A new, simple method for fabricating high performance sub-mm focal plane arrays by direct machining using shaped drill bits.

J. Leech, G. Yassin, B.K. Tan, M. Tacon, P. Kittara, A. Jiralucksanawong and S. Wangsuya

***Abstract*—Large focal–plane arrays consisting of tens, hundreds or thousands of elements will dominate the next generation of sub–mm mapping instruments. While "CCD–style" filled–aperture bolometer arrays, such as SCUBA–2, are suitable for some mapping applications, heterodyne and sub–mm CMB polarisation mapping receivers, such as HARP–B and Clover, continue to consist of close packed arrays of feedhorns. Such feedhorn arrays are popular since they offer the high aperture efficiencies, low sidelobes, low stray light sensitivities and low–cross polarisations required for many astronomical applications. The problem of fabricating large numbers of high quality feeds at a low cost is becoming increasingly acute, and the cost of horn array fabrication is rapidly becoming a large fraction of the total instrument cost.**

In previous work, we have described novel multi–flare angled smooth–walled horns designed using a genetic algorithm. These horns have one or two flare–angle discontinuities and promise to be much easier to machine than corrugated horns at sub–mm wavelengths and yet offer similar radiation patterns. We have previously measured very good beam patterns for electroformed prototypes of these horns across a 17% bandwidth at 230 GHz.

In this paper, we describe our fabrication process for these horns by direct machining into a block of aluminium using shaped drill bits. This is a new fabrication technique and is very rapid compared to the electroforming or direct machining of corrugated horns. We describe the construction of prototype 230 GHz horns using this technique and present experimentally measured beam patterns. We also present photographs of a split prototype horn and discuss the overall machining quality achieved.

***Index Terms*—Antenna array feeds, Genetic algorithms, Horn antennas, Reflector antenna feeds.**

I. INTRODUCTION

The ability to rapidly map large areas of the sky to a high sensitivity is of prime importance for many scientific goals at mm and sub–mm wavelengths [1], [2]. The scientific productivity of all–sky surveys, Galactic plane surveys, and cosmic microwave background mapping all increasingly depend on integrating larger numbers of individual feed horns into the telescope's focal plane. The next generation of telescopes will incorporate hundreds or thousands of horns feeding ultra–sensitive detectors into focal plane array receivers. Therefore, the ability to manufacture large numbers of high quality telescope feed horns rapidly, reliably and at a manageable cost is vitally important.

Traditional corrugated horns have many $\sim 1/4$ wavelength deep azimuthal grooves (corrugations) along their interiors. These are the usual choice for sub–mm telescope feed horns and give excellent beam patterns over bandwidths of up to 50%. Unfortunately, to obtain this performance, several corrugations per wavelength are required, so these horns become more difficult and expensive to fabricate at increasingly smaller wavelengths. For the next generation of large format focal–plane arrays, with many hundreds or thousands of such horns, the cost of the corrugated horns alone can be a significant fraction ($\sim$ 50%) of the entire cost of the complete receiver.

A much simpler horn design is the Potter horn [3],[4] which uses either a step or angular discontinuity to excite a combination of TE_{11} and TM_{11} modes to give a close to uniform plane polarised field at the horn aperture. In the far field, this results in sidelobe cancellation and low–cross polarisation in the horn radiation pattern. The size of the discontinuity is carefully chosen to excite the required amplitude ($\sim$16%) of the TM_{11} mode with respect to the incident TE_{11} mode. The length of the rest of the horn is then chosen to ensure that these two modes arrive at the aperture in phase. The conventional analytical analysis of Potter horns assumed only TE_{11} and TM_{11} modes propogate to the horn aperture. In reality, however, higher order modes will also be excited by the discontinuity, which can carry energy to the horn aperture. To successfully account for these modes, the numerical technique of modal matching[5] is commonly used to propogate these higher order modes to the horn aperture. This analysis method can be used to accurately calculate far–field patterns for lossless horns with a rectangular or cylindrical geometry.

