Measured performance of a 230 GHz prototype focal-plane feedhorn array made by direct drilling of smooth-walled horns

J. Leech*, B. K. Tan*, G.Yassin*, P. Kittara†, A. Jiralucksanawong† and S. Wangsuya †
*Department of Physics
University of Oxford
Email: jxl@astro.ox.ac.uk
†Department of Physics
Mahidol University.

***Abstract*—We present the first, complete 230 GHz feedhorn array manufactured by direct drilling of smooth–walled horns into a single plate of aluminium. The horn design process, based on a genetic algorithm, is described and the fabrication process, via direct drilling using shaped drill bits, is presented. We present cross coupling and beam pattern measurements of a close–packed pair of the smooth–walled horns fabricated in a single block of aluminium. We also present a prototype 37 horn array, again fabricated by drilling into a single block. Our measurements show that our designs and fabrication techniques will be robust when applied to large focal arrays of horns consisting of hundreds or thousands of feedhorns. We expect our smooth–walled horn designs and novel manufacturing techniques will offer an attractive, low-cost alternate to traditional horn arrays consisting of electroformed corrugated horns.**

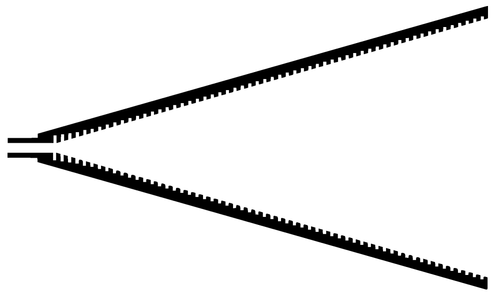

Fig. 1. The cross-section of a corrugated horn.

I. Introduction

High quality feed horns for astronomical telescopes are usually *corrugated horns*, where the hybrid HE_{11} is made to propagate by fabricating many $\sim \lambda/4$ corrugations along the interior of the horns (Figure 1). While these horns offer excellent beam patterns with high circularity and low cross polarisations over wide ($\sim$ 50%) bandwidths, they suffer from the disadvantage of being time consuming and expensive to manufacture, particularly as the wavelength decreases into the submillimetre regime. Corrugated horns are usually manufactured by micromachining a mandrel which is then electroplated before the mandrel is dissolved in a process known as *electroforming*. This process is time-consuming and expensive and individual submillimetre horns made in this way can cost of order of 1000 USD each. This is not a problem when only a few horns are required, but for large format focal plane array receivers[1][2] requiring hundreds or thousands of horns, the cost of the feed horns themselves can become a large fraction of the entire cost of the instrument.

In this paper, we describe the design of smooth-walled feed horns which use discontinuities in flare angle near the throat of the horn to excite a balance of higher order modes which are then phased by choosing the length of the horn to give a uniform horn aperture illumination and hence a high quality far-field beam pattern. These horns are similar to Potter horns[3],[4], where a balance of TE_{11} and TM_{11} modes are excited by step or flare angle discontinuities near the throat. Traditionally, Potter horns have been difficult to design analytically since the throat discontinuities will in general excite a spectrum of higher order modes, which effect the aperture field distribution in complicated ways, especially as one moves away from the central design frequency. These higher order modes make it hard to produce broadband designs analytically and thus the problem suggests the use of numerical optimisation techniques. Here we use a combination of a *genetic algorithm*[5] and *modal matching*[6] to produce optimised broadband horn designs. We have previously reported the successful use of this technique to design Potter horns with both step and flare angle discontinuities[7].

The simplicity of the interior shape of our multi-flare angle horns means that they lend themselves well to novel fabrication techniques. In this paper we describe a “drilling” technique which uses a machine tool whose cutting edge is shaped to match the interior profile of the required horn. We present experimental beam pattern results measured for horns and horn arrays manufactured using this technique. We also measure the cross coupling between two horns and present new results from modelling these horns using the full 3D electromagnetic simulation package, Ansoft’s HFSS. Such HFSS modelling will be useful in understanding the effects of non-axisymmetric machining errors on the far–field beam patterns of the horns.

