A High Performance Horn for Large Format Focal Plane Arrays

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We describe the design and performance of an easy to machine horn which exhibits excellent beam circularity and low cross polarisation over a relatively large bandwidth. No grooves are machined into the horn walls but, alternatively, flare angle discontinuities are generated along the horn profile. In other words, the horns will have several flare angles or sections instead of one. For example, if the horn consists of two flare angles, it could then be considered as a conventional Potter horn. As can be seen below, even with this simple design, excellent radiation patterns can be obtained over 15% bandwidth. The bandwidth could be further increased by adding more subsections with 30% bandwidth obtained when the profile is based on 4 sections. The operation of the horn is based on generating higher order modes at the correct amplitude ratio and phase with respect to the incident TE_{11} mode in the circular waveguide, which is achieved by accurate determination of the magnitude and location of the flare steps. This in turn yields a field distribution at the horn aperture that has low sidelobes and cross polarization in the radiation pattern.

A key component in the design package is the optimization software that searches for the correct magnitude and location of the flare discontinuities. We have generated a software package based on the combination of modal matching, genetic algorithm (GA) and simplex optimization. The genetic code is first used to locate the proximity of the global minimum. The set of parameters obtained are then used as a starting point for the simplex method, which refines the parameters to the required accuracy. We shall illustrate our method by showing radiation patterns using two and three step discontinuities and also patterns for a spline profiled horn based on work by other investigators who used different optimization techniques.

1. Introduction

High performance feeds are extensively used at millimetre and submillimetre wavelengths, in particular in astronomical instruments. Examples include the HARP array receiver on the James Clark Maxwell Telescope, the Atacama Large Millimetre Array (ALMA) and the newly emerging cosmic microwave background polarization experiments (CLOVER, EBEX and QUIET) [1], [2], [3]. All of these instrument projects intend to employ corrugated horns that offer excellent performance over a relatively large bandwidth. It is, however, evident that corrugated horns are time-consuming and expensive to fabricate, in particular when a large focal-plane array consisting of several hundred feeds is needed at submillimetre wavelengths. In this paper, we present the design of multi flare angled horns which are much easier to fabricate than corrugated horns. This type of horn provides an excellent option for many applications such as THz mixers and local

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oscillators, general purpose submillimetre telescope feeds and specialized CMB polarization experiments.

The principle of the new horn design may be considered as a generalisation of the Potter horn idea [4]. Conventionally, a Potter horn consisted of a conical horn with a single groove-step discontinuity at the horn throat whose dimensions were chosen in order to excite the TM_{11} mode at a carefully selected amplitude (~16%) with respect to the amplitude of the incident TE_{11} mode. This "dual-mode" was then made to propagate through a cylindrical "phasing section" to make the two modes arrive at the horn aperture in phase. The remarkable similarity in the sidelobe structure of the TE_{11} and TM_{11} modes resulted in sidelobe cancellations and a lowering of the cross polarization in the horn radiation pattern.

A simplified version of the conventional Potter horn was proposed by Pickett *et al*. [5]. The phasing section of the Potter horn is removed, resulting in a more compact and easier to machine horn. The phasing of the modes is now achieved during propagation through the flared horn section. In other words, the simplification is achieved by sacrificing one degree of freedom in choosing the horn dimensions.

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 start of the horn.

