The Cloverleaf Antenna: A Compact Wide-bandwidth Dual-polarization Feed for CHIME

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Abstract—We have developed a compact, wide-bandwidth, dual-polarization cloverleaf-shaped antenna to feed the CHIME radio telescope. The antenna has been tuned using CST to have smaller than -10dB s11 for over an octave of bandwidth, covering the full CHIME band from 400MHz to 800MHz and this performance has been confirmed by measurement. The antennas are made of conventional low loss circuit boards and can be mass produced economically, which is important because CHIME requires 1280 feeds. They are compact enough to be placed 30cm apart in a linear array at any azimuthal rotation.

Keywords: antenna, dual polarization, wide bandwidth, radio telescope

I. INTRODUCTION

We have built a novel, cloverleaf shaped compact dual-polarization feed for the Canadian Hydrogen Intensity-Mapping Experiment [1]. CHIME is a radio telescope designed to measure Baryon Acoustic Oscillations (BAO) by measuring the intensity of neutral hydrogen over half the sky through the redshift range $0.8 \leq z \leq 2.5$. At these redshifts the 21cm line of neutral hydrogen appears in the frequency range 400MHz to 800MHz. CHIME has no moving parts; it consists of five parallel cylindrical parabolic reflectors, each 20m wide, 100m long and f/0.25. Feeds are spaced 30cm apart along each focal line. Signals are amplified and brought to a single custom digital correlator.

The full instrument requires 1280 dual polarization feeds with an acceptable beam pattern, low material loss and s11 lower than -10dB from 400MHz to 800MHz. With this many feeds, it is important that uniform, reliable feeds can be manufactured economically. Other solutions considered as CHIME feeds are the four-square antenna [2] [3] developed for the Molonglo Telescope [4] , the four-point antenna [5] and the four-point antenna with tuning plate [6]. All these feeds generate an approximately circular beam suitable for feeding deep paraboloidal reflectors. The performance of these feeds differs mostly in their matching bandwidth.

II. RADIATION MECHANISM

Our feeds are a modification of four-square antennas developed for the Molonglo Observatory. The petals, stem and base are all made from printed circuits boards (PCB). To broaden the bandwidth, we have modified the petals to have curved outer edges as shown at left in Figure 1, eliminating the depedence on a single dimension. The curves are smooth and each petal is symmetric. CST simulated current pattern is shown at right in Figure 1 for one linear polarization at
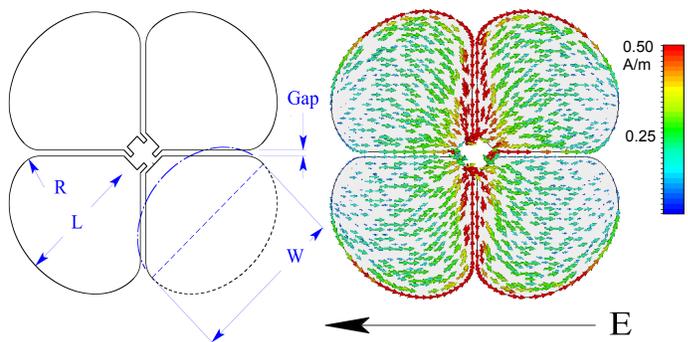

Fig. 1. At left, the shape of each petal consists of two perpendicular straight lines, two 45 degree circular arcs with radius R and one half an ellipse. W is the major axis of the ellipse and L is the length from the intersection of the straight sides to the outer edge of the ellipse. The shape is illustrated here for the adopted values of gap, R, L, and W. Each of the four tabs shown at the centre is connected to one side of a vertical microstrip transmission line and in each case the full width of the adjacent petal is connected to the other lead. At right, CST simulated currents for one linear polarization at 600MHz are shown. Note the small asymmetry in the curent distribution near the centre becasue of the tab geometry.

600MHz. The currents near the gaps between petals run in opposing directions so they cancel, and do not contribute to the radiation pattern. For this polarization, farfield radiation arises from the coherent currents running along the curved outer edges of the top and bottom pair of petals. For each linear polarization, two differential signals, each from a pair of petals, are combined through tuned baluns to form one single-ended output. Thus each single polarization signal involves currents in all four petals. This is called in-pair feeding. Full baluns, from both polarizations, consist of four identical microstrip transmission lines along four vertical support boards(stem) and a horizontal base board. Both of the single-ended outputs are on the base board. Each transmission line is varied in several abrupt steps, and the lengths and characteristic impedances of the transmission line segments are tuneable. We have demonstrated that electrical losses in conventional circuit board materials generate unacceptable noise levels for astronomical instrumentation. Teflon-based PCB is used everywherethere is a transmission line.

III. TUNING THE ANTENNA PERFORMANCE

In order to tune the antenna parameters to produce acceptable performance we have constructed a full CST model

of a cloverleaf antenna(only one polarization present). To verify the procedure, we first built two different cloverleaf antennas with arbitrarily chosen shapes, measured their s11 and compared these measurements to CST simulations. The comparison proves our CST simulation is reliable.

