Development of 6-inch 80–170 GHz Broadband Silicon-Plated Horn Antenna Arrays for Primordial Gravitational Wave Search (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

Searching for primordial gravitational waves in the cosmic microwave background (CMB) polarization signal is one of the key topics in modern cosmology. Cutting-edge CMB telescopes require thousands of pixels to maximize mapping speed. Using a modular design, the telescope focal plane is simplified to several detector modules, each containing hundreds of pixels including antenna arrays, detector arrays, and readout arrays. The antenna arrays, as the beam-defining component, determine the overall optical response of the detector module. In this article, we present the development of 6-inch broadband antenna arrays operating from 80 to 170 GHz for the future IHEP focal plane module. The arrays are fabricated from 42 6-inch silicon wafers including 456 antennas—7% more pixels than the usual design. The overall in-band cross-polarization is smaller than −20 dB and the in-band beam asymmetry is smaller than 10%, fulfilling the requirements for primordial gravitational wave searches.

Key words: instrumentation: detectors – Astronomical Instrumentation, Methods and Techniques – (cosmology:) cosmic background radiation

1. Introduction

Observations of the cosmic microwave background (CMB) hold immense significance in cosmology research. This ancient light, leftover from the Big Bang, provides crucial insights into the early universe's conditions, such as its temperature, density, and composition [?]. The CMB primarily has two polarization modes: E-mode and B-mode, analogous to the electromagnetic field [?, ?].

B-mode polarization could be generated by primordial gravitational waves, which could provide crucial information about the inflation process. Therefore, searching for large-scale CMB B-mode polarization signals has become the next major goal in observational cosmology [?].

For ground-based CMB observations, the atmosphere poses a significant challenge. It absorbs CMB signals and emits radiation in the same frequency range, which degrades the signal-to-noise ratio. Among all atmospheric components, water vapor plays a crucial role due to its strong absorption. Consequently, CMB telescopes are located at the driest sites in the world. For example, the South Pole Telescope [?] and the BICEP telescopes [?] are located in Antarctica, the Atacama Cosmology Telescope [?] and the Simons Observatory are located in Chile [?], and the Ali CMB Polarization Telescope (AliCPT), the first telescope of which is currently being deployed, is located on the Qinghai-Tibet Plateau in Xizang, China [?, ?]. All these telescopes use a modular focal plane design, with cutting-edge detector modules based on 6-inch micro-fabrication processes [?].

Each detector module consists of three main parts: antenna arrays, superconducting detector arrays, and readout arrays. As the signal-receiving component, the antenna array design is crucial for overall observation performance. Horn antennas are widely used because of their excellent polarization definition and broadband frequency coverage [?]. There are two main types of horn antennas used in B-mode detection: corrugated horns and smooth-walled horns. Corrugated horns have nearly ideal beam symmetry, but the loaded rings are larger than the aperture, decreasing the number of pixels in a given module size and thus limiting mapping speed. Smooth-walled horns with no wasted area can achieve the optimal number of pixels [?]. We present our single horn design and antenna array design below.

Fabrication of horn arrays involves many aspects of detector module assembly. Direct machining has the advantages of low cost and easy fabrication, but the machining precision and the discrepancy in coefficients of thermal contraction between metal and silicon require special care. Micro-fabrication technology provides fabrication precision at the level of several micrometers. Since both the antenna arrays and detector arrays are fabricated from silicon wafers, there is no relative thermal contraction at cryogenic temperatures [?].

In this paper, we present the fabrication and measurements of a 6-inch silicon-plated smooth-walled horn array. The frequency range extends from 80 to 170 GHz, covering the two main atmospheric windows for CMB observations.

AliCPT-1 [?] is the first CMB telescope of the AliCPT project, led by the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, and also the first CMB telescope in China. Its focal plane can hold 19 detector modules. Currently, one detector module has been deployed in the initial phase, fabricated by Stanford University and the National Institute of Standards and Technology [?]. The new antenna array design presented in this paper has a total of 456 pixels—7% more than the current AliCPT-1 module—and could be used for future AliCPT telescopes.

