Experimental Investigation of a Low-Cost, High Performance Focal-Plane Horn Array

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***Abstract*—In previous work, we have described novel smooth-walled multiple flare-angle horns designed using a genetic algorithm. A key feature of these horns is that they can be manufactured very rapidly and cheaply in large numbers, by repeated direct drilling into a single plate of aluminum using a shaped machine tool. The rapid manufacturing technique will enable the construction of very low cost focal-plane arrays, offering an alternative to conventional electroformed corrugated horn arrays.**

In order to experimentally demonstrate the new technology, we constructed a 230 GHz focal-plane array comprising 37 smooth-walled horns fabricated by direct drilling. We present the measured beam patterns for a large sample of these horns across the array, demonstrating the suitability of our manufacturing techniques for large format arrays. We have measured the cross coupling between adjacent feeds and have shown that it is negligible. We also present high quality beam patterns measured for a much smaller 700 GHz horn, showing the promise of the extending this technology to THz frequencies.

***Index Terms*—Antenna radiation patterns, genetic algorithms, horn antennas, radio astronomy.**

I. Introduction

The construction of high quality feed horns for millimeter and sub-millimeter astronomy has historically been much more challenging than the construction of feed horns at longer wavelengths. The expense and time required to construct these horns is becoming particularly problematic in an era where it is highly desirable to build focal-plane array receivers with large numbers of horns for large single dish telescopes. The usual choice of high performance feed horn, the corrugated horn, requires the construction of many azimuthal corrugations per wavelength and becomes expensive and time-consuming to manufacture below wavelengths of around 1 mm. There has therefore been considerable interest [1]–[6] in designing horns that offer performance similar to corrugated horns, but which are much easier to construct at short wavelengths.

For a single dish telescope, telescope mapping speeds are proportional to the number of independent detectors in the focal-plane. As the performance of bolometric and heterodyne detectors approach the limits imposed by the atmospheric background or by inherent quantum noise, increasing the number of detectors in the focal-plane is the only way to significantly increase telescope mapping speeds. Such multi-pixel receivers have been constructed to map emission from cold gas and dust in extended Galactic star forming regions [7], [8] and also to map the anisotropy in the cosmic microwave background [9]. For the next generation of instruments, there is considerable interest in the construction of wide-field multipixel cameras for deep, wide-area Galactic CO surveys [10], and also for mapping the CMB polarization anisotropy [11], [12]. The latter application will require instruments with many hundreds or thousands of very high performance, low cross-polarization feed horns over a range of frequencies from 90 GHz up to around 350 GHz.

Corrugated horns [13] are traditionally used for high performance astronomical feed horns from centimetric to sub-mm wavelengths. These horns have many azimuthal approximately quarter-wavelength corrugations along their interiors which impede the flow of those current components not tangential to the horn's circular cross-section. The result of this altered boundary condition is the propagation of a so-called *hybrid* HE_{11} mode within the horn [14]. This leads to a highly uniform, highly polarized illumination of the horn aperture, giving a beam pattern with low sidelobes and low cross-polarization in the far-field. Conical corrugated horns can be designed to give an operating bandwidth of more than 30%, and corrugated horns with profiled interior flare-angles can give very low cross-polarization and sidelobe levels [15] over bandwidths of 50%.

While corrugated horns offer excellent performance, construction of the azimuthal corrugations becomes increasingly difficult at smaller wavelengths. Corrugated horns for sub-mm wavelengths are usually constructed by an electrochemical process known as electroforming. The electroforming process is time-consuming and expensive, and single horns can cost between $1000–$2000 and take several weeks to construct. Alternatively, one can fabricate corrugated horns by direct machining into two halves of a so-called "split-block". These two halves are then bolted together to form the final horn [7]. Here again the process is time consuming, with the corrugations near the horn's throat becoming particularly difficult to machine at smaller wavelengths. Such fabrication difficulties have, in recent years, lead to the exploration of alternative fabrication techniques for sub-mm corrugated horns such as platelet stacking [16], and also renewed interest in smooth-walled horns.

The traditional Potter horn [17], [18] is a smooth-walled conical horn that uses a step or flare-angle discontinuity near

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the throat of the horn to excite the TM_{11} mode, in addition to the fundamental TE_{11} circular waveguide mode. By designing the discontinuity very carefully to excite a certain proportion ($\sim$16%) of the TM_{11} mode, and by choosing the length of the horn so that the two modes arrive at the aperture in phase, one can significantly improve the uniformity of the aperture illumination, leading to sidelobe cancellation in the far-field. It has been found, however, that the step discontinuity in a Potter horn needs to be fabricated very precisely, both in terms of position and depth, to give consistent, reproducible performance at sub-mm wavelengths [19]. Also the amplitude and phase of TM_{11} mode generation is a strong function of wavelength, limiting the bandwidth of Potter horns to around 10%. Step discontinuities also inevitably generate higher order modes, which interact at the aperture in ways that are hard to predict analytically, and these unwanted modes can also conspire to reduce the horn's effective bandwidth.

Accurately calculating the predicted radiation patterns for horns of a given geometry is clearly important in the horn design process. Fortunately, the modal matching technique [14] allows accurate beam patterns to be calculated relatively rapidly (e.g., within a minute or two on a modern desktop PC). Given how rapidly the expected beam patterns can be calculated from a particular geometry definition, it is a logical next step to combine this modal matching code with automated optimization algorithms. In work reported by Granet *et al.* [1], the authors combined quasi-Newton minimization algorithms with modal matching to optimize smooth-walled spline horns with six free parameters. Zeng *et al.* [2] employed a variant of Powell's method to optimize a 20 point spline profiled horn leading to a somewhat complicated profile which gave a high fractional bandwidth of 30%. We have previously reported using a genetic algorithm to design Potter horns with a single step or flare-angle discontinuity [Fig. 1(a)] [3]. We then generalized this approach to design horns with multiple flare-angle discontinuities [4]–[6] leading to designs with significantly higher bandwidths that still have a simple profile which is easy to fabricate at sub-mm wavelengths.