While modal matching can calculate far–field patterns accurately given a horn geometry, predicting the horn geometry that will yield optimum performance over a required bandwidth is not straighforward. The performance depends in a complicated way on details of the excitation and phasing of modes higher than TE_{11} and TM_{11}. The design of a horn is thus well suited to numerical optimisation (minimisation) techniques, where the horn parameters are varied and the quality of the resulting beam pattern, calculated using modal matching, is evaluated using a suitable cost (or quality) function. We have previously reported [6] [7] our use of a genetic algorithm, followed by a simplex technique, to perform horn optimisation. We have had considerable success in designing horns with one flare angle discontinuity (2–section, Fig. 1(a)) and two flare angle

---

J. Leech, G. Yassin, B.K. Tan and M. Tacon are with the Astrophysics group, Department of Physics, University of Oxford, UK, (email: jxl@astro.ox.ac.uk).

P. Kittara, A. Jiralucksanawong, and S. Wangsuya are with Physics Department, Mahidol University, Bangkok, Thailand.

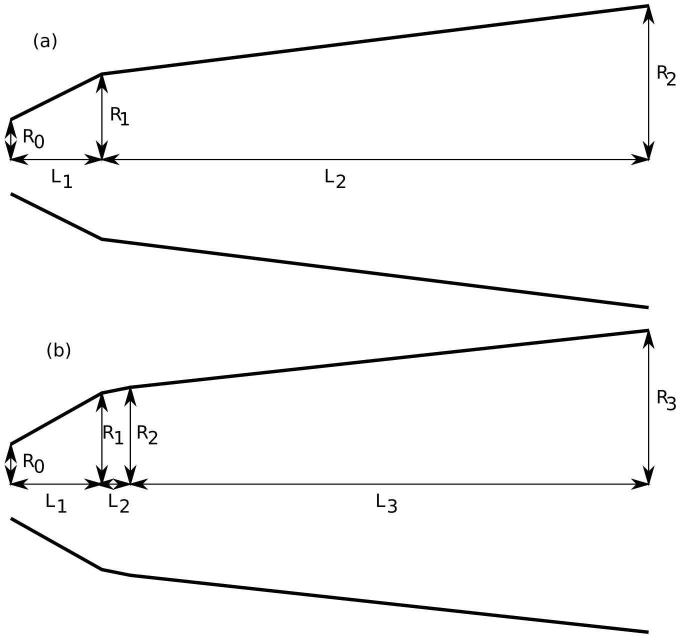

Fig. 1. A schematic of (a) a 2–section and (b) a 3–section smooth walled horn with one and two discontinuities in flare angle, respectively.

discontinuities (3–section, Fig. 1(b)). We have also constructed a prototype 3–section horn using traditional electroforming. The experimental beam pattern measurements of this horn showed good agreement with theory, validating our design procedure.

One attraction of the relatively simple geometries of these smooth–walled horns is the fact that they readily lend themselves to much simpler fabrication techniques compared to corrugated horns, which are usually made by electroforming. In this paper, we describe our fabrication of 3–section 230 GHz prototype horns by direct drilling into a block of aluminium. We have been developing this technique with the aim of rapidly contructing large arrays of horns by simply repeatedly drilling into a single plate of aluminium. We present photographs and measurements of the interiors of these horns, showing the overall surface quality and feature sharpness. Finally, we present experimental beam patterns for our prototype horns and outline our plans to constuct a 37 horn prototype array.

II. HORN DESIGN USING A GENETIC ALGORITHM

Genetic algorithms employ a “natural selection” process which is similar to biological evolution[8]. 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[5], across the required frequency band [6],[7]. 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 optmisation 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 explicity 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 pararameter in the cost funcion. Our cost function, at single frequency f may be written as

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

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

III. PERFORMANCE OF AN ELECTROFORMED 230 GHZ PROTOTYPE HORN

In order to verify the efficacy of the design technique described above, we had a prototype horn made commercially using traditional electroforming. This prototype horn was designed for a centre frequency of 230 GHz and had 3 conical sections (2–flare angle discontinuities, Fig. 1(a)). The dimensions for this horn are given in Table I. We chose

