Design and development of a 600-720 GHz receiver cartridge for ALMA Band 9

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Abstract— **This paper describes the design of the Band 9 receiver cartridges for the Atacama Large Millimeter Array (ALMA). These are field-replaceable heterodyne front-ends offering high sensitivities, 602-720 GHz frequency coverage, 4-12 GHz IF bandwidths, and high quasioptical efficiencies. Because the project will ultimately require 64 cartridges to fully populate the ALMA array, two key aspects of the design of the Band 9 cartridge have been to take advantage of commercial manufacturing capabilities and to simplify the assembly of the cartridge. Preliminary test results of the first (prototype) cartridge are also presented.**

***Index Terms*—radio astronomy, submillimeter wave receivers, superconductor-insulator-superconductor mixers**

I. Introduction

The Atacama Large Millimeter Array (ALMA) is a collaboration between Europe, North America, and Japan to build an aperture synthesis telescope with 64 12-m antennas at 5000 m altitude in Chile [1]. In its full configuration, ALMA will observe in 10 bands between 30 and 950 GHz, and will provide astronomers with unprecedented sensitivity and spatial resolution at millimetre and sub-millimetre wavelengths.

Band 9, covering 602-720 GHz, is the highest frequency band in the baseline ALMA project, and will thus offer the telescope's highest spatial resolutions. Furthermore, sub-mm observations with Band 9 of ALMA will provide complementary information to observations with the observatory's lower frequency bands, due to the fact that sub-mm line observations typically probe warmer, denser material than mm-wavelength observations, while continuum observations over a broad range of frequencies will better constrain dust temperatures.

The ALMA Band 9 cartridge is a field-replaceable unit containing the core of a 600-720 GHz heterodyne front-end. Primary requirements of the Band 9 cartridges include:

- double side-band (DSB) operation with $T_{N,rec}$ = 169 K over 80% of the 614-708 GHz LO frequency range;
- an intermediate frequency (IF) bandwidth of 4-12 GHz with low power variation across the band (6 dB peak-to-peak and 4 dB within any 2 GHz) and a total output power level of -37 to -24 dBm;
- detection of two orthogonal linear polarizations with cross-polarization levels of -20dB;
- 90% coupling of the cartridge's optical beam to the telescope secondary;
- long lifetime and high reliability; and
- the design must be consistent with the need for series production of 64 cartridges.

This paper presents the design of the first (prototype) Band 9 cartridge, together with results of first-light tests.

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II. Cartridge Design Overview

The overall design of the Band 9 cartridge is highlighted in Figure 1. The Band 9 cartridge contains a electronically tunable LO, low-noise DSB superconductor-insulator-superconductor (SIS) mixers, and a low-noise, broad-band IF chain. These are combined in a compact opto-mechanical structure that interfaces with the ALMA cryostat. Each of these elements in the cartridge design is discussed in the following sections.

A. Basic Cartridge Structure

The basic structure of the cartridge body is defined by the design of the ALMA cryostat from the Rutherford Appleton Laboratory [2]. It consists of 4 plates separated by thermally