In this paper, we describe the design, fabrication and experimental testing of a complete 37-horn array of multiple flare-angle smooth-walled horns designed using a genetic algorithm (GA). In Section II, we outline our design process using the genetic algorithm, and describe our choice of quality function that is minimized by the GA. Section III describes our fabrication method for these horns using a novel drilling technique and the experimental verification of our design process and fabrication technique. In Section IV, we describe the construction and testing of the complete 37-horn focal-plane array prototype at 230 GHz, and Section V describes our success in fabricating and testing these horns for use at higher frequencies (700 GHz). Section VI describes new horn designs that feature three flare-angle discontinuities and have a wider expected bandwidth of 25%.

II. Design Using a Genetic Algorithm

The horns described in this paper were designed using a genetic algorithm [20], which mimics the process of natural selection to perform an optimization. We shall now briefly summarize this technique (see [3]–[6] for a more complete description). Firstly, we generate a pseudo-random *population* of horns, with each individual horn being represented by a set of parameters, $R_0, R_1, R_2, R_3, L_1, L_2, L_3$, describing the radii and lengths of each conical section for the horn in Fig. 1(b). Next, each horn parameter is encoded into a binary string or *chromosome*, with each collection of chromosomes describing an *individual* horn within the population. For each individual horn in the population, the far-field beam patterns are calculated using modal matching, and the cost function described below is evaluated. The *fittest* half of the population (i.e., those with the lowest cost functions) is selected and then used to form a new population, or *generation* of individuals via a *mating* process that combines the genome of pairs of individuals to form new offspring. The mating is carried out using *crossover* and *mutation* in a process analogous to biological reproduction. By repeating the process over many generations, the average population fitness tends to increase, with the population variation introduced by crossover and mutation allowing the optimization routine to escape local minima. After a sufficient number of generations (~ 1000), the fittest member of the population is selected, which represents the best horn design. This design is then further optimized using Simplex minimization [21].

For our purposes, we chose a cost function that is minimized for horns having a high beam circularity and low cross-polarization. This cost function, at single frequency f may be written as

$$\delta_f^2 = w_X \left[\sum_{P=-1}^{P=-30} \left(\frac{\sigma_P}{\sigma_P^{\mathrm{av}}} \right)^2 w_P \right] \tag{1}$$

where P is the power level in dB, $w_P = 10^{P/15}$ is the weighting function for the beam circularity, w_X is the peak cross-polar power relative to main-beam peak power, σ_P is the difference

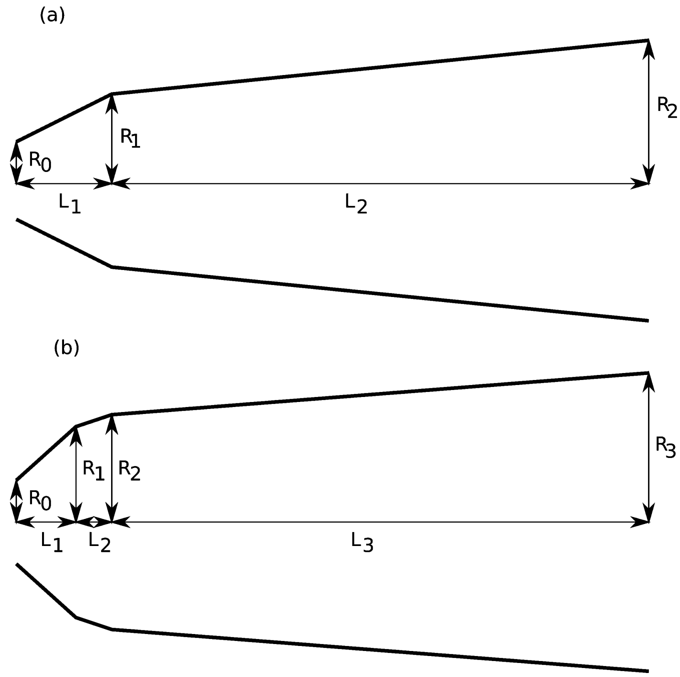

Fig. 1. A schematic diagram of (a) 2-section and (b) 3-section multiple flare-angle horns.

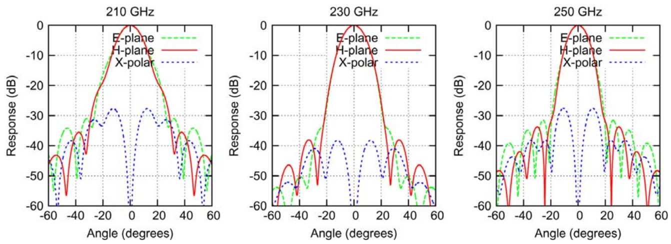

Fig. 2. Theoretical beam patterns (E plane, H-plane and cross-polarization) calculated using modal matching.

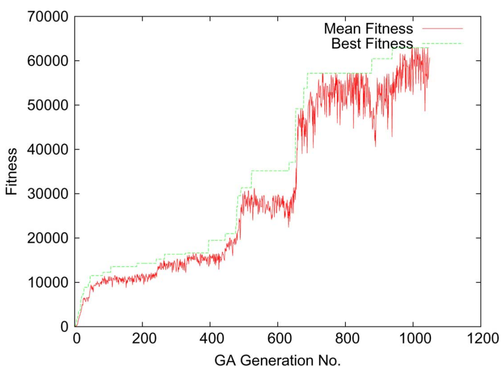

Fig. 3. A typical plot showing how the mean and peak fitness ($\equiv 1/\delta^2$) increases with each successive GA generation.

between the E and H-plane beamwidths at power level P dB and $\sigma_P^{\rm av}$ is the mean E and H-plane beamwidths at power level P dB. We calculate our final cost function across bandwidth $\sigma_f = f_U - f_L$ centered at frequency f_0 via

$$\delta^2 = \sum_f \delta_f^2 w_f \tag{2}$$

where $w_f = \exp(-(f - f_0)^2/2\sigma_f^2)$ is a frequency dependent weighting factor. We note that it is possible to use the same genetic algorithm with other cost functions, which could select other desirable features in the horn patterns, dependent on the required application—e.g., high beam efficiency, high Gaussianity, etc.

