Towards a High Sensitivity Cryogenic Phased Array Feed Antenna for the Green Bank Telescope

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Abstract

Efforts have been underway for the last several years to develop phased array feed antennas for large reflectors such as the Green Bank Telescope (GBT) as well as mid-size reflectors for Square Kilometer Array demonstration instruments. We report on recent work on a cryogenic L-band phased array feed with the goal of reducing the beam equivalent system noise temperature so that it is competitive with that of traditional horn type feeds.

1 Introduction

The last few years have seen good progress towards phased array feeds for wide-field, "radio camera" astronomical observations. Key developments include successful phased array images of astronomical sources [1], novel array designs [2], arrays permanently mounted on a WSRT dish [3], interference mitigation algorithms [4], beamforming and calibration techniques [5], rigorous figure of merit and efficiency definitions suitable for phased arrays [6], and methods for overcoming array mutual coupling effects [7, 8]. Research challenges that are currently being addressed include real time signal processing, array calibration, and maximizing the achievable formed beam sensitivity over the array field of view.

As of early 2011, all existing phased array feed prototypes for which published results are available have used ambient temperature low noise amplifiers (LNAs). System noise temperatures near 60 K have been reported by groups at ASTRON and BYU/NRAO. While ambient temperature systems have value in the technology development path for wide-field radio camera instruments, the question as to whether lower system noise temperatures can be achieved with phased array feeds remains open. To move closer to system temperatures that are competitive with single pixel feeds, we report on antenna element design efforts aimed at realizing a cryogenic phased array feed system.

2 Ambient Temperature PAF

To gain the understanding of array impedance matching issues needed for the design of a cryogenic PAF, an ambient temperature phased array feed with active impedance matched elements was developed and tested [9, 10]. Single-polarization and dual-pol versions of the array were mounted on the Arecibo telescope in June and August, 2010. The single-pol array (Figure 1) was installed on the Green Bank 20-Meter Telescope in December. The dominant controllable contribution to the system noise budget is the front end amplifier noise, which is determined by the interaction between the array S-parameter matrix, amplifier noise parameters, and beamformer coefficients. To account for mutual coupling effects, the array is optimized so that the beam-dependent active impedances presented by the elements to front-end amplifiers are close to the amplifier optimal source impedance over the PAF field of view.

Figure 1 (right) shows modeled and measured boresight beam amplifier noise temperature and sensitivity figure of merit as a function of frequency. Array Y-factor measurements using hot absorber and cold sky provide a beam system temperature at 1600 MHz of 38 K, which is significantly better than that of an earlier array prototype [1]. Preliminary on-reflector measurements on the Green Bank 20-Meter indicate that the peak sensitivity figure of merit over frequency is $T_{\mathrm{sys}}/\eta_{\mathrm{ap}} = 87\,\mathrm{K}$ at 1740 MHz, however, which suggests that the antenna efficiency is below 50%. Tests and further data analysis are currently underway to understand the unexpectedly low efficiency of the ambient temperature PAF.

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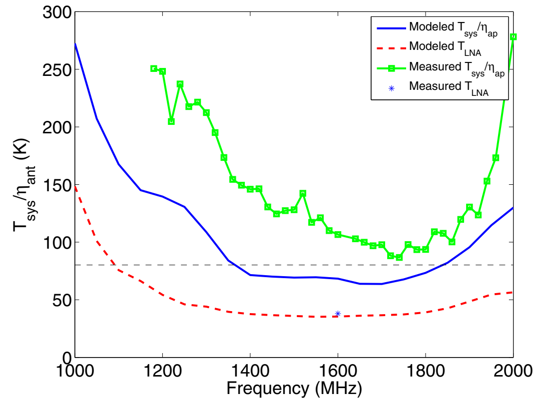

Figure 1: Left: 19 element single polarized ambient temperature PAF. Right: Modeled and measured amplifier noise temperature and system sensitivity figure of merit. The horizontal dashed line marks a sensitivity figure of merit 1 dB larger than the minimum modeled value.