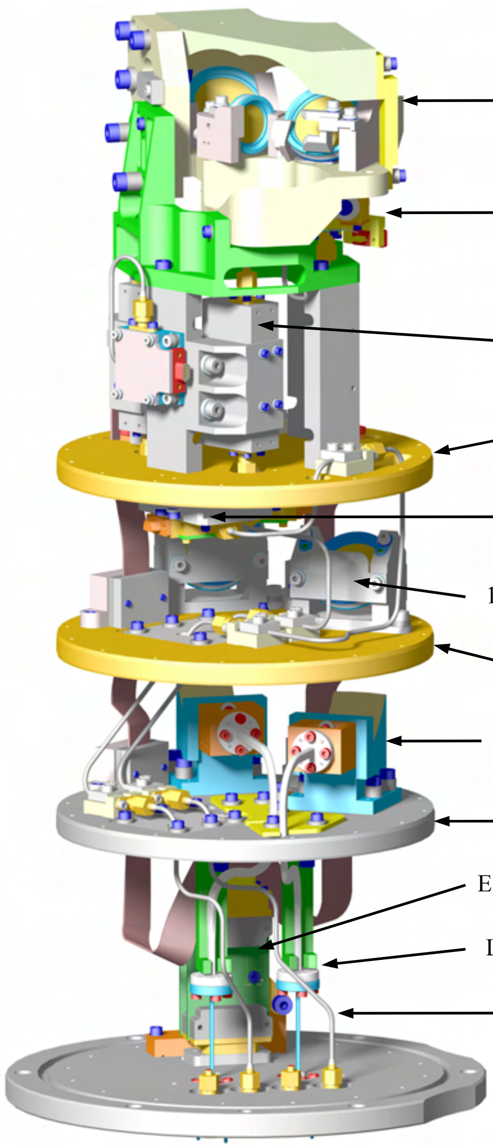


Fig. 1 – Layout of the ALMA Band 9 cartridge. The fibre-glass cylinders that separate the cartridge's four temperature levels are not shown.

insulating fibre-glass cylinders (not shown in Figure 1 to allow the cartridge's internal components to be seen). The lowest plate – the baseplate – is a vacuum flange in the base of the cryostat, while the 3 cold plates (at 90, 15, and 4 K) are connected to the cold plates of the ALMA cryostat by flexible thermal links (on the cryostat side of the interface).

B. *Local Oscillator Injection*

The ALMA Band 9 local oscillator (LO) is an electronically-tunable solid-state LO based on mm-wave (100-120 GHz) power amplifiers and Schottky diode frequency multipliers.

As described in [3], the LO signal is generated in a YIG oscillator operating at 16-20 GHz, followed by an active multiplier chain (x6). A portion of the output of the active multiplier is coupled into a phase-lock loop which phase-locks the 6^{th} harmonic of the YIG oscillator to an externally

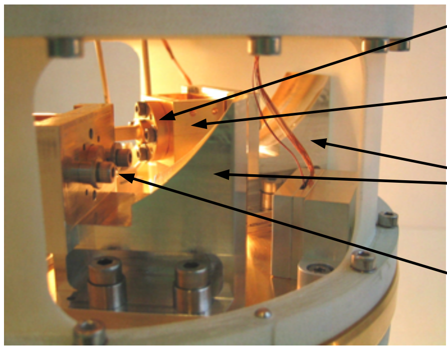


Fig. 2 – The LO multiplier assemblies mounted on the 90K stage of the first cartridge. The front of the diagonal horn of the nearest assembly is visible, as is the integrated x2x3 multiplier of the rear assembly.

generated reference signal. The remainder of the output from the active multiplier chain is coupled into the power amplifier unit, which amplifies, splits, and then further amplifies the signal to produce 2 high-power mm-wave outputs. The power of these two channels can be independently adjusted to allow the drive level of the cartridge's 2 SIS mixers to be independently tuned.

The output from the power amplifiers enters the cartridge via vacuum feedthroughs (with a thin Kapton windows sealing the cryostat vacuum), and is transported to the cartridge's 90K stage via WR8 waveguides. Short, straight sections of gold-coated thin-walled stainless steel waveguide are used as thermal breaks, while longer, bent sections of coin silver waveguide are used to accommodate differential thermal expansion between the cartridge's 300 and 90K stages.

The 90K stage contains 2 integrated x2x3 LO multipliers [4] that frequency multiply the 100-120 GHz outputs of the power amplifiers to produce the 600-720 GHz LO power that drives the cartridge's SIS mixers (see Figure. 2). This high frequency LO signal is optically coupled from the 90K stage to the 4K optics assembly via a diagonal horn and collimating mirror at 90K and an infrared heat-filter in the 15K stage. Within the cold optics assembly, each of the LO beams is refocussed and coupled into the mixer via a thin (14 µm) Mylar beamsplitter located in the optical beam in front of the mixer.

The YIG oscillator, active multiplier chain, and mm-wave power amplifiers, together with their associated control electronics and phase-lock loop are contained in a warm cartridge assembly that bolts to the outside of the cartridge baseplate (not shown in Figure 1). The warm cartridge assembly, including the LO components that it contains, together with the cold frequency multipliers, are developed and produced by the National Radio Astronomical Observatory (NRAO) and Virginia Diodes Inc. (VDI).