2.1. Antenna Profile Definition

To match the starting frequency of 80 GHz, an input radius $r_{\text{in}} = 1.15$ mm is used, corresponding to a cut-off frequency $f_{\text{cut-off}} = 76.4$ GHz. The horn diameter is determined by optimizing the observing speed. In general, the aperture efficiency is determined by the spillover efficiency and the edge taper. The maximum aperture efficiency occurs when the horn diameter $2r_{\text{out}} = 2F\lambda$, where F is the f-number of the telescope and λ is the wavelength [?]. Here, we adopt the optical parameters of the AliCPT-1 telescope [?, ?] as inputs for our antenna design. AliCPT-1 has $F = 1.4$ and $\lambda = 2.4$ mm at the center of the 80–170 GHz observation band. The horn diameter is calculated to be $2r_{\text{out}} = 2F\lambda = 6.72$ mm for maximum aperture efficiency. However, maximum aperture efficiency does not guarantee maximum observing speed. Given a fixed focal plane size, more pixels are preferred in CMB observations. In our case, $1.54F\lambda$ is designed as the horn diameter with $r_{\text{out}} = 2.6$ mm.

The horn antenna profile is defined by a monotonically increasing curve given by Simon et al. [?]. This curve provides the flexibility to produce a continuous multi-section smooth-walled profile with only 42 parameters. The horn profile is simulated in CORRUG software, an antenna simulation tool based on the mode-matching method [?, ?]. The curve step is 0.25 mm, as two different wafer thicknesses (0.25 mm and 0.50 mm) of 6-inch wafers are used for practical reasons. The initial profile has a length of 19.5 mm with 78 sections for further optimization.

2.2. Antenna Profile Optimization

Beam asymmetry introduces extra difficulty for polarization calibration. Additionally, it is challenging to obtain a high-symmetry antenna across such a broad band from 80 to 170 GHz, so the primary optimization goal is to minimize the overall in-band beam asymmetry. The penalty function P is defined as

$$P = \int_{\text{Frequency}} \int_0^{\theta_{\text{stop}}} \left| \frac{E(\theta) - H(\theta)}{E(\theta)} \right| d\theta \, df$$

where the frequency range is calculated from 80 to 170 GHz and the cold stop has a cut-off at $\theta_{\text{stop}} = 18.5^\circ$. The Markov Chain Monte Carlo (MCMC) method is used to randomly generate parameters based on the current best P. When a smaller P is achieved, the process is repeated.

The initial values of the 42 parameters are randomly assigned. Three parameters are fixed: $r_{\text{in}} = 1.15$ mm, $r_{\text{out}} = 2.6$ mm, and the total length of 19.5 mm. The calculated horn profile with a resolution of 0.25 mm is simulated in CORRUG. Far-field beam patterns are calculated with a frequency resolution of 1 GHz and an angular resolution of 1°. P is calculated from these beam patterns. In general, a monotonically increasing profile usually provides broadband low return loss S_{11}, so we only check S_{11} at the end of the full optimization.

Compared with three-dimensional (3D) finite element simulation software such as Ansys HFSS and CST, software using the mode-matching method like CORRUG provides much faster simulations. In our case, far-field beam calculation in CORRUG costs only 14 seconds, while it takes about 30 minutes in CST. Since we need tens of thousands of optimizations for this 42-parameter design, CORRUG is selected. CORRUG uses mode-matching calculations in each waveguide section but assumes the aperture is well-matched to free space. This assumption works well when the aperture diameter is 2.5 times larger than the wavelength, according to the software manual. In our case, with $r_{\text{out}} = 2.6$ mm, this assumption only holds when the frequency is higher than 144 GHz. According to the CORRUG manual, adding an extra large-diameter waveguide section with zero thickness in the calculation may provide more accurate results. We compared CORRUG results with and without this extra zero-thickness waveguide in Figure 1 [Figure 1: see original paper]. Here we use CST results as the benchmark, which is validated by our measurements in Section 4. Compared with CST results, CORRUG gives similar results within 20°, especially at high frequencies. The discrepancy becomes noticeable when the angle exceeds 20°. At 90 GHz, CORRUG with an extra waveguide gives a more accurate H-plane pattern, but there is a large discrepancy in the E-plane around 20°. Therefore, no extra waveguide is added in our CORRUG simulations. The discrepancy between simulation and measurements will be discussed in Section 4.

[Figure 1: see original paper] The solid line represents the beam pattern of the antenna simulated by CORRUG without the zero-length waveguide section. The two different dashed lines represent the beam patterns simulated by CORRUG with the zero-length waveguide section and by CST, respectively. The CST simulation uses an antenna model consistent with the actual fabricated antenna.

[Figure 2: see original paper] (a) The final optimized antenna profile, which consists of 78 layers of 0.25 mm sections. (b) The combined antenna profile obtained from panel (a), which consists of 24 layers of 0.25 mm sections and 27 layers of 0.5 mm sections.