We have written a suite of design software, incorporating both modal matching and the genetic algorithm, to implement the complete design method described above. Genetic algorithm optimizations are straightforward to parallelize, and our software can run on multiple CPU Beowulf clusters, with the time-consuming modal matching beam pattern calculations being performed for each individual horn simultaneously on different CPUs. A typical plot of the performance of the genetic algorithm is shown in Fig. 3. There is a rapid increase in both mean and peak population fitness ($\equiv 1/\delta^2$), and the steps in the mean population curve show how the population of horns escapes successive local minima of the cost function. Plots of this kind show the suitability of stochastic minimisation algorithms, such as the genetic algorithm, for these type of horn optimisation problems. We are currently optimising horns with three flare angle discontinuities in parallel across 24 CPU cores, with typical runs of around 1000 generations requiring 24 hours of computing time.

A particular horn with a FWHM beamwidth of 14.6 degrees, designed using the GA, for a 20% bandwidth centered at 230 GHz, is described in Table I. The theoretical far-field beam patterns, calculated using modal matching, are shown in Fig. 2.

Fig. 4. The high speed steel machine tool used for the fabrication of the 230 GHz drilled horn prototype.

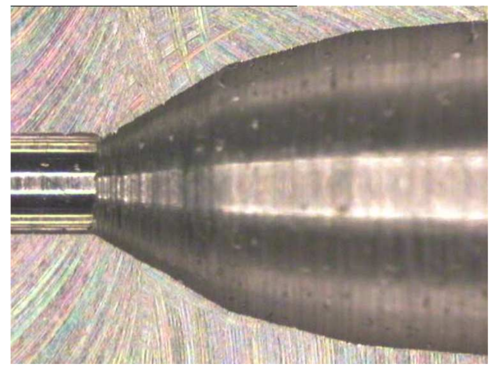

Fig. 5. The throat region of one half of the 230 GHz split drilled horn. For scale, the input waveguide on the left has a diameter of 1.24 mm.

III. Fabrication and Verification of Single and Dual Horn Prototypes

An attractive feature of our multiple flare-angle smooth-walled horns is that their simple interior profiles make them much easier to manufacture than corrugated horns. We have developed a simple technique where the horn is drilled out of an aluminum block using a machine tool (Fig. 4) whose cutting edge has been manufactured with the shape of the required interior horn profile. We complete the horn by drilling a circular waveguide into the opposite side of the aluminum block. This technique lends itself well to the rapid and inexpensive fabrication of large focal-plane arrays, which can be made simply by repeatedly drilling into a single plate of aluminum (see Section IV). In previous work [4]–[6], we have successfully manufactured and experimentally tested several individual horns using this technique. We split one of these horns in half using a milling machine to examine the machining quality of the interior of the horn (Fig. 5). The overall quality of the horn's interior was seen to be very good, having a surface roughness of a few μm. The discontinuities near the throat was seen to be sharp and well defined, with the horn's interior conforming accurately to the shape of the cutting tool.

To first verify our design procedure and our 3-section design described in Section II in the absence of significant manufacturing errors, we had two prototype feed horns manufactured using the traditional electroforming technique. We measured the far-field beam patterns for these horns directly using an ABmm vector network analyzer as a simple power detector in an anechoic chamber. Two identical prototype horns were used for transmission and reception, separated by 350 mm ($\sim 9D^2/\lambda$), where D is the horn aperture diameter. The H-plane, E-plane, co-polar and cross-polar patterns for these electroformed prototypes (Figs. 6 and 7) agreed well with

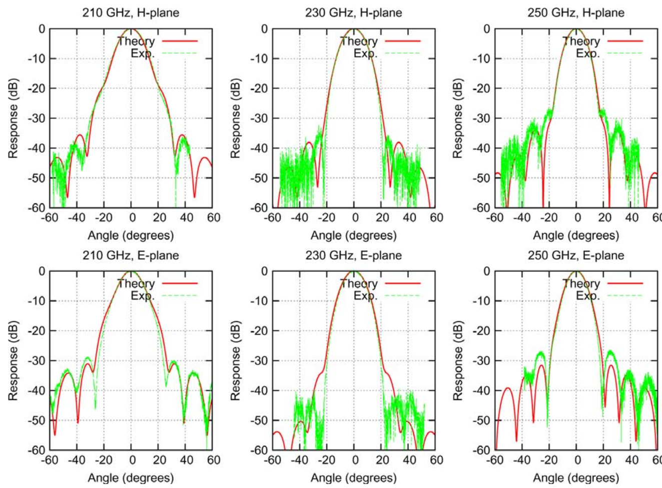

Fig. 6. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns for the electroformed prototype horns.

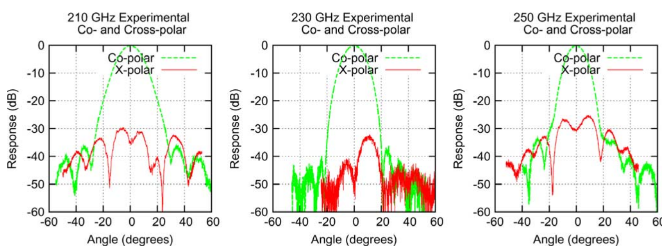

Fig. 7. Experimental co-polar and cross-polar beam patterns for the electroformed prototype horns.