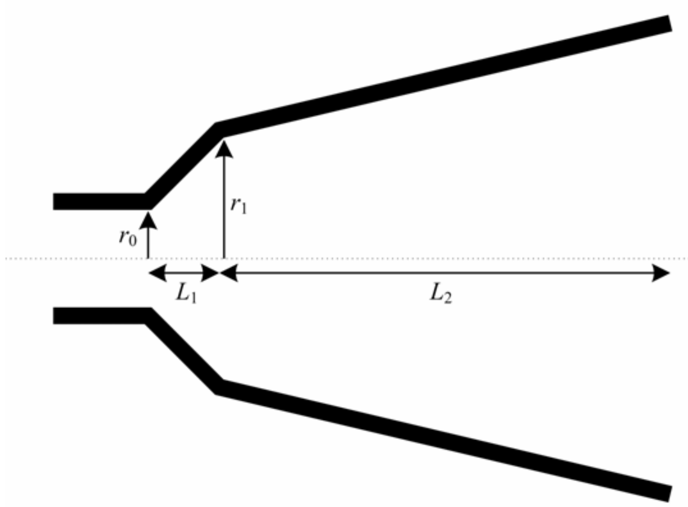


Figure 1: Geometry of the Potter horn with a flare angle discontinuity. r_0 is the radius of the circular waveguide. r_1 and L_1 are the radius and the length of the first conical section. r_2 and L_2 are the radius and length of the second conical section, respectively.

Although this method was reported previously [6], it was not thoroughly investigated or commonly used in conjunction with conical horns. Our simulations show that the pattern obtained with a flare-step potter horn is in fact superior to the pattern of a groove-step horn. The choice between the two types of horn could also depend on the method of fabrication. The availability of programmable lathes for precision machining makes the fabrication of the first type fairly straightforward, in particular if electroforming is used. If, on the other hand, the horn is machined from a split-block of metal then turning a single groove at the throat with a reasonably large flare angle is straightforward.

The conventional analysis of either type of Potter horn, which relied on an analytical method, assumed that only the TE_{11} and TM_{11} propagate to the horn aperture. This assumption, however, is not realistic, since higher order modes that are evanescent at the throat can later become oscillatory and carry energy to the aperture. Thus the analysis described in the original Potter horn papers cannot accurately predict the horn radiation patterns. Higher order modes can, however, be easily accounted for if the modal matching method [7, 8] is used to propagate the electromagnetic fields components numerically from the waveguide to the aperture. This method yields precise and fast converging solutions for the analysis of lossless horns with rectangular or cylindrical geometry.

Similarly, predicting the horn dimensions that yield optimum performance is not straightforward. Consequently, an optimization (minimization) technique is required to calculate the optimum horn parameters, for a required horn performance. In this paper, we shall describe a new technique of reliable and efficient minimization based on a genetic algorithm (GA) [9] combined with a downhill simplex technique. First the approximate position of the global minimum is found using the GA and then this is used as a starting point for the iterative simplex procedure which accurately locates the position of the minimum. The analysis is clearly not restricted to Potter horns but can be used to generate designs with a larger number of horn sections. Since our aim is to design easy to machine horns, we will mainly deal with flare rather the groove discontinuities.

2. Method of computation

2.1 The general scheme

The design method of the multi-flared angle horn is done by using a combination of analysis and synthesis packages. The analysis package is a modal matching routine that computes the radiation pattern and the electrical properties of a given horn geometry (e.g. cross-polarisation) and the synthesis package which consists of an optimisation routine that searches for a new improved horn design. We have written modal matching and genetic algorithm minimisation software and combined these into a single horn design package (***hornsynth***) with a graphical user interface.

Finding the optimum horn geometry that satisfies a pre-determined specification is done using a genetic algorithm (GA), which is a powerful computational method for solving optimization problems [10]. It employs a "natural selection" process which is similar to biological evolution. One usually begins by choosing a random set of parameters which form the *chromosomes.* A set of chromosomes is called a *population*. The *cost function* of the problem is then used to compute values corresponding to each chromosome (for example, the chromosome could be an array of the parameter set we want to optimise). Only half of the population, forming a subset $\{S_n\}$, comprising the *fittest* members (e.g. the ones that return the lowest values in the case of minimisation) is left to take part in forming the next generation while the "*weak*" members are discarded. The elected members of $\{S_n\}$ are then *paired* and allowed to produce *offspring* that form a new generation. The algorithm is motivated by the expectation that the new generation will be fitter than the old one and so this evolutionary process will eventually yield a solution consisting of the fittest population.