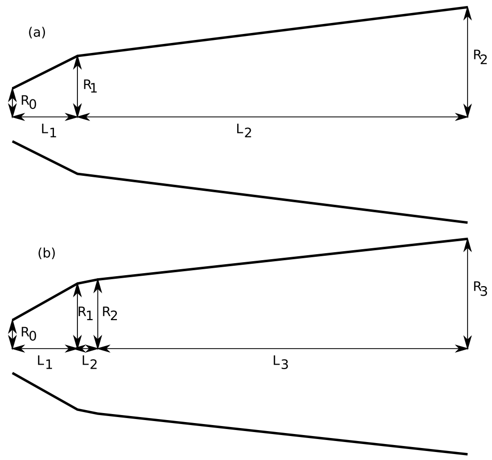

Fig. 2. A schematic of (a) a 2–section and (b) a 3–section smooth walled horn with one and two discontinuities in flare angle, respectively.

II. Design with a Genetic Algorithm

Genetic algorithms employ a "natural selection" process which is similar to biological evolution[5]. We begin by encoding the parameters which describe a certain horn design to form a "chromosome". We then construct a random set of horn designs and their corresponding chromosomes to form a population. We then evaluate a cost (or quality) function for each design to measure its fitness. Our cost function incorporates weighted measures of beam circularity and cross–polarisation, calculated using modal matching[6], across the required frequency band [7][8]. The chromosomes forming the fittest half of the population are then randomly paired to form parents which produce offspring to form a new generation. When the offspring are generated, crossover and mutation are used to introduce variation into the next generation. The whole process is then repeated with the new population. After many iterations, this evolutionary process yields an increasingly fitter population, with the optimised design being the fittest individual. Once the position of the global cost function minimum has been approximately found using the genetic algorithm, the precise position of the minimum can be quickly found using a downhill simplex technique.

A careful choice of the cost function is important for efficient optimisation with the GA. Our cost function is chosen to maximise far–field beam circularity and minimise the peak cross–polar level. A Potter horn with good beam circularity and low cross–polarisation will also tend to exhibit low sidelobe levels and high beam efficiency, so we have not included the latter parameters explicitly in the cost function. The return loss for smooth walled Potter horns is usually low and does not depend strongly on the horn profile, so we have not explicitly included this parameter in the cost function. Our 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 between the E and H–plane beamwidths at power level P dB and σ_P^{av} is the mean E and H–plane beamwidths at power level P dB. We calculate our final cost function across bandwidth $\sigma_f = f_U - f_L$ centred 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 the frequency dependent weighting factor. While this cost function works well for our purposes, it should be emphasized that other cost functions can be easily incorporated into the design software, depending on the design requirements.

We have developed a fully automated suite of horn design software using a genetic algorithm for design synthesis and modal matching for pattern computation, and produced designs with excellent predicted patterns over a bandwidth of up to 20%. We have also successfully parallelized the code to run on multiple CPU Beowulf clusters using MPI messaging for communication between tasks. We are using this code to optimise designs with a larger number of discontinuities, and hope to produce designs with bandwidths of up to 50%.

TABLE I
Geometrical parameters for the 3–section 230 GHz 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

III. A 3-section, 230 GHz design

Table I shows the optimised parameters for a horn with 3 conical sections (2 flare angle discontinuities, Fig. 2(b)). The input waveguide radius, R_0 and the aperture radius R_3 were fixed prior to the optimisation of the remaining five parameters. The FWHM beam width is 14.7 degrees at 230 GHz.

IV. Fabrication of single horns by electoforming and drilling

We have previously reported [9] the measured far-field beam patterns for electroformed horn prototypes with the design shown in Table I. We measured these beam patterns directly the far–field using a vector network analyser as a direct detector. These measured patterns agreed well with the expected far field patterns calculated using modal matching. This agreement with theory for these prototype horns demonstrates that the horns work well when constructed with the close tolerances typically obtained with electroforming ($\sim 5\mu$m).