C. *4K Optics Assembly*

The 4K optics assembly combines and focuses the incident astronomical beam from the ALMA telescope and the two LO beams originating on the 90K stage into two SIS mixers. As

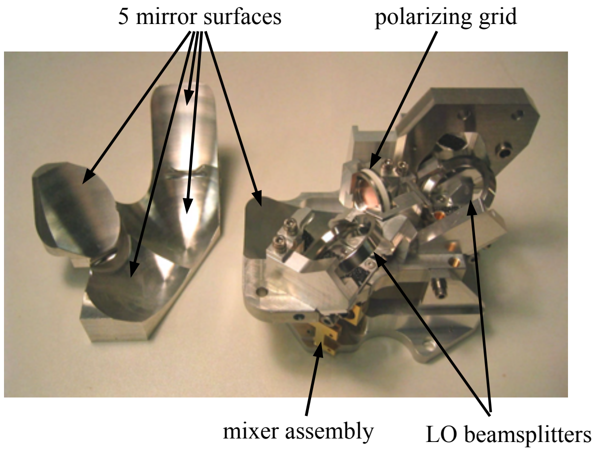


Fig. 3 – ALMA Band 9 optics assembly. The optics assembly is composed of two primary blocks – the upper block (left) contains 4 of the 5 mirror surfaces; while the lower block (right) contains 1 mirror surface plus the polarizing grid, 2 LO beamsplitters, and the 2 mixer assemblies.

is described in more detail in [5], the beam from the telescope is refocussed by a common mirror and then split into to linear polarizations with a polarizing grid. Each linearly polarized signal beam is then focussed into a single SIS mixer, with a beamsplitter between the focussing mirror and the mixer being used to inject the local oscillator beam.

In total, the 4K optics assembly thus contains five mirrors, a polarizing grid, and two LO beamsplitters, which must be packed into a compact assembly to fit within the available space. Because of the complexity of this assembly, and its criticality to the overall performance of the Band 9 cartridge, specific attention has been paid in the design to making the assembly as easy as possible to manufacture and assemble. In particular, the system has been designed without any means for alignment of either the optics or the grid and beamsplitter mounts. As seen in Figure 3, this has been accomplished by machining four of the five mirrors into a single aluminum block (the upper block in Figure 1), with the fifth mirror and the mounting interfaces for the grid and beamsplitter mounts in the second (bottom) block. The alignment accuracy and optical quality of the cartridge's optical beam is thus determined by the accuracy with which these blocks are machined. However, as is shown in [5], the accuracy of modern precision CNC machines is sufficient to ensure that the desired optical performance is obtained.

D. *SIS Mixers and Mixer Mounts*

The incident astronomical signal is detected by two orthogonally polarized DSB SIS mixers to both maximize sensitivity, and to allow the polarization of the incident signal to be measured. The RF design and performance of the SIS mixers used in the ALMA Band 9 cartridge is described in [6]. As described previously and shown in Figure 4, the core of the mixer contains a corrugated horn (from Radiometer Physics [7]) and a SIS device mount that are clamped together by a so-called cap-nut that threads onto the horn, clamping the device mount to the back of the horn. A centering ring and two magnet pole pieces are used to both center and

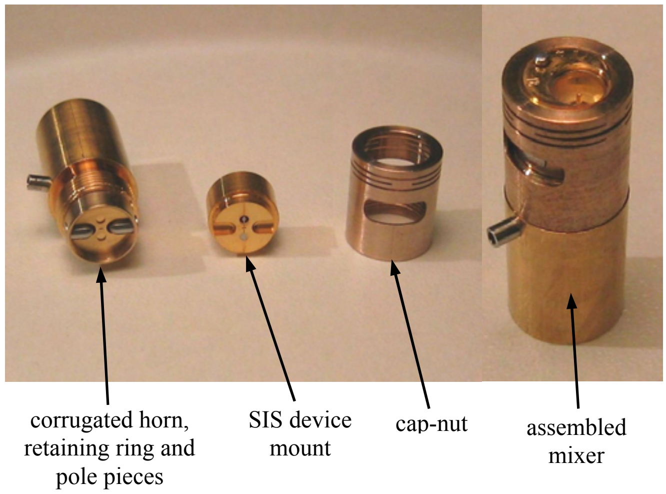


Fig. 4 – ALMA Band 9 SIS mixer. (left) The components of the mixer, including the new cap-nut with a multi-section spring cut into its walls. (right) The assembled mixer. The pin inserted into the horn is used for rotational alignment of the mixer in the mixer mount. (see Figure 5)

rotationally align the backpiece with respect to the horn. One new feature that has been introduced to this design is a multiple-section leaf spring that is machined into the side-walls of the phosphor bronze cap-nut (see Figure 4). This spring ensures that tightening the cap-nut onto the horn produces a controlled clamping force between the horn and device mount.