3 Cryogenic PAF Element Design

In the next stage of this effort, L-band phased array feed elements were designed and fabricated for a cryogenic PAF system. The process began with an isolated dual-pol crossed dipole which was tuned using a full-wave EM model to an input impedance of $50\,\Omega$. Several variants of the dipole arms were tested in this initial design stage, and a "kite" design was selected as the best combination of manufacturability and adjustable degrees of freedom for tuning. In the next stage of the design process, an infinite array model was used to estimate the embedded array element active impedances and thereby account for array mutual coupling effects in the element design optimization. A genetic algorithm was used to tune the design to achieve active impedances matched to the cryogenic amplifier noise parameters ($Z_{\rm opt} = 72 + j15\,\Omega$, $T_{\rm min} = 6.3\,$K, and $R_{\rm N} = 0.7\,\Omega$ at 1.6 GHz, measured by S. Weinreb, Caltech). The infinite array model neglected edge effects, but is much less computationally intensive than a finite array simulation. The infinite-array design was then used to initialize a hexagonal seven element array. The seven element array was optimized to retune the active impedances to $50\,\Omega$ using both a genetic algorithm and simulated annealing. Finally, the element design was embedded in a nineteen element array and optimized to achieve an active impedance match and maximum sensitivity over the PAF field of view.

Throughout the optimization process, seven element geometrical parameters were allowed to vary: the length of the kite arm from feed to center tip, the length of the kite arm from feed to outside tips, the thickness of the arms, the separation of the feed point and ground plane, the radius of the conductor feeding the coax line, the angle of kite sweep, and the angle of the kite from horizontal (the angle between the arms and support posts).

The designed array element is shown in Figure 2 (left). The cryostat including cooled low noise amplifiers and cryogenic system designed by R. Norrod (NRAO) is shown in Figure 2 (right). Further description of the cryostat and measured amplifier noise temperature results were reported in [11].

4 Numerical Results

To verify the element mechanical fabrication, the isolated impedance of one element over a ground plane was measured and compared to modeled results. Figure 3 (left) shows the self impedance over the range 1200 MHz to 1750 MHz. Figure 3 (right) shows the measured and modeled return loss. A frequency shift between the modeled and measured isolated element impedance is evident, but the Smith chart view shows that measured values for the fabricated elements are reasonably close to the model results.

The expected performance of the 19-element cryogenic PAF on a 20-meter reflector (f/D = 0.43) was modeled using the physical optics approximation for the reflector, microwave network theory for the low noise amplifiers and receivers, and a full-wave electromagnetic model for the array. Amplifier noise was accounted for using measured,

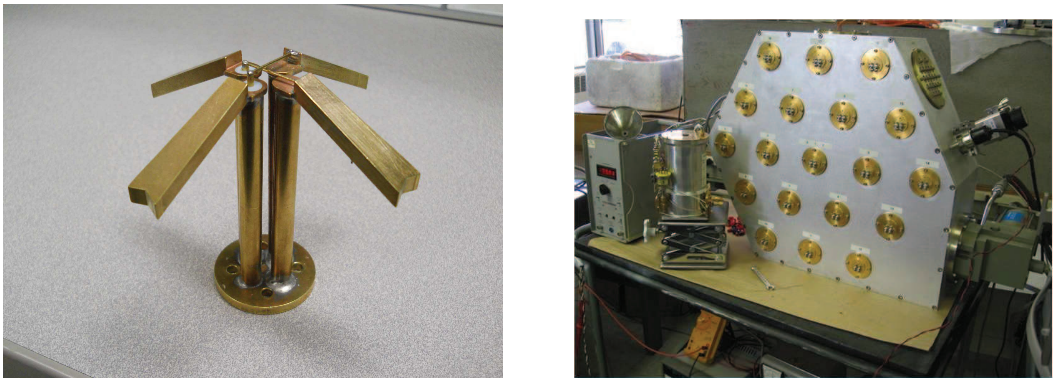

Figure 2: Left: Dual-pol phased array element "kite" design matched to cryogenic low noise amplifiers. Right: L-band phased array feed cryostat (R. Norrod, NRAO).