An important feature of the GA is that it avoids convergence to a local extremum by exploring the search space. However, searching for the final solution is very time consuming hence the GA is only used to find the global optimum. This output is then fed to a downhill simplex which is an efficient search iterative minimization algorithm for problems that do not have a very large number of variables.

2.2 Optimisation Criteria

The quality of the radiation pattern of a horn is normally characterised by several parameters, depending on the application. An antenna feed, for example, is expected to have good beam circularity (beamwidth independent on polarization), low cross polarization and sidelobes, good return loss and high beam efficiency, over a given bandwidth. Some of these properties are generally related. For example, good beam circularity is associated with low cross polarization level and high beam efficiency corresponds to low sidelobe level. However, considering that we are dealing with trade-offs between the quality of these parameters, we found it necessary to optimize several of them at the same time. Since the return loss of a smooth-walled horn is normally good we did not include it in the optimization parameters. Also, the beam efficiency was excluded since it requires a large number of time consuming integrations. We would like to emphasise, however, that different criteria can easily be incorporated into our software.

Based on the above discussion, we have chosen to optimize for beam circularity and cross polarization. The problem constraints included specifying the frequency band edges and the central frequency, in addition to geometry parameters, namely the waveguide radii at the flare steps and the value of the flare angles. These parameters were incorporated in the software using a quality function $\delta_f\ (P)$ and a weighting function $W_f(P)$ for a given frequency f where P is the power level in the radiation pattern. The quality function was defined as

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

where

P = power level in dB,
w_P = the absolute power, $(P = 10\log_{10} w_P)$,
X = peak power of the cross polar in dB,
w_X = absolute peak power in the cross polar, $(X = 10\log_{10} w_x)$,
σ_P^E = width of the E-plane at the P dB power level,
σ_P^H = width of the H-plane at the P dB power level,
σ_P = the difference between the widths at P dB, $\sigma_P = \left|\sigma_P^E - \sigma_P^H\right|$,
σ_P^{av} = the average width, $\sigma_P^{av} = \left(\frac{\sigma_P^E + \sigma_P^H}{2} \right)$.

