High performance smooth-walled feed horns for focal plane arrays

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***Abstract*— We describe the design and testing of an easy-to-machine smooth-walled horn which exhibits excellent beam circularity and low cross polarisation over a relatively large bandwidth. The design comprises three coaxial conical sections and two flare discontinuities joining the three sections together. The discontinuities generate appropriate higher order modes which combine to give a circular field distribution at the aperture. The positions and sizes of these discontinuities were calculated using a genetic algorithm. The horn was fabricated either by using the well known electroforming method or simply by a drill tool, shaped into the horn profile, and a standard mill. The measured radiation patterns or the electroformed horns show good excellent circularity and agree well with the calculated curves. They also show that the three-section horn has a substantially wider bandwidth than the conventional Potter horn. Preliminary measurements of the drilled horns patterns are also shown and compared with theory.**

I. Introduction

A high-quality astronomical feed usually employs a conical corrugated horn. The presence of azimuthal corrugations in the horn presents isotropic surface boundary conditions to the electric and magnets field on the wall, resulting in the propagation of a “hybrid mode”. This configuration produces a circular beam with low cross polarization and sidelobes over a substantial fractional bandwidth, which is required for many applications. Corrugated horns, however, require the fabrication of several corrugations per wavelength, which can be technically complicated and expensive at THz frequencies.

The Potter horn [1] has many of the desired properties of a corrugated horn and yet is much simpler to construct. Conventionally, it consists of a conical horn with a single step discontinuity at the horn throat whose dimensions are chosen in order to excite the TM_{11} mode at carefully selected amplitude (~16%) with respect to the amplitude of the incident TE_{11} mode. The “dual-mode” is then made to propagate through a cylindrical “phasing section” to make the two modes arrive at the horn aperture in phase. This results in sidelobe cancellation and low cross polarization in the horn radiation pattern. A simplified version of the Potter horn without the phasing section was suggested in [2] and used in a 700 GHz finline mixer [3].

A well known disadvantage of the Potter horn however is the relatively narrow bandwidth of approximately 10%.

The corrugated horn increases the bandwidth substantially, by adding many more equally spaced, identical discontinuities along the horn. An optimized location and magnitude of theses discontinuities however is likely to reduce the large number of corrugation to only a few.

An alternative method of exciting the TM_{11} mode is a sudden change in the horn flare angle as shown in Fig. 1. Here, a second section is formed by changing the flare angle when the horn radius is r_1, at an axial distance L_1 from the throat of the horn [4].

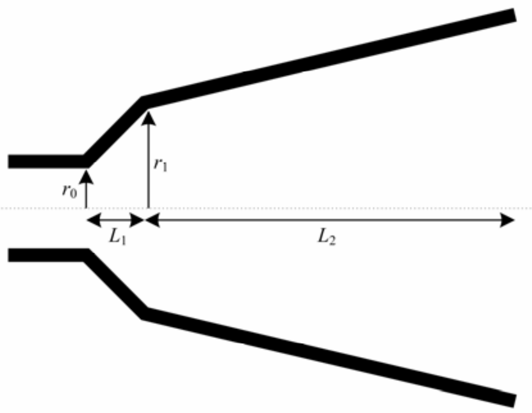

Fig. 1. Geometry of the dual-mode two-section horn with a flare angle discontinuity. r_0 is the radius of the circular waveguide. r_1 and L_1 are the radius and the length of the first conical section. L_2 is the length of the second conical section.

Here again, the bandwidth is also limited to a similar percentage of 10% since the correct phasing of the two mode modes can only be achieved over a small fraction of the wavelength. We have found however that adding a one more flare discontinuity doubles the bandwidth and we expect that a bandwidth comparable to a corrugated horn can be achieved by generating a few (~5) flare discontinuities at optimized locations along the horn.

We have previously reported [5], [6] success in optimising the design of both types of Potter horn using a technique based on genetic algorithm. We have developed a complete design software package which combines the modal matching method [7] with genetic algorithm [8] and downhill simplex optimisation routines. This allows design of easy to fabricated Potter horns with multiple discontinuities in the horn profile.

