The experimental demonstration of a low-cost 37-horn focal-plane array consisting of smooth-walled multiple flare-angle horns fabricated by direct drilling

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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 aluminium 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 extending this technology to THz frequencies.

I. Introduction

The construction of high quality feed horns for mm and sub-mm 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 smooth-walled horns that offer performance similar to corrugated horns, but which are much easier to construct at short wavelengths. Large format focal-plane arrays, consisting of many hundreds or even thousands of horns will be essential for maximising the mapping speeds of large single dish telescopes for sub-mm astronomy. Thus the rapid and inexpensive fabrication of large numbers of horns is a critical requirement.

Much recent work [1], [2] has focussed on using the modal matching technique [7] to calculate the far-field beam patterns for horns which are then optimised using a suitable automated algorithm. The authors of this paper have previously reported using a genetic algorithm (GA) to design Potter horns with a single step or flare-angle discontinuity (Fig. 1 (a)) [3]. We then generalised 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.

The horns we describe in this paper were designed using a genetic algorithm [8], which mimics the process of natural selection to perform an optimisation by minimising a *cost function*. We have outlined our algorithm and its implementation in detail in [3]–[6]. For our purposes, we chose a simple cost function that is minimised for horns having a high beam circularity and low cross-polarisation [3]. Other cost functions could be used with the same GA, selecting 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. The software can run on single desktop PCs or on multiple CPU Beowulf clusters.

A 230 GHz horn with 2 flare-angle discontinuities (Fig. 1 (b)), designed using the GA with a FWHM beamwidth of 14.6 degrees and a 20% bandwidth is described in [6]. The horn has the following dimensions (in mm): $R_0 = 0.62$, $R_1 = 1.486$, $R_2 = 1.812$, $R_3 = 3.6524$, $L_1 = 1.479$, $L_2 = 1.212$, $L_3 = 24.0$ (Fig. 1 (b)). The theoretical far-field beam patterns, calculated using modal matching, are shown in Fig. 2.

II. 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 aluminium block using a machine tool (Fig. 1, Bottom) whose cutting edge has been manufactured with the shape of the required interior horn profile. In previous work [4]–[6], we have successfully manufactured and experimentally tested several individual horns using this technique at 230 GHz. In

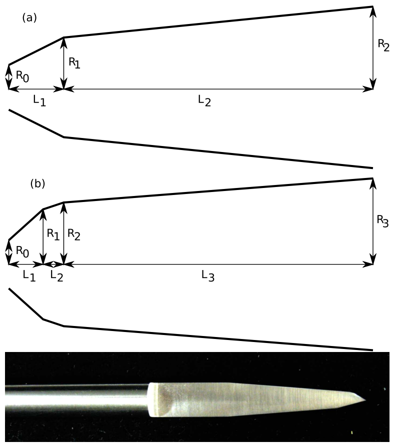

Fig. 1. Top: A schematic diagram of (a) 2-section and (b) 3-section multiple flare-angle horns. Bottom: The high speed steel machine tool used for the fabrication of the drilled horn prototype.

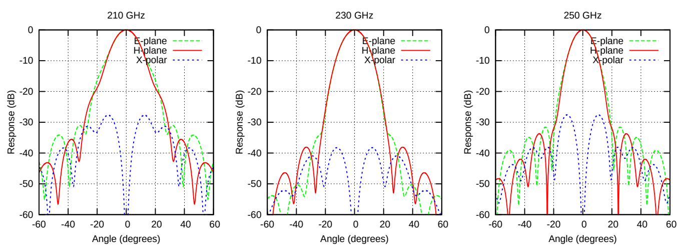

Fig. 2. Theoretical beam patterns (E plane, H-plane and cross-polarisation) calculated using modal matching.

particular, we compared the beam patterns for horns made using conventional electroforming and horns made using the new drilling technique. In both cases the measured beam patterns agreed well with theory with low sidelobes and cross polarisation between 210-250 GHz (20% bandwidth), with little difference between patterns for different horns, validating our new fabrication technique [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 aluminium block. Using a vector network analyser 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 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 and again found good agreement with the beam patterns calculated using modal matching, with each horn giving very similar beam patterns.

III. 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

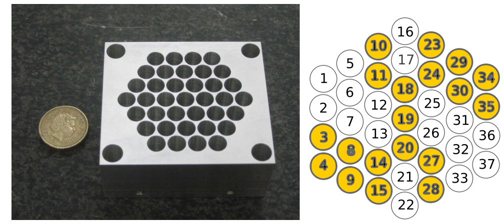

Fig. 3. Left: The 37-horn array prototype, made by repeated drilling into a single block of aluminium. Right: Schematic of the horn array highlighting the sample of 19 horns tested.

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 aluminium plate (Fig. 3, Left). 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 aluminium plate within the milling machine to ensure good alignment with the axes of the horn and the waveguide machining tools.