Using only asymmetry as the optimization objective will result in a wide main beam by decreasing the diameter near the aperture, meaning the fixed horn aperture is not fully utilized. In this case, the beam coupling efficiency would be surprisingly low. To avoid this situation, three criteria are established based on Simon et al. [?] and practical considerations: (1) the profile gradient must not exceed 0.1 mm per section near the aperture; (2) the maximum difference in radius between adjacent layers must not exceed 0.49 mm; and (3) the last third of the total antenna profile length must be greater than 0.69 times but less than 0.88 times the aperture diameter.

The beam asymmetry coefficient at each frequency is defined as

$$\text{Beam asymmetry coefficient} = \frac{\sum_{\theta=0}^{\theta_{\text{stop}}} |E(\theta) - H(\theta)|}{\sum_{\theta=0}^{\theta_{\text{stop}}} E(\theta)}$$

This equation sums the difference between radiated power in the E-plane and H-plane over angles from $\theta = 0$ to $\theta_{\text{stop}} = 18.5^{\circ}$, then normalizes this summation to the E-plane radiated power. A small beam asymmetry coefficient is preferred.

2.3. Final Design

Initially, five random linear horn antenna profiles are generated. The configuration file for each profile is sent to CORRUG for simulation and optimization, with each initial profile undergoing 10,000 iterations. Finally, the profile with the lowest penalty function value is selected from the five iteration results as the final antenna design. The final optimization result is shown in Figure 2(a). We further manually combined sections with similar radii into 0.5 mm-thick sections, reducing the total number of sections from 78 to 51. The combined antenna profile is displayed in Figure 2(b). Only two 6-inch silicon wafers are required to fabricate a single silicon horn antenna: one 0.25 mm-thick wafer patterned into 24 pieces and one 0.5 mm-thick wafer patterned into 27 pieces. The S_{11}, beam asymmetry, maximum cross-polarization, and beam coupling efficiency are compared in Figure 3 [Figure 3: see original paper]. The difference after combination is negligible.

To account for unavoidable fabrication errors, we applied random error to the radius of each layer in the 51-section final design. The error follows a uniform distribution within ± 7 m, representing our estimate of fabrication and assembly tolerances. With 1000 simulations, the floating range of deviation in the antenna beam asymmetry coefficient is below 10% for most frequency points, as shown in Figure 3 [Figure 3: see original paper], indicating that errors do not significantly affect antenna symmetry and are acceptable. There is a large deviation at 159 GHz due to a specific structure from only one of the 1000 random profiles at that particular frequency. This error analysis suggests that antenna performance is quite robust to geometry errors.

The mask design for single horn fabrication is depicted in Figure 4 [Figure 4: see original paper]. Each piece contains one antenna hole, two alignment holes, and four screw holes for stacking, following our previous design [?]. Only circular rings are etched for these holes to decrease the etching area and increase etching uniformity.

To match standard rectangular waveguides in measurements, two rectangle-to-circle waveguide adapters were designed and machined: a WR-10 adapter for 75–110 GHz and a WR-6 adapter for 110–170 GHz. The design is a simple linear transition structure with a length of 25.4 mm. The S_{11} of both adapters is less than -30 dB.

3. Fabrication of a Single Silicon-Plated Horn Antenna

A set of 6-inch silicon wafers is used in our single horn fabrication as a pathfinder for the final 6-inch horn array fabrication. Contact lithography provides an accuracy of 1 m, which is much higher than conventional metal machining. The entire fabrication process, illustrated in Figure 5 [Figure 5: see original paper], was performed in the cleanroom of the Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO), Chinese Academy of Sciences. After contact lithography, wafers are etched through the Bosch process in an SPTS deep reactive-ion etching tool. An etched sidewall angle of 89° is achieved at one end, as displayed in Figure 4 [Figure 4: see original paper]. Given wafer thicknesses of 0.25 mm and 0.5 mm, this angle produces maximum geometry deviations of 4.4 m and 8.7 m, respectively. As the slope is very close to 90° at the other end, the overall deviations are smaller than these calculations.