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

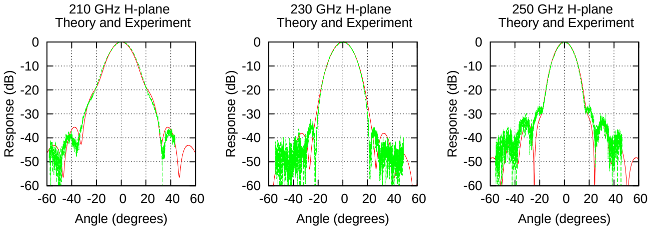

Fig. 2. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured H–plane beam patterns, for the electroformed prototype.

to fabricate this prototype using electroforming to enable a precise realisation of the horn design enabling verification the expected beam patterns in the absence of significant manufacturing errors. We have reported the experimentally measured the beam patterns of these horns previously [9][1] and we reproduce them here (Figs. 2 and 3). Agreement of the experimental beam patterns with theoretical expectation was seen to be very good, confirming the performance of our designs in the absence of significant manufacturing errors. The experimental copolar and crosspolar beam patterns (Fig. 4), show a low cross polarisation $<$-27 dB across the measured 17% fractional bandwidth.

IV. HORN FABRICATION BY DRILLING

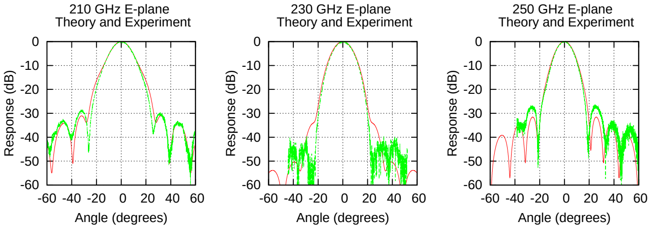

Fig. 3. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured E–plane beam patterns, for the electroformed prototype.

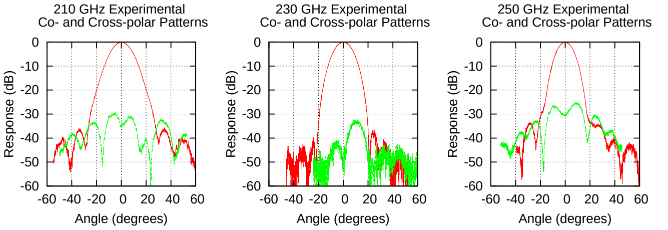

Fig. 4. Experimental co–polar and cross–polar beam patterns, measured for the electroformed prototype.

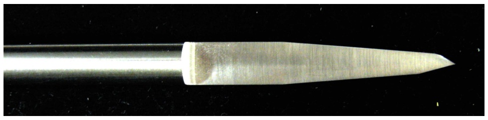

Fig. 5. The machine tool used for the fabrication of the drilled horn prototype.

By measuring the beam patterns for an electroformed prototype horn, we had a suitable benchmark with which to compare our horns manufactured using our experimental direct drilling technique. This method is much faster and less expensive than electroforming or split block machining, and should lend itself well to the fabrication of large focal plane arrays by repeated drilling into a single aluminium block.

To demonstrate the technique, we had a high–speed steel tool (Fig. 5) produced with the required horn profile for our 230 GHz 3–section horn described above (Table I). We first machined an accurate aluminium cuboid which was bolted into our milling machine. We used our shaped tool to drill into the front side of the block, forming the horn interior and then drilled a cylindrical waveguide into the rear of the block using a standard reamer of an appropriate size. A standard UG/387 (modified) flange was then drilled into the rear of the block, and the block finally turned down on a lathe to give the finished horn (Fig. 6).

We produced three prototype horns by direct drilling, splitting one of the horns in half using a milling machine while retaining the other two for beam pattern measurements. We then examined the split horn under a microscope to examine the machining tolerance and accuracy of the interior finish. As can be seen from Fig. 7, the interior surface quality is quite smooth, with surface machining marks no larger than $\sim 10\mu$m. The flare angle discontinuities are also seen to be sharp and well defined, which is important since the spectrum of higher order modes generated at these discontinuities is expected to depend strongly upon their sharpness.