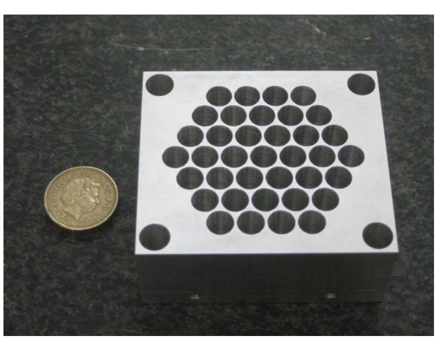

Fig. 8. The 37-horn array prototype, made by repeated drilling into a single block of aluminum.

theory with low sidelobes and cross-polarization across a bandwidth of 210–250 GHz (20%). We next measured the far-field beam patterns of individual drilled horns and found similar good agreement, with very little difference between patterns for different horns, validating our new fabrication technique for single horns [5].

For focal-plane arrays, it is important to have negligible cross-coupling between two adjacent horns within the array. In order to test this for our horns, we drilled two close packed horns (separation = 8 mm) into a single aluminum block. Using a vector network analyzer and a carbon loaded epoxy cone in front of the horns as an absorber we measured the cross coupling between the two horns. We found the measured cross-coupling to be

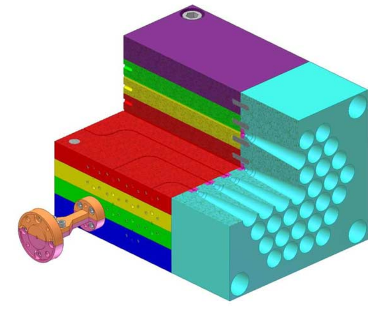

Fig. 9. The multi-plate split block enabling RF power to be delivered to each of the horns from a split block waveguide at the sides and rear.

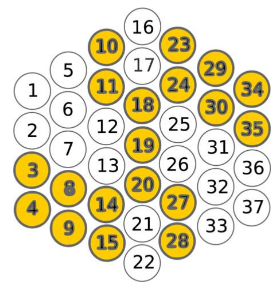

Fig. 10. Schematic of the horn array highlighting the sample of horns tested.

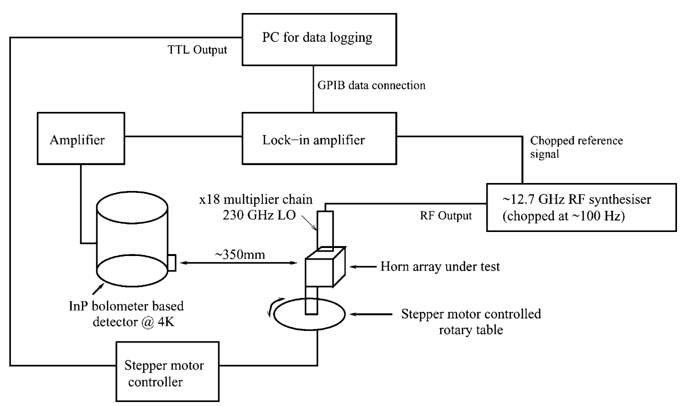

Fig. 11. A schematic diagram of the experimental test system used to test the 230 GHz 37-horn array.

TABLE I
GEOMETRICAL PARAMETERS FOR THE 3-SECTION 230 GHZ HORN DESIGN

Parameter	Length (mm)
R_0	0.62
R_1	1.486
R_2	1.812
R_3	3.652
L_1	1.479
L_2	1.212
L_3	24.0

below −67 dB across the operating bandwidth of 210–250 GHz [6]. This result was compatible with that obtained from modelling the cross-coupling of the two horns using Ansoft's HFSS, a full 3-D electromagnetic simulation package. We also measured the far-field beam patterns for each horn in the two-horn block