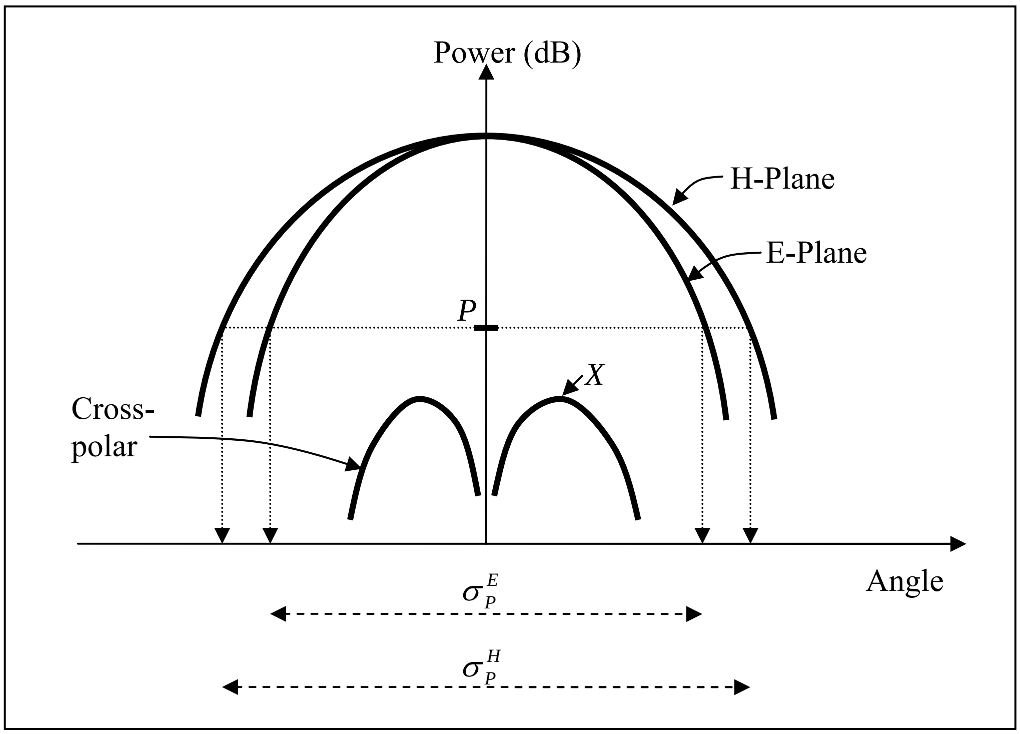


Figure 2: A sketch of radiation patterns and variables used in the quality function. When the cross-polarization is small and the beam is circular $\left(\sigma_P^E = \sigma_P^H\right)$, the quality function becomes small.

3. Computed radiation patterns

We start by simulating the radiation pattern of a dual flare angle (two section) horn that was designed using *hornsynth* optimisation. The centre frequency was chosen at 700 GHz and the parameters of the horn are given in Table 1. These parameters were then fed to the commercial software *corrug* in order to confirm the integrity of our design procedure. The beam patterns are shown in Fig. 3 – they exhibit excellent beam circularity and low cross polarisation levels over a bandwidth of 80 GHz. In fact the cross polarization level was approximately -30 dB across this bandwidth, reflecting our stringent criteria regarding cross polarization.

Initial waveguide radius, r_0	0.1752 mm
Length of the 1st conical section, L_1	0.7163 mm
Radius of the 1st conical section, r_1	0.6145 mm
Length of the 2nd conical section, L_2	11.256 mm
Aperture	1.500 mm

Table 1: The geometry of the two-angle horn with an aperture of 3.5 wavelengths. The dimensions are scaled to the centre frequency 700 GHz. See Fig. 1 for the description of each dimension. The beamwidth of this horn is 12.4 degrees

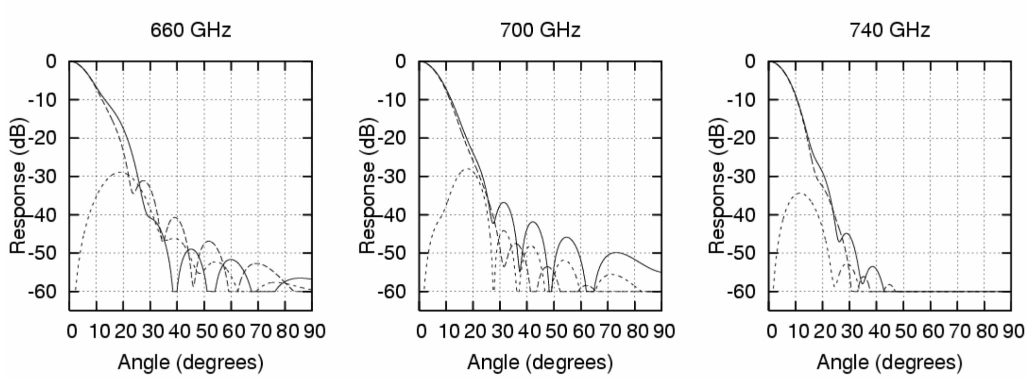
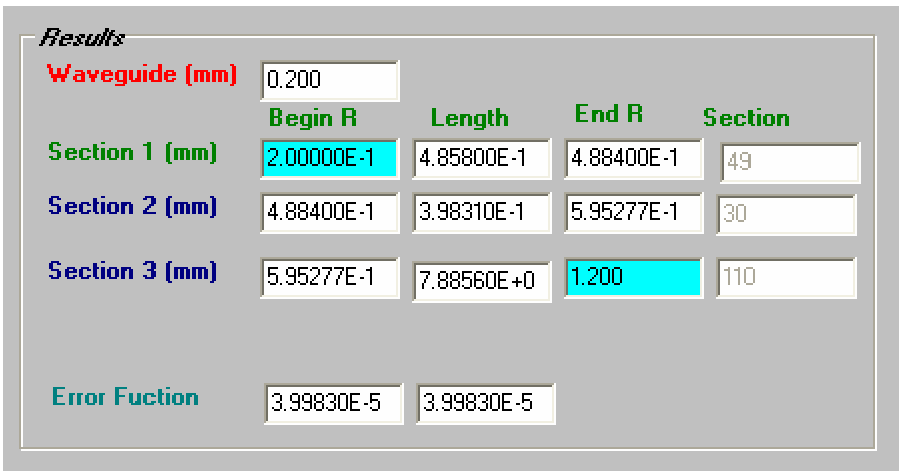