Measurements show that coupling between two polarizations and coupling between adjacent antennas do not affect s11. Therefore, we proceeded to iterate the cloverleaf design using CST following the plan listed below.

We initially fixed the parameters of the transmission lines to a design chosen for ease of manufacture: the transmission line has two characteristic impedances, one on the vertical support board and the other on the horizontal baseboard.

We set the initial petal parameters to be $(R, W, L) = 80, 140, 150)$mm and altered R, W, and L successively, to learn which parameters have the most impact on the antenna's s11. Altering R has very little impact, and we fixed it to $R = 20$mm, the peak of a very shallow performance curve.

We used the optimization algorithm implemented in CST to explore s11 in (W, L) space. Varying W and L simultaneously until CST finds the smallest s11 across the band. Optimization was still running after two days and we manually stopped it.

We found that for these transmission lines and for $R = 20mm$, s11 has strong dependence on W and L. However, all s11 curves pass through an apparent fixed point at approximately $f = 580$MHz, $S_{11} = -12$dB. From this result and from a manual exploration of transmission line impedance we concluded that this optimization step is essentially minimizing s11 by matching the petal shape to the fixed balun parameters.

We introduced an additional degree of freedom by dividing the vertical portion of the transmission line from one segment to two segments with different impedances. From among more than 60 sets of parameters returned by CST, we picked $(W, L) = (138.5, 131.9)$mm which has the smallest s11 across the band although it does not meet our specifications and explore transmission line properties. We held total length of vertical transmission line fixed to ensure $\frac{1}{4}\lambda$ separation between radiating petals and reflective ground plane, and varied characteristic impedances and the step location.

With the upper trace width 3.5mm, length 92mm and lower trace width 2.5mm, length 40mm, the result is dramatic. The fixed point is removed and the s11 is below -15dB across the band except for near 400MHz, where we just meet our requirement of -10dB.

We stopped our tuning procedure at this point. Although a solution has been found which exceeds our requirements, the system has not been optimized. Petal shape parameters and transmission line parameters have been varied separately but the full space of these parameters has not been explored. We can use this in future work to add additional performance criteria to the design procedure.

IV. RESULTS

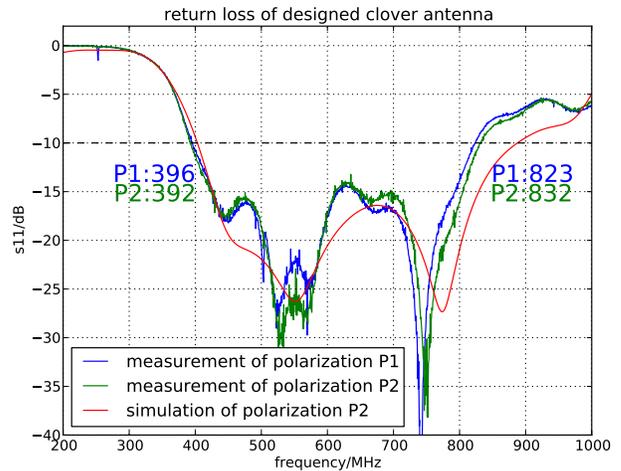Four petals of the chosen shape are built into one piece of double-sided PCB with FR4 as substrate to save cost. Vias

Fig. 2. The measured s11 spectrum for both linear polarizations is plotted along with the CST simulation. Note the similarity between two polarzations. This design exceeds the requirement of $S_{11} \leq -10$dB over the full band from 400 to 800 MHz.

Fig. 3. A linear array of eight cloverleaf antennas installed at the focal line of the CHIME Pathfinder at the Dominion Radio Astrophysical Observatory in Penticton, BC, Canada. The picture is taken through the wire mesh reflective surface (mesh spacing 19 mm) illustrating a photonsview of the antennas and ground plane. Notice that each feed has an image-feed in the ground plane, $\frac{1}{2}\lambda$ away at the passband centre frequency. Notice also the four slots cut to remove dielectric material from the gaps between the petals.

connect the two copper surfaces to reduce material loss in FR4. The circuit boards are slotted to remove FR4 in the gaps between petals because leaving FR4 in the gaps has a serious effect on both antenna impedance and material losses. Note that the resulting petal size and shape are compatible with 45 degree aimuthal rotation in an array. The s11 of an assembled feed is shown in Fig. 2 for both polarizations and in comparison with simulations. According to simulation, the beam pattern is smooth in both the E-plane and the H-plane. HPBW varies within several degrees across the band. The six PCB pieces of the cloverleaf antenna are soldered together using a mechanical jig. A photo of eight antennas in a linear array installed on the CHIME pathfinder is shown in Fig.3.

V. ACKNOWLEDGEMENTS

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