After deep silicon etching, small pieces are released from the wafer. On both sides of these pieces, 40 nm-thick Ti and 100 nm-thick Au are sputtered as a thin seed layer for subsequent gold electroplating. Sputtering is selected for good step coverage. We stack small silicon pieces on a custom jig using two alignment pins with a tolerance of $±$1 m. To complete the assembly, two screws are used as shown in Figure 4 [Figure 4: see original paper]. The single antenna is then electroplated with 1.5 m-thick gold. Epoxy resin STYCAST 2850FT is applied to the sidewalls as glue to secure the entire antenna assembly, after which the screws are removed.

4. Measurements of a Single Horn Antenna

All measurements except antenna gain were performed in the microwave darkroom at the Key Laboratory of Particle Astrophysics, IHEP. The antenna gain was measured separately. The frequency range was 75–170 GHz to cover the cut-off frequency. Two standard gain antennas from ERAVANT, SAR-2309-10-S2 (23 dBi) and SAZ-2410-06-S1 (24 dBi), were used as transmitters for the 75–110 GHz and 110–170 GHz ranges, respectively.

In Figure 6 [Figure 6: see original paper], the S_{11} has been calibrated to remove reflections from the rectangular-to-circular waveguide adapter. The measured S_{11} agrees well with both simulations, particularly the CST result, and captures the ripple at low frequency. The S_{11} is below -10 dB from 78 to 170 GHz as designed. The gain is measured by comparing the antenna under test (AUT) with a standard gain antenna. The overall gain also agrees well with simulations. Given a fixed aperture size, the gain varies from 10 dBi to 17 dBi across the designed broad frequency range.

For far-field measurements, the antenna distance must satisfy $R > 2D^2/\lambda$, where λ is the wavelength and D is the antenna aperture size. The aperture diameter of the AUT is 5.2 mm, and the shortest wavelength corresponding to 170 GHz is 1.76 mm. Calculation shows the far-field distance must be greater than 30.7 mm. Our setup allows for a wide range of far-field distances, and for ease of installation and measurement accuracy, we set the far-field distance to 1050 mm.

During far-field measurements, the AUT is rotated about an axis located approximately 1 mm from the aperture toward the waveguide, as the phase center of this design varies between 0.5–1.7 mm from the aperture toward the waveguide when calculated from 80 to 170 GHz within $±$20° in CST. The AUT is scanned from $-90°$ to $90°$ in $1°$ steps. Cross-polarization is scanned at $\phi = 45°$, where cross-polarization reaches its highest level. All far-field patterns follow Ludwig's 3rd definition.

Measurement results are shown in Figure 7 [Figure 7: see original paper] compared with beams simulated by CORRUG and CST. The measurements are very consistent with CST results at almost all frequencies and angles. CORRUG results agree with measurements when the angle is smaller than 40°, primarily due to the mismatch between the aperture and free space in mode-matching calculations, as discussed in Section 2.2. As expected, when the aperture is 2.5 times larger than the wavelength (corresponding to 144 GHz in our case), the measurements agree well with CORRUG simulations.

The beam asymmetry coefficients, plotted in Figure 8 [Figure 8: see original paper], generally follow both simulations. Around 80 GHz, the asymmetry coefficient peaks at 24%, which will be discussed in Section 5. As the final beams will be weighted across two frequency bands (80–110 GHz and 125–165 GHz), the final beam asymmetry will still be smaller than 10%, meeting our design goal. The beam coupling efficiency is very consistent with simulations. The maximum cross-polarizations within the cold stop are all smaller than -20 dB at all frequencies.

5. A 6-inch Silicon-Plated Horn Antenna Array

With the performance of a single silicon horn antenna verified, the same design is applied to a 6-inch large array for our 6-inch CMB detector module. The pixel design is briefly discussed in Chai et al. [?]. Either transition-edge sensors (TES) [?] or kinetic inductance detectors (KIDs) [?] could be used. This new module design has 456 pixels in total—7% more than the detector module used by the Simons Observatory [?]—with a pitch size of 5.3 mm. As the horn aperture is 5.2 mm, the narrowest width between horn apertures is only 100 m.

The total of 51 layers in the single horn design, depicted in Figure 2 [Figure 2: see original paper], is reduced to 42 layers by removing 4.5 mm-long circular waveguides at the beginning of the horn profile without compromising performance. The total length is decreased to 15 mm with 24 layers of 0.25 mm-thick 6-inch silicon wafers and 18 layers of 0.5 mm-thick 6-inch silicon wafers. The final assembled array is displayed in Figure 9 [Figure 9: see original paper]. In the ideal case, 469 antennas could be accommodated, but 13 are used for packaging purposes. The central position is converted to an alignment hole for all detector-related wafers. To fasten the array during gold plating, six positions in the middle are used as through-holes for screws. The six corners are also used as screw holes for spring connections between the silicon antenna array and metal packages to compensate for contraction at low temperature. On all six edges of the array, three screw holes and four glue grooves are designed for fastening.