Figure 3 shows the shaped cutting tool we use for machining our drilled horns. The tool is made from high speed steel, and has the form of the horn described in Table I in its upper cutting edge. We used this tool to manufacture three

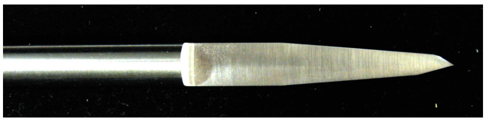

Fig. 3. The machine tool used for the fabrication of the drilled horn prototype.

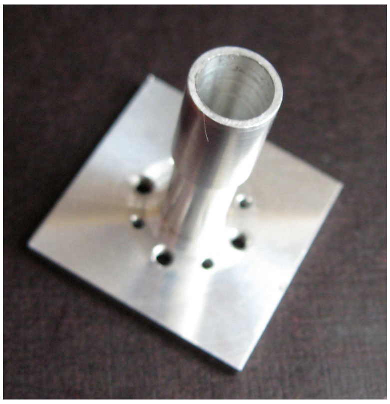

Fig. 4. A completed 230 GHz prototype drilled horn.

individual horns (Figure 4), measuring the beam patterns of two of the horns[10] while splitting the third horn to examine the machining quality of its interior (Figure 5). The measured beam patterns (presented in [10]) matched the expected beam patterns well, with good beam circularity, low sidelobes and low measured cross polar response (below -20dB across the 17% measured bandwidth). In particular each of the drilled horns gave a virtually identical beam patterns, an important result for the use of this horn construction method to make large format focal plane arrays. We observed some asymmetry (around 3 dB) in the sidelobe levels in each of the drilled horns. We expect that this might arise from non-axisymmetric machining errors, either in the positional or angular alignment of the axis of the input waveguide and horn itself. A close examination of Figure 5 shows that there is indeed a slight mismatch ($\sim 50\mu\mathrm{m}$) between the axis of the waveguide drill tool and horn tool.

V. Horn simulations in HFSS

While modal matching is well suited for the analysis of axisymmetric horns, it is less useful for analysing horns with

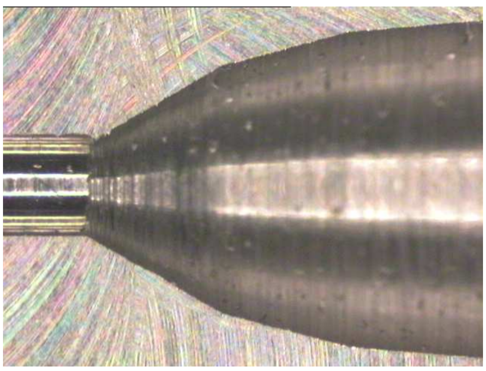

Fig. 5. The throat region of one half of the split drilled horn.

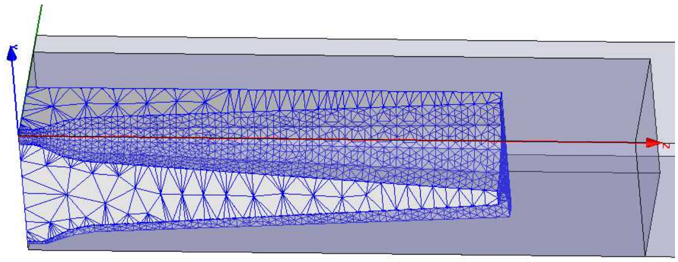

Fig. 6. A section of the HFSS model used to calculate the cross coupling between two horns, showing the mesh points used.

axial asymmetry, such as those that might arise from errors in the alignment of the horn and waveguide cutting tools. For circular waveguide sections with a common centre, the overlap integrals between waveguide modes can be expressed analytically, which is not the case when the waveguide sections are offset. In order to examine the effect of off-axis machining errors, as well as calculate the cross coupling between horns, we created a model of the 3-section horn described above in Ansoft's HFSS, a full electromagnetic simulation package. Unlike corrugated horns, which have many corrugations per wavelength, Potter-type horns with long, smooth phasing sections are much more amenable to analysis using HFSS, since these phasing sections do not require a large number of mesh points per wavelength for an accurate treatment. Nevertheless accurate HFSS models for these horns do require a relatively large number of mesh points and consequently a reasonably large amount of available RAM for analysis. The model whose meshing is shown in Figure 6 required 12 GB of RAM for analysis.