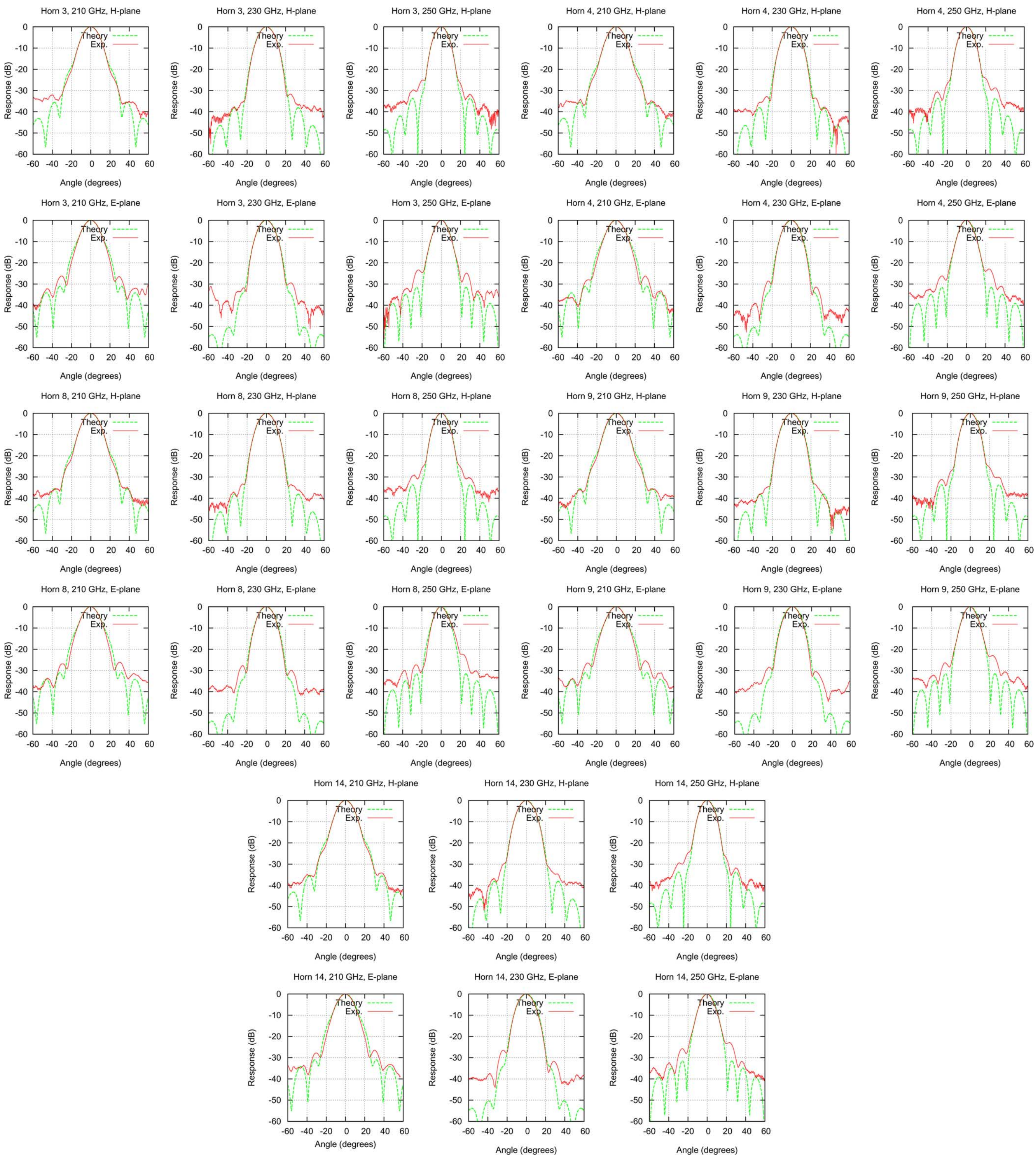

Fig. 12. Experimental and theoretical beam patterns for horns 3, 4, 8, 9, and 14 from the 37-horn array. See Fig. 10 for their location within the array.

and again found good agreement with the beam patterns calculated using modal matching, with each horn giving very similar beam patterns.

IV. A 37-Horn Array for 230 GHz

The high quality beam patterns and low cross-coupling measured for our prototype two-horn array enabled us to proceed confidently with the construction of a larger array with drilled horns of the same design. We constructed a 230 GHz, 37 horn hexagonally close packed array, with a horn spacing of 8 mm, by repeated drilling into a single aluminum plate (Fig. 8). The array was constructed using a standard 5 axis CNC milling machine, taking around two days to manufacture. Making larger arrays with several hundred horns will be a similarly rapid process, once care is taken to accurately align the aluminum plate within the milling machine to ensure

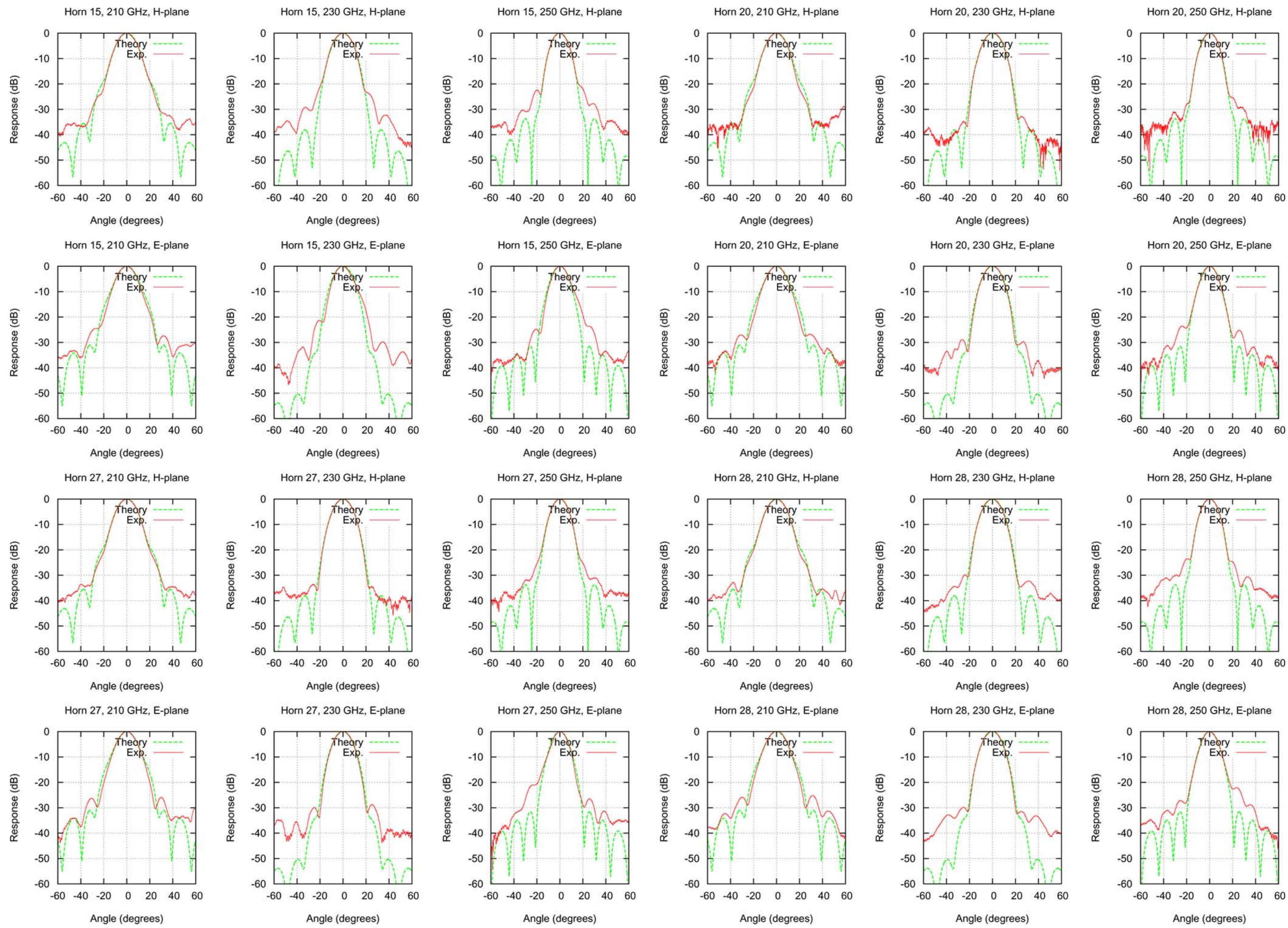

Fig. 13. Experimental and theoretical beam patterns for horns 15, 20, 27, and 28 from the 37-horn array. See Fig. 10 for their location within the array.

good alignment with the axes of the horn and the waveguide machining tools.