In this paper, we present simulations and measured radiation patterns for 230 GHz prototype horns with 3 flare angles. Some of the prototype horns were fabricated using a drill tool, shaped into the horn profile, and a standard mill. For benchmark comparison, we fabricated two prototype horns using electroforming. The measured radiation patterns have good beam circularity and agree with the calculated curves. They also show that this three-section horn has a substantially wider bandwidth than a conventional Pickett-Potter horn. The beam circularity is good to almost -30 dB. The peaks of the cross-polarization levels were below -30 dB for a fractional bandwidth of 10% near the centre frequency, and below -25 dB for 20% bandwidth.

II. Horn design using a Genetic Algorithm

The positions and sizes of the flare-angle discontinuities for broad bandwidth operation of Potter horns have traditionally been only obtained approximately since it was based on analytical computation, assuming that only the TE_{11} and TM_{11} propagate to the aperture. Our approach has been to use a genetic algorithm to determine the optimal positions and sizes of these discontinuities. This procedure has already been reported [5], hence it will only be mentioned very briefly. We calculate the horn patterns, using modal matching, for a "population" of initially random horn designs, and compute the fitness of each design from the quality parameter of the pattern. Then, by using crossover and mutation techniques upon a "chromosome" which is constructed from the horn parameters, we produce a new generation of horn designs from the fittest members of the old population. After using the genetic algorithm to locate the approximate position of the quality function global minimum, we then optimise the design using a traditional downhill simplex method.

Details of the optimization criteria are given in [5,6]. In brief, the fitness of an individual is inversely proportional to the 'cost function'. This cost function measures the deviation of the beam pattern from a desired pattern. In our design, the cost function of an individual at a selected frequency is calculated from two factors: the beam circularity and cross-polarization level. The beam circularity and cross polarization target level were stringent. The peak cross polarization was requested to be less than -30 dB. Higher cross-polarisation and lower beam circularity produce higher values of the cost function and hence lower fitness. These two factors are computed at different frequencies across the required band with a frequency step of 0.02 times the centre frequency. The total cost function is then calculated from the sum, with a Gaussian weight, of the products of the two factors for all frequencies. The Gaussian weight of the total cost functions forces the beam circularity near the centre frequency to be better than near the edges.

The problem constraints include specifying the frequency band edges and the central frequency, in addition to the geometry parameters such as the waveguide radius and the horn flare angle. The problem variables include the radii and lengths of the three sections. The length of each section is constrained to be between from $0.1\lambda_0$ to $30\lambda_0$, and the radii are constrained to be between $0.1\lambda_0$ and the size of the aperture.

III. A 230 GHz 3-Section Horn Design

In Table I we show the dimensions of the prototype horn designed using the above method. The centre frequency of the design is 230 GHz with a wavelength λ_0 = 1.204 mm. The horn was designed to have a beamwidth of around 15 degrees for testing. This beamwidth is largely determined by the horn aperture, so both the horn aperture and initial waveguide size were fixed to $0.467\lambda_0$ and $5.600\lambda_0$ before optimizing the other horn dimensions using the genetic algorithm. The optimized dimensions and a schematic of the horn profile are shown in Table I and Fig. 2.

TABLE I

Dimensions of the Three-Section Horn

	Start radius	Length	End radius
Conical Section 1	$0.467\lambda_0$	$1.134\lambda_0$	$1.140\lambda_0$
Conical Section 2	$1.140\lambda_0$	$0.929\lambda_0$	$1.389\lambda_0$
Conical Section 3	$1.389\lambda_0$	$18.400\lambda_0$	$2.800\lambda_0$

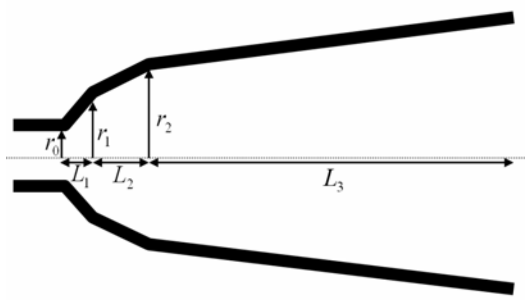

Fig. 2 Cross section of a three-section horn. r_0 is the radius of the circular waveguide. r_1 and L_1 are the radius and the length of the first conical

