Assembling the Cryogenic Front-end for the ALPACA Phased Array Feed

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***Abstract*—The Advanced L-band Phased Array Camera for Astronomy (ALPACA) is a 69-element, fully cryogenic, phased array feed operating from 1.3-1.7 GHz proposed to be deployed at the prime focus of the 100-m Green Bank Telescope. Here we report on the progress towards assembling the front-end including a large RF-transparent vacuum window, the receiving elements, and several solutions we have deployed to significantly reduce the complexity of scaling the number of elements in an array. All the cryogenic low-noise amplifiers (LNAs) have been thermally cycled and rigorously tested. LNA bias and readout is shared on multi-channel flexible striplines that route from outside the cryostat through a vacuum interface and terminate at the cold stage where the antenna elements are deployed. ALPACA will act as a 'Radio Camera' by digitally forming 40 simultaneous dual polarization beams enabling large surveys for various radio astronomical applications.**

I. INTRODUCTION

Focal plane phased array feeds have demonstrated the ability to increase the instantaneous field of view available to a telescope and are enabling large radio astronomical surveys, e.g., [1]. Active development continues to extract further gains by reducing the operating system temperature and increasing the bandwidth, thereby gaining several orders of magnitude advantage over traditional feed-horn arrays [2]. The interest in cryogenic phased array systems is driven by the fact the the survey speed of the instrument is inversely proportional to the system temperature squared ($1/T_{sys}^2$). The sky and atmosphere contributions to the noise are relatively fixed at L-band, and the scatter from the telescope optics is a function of its design, therefore for an existing telescope, receiver noise is the only variable that can be reduced to achieve a lower T_{sys} and improve survey performance.

II. ANTENNA ARRAY

In order to achieve large operational bandwidth and reduce detrimental mutual coupling effects, we heavily leveraged electromagnetic simulations to co-optimize the antenna element, element spacing and the array geometry [3]. A dipole design with pie-shaped wedge arms was chosen for the antenna element. The ALPACA instrument utilizes 69 dual-pol dipoles in a hexagonal close packing with an element spacing of 0.64λ at 1.4 GHz. This results in an antenna array with a ground plane 1300 mm in diameter [4].

For each polarization, an air-coax couples the received signal to a cryogenic LNA through a field-replaceable SMA connector. The wedge arms and the coax core are plated with 2.5 μm of gold to ensure surface currents are largely contained within high conductivity material. The LNA has a SMP connector at its output to allow blind-mate functionality with the signal transport cables. A machined part holds the cables at the correct height and a guide pin helps to properly align them with the amplifiers at install. We exploit the differential thermal contraction between aluminum and nylon to create a thermal clamp to secure and cool the receiver module.

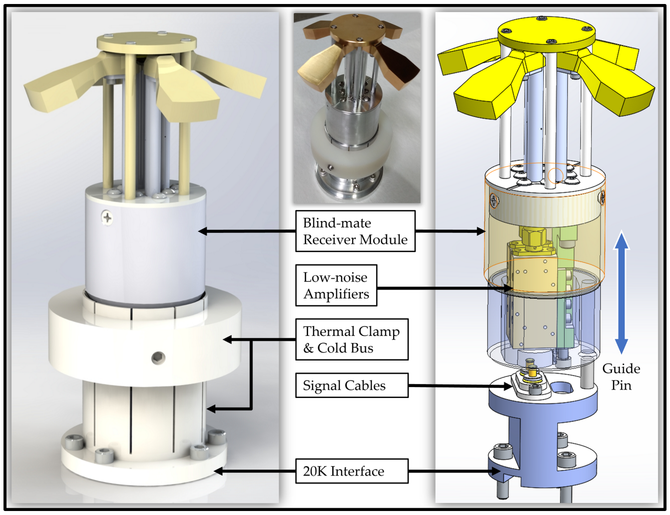

Fig. 1. ALPACA Dipole: A detailed view of the dipole showing the thermal interface (left) and the mechanical and RF interface (right). A fully assembled dipole is shown in the center inset.

III. CRYOGENIC VACUUM VESSEL

The most important consideration for the ALPACA vacuum vessel is to implement a large, RF-transparent vacuum window that allows an unimpeded 2π steradian view of the array to the sky. The window also needs to be structurally sound to support against the vacuum load (160 kN). Additionally, we need to consider the radiation load due through such a large window, as it can be a significant contribution to the total heat load on the internal cryogenic stages.