In order to supply RF power to each horn from a 230 GHz local oscillator, it was necessary to construct an interface block to be attached to the rear of the horn array plate (Fig. 9). This consisted of waveguide sections, terminated with suitable flange fittings, milled into several layers of a split aluminum block. The outputs of the waveguide were routed to the rear face and two side faces of the interface block, enabling the convenient connection of our local oscillator source to each horn in the array. Circular-to-rectangular waveguide transitions were fabricated by drilling smooth cones into the ends of the rectangular waveguides using a simple conical cutting tool with a semi-flare angle of 9 degrees. These circular-to-rectangular waveguide transitions were fabricated in the front face of the interface block, which was dowelled and bolted directly onto the rear of the horn array plate. An adjustable height mounting jig was constructed which enabled the complete assembly to be rotated by 90 degrees to enable the testing of the perpendicular E and H polarization planes for each horn in the array.

After construction of our 37-horn array prototype, interface block and mounting hardware we measured the far-field patterns of the array directly in the far-field using a cooled bolometer detector in a custom built anechoic chamber (Fig. 11). The subset of horns chosen for testing (Fig. 10) was spread across the whole array, enabling us to look for any trends in beam pattern behavior which might arise from differences in machining tolerances across the array. The experimentally measured beam patterns for the 19 horns tested are shown in Figs. 12–15. The measured beam patterns show high beam circularity, low sidelobe levels (below -20 dB) and good agreement with theory for the tested horns. These experimental results show a high degree of beam uniformity across the array, demonstrating the applicability of the direct drilling fabrication technique to future large format focal plane array receivers. While we saw no obvious trends in beam quality as a function of position within the array, we did notice some E-plane main-beam asymmetry at the high end of the measured bandwidth for two of the nineteen horns tested (horns 15 and 27 in Fig. 13). We intend to investigate the causes of these asymmetries by splitting the horns in question in half, to examine machining quality near the critical throat region of the horn. We will then model the effect of any measured asymmetrical machining imperfections by simulating these horns using Ansoft's full 3D electromagnetic modelling package, HFSS [6]. We intend to present a full analysis of the machining tolerances required for fabrication of these horns as a function of frequency in a future paper.

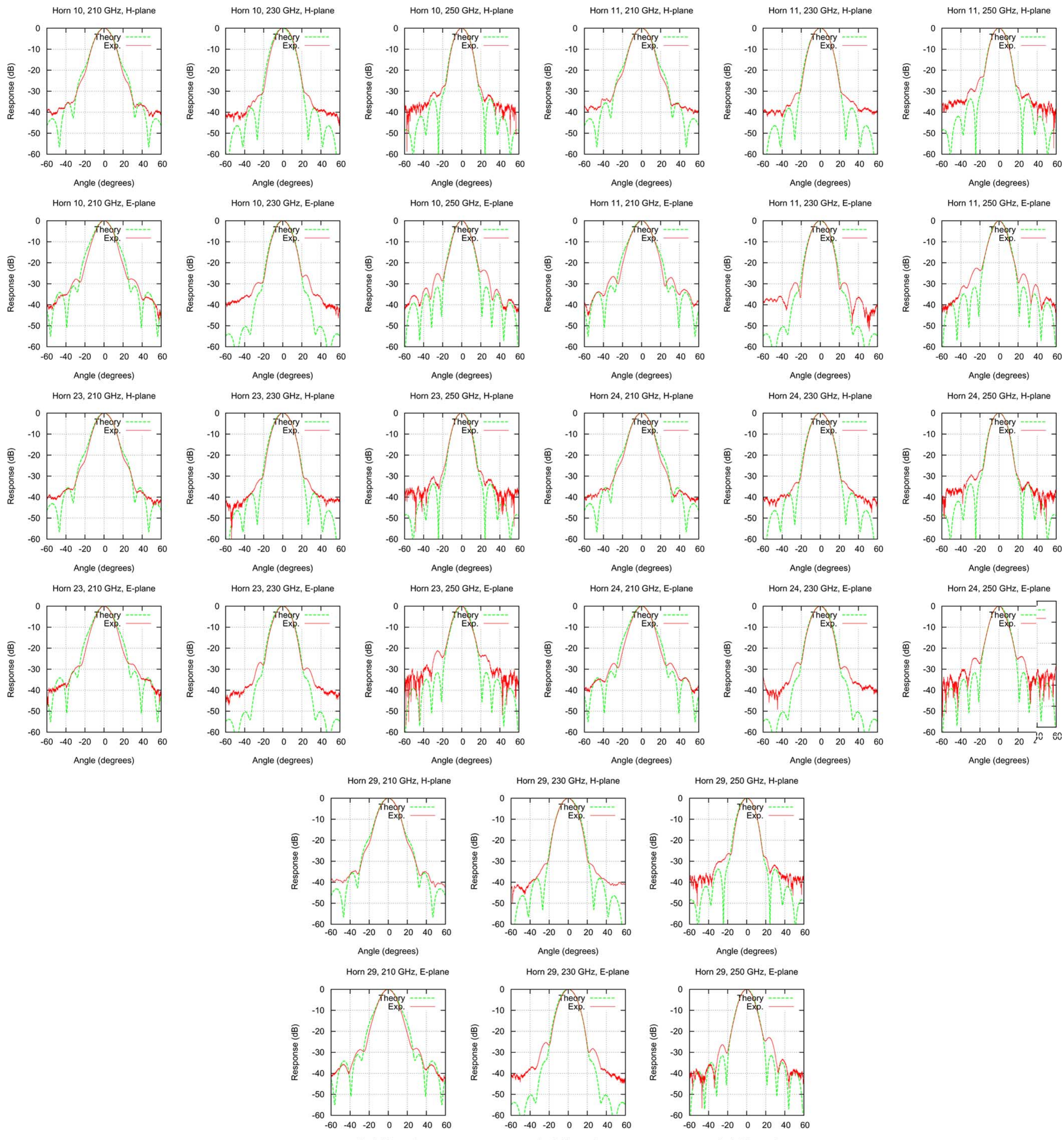

Fig. 14. Experimental and theoretical beam patterns for horns 10, 11, 23, 24, and 29 from the 37-horn array. See Fig. 10 for their location within the array.

