by the same amount as the dimensions (~0.5%); because electromagnetics is scale-invariant, the far-field *angular* pattern is unchanged. Stage 2: restore the original wavelength; because the design is wavelength-independent, the angular beam pattern is again unchanged.

Both the prototype and the #1 optics have been verified at room temperature using the IRAM antenna range and Schottky mixers. Using the complex (amplitude and phase) measurements acquired in the measurement, the far-field pattern has been derived, and is shown below

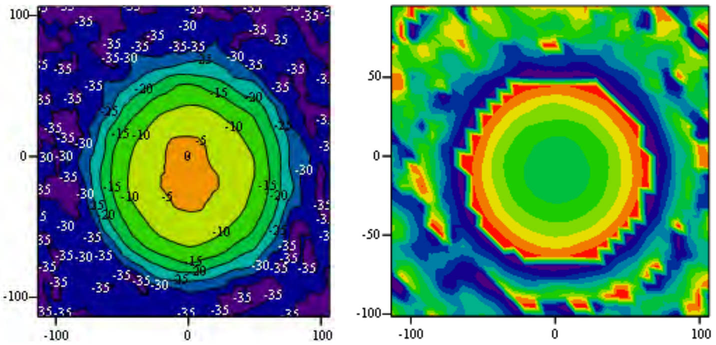

Figure 4. Far field pattern of the optics, derived from complex (amplitude and phase) near-field measurements. Frequency: 330GHz, polarization: P0 (grid reflecting). Left: amplitude, contour interval 5dB; right, phase. Angular units: milliradians. The vertical offset (-0.955°=-16.7mrd) is required for aperture plane alignment from the off-axis cartridge location in the focal plane.

C. Cold optics mechanical design

In order to avoid the buildup of tolerances, the 4K mechanical supports and optical mirrors assembly has been machined out of bulk metal, with a reduced parts count to minimize the tolerance buildup. This design consists of just three main parts:

1. Bottom level: bottom plate, mirror M2, and bottom halves of three vertical legs;
2. Middle: a three-arm star extending to the vertical legs, and holding the two 2SB mixer assemblies and the grid;
3. Top level: top half of the vertical legs, and the two M1 mirrors.

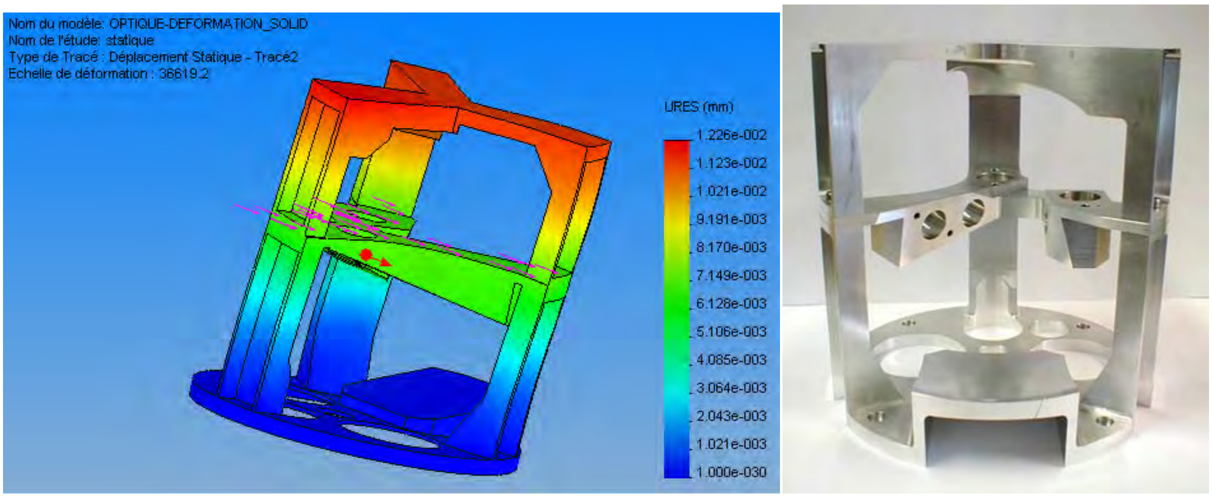

Figure 5. Left: Cold optics under gravitational load; maximum deformation 12µm; right: the actual part

D. *Tolerance analysis*

A cold optics internal tolerance analysis has been performed. This includes gravity deformations of the structure loaded by its payload (0.7kg mass on the center piece), see Figure 5, and machining/assembly tolerances. An analysis was made of the sensitivity of the beam direction to various misalignments of the optical elements; this was combined with the results of the gravity deformation analysis and estimates of machining tolerances on modern CNC equipment (≈10µm for individual contributions). While this does not prove the correctness of the analysis, antenna range measurements of both the prototype and the #1 pre-production cartridge show that the beam orientation is within the 4mrd tolerance.