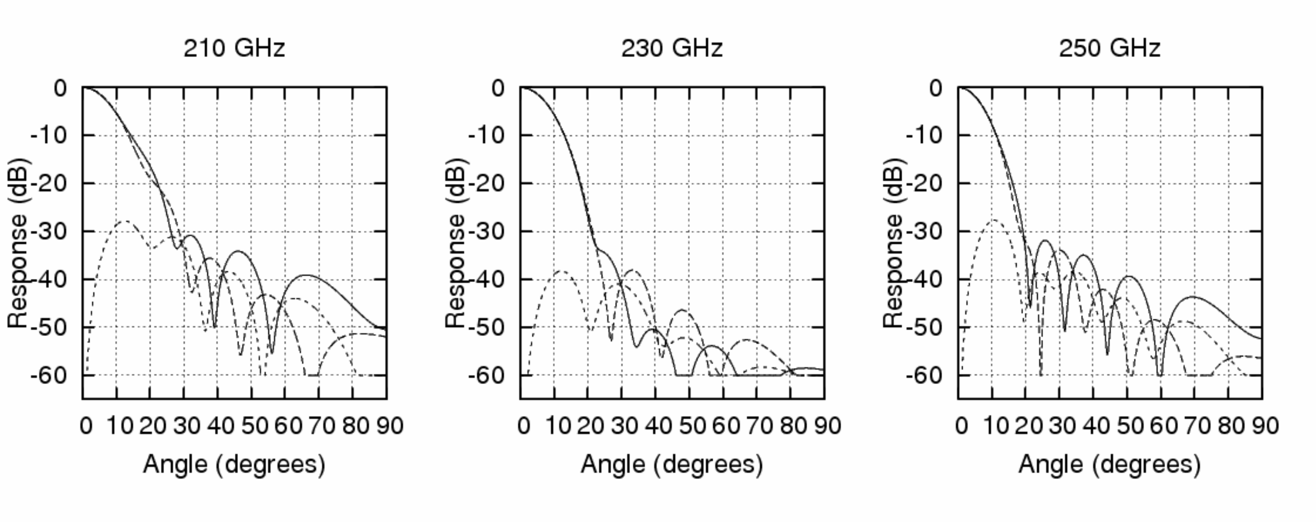

Fig. 3. Calculated radiation pattern for the three sections smooth-walled 230 GHz horn at 210 GHz (left), 230 GHz (middle) and 250 GHz (right).

section. r_2 and L_2 are the radius and the length of the second conical section. L_3 is the length of the third conical section.

IV. Computed Radiation Patterns

The radiation patterns at three frequencies, computed using our modal matching software are shown in Fig 3. Notice that the patterns are of excellent quality with low cross polarization. Near the centre frequency, the beam remains circular down to -30 dB. In Fig. 4 we show the plot of the maximum cross-polarization levels at various frequencies. The cross polarization of below -30 dB are obtained over a bandwidth of 10%. In fact, a cross polarization level below -25 dB was maintained across a bandwidth of 20% which is remarkably broad.

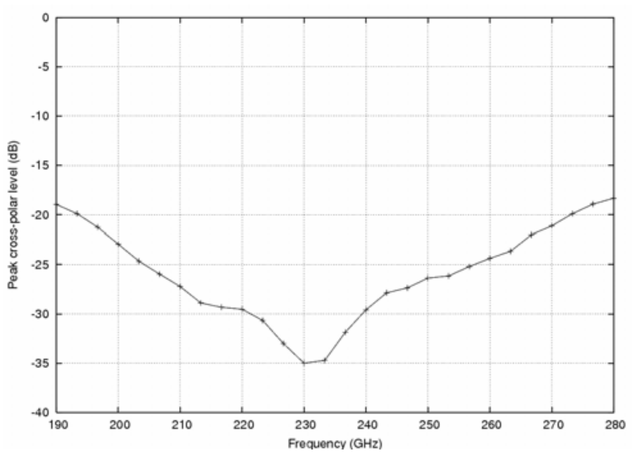

Fig. 4 Peak cross-polarization level against frequency. The cross-polarization levels are below -30 dB for about 10% of the band, and below -25 dB for about 20% of the band.