V. Prototype Horns for 700 GHz

As well as fabricating complete horn arrays at 230 GHz, we are also extending the technology to sub-mm wavelengths by fabricating horns for a band center of 700 GHz ($\lambda = 429\ \mu$m). We fabricated three individual horn prototypes, each with dimensions as shown in Table I, scaled by a factor of 0.329 to give a central frequency of 700 GHz (Fig. 16). The cutting tool for horns at these frequencies is much smaller, with a maximum radius of 1.2 mm, set by the required aperture of the horn. The circular-to-rectangular waveguide transitions were made in a similar way to those described in Section IV by direct drilling with a conical cutting tool with a semi-flare-angle of 9 degrees. Standard UGC 387/U flanges were machined for attaching the horns to the circular-to-rectangular transitions and then to a 700 GHz local oscillator source for testing.

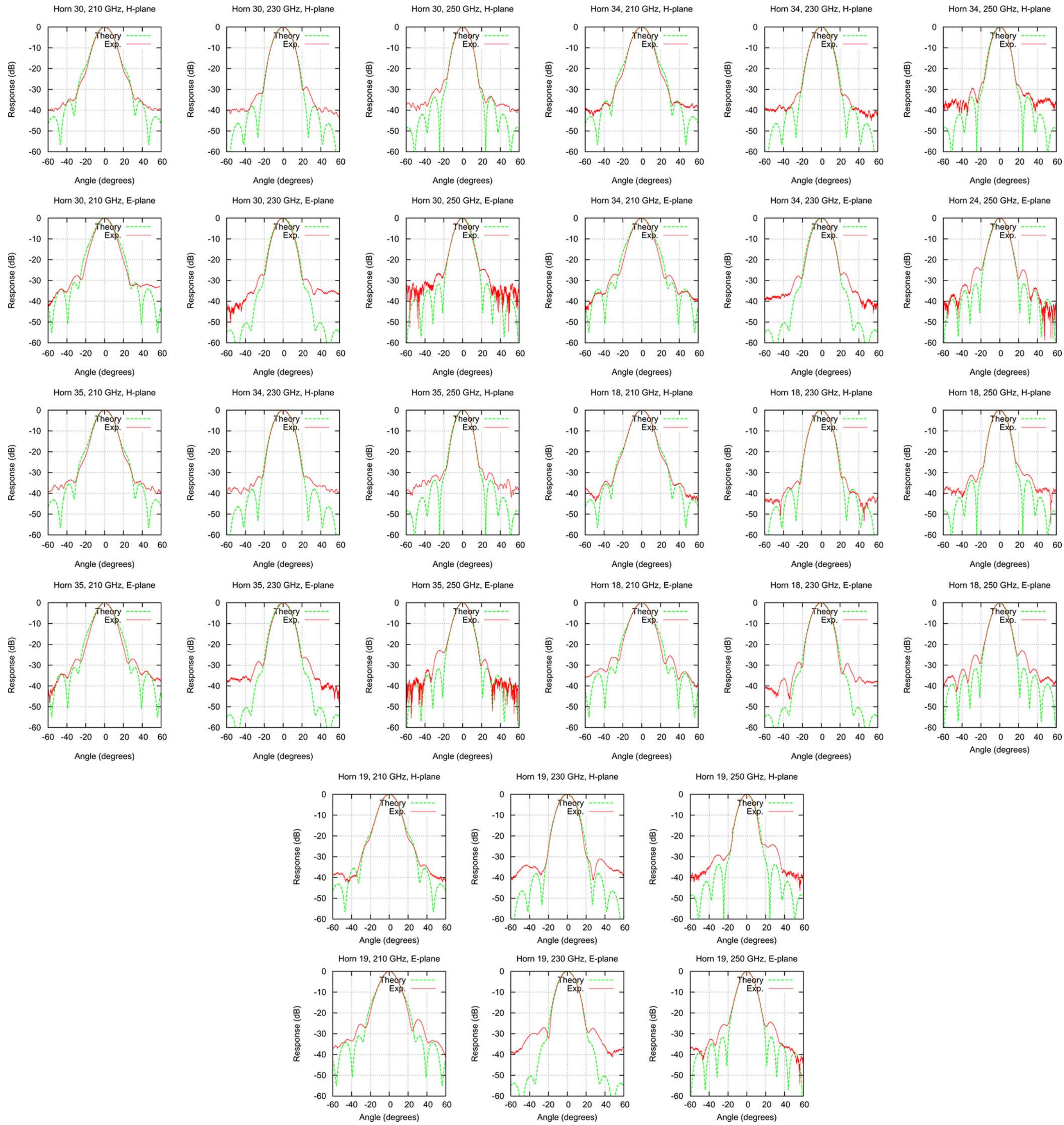

Fig. 15. Experimental and theoretical beam patterns for horns 30, 34, 35, 18, and 19. See Fig. 10 for their location within the array.