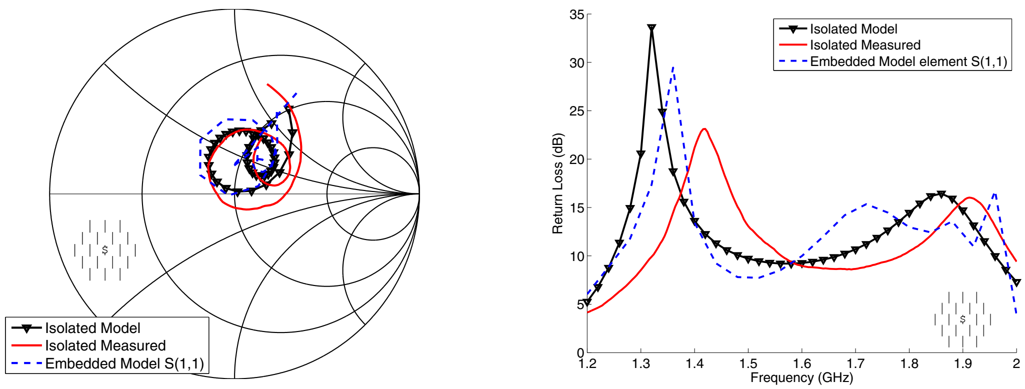

Figure 3: Left: Modeled and measured isolated element input impedance and active impedance over the range 1200 MHz to 1750 MHz. Also shown is the modeled embedded element self reflection coefficient (S_{11}). Right: Modeled and measured isolated element return loss.

frequency-dependent noise parameters. The modeled beam equivalent system noise temperature and sensitivity figure of merit are shown in Figure 4 (left) for the boresight beam with maximum-sensitivity beamformer coefficients.

A comparison of the array performance with the tuned, active impedance matched elements optimized for the 19-element hexagonal array configuration and cryogenic low noise amplifiers, and an array of elements matched to an isolated input impedance of 50 Ohms is shown in Figure 4 (right). The effect of mutual coupling in shifting the realized active impedances away from the isolated impedances is apparent. If mutual coupling were negligible (e.g., array elements spaced far apart), the active impedances are identical to the element isolated input impedance. With mutual coupling, the effective source impedance presented by each element port to its connected amplifier is different from the isolated element impedance. The active impedance matched design overcomes this effect by tuning the design parameters to shift the active impedances closer to the amplifier optimal source impedance value. The reduction in amplifier noise is indicated in Figure 4 (right) as a difference between the "kite" curves and the "50 Ω matched" curves.

The next step in this research will be to integrate the fabricated array elements and cryostat for on-reflector tests planned for early 2011. Other ongoing PAF-related work at BYU and NRAO include studies of long term calibration stability, pattern-controlled beamforming algorithms, real time signal processing backend development, and phased array image formation algorithms, with the goal of realizing a science-capable PAF instrument on the Green Bank Telescope, the Focal L-band Array for the GBT (FLAG).

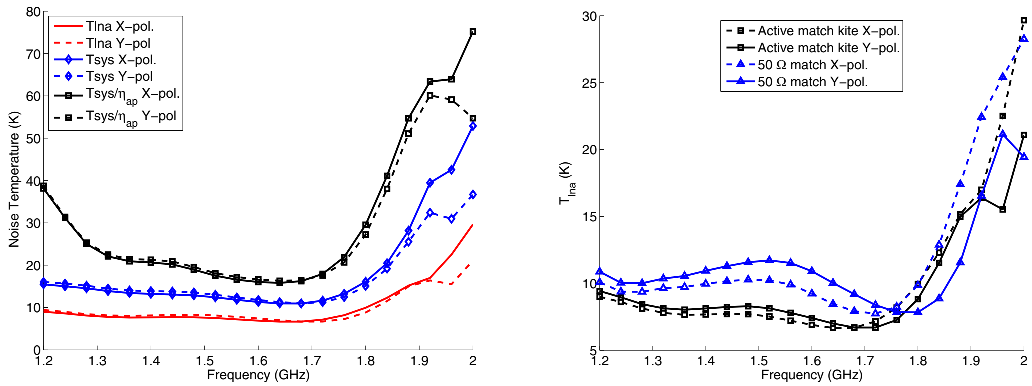

Figure 4: Left: Modeled boresight beam equivalent system noise temperature and sensitivity figure of merit as a function of frequency. Right: Comparison of active impedance matched elements and an array of elements matched to an isolated impedance of 50 Ohms.

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