Table 1. Summary of tolerance analysis. Beam deviation from nominal, milliradians.

Cartridge			***System***
RSS	*Worst case*	*Spec*	*Spec*
1.3	3.5	4.0	6.0

III. WIRING

A. *Requirements*

The wiring is intended to carry voltages and currents to and from various electronic components, to supply electric power and to monitor voltages. Beyond that basic role, it must be reliable, noise-free, provide low voltage drop, add minimum heat load to cryogenic stages from conduction and Joule heating; and outgas below prescribed limits

B. *Choice of wiring material and diameter*

Minimizing the sum of conduction and Joule heating leads to conflicting requirements from the two individual terms, regarding the wire diameter. We have determined an optimum diameter for various metals, as a function of current load and length. We find that the thermal load (conduction+Joule) at optimum diameter is virtually the same for all metals (Wiedemann-Franz). On the other hand for, e.g., copper, the optimum diameter is impractically small. We chose 0.2mm diameter manganin for small currents and 0.2mm diameter brass for high currents (coils, heaters).

C. *ESD protection and routing board*

In order to protect the cartridge sensitive components (i.e. SIS junctions and HEMT amplifier transistor) from both excessive DC bias and electro static discharges (ESD); we need a protection board at the cartridge bias input. ESD protection is realized by parallel-connected 2-terminal devices with appropriate threshold voltages

D. *Harnesses and connectors*

All the harnesses are made from braids consisting of 8 twisted pairs (manganin of brass, see above). Heat sinking at each temperature stage is realized (for each 8-twisted-pair braid) by inserting the braid in a two-piece OFHC copper clamp, with the inner space filled with Stycast 2850FT. Compared with discrete heat sinks that break the physical continuity of the wiring, this construction requires less manpower and is more reliable

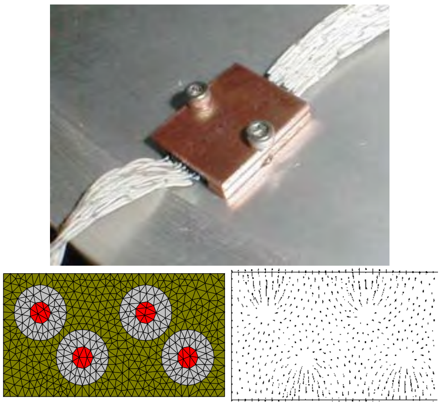

Figure 6. Wiring heat sink: device and FE conduction modeling.

Figure 7: Thermal Budget

Together with the thermal resistance of the wires from the next-higher temperature stage, the thermal conductance of the shunt acts as a resistive divider. Based on modeling, the worst case ΔT between the heatsunk wire and stage is 0.5K for the 80K sink, and much smaller at lower temperatures. The measured difference in the worst case is 1K.

IV. LO PATH INSIDE THE CARTRIDGE

A. Design choices.

The LO power enters the cartridge at 1/3 the final frequency (90-120GHz approx). Transport to the cryogenic triplers (one for each polarization) is via a stainless steel (low thermal conduction) gold plated (low RF loss) WR10 waveguide. We have experimentally verified that with 1μm gold plating the increase in thermal conductivity is negligible, while the RF losses are close to that of a copper waveguide. From the output of the triplers to the 2SB mixers, fundamental mode stainless steel would have prohibitive losses, and is near impossible to gold plate inside. We have decided to use overmoded stainless steel WR10 waveguide. Because the optics imposes a 15° bend, and because of the issues discussed below, we have left that waveguide unplated, to keep a controlled amount of loss.

The power to drive the cryo tripler is supplied by the AMC (active multiplier chain), designed and built within the ALMA project by NRAO (USA); the cryo tripler itself is designed and built by Virginia Diodes, Inc (USA).

B. Overmoded waveguide: resonant absorption caused by bends.

In an overmoded waveguide, bends introduce coupling between the fundamental mode and overmodes. We have performed a study of these couplings, as a function of the two dimensionless parameters: a/λ and R/a, where a is the waveguide width and R the bend radius. In our case, the two ends of the overmoded waveguide are terminated by transitions to fundamental-mode guide: overmodes are trapped in a resonant cavity; this will give rise to absorption dips in the main transmission path.