We also used the microscope to measure the aperture radius of the horn, this was found to be 3.652 mm, within 0.005 mm of the specification. This indicates that the drill bit was inserted to the correct depth with a high positional accuracy. A close examination of the throat region in Fig. 7 indicates that there may have been a slight mismatch between the axis of the waveguide drill and the waveguide of the horn drill by around $\sim 50\mu$m. The expected effects of such non–axisymetric errors are hard to model using modal–matching, which usually assumes that each waveguide segment shares a common axis to enable the use of analytical expressions for the waveguide mode overlap integrals. We are currently determining the likely accuracy and systematic errors in our microscope measurements and investigating the possibility

---

[1] This previous work also presents beam patterns measured for drilled horns – these should be disregarded as it was subsequently found that these horns were incorrectly fabricated with the correct 3–section horn aperture ($R_3 = 3.652$ mm) but with a tool for an older 2–section horn design.

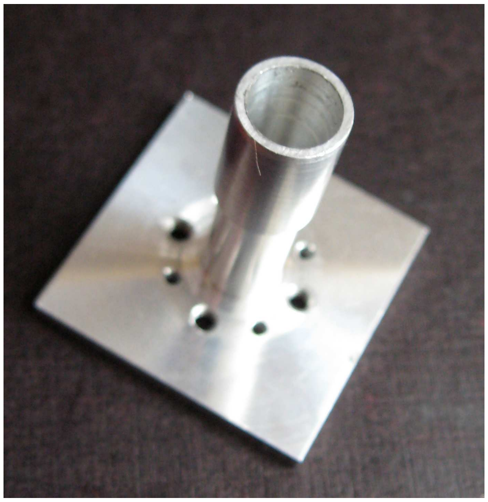

Fig. 6. The completed prototype drilled horn.

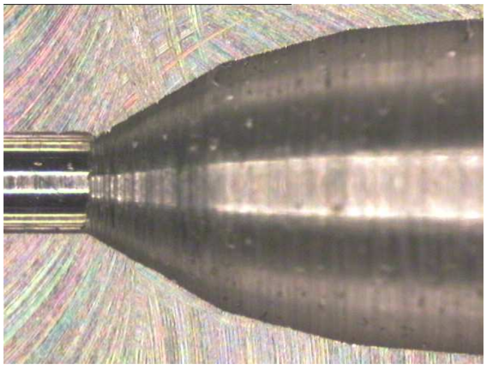

Fig. 7. The throat region one half of the split drilled horn.

of extending the usual modal matching technique to handle circular waveguide segments which have an offset axis.

V. DRILLED HORN BEAM PATTERNS

The far field radiation patterns for the drilled horns were measured directly in an anechoic chamber at the Rutherford Appleton Laboratory. We used an ABmm vector network analyser as a simple total power detector and rotated the horn under test with a motorised rotary table under computer control. Two identical prototype horns were used for transmission and reception, separated by 350 mm ($\sim 9D^2/\lambda$). We removed the effect of stray reflections and standing waves by careful positioning of Eccosorb RF absorber, and we were confident that we successfully eliminated stray power pickup to within the dynamic range of our measurements, which was around 50 dB.

Figures 8 and 9 show a comparison with the experimental and theoretical beam patterns in the H–plane and E–plane respectively, for the drilled horn prototype No. 1. Figures 10 and 11 show the corresponding patterns for drilled horn prototype No. 2. One notices immediately that the experimental beam patterns obtained from horn No. 1 and horn No. 2 are essentially identical, an important result which shows that the manufacturing tolerances between drilled horns on a large array are unlikely to be significantly different.

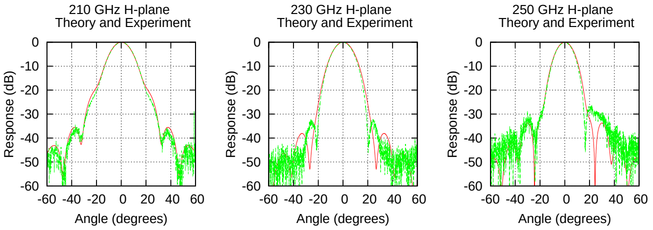

Fig. 8. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured H–plane beam patterns, for the drilled horn, prototype No.1.