The SIS mixer slides into a mixer mount (see Figure 5) that contains the SMA connector for the mixer's IF output and all of the mixer's auxiliary circuitry, including an electromagnet for suppressing the Josephson effect in the SIS junctions, a contact spring that makes electrical contact to a resistive de-flux heater soldered into the SIS device mount, and a temperature sensor. This separation of the critical RF components of the mixer from the mixer mount ensures that the two halves can be separately assembled and tested, so as to

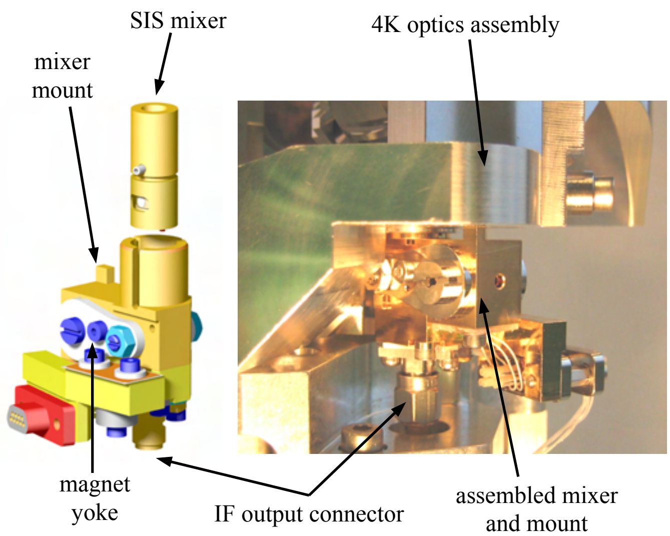


Fig. 5 – ALMA Band 9 mixer mount and mixer. (left) A 3-D model of the mixer and mixer mount. (right) An assembled mixer mounted in the 4K optics assembly of the first cartridge.

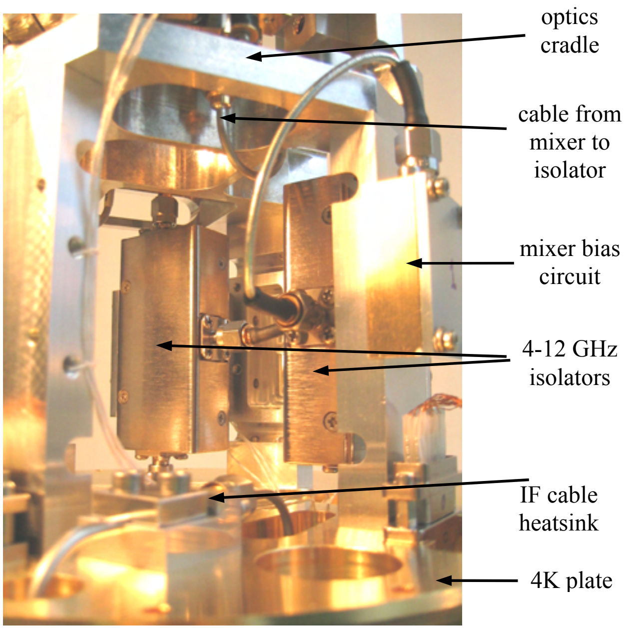


Fig. 6 – Two 4-12 GHz isolators from Pamtech [8] mounted on the 4K level of the first Band 9 cartridge. Note that the RF load port of the isolator has a DC connection to its RF input port, allowing the isolator to be used as a bias-T for the DC bias to the mixer.

further streamline the assembly (and eventual repair) of the cartridge. The mixer mount also provides an opto-mechanical interface between the mixer's corrugated horn and mounting holes that are bored in the 4K optics assembly.