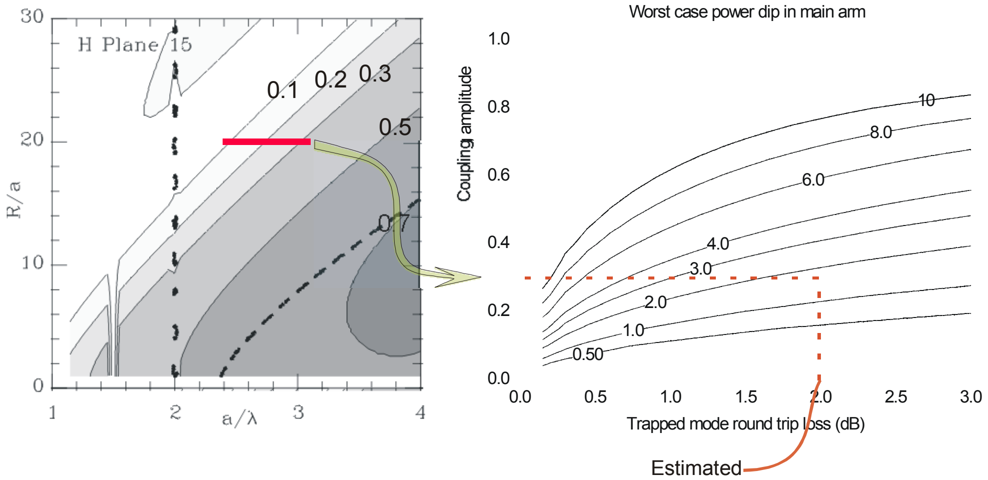

Figure 8 : Design graphs for the 15° bent, overmoded LO waveguide. Left: coupling amplitude from TE10 to TE11/TM11; right: the worst case resonant loss is found to be less than 2dB.

V. IF SUBSYSTEM DESCRIPTION

A. Requirements

- The contribution of the IF subsystem to the global noise budget should be as small as possible; in view of the large electronic gain of the HEMT amplifier, the noise contribution of the IF is essentially determined by the input noise of the HEMT.
- The contribution of the IF susbsystem to the cartridge gain and phase instabilities should be as small as possible, allowing the global budget to remain within the envelope of the specs.
- The gain of the IF chain should be such that — including allowance for the gain dispersion of all elements in the signal chain, including the mixer — the output level at the interface between the cartridge and the FE subsystem IF switch should be between –40dBm and –27dBm.
- The design should be robust, with easy access to any of the component and ensure that critical components are interchangeable; in particular, the warm cartridge assembly should be interchangeable independently from the cold cartridge, while still meeting the specifications.
- Finally, no more than 36 mW must be dissipated on the 4K stage.

B. Signal chain implementation

The IF chain comprises:

- A three stage cryogenic amplifier designed and built by C.A. Yebes (Spain). Gain 38dB (typ), noise 5K (max).
- A 2 stage room-temperature amplifier with 25 dB of gain (nominal), mounted outside the cartridge (warm cartridge assembly).

C. Thermal Stress Relief (IF and LO paths):

During the cryostat cool-down, the cartridge body as well as the components fitted into it will contract. The amount of contraction will vary depending on the temperature and manufacturing material used. A diagram illustrating the cumulative deflection in the IF path is shown in the Figure 9

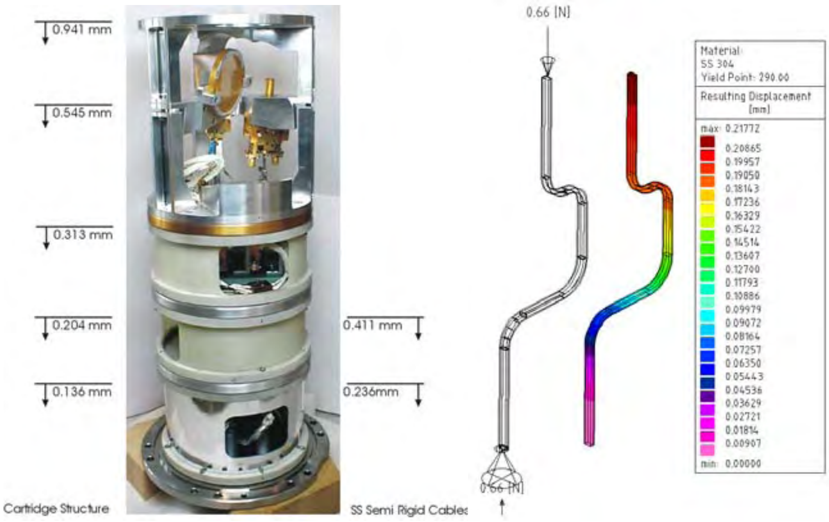

Figure 9 Left: Cartridge and stainless steel semi rigid cable no-load deflection due to thermal contraction. Right: IF coaxial cables and stainless steel waveguides have been bent to accommodate the differential contraction with minimal stress. Waveguides between the tripler and the mixer have no extra bends; the compliance is provided by the support of the tripler.