We measured the beam patterns of these horns using our far-field test range, between 600 and 740 GHz, the upper frequency measurement being limited by the power available from our LO source (Fig. 17) [22]. The co-polar and cross-polar patterns (Fig. 18) were measured using a terahertz polarizing grid, oriented at 45 degrees to the rotation plane, positioned in front of the cooled bolometric detector. The beam circularity is excellent, the measured sidelobes are below -25 dB and the cross polarization is below -22 dB across a bandwidth of 140 GHz. We note that the cross-polarizations measured will be upper limits, limited by the performance of the polarizing grid. These results demonstrate that our horn fabrication technology is effective into the scientifically important high end of the sub-mm wavelength range, with a bandwidth sufficient to cover the entire atmospheric window centered at 660 GHz.

VI. New 4-Section Broadband Designs

The horns in both the 2-horn and 37-horn arrays described above have two flare-angle discontinuities near the throat of the horn, i.e., the horn consists of three conical sections. The horns

Fig. 16. The 700 GHz drilled horn prototype.

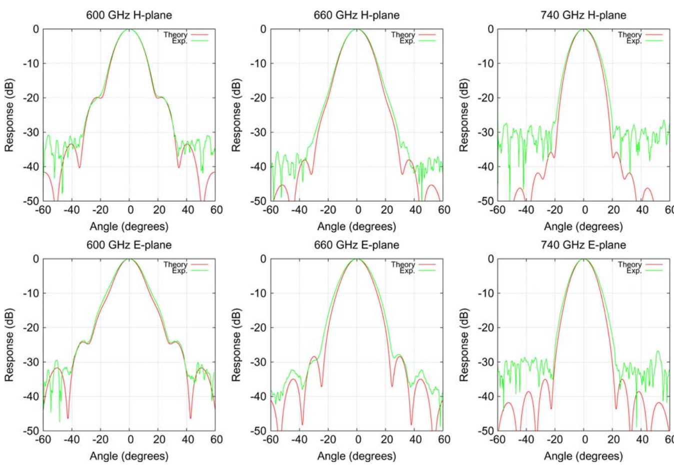

Fig. 17. Experimental and theoretical H and E plane beam patterns measured for the 700 GHz prototype horn, measured between 600 and 740 GHz. Top: H-plane, Bottom: E-plane.

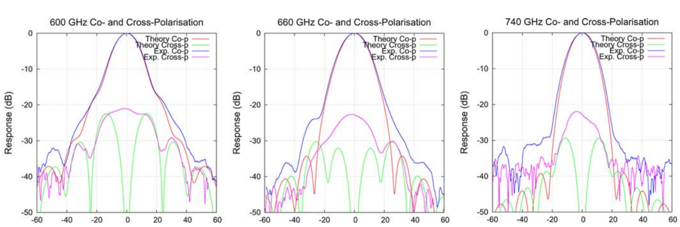

Fig. 18. Experimental and theoretical co-polar and cross-polar beam patterns measured for the 700 GHz prototype horn, measured between 600 and 740 GHz.

perform well over a bandwidth of around 20%. Since fabricating these horns we have designed, using the genetic algorithm optimization software, horns with more flare-angle discontinuities optimized over a greater target bandwidth. These software simulations have been run using the parallelized version of our horn software across 24 CPU cores. We have produced some new designs with good expected performance, including the 700 GHz 4-section design illustrated in Fig. 19, which has an increased fractional bandwidth of 25%. We now intend to have horn cutting tools with this profile made in order to fabricate and test some prototypes of these extended bandwidth horns.

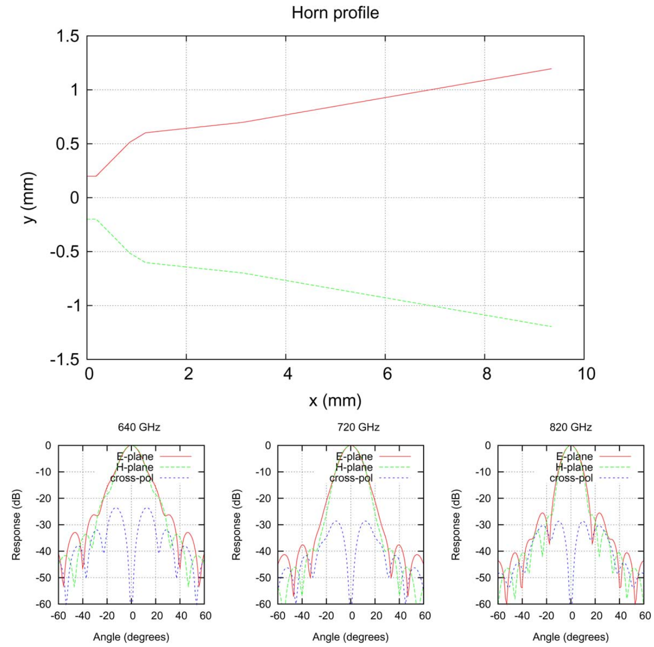

Fig. 19. Top: Profile of a new horn design designed with our GA software for extended bandwidth. Bottom: Simulated beam patterns for this horn design. The fractional bandwidth illustrated is 25%.

VII. Conclusion

We have described multiple flare-angle smooth-walled horns, designed using a genetic algorithm, that are simple and inexpensive to fabricate. Previously reported measurements with single horns and two-horn arrays have demonstrated the promise of our new fabrication technique using drilling with a shaped machine tool. The suitability of these horns for use in large format focal plane arrays has now been demonstrated by fabricating and testing a complete 37-horn prototype array for use at 230 GHz. Horns fabricated and tested at 700 GHz show that the technology scales well to shorter wavelengths. Our future development work will consist of performing a thorough analysis of the machining tolerances required to fabricate these horns at a given wavelength, as well as the design and testing of new broader bandwidth designs incorporating >4 flare-angle discontinuities. Increasing the number of flare angle discontinuities should enable us to design horns with a fractional bandwidth of 30% or more, making these types of horn very attractive for many astronomical applications.

Acknowledgment

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Bon Kok Tan, biography not available at the time of publication.

Ghassan Yassin, biography not available at the time of publication.

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