V. Method of Prototype Fabrication

Many astronomical instruments, such as CLOVER [9] and EBEX [10] contain hundreds of horns and detectors in the focal plane arrays. It is therefore crucial that a fabrication technique is found to fabricate these horns cheaply. We are proposing to fabricate the array by drilling the horns into a block of aluminum using drill-bit tools that have the shape of the horn profile. We believe that this technique can be realized with a standard mill and a high-speed steel tool. Whence the method is optimized, it should be possible to reduce both the cost and the time of fabrication substantially.

Fig. 5 The tool used for machining the three-section, 230 GHz horn. The cutting edge along the top of the tool has the required shape of the horn profile

We have fabricated three sections horns at 230 GHz using both electroforming and drilling. To test the fabrication repeatability, we drilled several horns using the same tool, shown in Fig 5. For comparison, we fabricated two horns of the same design by electroforming. The tolerances on the dimensions of the electroformed horns are expected to be essentially perfect at this frequency, hence they could be used as benchmark. The aim of the tests was two fold: verification of the integrity of the design method by comparing the measured patterns of the electroformed horns with theory, and the drilling technology by comparing the drilled horns with those of the electroformed ones. Measured Radiation Patterns

A. *Experimental Setup*

Tests were conducted using the Rutherford Appleton Laboratory (RAL) ABmm vector network analyzer (VNA)