The fabrication process adapts the single horn antenna process shown in Figure 5 [Figure 5: see original paper]. The full 6-inch wafer stacks dramatically increase fabrication difficulty. After four months of fabrication in the public SINANO cleanroom, all wafers were completed with no broken structures. As shown in Figure 10 [Figure 10: see original paper], assembly was performed on a custom jig in our cleanroom to prevent particle trapping between wafers. Wafers are aligned by two alignment pins with a tolerance of $±$1 m. After stacking, screws secure the whole array for gold plating. A 2 m-thick gold layer is plated to define the antenna and cover any possible gaps between wafers. Stycast 2850, which has good thermal conductivity at low temperature, is used as glue in the module grooves. The final antenna array is shown in Figure 9 [Figure 9: see original paper].

Six labeled horn antennas are measured using a custom test tray. These antennas are positioned progressively farther from the module center to evaluate uniformity and performance across the entire array. The far-field setup, depicted in Figure 11 [Figure 11: see original paper], is identical to that used for single antenna measurements in the IHEP darkroom.

Beam patterns for the six horn antennas are plotted in Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper]. In general, measurements are consistent with simulations, especially within 20°. When the angle exceeds 80°, the absorber used to remove reflections in measurements begins attenuating certain beam power, making measured beams lower than simulations. All side lobes are below -10 dB as expected. Cross-polarizations are smaller than -20 dB for most measured beams within 20°. The average maximum cross-polarization within 18.5° is lower than -20 dB, as confirmed in Figure 14 [Figure 14: see original paper].

The average beam asymmetry coefficient is smaller than 10% at all frequencies except 82 GHz, consistent with simulations. For frequencies below 115 GHz, beam asymmetry shows unexpectedly large variation compared with our fabrication error analysis in Figure 3 [Figure 3: see original paper]. In that error analysis, alignment errors were not considered, as misalignment of two circles with similar radii creates irregular overlap that is difficult to calculate. Hu et al. [?] simulated alignment errors for silicon-plated corrugated horns, showing statistically that beam waists at frequencies below $1.3f_{\text{cut-off}}$ have larger standard deviation than high-frequency results. In our case, $f_{\text{cut-off}} = 76.4$ GHz, and scattering of beam asymmetry becomes much smaller above 100 GHz ($1.3f_{\text{cut-off}}$), consistent with Hu et al. [?]. We suggest that wave propagation parameters vary rapidly near $f_{\text{cut-off}}$, and even small changes in $f_{\text{cut-off}}$ caused by misalignment can dramatically affect the beam. Although the final in-band (80–110 GHz and 125–165 GHz) beam asymmetry of this array will still be smaller than 10%, suitable for CMB observations, this appears to be a typical problem for silicon-plated horn antennas. Metal horn arrays may not have this issue if the final profile is machined by the same tool.

The coupling efficiency is consistent with simulation. As the H-plane is lower than simulation at large angles and the absorber attenuates some signal, the coupling efficiency is slightly higher than simulation below 130 GHz. The high uncertainty around 80 GHz is also due to the aforementioned misalignment.

Thus far, the performance of the presented antenna arrays is acceptable for observations. For future improvements, we may reduce misalignment by using more alignment pins and thicker wafers to decrease the number of layers. A new algorithm for simulating misalignment in non-circular waveguides would also help error analysis. Additionally, with the current $1.54F\lambda$ aperture size, optimizations could be improved by combining 3D simulations as a final step with mode-matching simulations, especially for low-frequency beams. We may also try lowering the cut-off frequency for better beam asymmetry, though this would worsen asymmetry at high frequencies. Further optimizations should explore this parameter space.

6. Conclusion

We have designed and fabricated 80–170 GHz broadband silicon-plated smooth-walled horn antenna arrays for primordial gravitational wave searches. The arrays contain 456 horn antennas based on a 6-inch micro-fabrication process. Measurement results are consistent with simulations, with overall in-band cross-polarization smaller than -20 dB and in-band beam asymmetry smaller than 10%. These antenna arrays will be packaged with detector arrays as a focal plane module for future CMB projects like AliCPT. Possible improvements are also discussed.

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Note: Figure translations are in progress. See original paper for figures.