E. Low-Noise 4-12 GHz IF Chain

Two of the significant technical challenges in the Band 9 cartridge are the requirement for a 4-12 GHz IF band and a low variation in output power across the IF band. Because the mixer and cryogenic amplifier are being designed and built independently, this has required the development of 4-12 GHz isolators (at Pamtech [8]) to suppress reflections in the cables between the mixer and the amplifier. As seen in Figure 6, the two isolators (one per mixer) are mounted on the side of the optics assembly's support legs. One additional feature of the 4-12 GHz isolator is that the RF load port has a DC connection to the signal input port, which allows the isolators to be used as bias-T's for supplying DC bias to the SIS mixers.

The cartridge's first-stage IF amplifiers are three-stage InP HEMT amplifiers mounted on the bottom of the cartridge's 4K stage. The 4-12 GHz amplifier that is under development at the Centro Astronomico de Yebes should offer an input noise temperature of ~ 5 K and 30 dB of gain, with < 9 mW of power dissipation per amplifier [9]. 4-8 GHz amplifiers are being used for preliminary tests of the cartridge while the 4-12 GHz amplifiers are being developed.

In order to ease assembly of the cartridge, the IF output from the cryogenic amplifier is coupled via a cable to top of the cartridge's 4K stage, where it is heat-sunk with a cable clamp and a bulkhead connector. Stainless steel cables are then used to couple the IF output signal out of the cartridge via bulkhead connectors and heat-sinks on each of the 15 and 90K stages and vacuum feedthroughs in the cartridge baseplate. Hand-formable semi-rigid cables with aluminum outer conductors are used to connect the components on the 4K stage (mixer-to-isolator, isolator-to-amplifier, and amplifier-to-bulkhead), due to their low loss and to minimize thermal-mechanical stresses.

The noise contributions of the ALMA front-end's IF system, including cabling and the IF switch that is used to select the active band, are minimized by placing a second-stage IF amplifier in the warm cartridge assembly that contains the warm LO components. A commercial amplifier is used for this purpose.

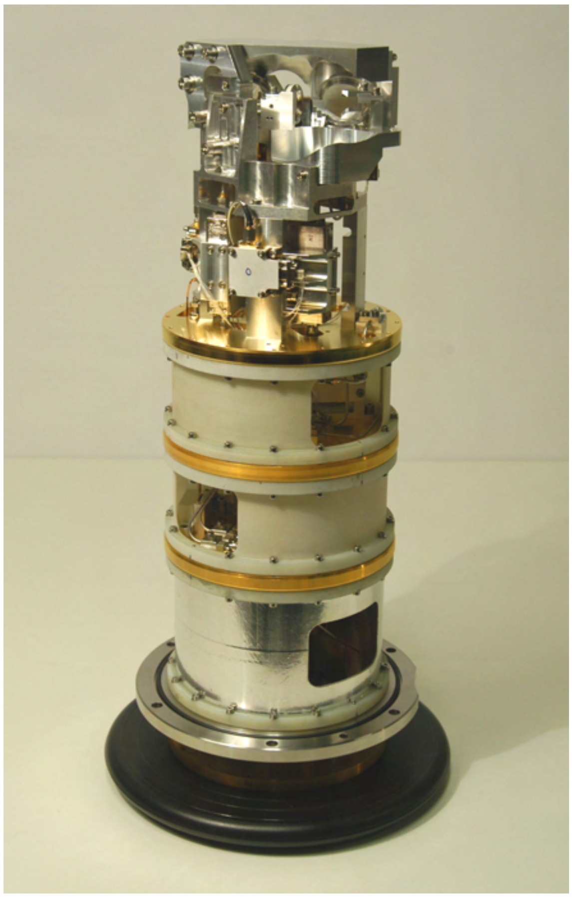
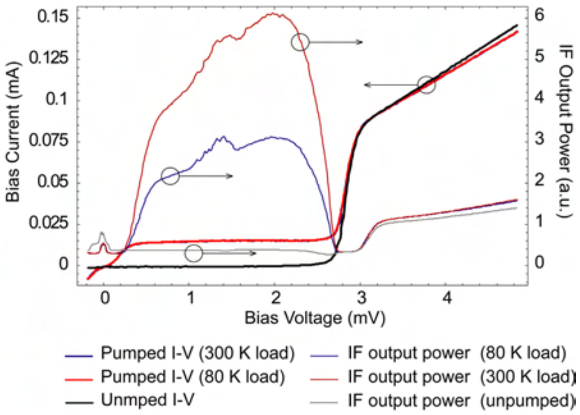


Fig. 7 – The first (prototype) ALMA Band 9 cartridge.