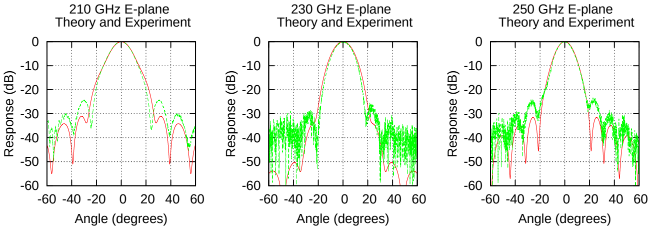

Fig. 9. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured E–plane beam patterns, for the drilled horn, prototype No. 1.

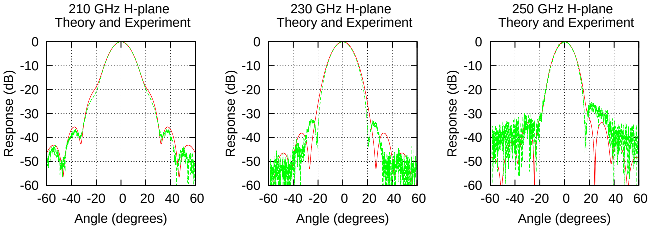

Fig. 10. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured H–plane beam patterns, for the drilled horn, prototype No. 2.

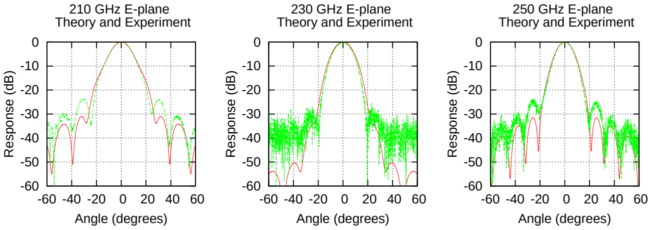

Fig. 11. A comparison with theoretical beam patterns calculated using modal matching and the experimentally measured E–plane beam patterns, for the drilled horn, prototype No. 2.

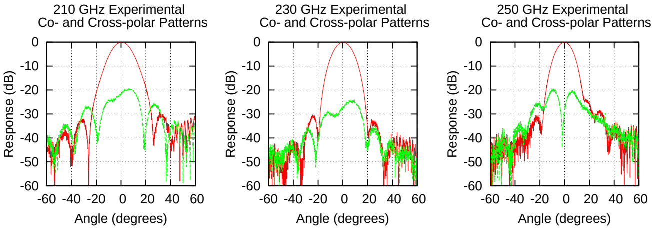

Fig. 12. Experimental co-polar and cross-polar beam patterns, measured for the drilled horn prototype No. 1.

Overall, the experimental beam patterns for the drilled horns show a good match to the theoretical expectations but this match is not quite as good as that found for the electroformed horns (Figs. 2 and 3). Nevertheless, the beam patterns show clean main beams, with none of the flattening of the beam at the centre of the patterns which often occurs when a horn becomes very overmoded. The positions of the sidelobes agree reasonably well with theory for the H–plane patterns, but are around +5 dB higher than expected in the E–plane patterns. Nevertheless, all sidelobes are below 25 dB across the measured fractional bandwidth of 17%. Beam circularity, as exhibited by the difference in main–beam width between the E and H–planes, is also very good over the band. An interesting feature is the fact that both the E and H–plane main–beam widths at 230 GHz are somewhat narrower than theory at 230 GHz, yet match theory quite well at 210 and 250 GHz. We also note that the first sidelobe in the H–plane at 250 GHz exhibits a slight asymmetry, with the right hand sidelobe being around 5 dB higher than the left for both prototype horns. The experimental co–polar and cross–polar beam patterns measured for the drilled horn prototype No. 1 are shown in Fig. 12. The cross polar levels are somewhat higher than measured for the electroformed prototype (Fig. 4), but remain below -20 dB across the measured fractional bandwidth of 17%.

VI. CONCLUSIONS AND FURTHER WORK

We have demonstrated that one can make smooth–walled multi–flare angle feed horns with good performance by using a novel direct drilling technique. The beam circularity and symmetry of the horns' far–field patterns are good and sidelobe levels are below -25 dB across a fractional bandwidth of 17%. The beam patterns obtained from two prototype drilled horns are essentially identical, a result which is very promising for the development of this technique to construct repeatable large format focal plane arrays by repeated drilling.