A comparison of the beam patterns calculated for a single 3–section horn using HFSS and modal matching are shown in Figures 7 and 8. The agreement down to the ~ -30 dB response level is seen to be very good indicating that HFSS is a promising tool for modelling this type of smooth walled horn. There are some slight disagreements in sidelobe levels around ~ -40 dB, which may be due to the automated HFSS meshing being slightly too coarse to capture the mode conversion at the discontinuities near the throat with sufficient accuracy. We are currently further investigating these slight differences between the HFSS and modal matching predicted patterns. Nevertheless, our results show that HFSS is a useful tool for investigating cross coupling between horns (discussed below) and also examining the effect of non-axisymmetric machining errors in tolerancing studies.

VI. A 2-horn array prototype

In order to investigate the suitability of our horns for use in an array, we produced a 2-horn array prototype with a horn centre separation of 8 mm, a packing density appropriate for focal plane arrays (Fig. 9). We measured the beam patterns for each horn in the array, using the far–field antenna test range described above. The results are shown in Figs. 10–13. The match between the theoretical patterns, calculated using modal matching, and the experimentally measured patterns is seen to

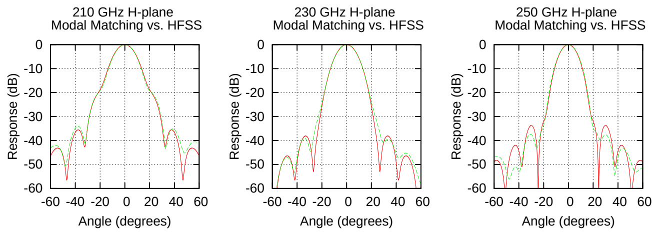

Fig. 7. A comparison of HFSS simulated H-plane beam patterns (green dashed line) and H-plane beam patterns calculated using modal matching (solid red line).

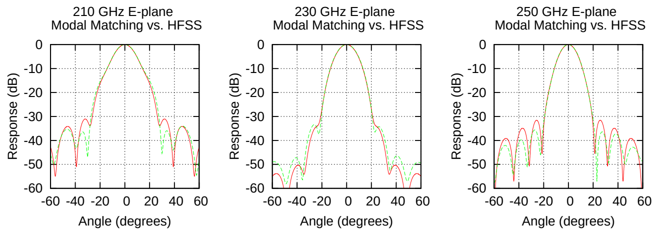

Fig. 8. A comparison of HFSS simulated E-plane beam patterns (green dashed line) and E-plane beam patterns calculated using modal matching (solid red line).

be very good. It should be noted that the slight asymmetries found in the patterns are very similar in magnitude for both horns and also that these asymmetries are oriented similarly for both horns. This indicates that they are very likely caused by a small axial misalignment, which would be of similar magnitude and orientation for both horns as they are machined in turn into a single plate.

We also used our two horn array prototype to measure the cross coupling between the two horns. We measured this coupling using a vector network analyser in an anechoic chamber, using an absorbing carbon loaded plastic cone in front of the two horn array. Our measured cross couplings should thus be viewed as upper limits, since some fraction of the coupling may be due to residual reflection from our absorbing cone. We also calculated the expected cross coupling for our horn array using HFSS. Figure 14 shows the measured and simulated cross coupling for our two horns across the operating bandwidth. The experimentally measured

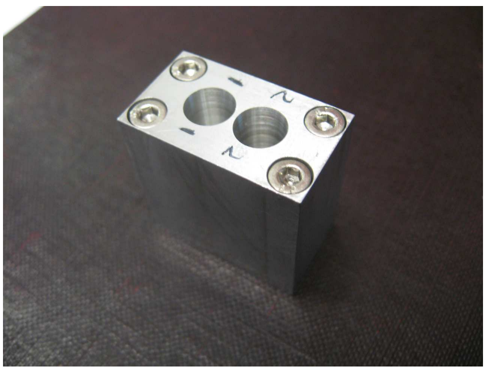

Fig. 9. The two horn array prototype, made by repeated drilling into a single block of aluminium.