VI. RESULTS

A. Receiver noise.

The receiver noise of cartridge #1 has been measured a) integrated over the 4-GHz bandpass, for each of the two polarization channels, for LSB and USB; b) at every 4GHz in LO frequency, across the IF bandpass, with a 0.1GHz stepping.

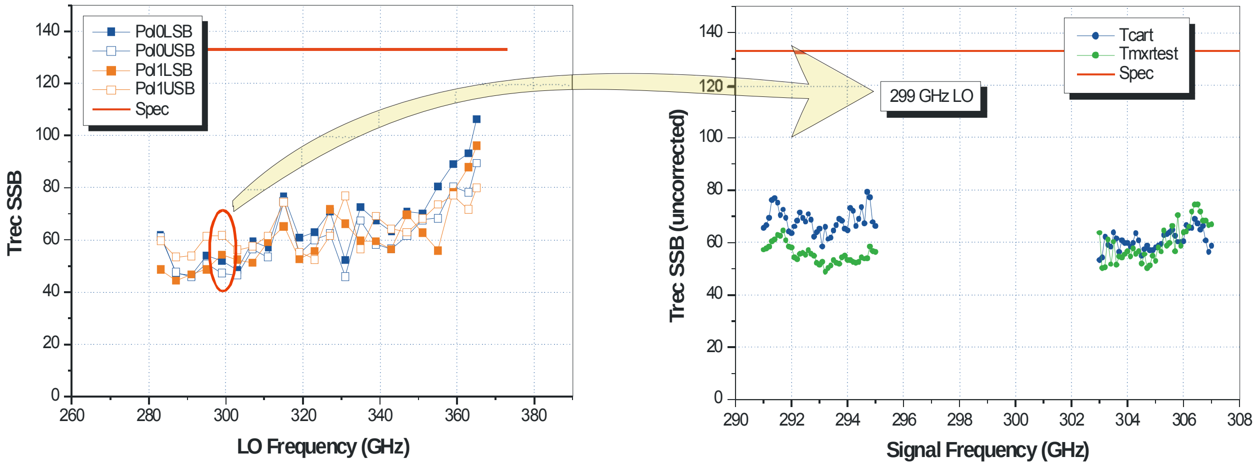

Figure 10. Left: receiver noise integrated over the IF bandpass; right: receiver noise across the IF bandpass, for an LO frequency of 299GHz, polarization 1, LSB and USB; blue: cartridge measurements; green: the same 2SB assembly as measured in the mixer test set (see Maier et al, this conference).

B. *Image rejection.*

The image rejection has not yet, at the time of writing been measured in the cartridge. Measurements performed in the 2SB mixer test station show, however, that the 10dB specification is generally met, except for a few combinations of LO frequency and IF frequency (see Maier et al, this conference). However, the significant margin by which the noise specification is met ensures that the scientifically significant figure of merit of SSB noise is within requirements in all cases.

C. *Cartridge Gain Stability*

The stability specification is defined by the Allan variance, that must be less than 4 10^{-7} between 0.1s and 1s. This corresponds to an Allan deviation ($\sqrt{\text{var}}$) 6.3 10^{-4}. The measured stability is within the specification; it is, however, worse (for the same 2SB mixer) than measured on the mixer test set; this needs further investigation.

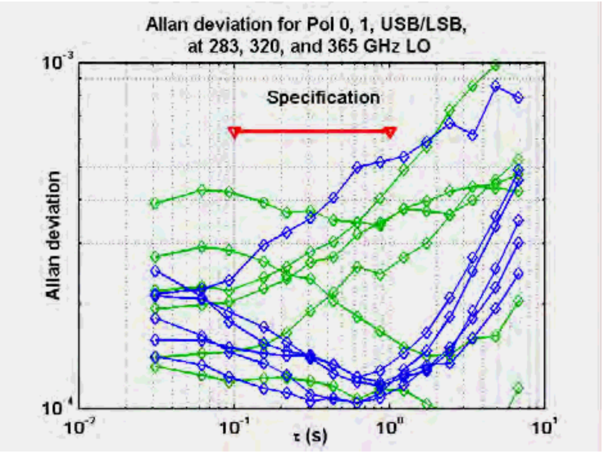

Figure 11: Total Power Stability, Allan deviation measured in the pre-production cartridge#1.

VII. CONCLUSIONS

We have designed and built a compact, modular, low-noise cartridge covering the signal frequency band 275-373 GHz, compliant with the requirements of the ALMA project. At the time of writing, the first pre-series cartridge is undergoing pre-delivery tests. The cartridge has been found to meet the specifications that have been tested so far.