Our implementation splits the requirements between a large welded HDPE cylindrical top-hat to satisfy the vacuum tight requirement while keeping a minimal thickness of HDPE (4mm), and a stack of high density, RF transparent foam, Rohacell HF71, to provide structural support against the vacuum loading. The foam layers also act as an infrared filter and a poor conductor thereby reducing the radiative heat load reaching the internal cryogenic stages. The overall height of the cryostat is 56 cm driven by the length of the cryocoolers and the height of the foam stack [5].

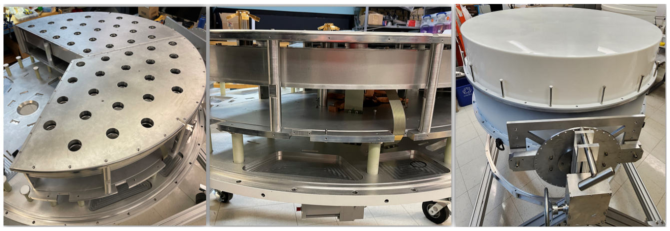

Fig. 2. ALPACA Cryostat: (Left) Top view showing two sections of the internal cryogenic stages installed up to the ground plane. (Center) Side view showing two dipoles above the ground plane, 2^{nd} cold stage that is entirely contained within the intercept stage, stripline routing, copper cold links that connect to the cryocooler and mechanical support structures. (Right) Fit check of the full vacuum vessel including the outer shell and the HDPE top-hat.

A. *Internal Thermal Stages*

Installing multiple cryocoolers on a monolithic plate can cause stresses to build up due to differential thermal contractions. We exploit the hexagonal symmetry of the array geometry to break the internal components into three 120-degree sections. This reduces the size and number of unique components, and also matches well with the three cryocoolers we need to achieve the cold operating temperature.

We utilize three CTI-1020 dual-stage cryocoolers to enable us to operate the antenna array and all LNAs under 25 K. The 1^{st} stage of the cryocoolers is expected to operate at 90 K and is designed to act as an intercept stage to reduce heat transfer to the 2^{nd} cold stage. The ground plane for the array and the foam layers will be thermally connected to this stage. All components on the 2^{nd} cold stage are completely enclosed within the first cold stage. The antenna array is installed on a base plate expected to operate at close to 20 K and made of high conductivity aluminum 1100 alloy to reduce end-to-end temperature variations. The cryocoolers are thermally connected to the respective base plates using cold links machined out of OFHC copper to maximize thermal conductivity. The three sections are supported and installed on the vacuum interface plate using standoffs made of G10 fiberglass laminate structures. The G10 blades can provide compliance needed as the metal parts contract while minimizing conductive heat transfer from one cold stage to another.

B. *Cryogenic LNAs*

The LNAs achieve a noise temperature of $<$10K and provide 35dB of gain while consuming $<$20mW of power each when operating at 25K. We have also implemented a bias-tee on the cryogenic LNAs which enable us to remove all bias wiring from the cryostat and use the same coax line that transports the signal out of the receiver to carry the bias in to the LNA.

Infant mortality of components on the LNAs can be a leading cause of failure when operating at cryogenic temperatures. We implement a rigorous testing procedure to ensure low failure rates at deployment. We thermally cycled each LNA several times and qualified the devices using pre and post measurements of the S-parameters. Finally, we fully test the performance of 20% of the qualified LNAs at 20 K and quantified that the noise temperature ($\mathrm{T_N}$) shows weak dependence on their operating temperature.

C. *Flexible Stripline Circuits*

The signal cables at the end of the dipole assembly feed to a stripline circuit that traverses through the cryostat and provides the signal transport interface immediately outside the vacuum vessel. These circuits are compact, flexible, lightweight, reduce the heat load transferred between cryogenic stages and are less lossy than stainless steel coax at cryogenic temperatures. However, a single non-functioning connector due to stresses from repeated mate/de-mate could require replacement of the entire multi-channel stripline. To address this issue, we created a custom, surface mount, ganged SMP connector that can be soldered on the stripline circuit using using pick and place machines to ensure optimal alignment and excellent RF performance. Additionally, they are mechanically secured using fasteners to ensure their durability against mate/de-mate forces. Only 18, 8-channel flexible stripline circuits will eliminate use of 276 stainless steel coax inside ALPACA.

IV. CONCLUSIONS

The assembly of the ALPACA cryogenic front-end is nearing completion. We will begin conducting vacuum tests soon and verify the cryogenic performance of the instrument by late spring. Integrated testing with the RFoF signal transport is expected to take place at BYU. We are planning to then move the instrument front-end and digital back-end to the GBT site and perform end to end system tests in the RF quiet zone.

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