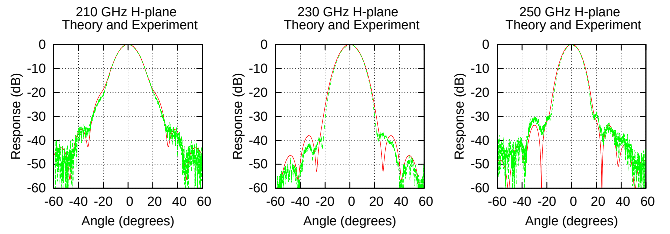

Fig. 10. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured H-plane beam patterns for horn No.1 of the 2 horn block.

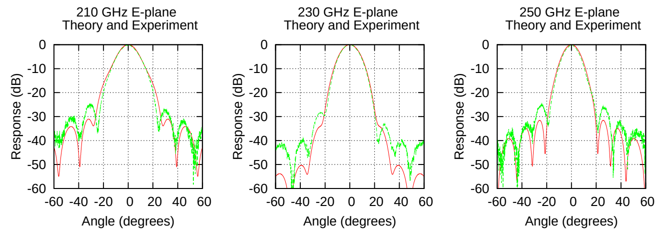

Fig. 11. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured E-plane beam patterns for horn No.1 of the 2 horn block.

cross coupling is below -70 dB across the band, an excellent result for the use of these horns in focal plane arrays. The predicted HFSS cross coupling are also low, but only agree with the experimentally determined cross coupling to within 10 dB or so. We are currently investigating this disagreement, which may be due to a lack of numerical precision within HFSS when the claculated S-matrices become very low (∼-60 dB). We are also investigating analytical approaches for calculating the cross coupling based on the methods presented

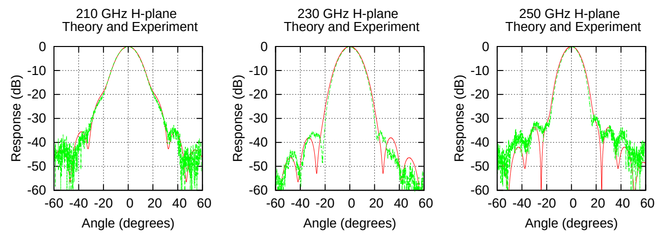

Fig. 12. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured H-plane beam patterns for horn No.2 of the 2 horn block.

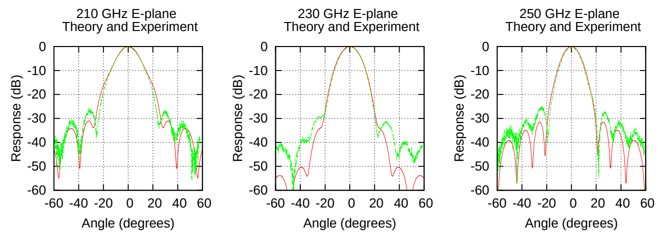

Fig. 13. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured E-plane beam patterns for horn No.2 of the 2 horn block.

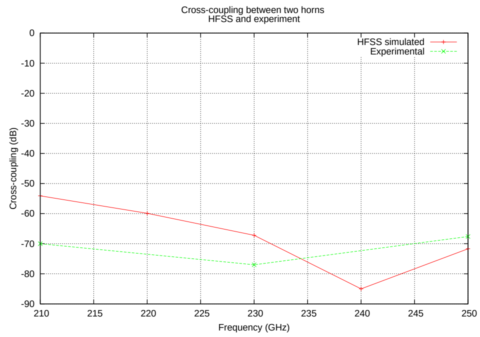

Fig. 14. Measured and HFSS simulated cross coupling between the two horns in the 2 horn prototype array.