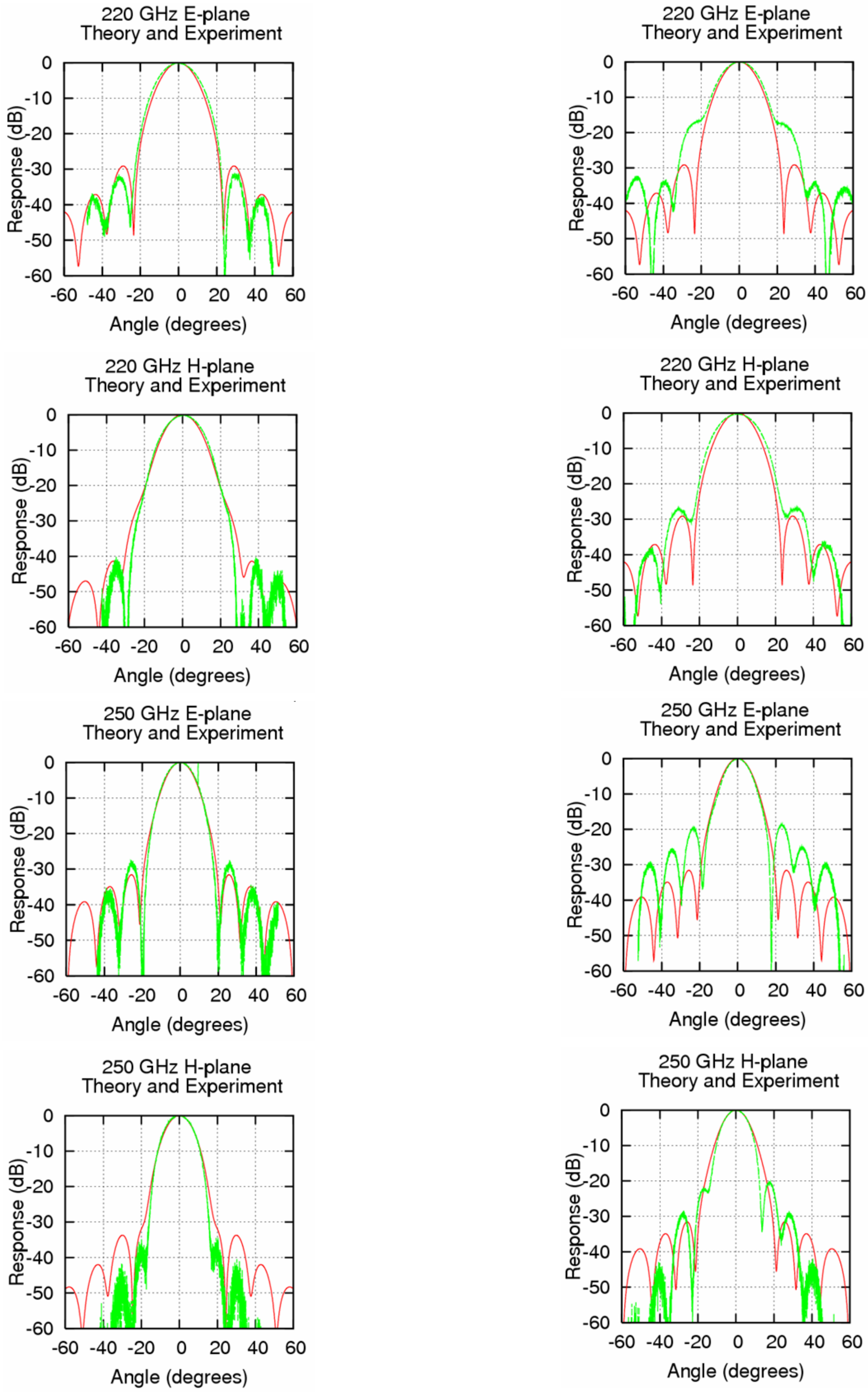

Fig. 6 Measured and calculated patterns of the electroformed horn (left column) and drilled horn (right column) at 220 GHz and 250 GHz. The measured pattern (green) of each plan is shown together with its corresponding calculated curve (red).

and a rotary scanner in an anechoic chamber to obtain direct far-field measurement of the beam patterns of. Two identical prototype horns were used for transmission and reception, separated by 350 mm (~ $9d^2/\lambda$). The transmitter horn was rotated by a stepper motor driving a computer controlled rotary table. By using the VNA as a simple total power detector, we were able to achieve a measurement dynamic range of 60 dB. We removed stray reflections and standing waves by the careful positioning RF absorber around the horns and the mounting brackets. The repeatability of the measured beam patterns shows that this arrangement was very satisfactory at 230 GHz.

B. Measured beam patterns

We measured the beam patterns of the two types of horn in the frequency range of 220- 250 GHz and the results are shown in Fig. 6. The measured patterns are compared with the calculated for both the E and H-planes.

The radiation patterns of the electroformed horn agree very well with the theory down to about -40 dB. They have very good beam circularity with sidelobe levels below -30 dB. This shows that the three-section design is correct and the tolerances are reasonable.

We have so far tested only one drilled horn out of seven fabricated. It can be seen that the radiation patterns of the drilled horns are not quite as good as their electroformed counterparts. In particular, sidelobes start to appear at about 5-10 dB higher than the predicted values. It is quite likely that that this effect is due to the fact that the machining tolerances achieved by the drilling technique are not quite sufficient to match the predicted behavior. Nonetheless, the patterns are symmetric which shows that the tool can be aligned with the waveguide accurately. We are currently investigating the effects of non-perfect machining accuracy on the far-field beam patterns using our modal matching simulation software and at the same time measuring the patterns of the rest of the drilled horns. We hope that this will provide an insight into the required tolerance and refining of the fabrication method.

CONCLUSION

We have presented the design and experimental results of three-section smoothed-wall horns with multiple flare discontinuity. Synthesis of the horn geometry is done using a software package which combines modal matching and the genetic algorithm. This design provides high performance feeds with good beam circularity, low cross polarization and low sidelobe levels. The bandwidth of the horn can be designed to suit the particular application. As an example, 20% useful bandwidth can be obtained for an application that requires cross-polarization level below -25 dB. If wider bandwidth is desired then a couple more flare discontinuities can be added to broadband the horn, with little impact on the fabrication complexity.

Fabrication of the present horn was done by electroforming and drilling using a tool that has the shape of the horn into a block of aluminium. A steel tool costing 75 pounds has demonstrated that several horns can be fabricated with the same tool. The radiation patterns of the electroformed horns agree well with the theoretical predictions, confirming the integrity of the design optimization method. First attempt of horn drilling is promising (good quality main beam) but the horn show higher sidelobes then predicted e indicating that the fabrication accuracy needs to be improved.

WE ARE CURRENTLY MEASURING THE CROSS-POLARIZATION OF THE HORNS AND ALSO PLANING TO TEST THE REMAINING DRILLED HORN. WE ARE ALSO DESIGNING HORNS WITH MORE SECTIONS TO INCREASE THE BANDWIDTH.

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