F. Opto-Mechanical Design

The cartridge components are built into a rigid opto-mechanical structure based upon the basic cartridge body from RAL (see Figure 7). With only a few exceptions, aluminum is used for all optical and mechanical components, in order to minimize the total mass of the cartridge and minimize differential thermal expansion. One notable exception to this is the 4K plate, which is copper, as defined by the design of the ALMA cryostat. Due to concerns about the potential effect of differential contraction on the alignment of the optics assembly (the two mirror blocks are aluminum), the optics are



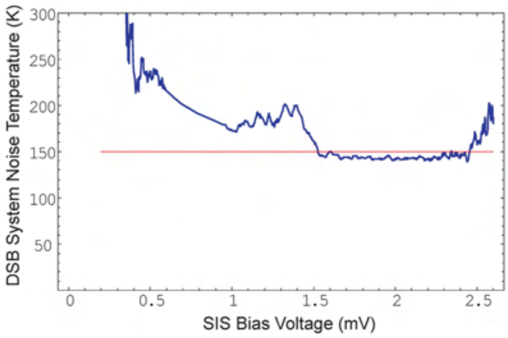


Fig. 8 – (top) Measured mixer bias current and IF output power as a function of bias voltage for one channel of the first cartridge, with and without LO power applied (at 638 GHz), and with LO power while looking at a hot (300 K) and cold (77 K) blackbody load. (bottom) DSB receiver noise as a function of bias voltage calculated from the hot and cold IF output power curves above. The mixer is driven by an external LO, coupled into the cartridge via an external beamsplitter. The optimum noise temperature of < 150 K is below the required level (169 K), despite the additional noise contributed by the external beamsplitter.

connected to the 4K plate by four rectangular posts that are flexible in the radial direction (to and from the centre of the cryostat), but stiff in the transverse direction. This geometry allows the posts to rigidly centre the optics assembly relative to the cartridge body, while also accommodating differential thermal expansion between the optics assembly and the 4K plate.

Because the cartridge will ultimately need to be produced in quantities of ~ 64 units, the cartridge design has been developed with the goal of simplifying its manufacturing and assembly. This is most strongly seen in the design of the 4K optics assembly described above. However, it also applies more generally to the cartridge as a whole – two of the primary design goals have been to maximize the use of standard commercial manufacturing methods (and standard commercial parts, where possible), and to minimize the assembly work that is required after commercially manufactured parts have been received.

III. First-Light Results

Manufacturing and assembly of the first (prototype) cartridge has been completed (see Figure 7), and testing of the cartridge is now proceeding. Figure 8 presents first-light measurements of the sensitivity of one channel of the first cartridge pumped by an external LO (and thus including additional noise contributed by an external beamsplitter). In particular, the measured SIS mixer bias current and the receiver's IF output power are plotted as a function of SIS bias voltage, with and without LO power (at 638 GHz) and looking at a hot (300K) and cold (80K) blackbody load. The DSB receiver noise temperature that is calculated from the measured IF output power is also shown. From this plot, it is seen that even with the additional noise contributed by the external beamsplitter, the measured receiver noise is still below the $T_{N,rec}$ = 169 K that is required. Measurements are now proceeding over a wider range of frequencies, and using the internal LO.

These measurements were performed at a mixer temperature of ~ 2.8 K (the base temperature of the cartridge test cryostat provided by the National Astronomical Observatory of Japan, NAOJ). The IF output from the cartridge is amplified, filtered with a YIG filter (with a bandwidth of 50 MHz at a center frequency of 6 GHz), and then detected with a power meter. The receiver noise temperatures are calculated from the measured IF output power and the blackbody load temperatures in the Rayleigh-Jeans limit. The external beamsplitter is 40 µm thick, offering an LO injection efficiency of ~ 10% for this polarization.

IV. Conclusion

The ALMA Band 9 cartridge is a low-noise SIS receiver covering the 602-720 GHz atmospheric window with low noise and a broad (4-12 GHz) IF band. Due to the large number of cartridges that will ultimately be needed for the ALMA project, the design of the cartridge has been optimized to take advantage of the capabilities of modern precision CNC machining to ease its manufacturing and assembly. First-light heterodyne sensitivity measurements at a single LO frequency have also been presented.

Acknowledgment

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