After construction of our 37-horn array prototype 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. The subset of horns chosen for testing (Fig. 3, Right) was spread across the whole array, enabling us to look for any trends in beam pattern behaviour which might arise from differences in machining tolerances across the array. The experimentally measured beam patterns for a representative sample of 9 of the 19 horns tested are shown in Fig. 4. 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 (horn Nos. 15 & 27 in Fig. 4). 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 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.

IV. 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 centre of 700 GHz ($\lambda = 429\,\mu$m). We fabricated three individual horn prototypes, identical to those described above, but scaled by a factor of 0.329 to give

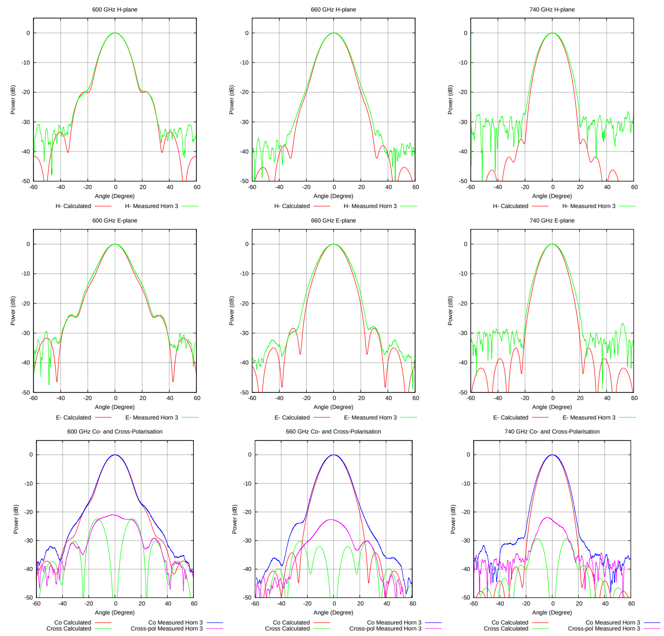

Fig. 5. Experimental and theoretical beam patterns measured for the 700 GHz prototype horn, measured between 600 and 740 GHz. Top: H-plane, Middle: E-plane, Bottom: co-polar and cross polar.

a central frequency of 700 GHz. The cutting tool for horns at these frequencies becomes much smaller, with a maximum radius of 1.2 mm, set by the required aperture of the horn.

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. 5) [9]. The co-polar and cross-polar patterns were measured using a terahertz polarising 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 polarisation is below -22 dB across a bandwidth of 140 GHz. We note that the cross polarisations measured will be upper limits, limited by the performance of the polarising 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 centred at 660 GHz.

V. 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 perform well over a bandwidth of around 20%. Since fabricating these horns we have designed, using the genetic algorithm optimisation software, horns with more flare-angle discontinuities optimised over a greater target bandwidth. These software simulations have been run using the parallelised version of our horn software across 24 CPU cores. We have produced some new designs with good expected performance, including a 700 GHz 4-section design 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.

VI. Conclusion and further work

We have described multiple flare-angle smooth-walled horns, designed using a genetic algorithm, that are simple and inexpensive to fabricate using direct drilling. 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.

Acknowledgment

This work was supported by an STFC follow-on fund grant and by the Keck Institute for Space Studies, at the California Institute of Technology. We thank Bertrand Thomas, Manju Henry, Jeanne Treuttel and M.L. Oldfield at the Rutherford Appleton Laboratories for their help in making beam pattern measurements for the single and dual horn prototypes. We are pursuing the commercialisation of this technology with ISIS Innovation Ltd, the technology transfer company of the University of Oxford.

References

[1] C. Granet, G. L. James, R. Bolton, and G. Moorey, "A smooth-walled spline-profile horn as an alternative to the corrugated horn for wide band millimeter-wave applications," *IEEE Trans. Antenna Propagat.*, vol. 52(3), pp. 848–854, 2004.

[2] L. Zeng, C. L. Bennet, D. T. Chuss, and E. J. Wollack, "A low cross-polarization smooth-walled horn with improved bandwidth," *IEEE Trans. Antenna Propagat.*, vol. 58(4), pp. 1383–1387, 2010.

[3] P. Kittara, A. Jiralucksanawong, G. Yassin, S. Wangsuya, and J. Leech, "The design of Potter horns for THz applications using a genetic algorithm," *International Journal of Infrared and Millimeter Waves*, vol. 28, no. 12, Dec. 2007.

[4] J. Leech, G. Yassin, B. K. Tan, M. Tacon, P. Kittara, A. Jiralucksanawong, and W. S., "A new, simple method for fabricating high perfromance sub-mm focal plane arrays by direct machining using shaped drill bits," in *Proceedings of the 20th Int. Symposium Space Terahertz Technology, Charlottesville, VA, USA, 2009.*, 2009.

[5] J. Leech, B. K. Tan, G. Yassin, P. Kittara, A. Jiralucksanawong, and S. Wangsuya, "Measured performance of a 230 GHz prototype focal-plane feedhorn array made by direct drilling of smooth-walled horns," in *Proceedings of the 21st Int. Symposium Space Terahertz Technology, Oxford, U.K.*, 2010.