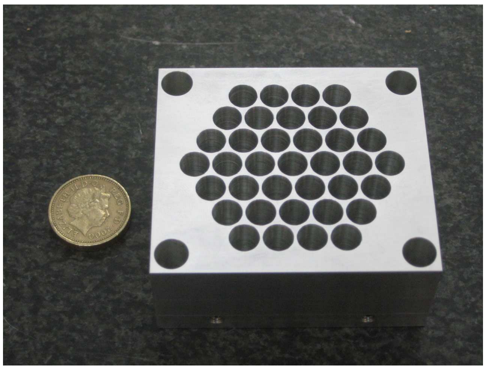

Fig. 15. The 37 horn array prototype, made by repeated drilling into a single block of aluminium.

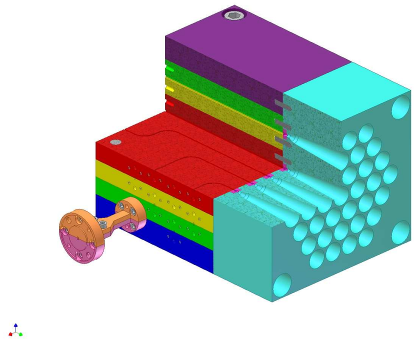

Fig. 16. The 37 horn array prototype showing a multiplate split block which enables power to be delivered to each of the horns from a split block waveguide at the side.

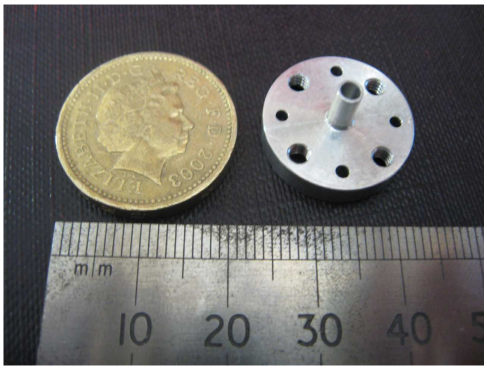

Fig. 17. The 700 GHz drilled horn prototype.

in [6].

VII. A 230 GHz, 37 Horn Array and 700 GHz Horn Prototypes

We have now constructed a prototype 37 horn hexagonally close packed horn array for use at 230 GHz (Figs. 15 and 16). We plan to measure the beam patterns for all of the individual horns in the array, as well as measuring the cross coupling between selected pairs of horns in the array. We are also extending our horn design to higher frequencies and have constructed an individual 700 GHz horn, with a design scaled from that presented above using the same drilling technique. We are currently constructing a custom far field test range with a 4K cooled bolometer detector (usable between 100 GHz – 1 THz) to test both the array and the 700 GHz horn prototype.

VIII. Conclusions and Further Work

We have developed a technique, based on a genetic algorithm and modal matching for designing smooth walled horns with several discontinuities in flare angle. We have verified our design technique by constructing 230 GHz prototype horns to a high tolerance using traditional electroforming and measuring the beam patterns using a far–field test range. The beam patterns agreed well with theory, showing excellent beam circularity and low cross polarisation over the measured bandwidth of around $\sim$ 17%. We are currently using our design software to design 4 section horn with the hope of extending the bandwidth to around 50%.

Our horns lend themselves well to the novel fabrication technique of repeated drilling using a shaped machine tool. We have constructed two separate horns using this technique, as well as a two horn close–packed array. The individual drilled horns and the horns in the 2-horn array exhibit high quality beam patterns, with excellent reproducibility between horns. We have seen slight asymmetries in these beam patterns which are likely to be due to small non-axisymmetric machining errors. We have successfully modelled our horns using the full 3D electromagnetic modelling package HFSS, which we intend to use to arrive at well understood target tolerances for the angular and positional alignment of the waveguide and horn drilling tools.

We have measured the cross-coupling of the close packed horns in the 2 horn prototype array and have found this to be below -68 dB across the operating bandwidth. We are also investigating the use HFSS and analytical techniques to characterise the expected cross coupling of close packed horns.

We have constructed a prototype 230 GHz, 37 horn close packed horn array by repeated drilling into a single aluminium plate, which we plan to test experimentally in the near future. We have also made a 700 GHz drilled horn, which we will test shortly. We are currently exploring the commercialization of this technology, including our design software, design methodology and horn fabrication techniques in collaboration with ISIS Innovation Ltd., the Oxford University technology transfer company.

ACKNOWLEDGMENTS

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