The beam patterns for our prototype drilled horns have been shown to be not quite as good as those obtained when the same horn design is constructed using traditional electroforming. We plan to obtain a deeper understanding of this discrepancy by making precision measurements of the interiors of the horns' profiles microscopically and then modelling the recovered horn geometries using the modal matching technique, perhaps extending the technique to handle non–axial geometries.

In parallel with this effort we intend to construct and test a 37 horn focal plane array of horns by repeated drilling into a single plate of aluminium. Our result so far show that this technique promises the rapid construction of large high performance arrays at a fraction of the cost of an equivalent array of corrugated horns. We are currently pursing the commercialisation of both our horn design software and our fabrication techniques, in collaboration with Isis Innovation, the technology transfer company of the University of Oxford.[2]

ACKNOWLEDGMENT

The authors would like to thank Henry Manju, Jeunne Treuttel, Peter Huggard and Matthew Oldfield for their assistance in setting up and using the ABmm Vector Network Analyser and 230 GHz antenna test range at the Rutherford Appleton Laboratories.

REFERENCES

[1] H. Smith, J. Buckle, R. Hills, G. Bell, J. Richer, E. Curtis, S. Withington, J. Leech, R. Williamson, W. Dent, P. Hastings, R. Redman, B. Wooff, K. Yeung, P. Friberg, C. Walther, R. Kackley, T. Jenness, R. Tilanus, J. Dempsey, M. Kroug, T. Zijlstra, T. M. Klapwijk, 2008, "HARP: a submillimetre heterodyne array receiver operating on the James Clerk Maxwell Telescope", Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol 7020.

[2] C. E. North, B. R. Johnson, P. A. R. Ade, M. D. Audley, C. Baines, R. A. Battye, M. L. Brown, P. Cabella, P. G. Calisse, A. D. Challinor, W. D. Duncan, P. G. Ferreira, W. K. Gear, D. Glowacka, D. J. Goldie, P. K. Grimes, M. Halpern, V. Haynes, G. C. Hilton, K. D. Irwin, M. E. Jones, A. N. Lasenby, P. J. Leahy, J. Leech, B. Maffei, P. Mauskopf, S. J. Melhuish, D. O'Dea, S. M. Parsley, L. Piccirillo, G. Pisano, C. D. Reintsema, G. Savini, R. Sudiwala, D. Sutton, A. C. Taylor, G. Teleberg, D. Titterington, V. Tsaneva, C. Tucker, R. Watson, S. Withington, G. Yassin and J. Zhang, 2008, "Detecting the B-mode Polarisation of the CMB with Clover". Proceedings of the XXXXIIIrd Rencontres de Moriond "Cosmology".

[3] Potter P., 1963. "A new horn antenna with suppressed sidelobes and equal beamwidths". Microwave J., 6, 71–78.

[4] Pickett H., Hardy J. & Farhoomand J., 1984. "Characterisation of a dual mode horn for submillimetre wavelengths". IEEE Trans. Microwave Theory Tech., MTT32(8), 936–937.

[5] Olver A., Clarricoats P., Kishk A. & Shafai A., 1994. "Microwave horns and feeds". Bookcraft, Bath.

[6] Yassin, G., Kittara, P., Jiralucksanawong, A., Wangsuya, S., Leech, J. and Jones, M.E. "A high performance horn for large format focal plane arrays", Proc. of the 18th International. Symposium Space Terahertz Technology, Pasadena, USA, 2007.

[7] Kittara, P., Jiralucksanawong, A., Wangsuya, S., Leech, J. and Yassin, G., 2007 "The design of potter horns for THz applications using a genetic algorithm" International Journal of Infrared and Millimeter Waves (2007) 28: pp.1103-1114.

[8] Haupt R.L. and Haupt S.E. (1998). "Practical genetic algorithms". Wiley-Interscience Publication.

[9] Kittara, P., Leech, J., Yassin, G., Tan, B. K., Jiralucksanawong, A. and Wangsuya, S., 2008 "The fabrication and testing of novel smooth-walled feed horns for focal plane arrays" Proc. 19th International Symposium on Space Terahertz Technology.

---

[2] The horn designs disclosed in this paper are available for licensing. Please contact Isis Innovation Ltd, the to discuss commercialising this opportunity (innovation@isis.ox.ac.uk).