[6] J. Leech, B. K. Tan, G. Yassin, P. Kittara, S. Wangsuya, J. Treuttel, M. Henry, M. L. Oldfield, and P. G. Huggard, "Multiple flare-angle horn feeds for sub-mm astronomy and cosmic microwave background experiments," Astron. Astrophys., vol. 532, pp. A61+, Aug. 2011.

[7] A. D. Olver, P. J. B. Clarricoats, A. A. Kishk, and L. Shafai, *Microwave horns and feeds*. Bookcraft, Bath., 1994.

[8] R. Haupt and S. Haupt, *Practical Genetic Algorithms.* Wiley-Interscience Publication., 1998.

[9] B. K. Tan, J. Leech, G. Yassin, P. Kittara, M. Tacon, S. Wangsuya, and C. Groppi, "High Performance, easy-to-machine terahertz feed horns," Submitted to the Journal of Infrared, Millimeter and Terahertz waves, June 2011., 2011.

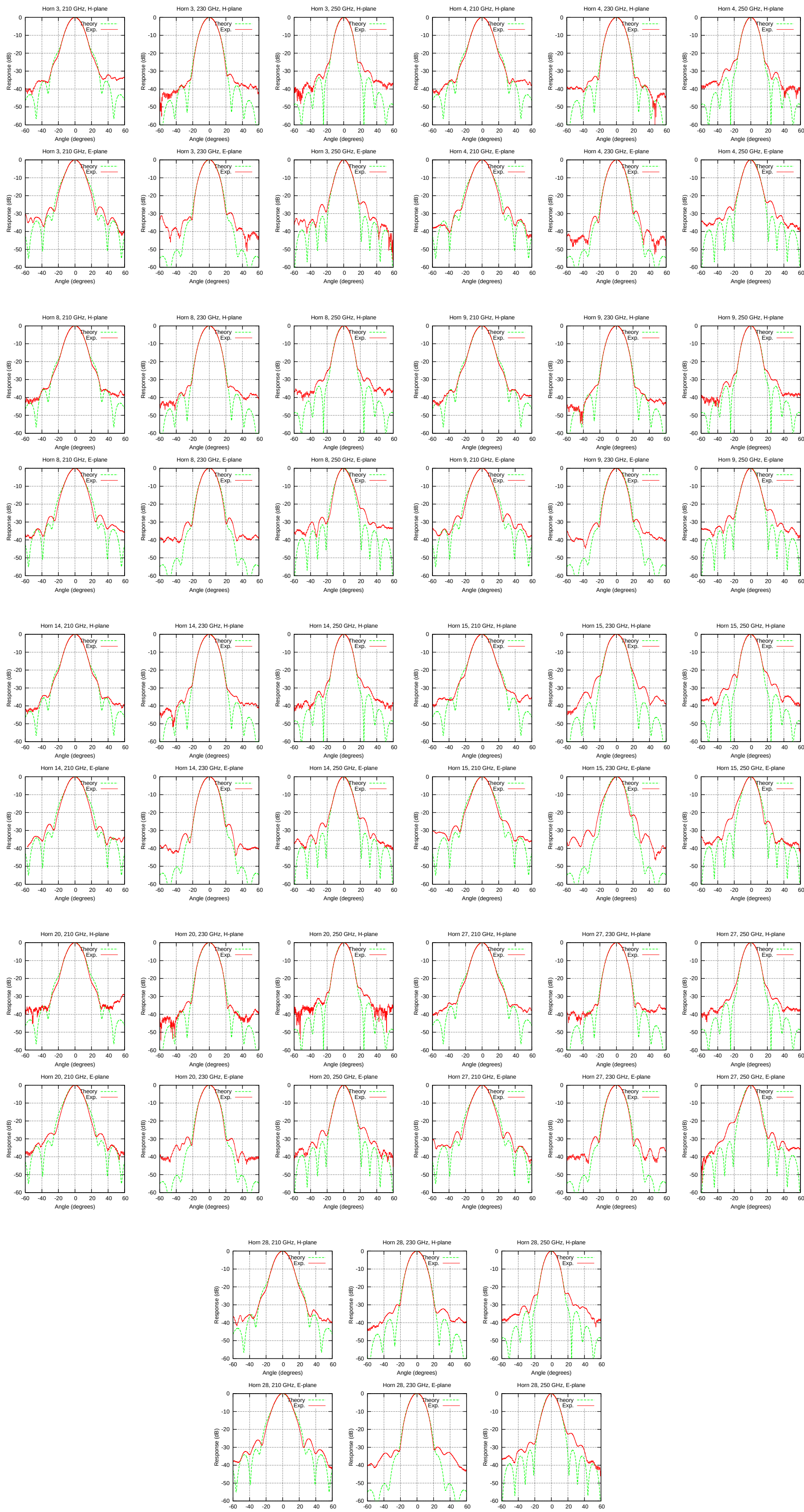

Fig. 4. Experimental and theoretical beam patterns for a sample of horns for the lower half of the array (Horn Nos. 3, 4, 8, 9, 14, 15, 20, 27 and 28). See Fig. 3 for their location within the array.