Figure 3: E-plane (solid line), H-plane (long dashes) and cross polar (short dashes) levels for the Potter horn consisting of two conical sections with a discontinuity in flare angle.

It is interesting to note that the radiation pattern obtained by a flare-step dual mode horn are significantly better than those obtained by the conventional groove-step Potter horn. This is because the ratio of the amplitudes TM_{11}/TE_{11} at the discontinuity varies much more slowly with frequency in the first case. Also it seems that the amplitude of the inevitably excited higher order modes, in particular the TE_{12}, is higher for the groove-step excitation.

The extension of the above ideas to a broadband design is clearly a multi-section horn, and perhaps to smooth the discontinuities into a profiled continuous curve if necessary. To this end we used hornsynth to generate a three-sectioned horn with the dimensions given in Table 2 and example radiation pattern given in Fig. 4.


Results

	Begin R	Length	End R	Section
Waveguide (mm)	0.200			
Section 1 (mm)	2.00000E-1	4.85800E-1	4.88400E-1	49
Section 2 (mm)	4.88400E-1	3.98310E-1	5.95277E-1	30
Section 3 (mm)	5.95277E-1	7.88560E+0	1.200	110
Error Fuction	3.99830E-5	3.99830E-5		

Table 2: Typical output of *hornsynth* showing the geometry of a three-section horn. The computed patterns are shown in Fig. 4.

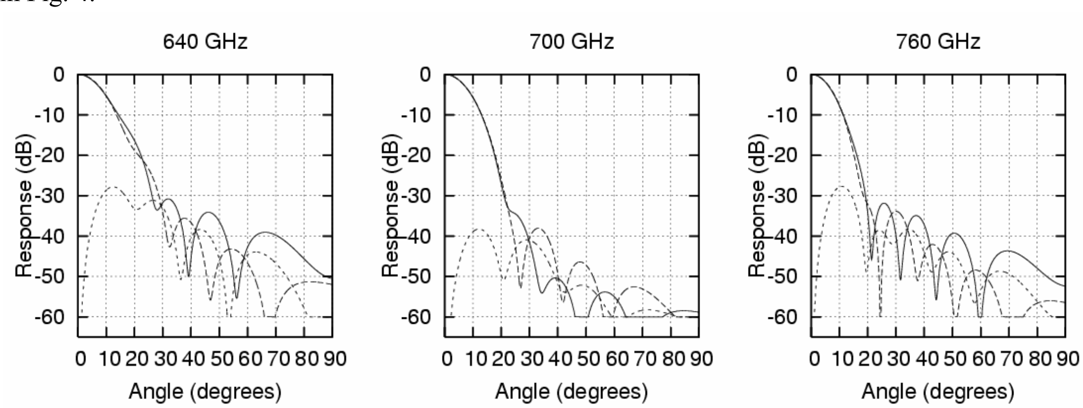


Figure 4: Radiation pattern for the three sections smooth-walled 700 GHz horn at 640 GHz (left), 700 GHz (middle) and 760 GHz (right).

Notice that excellent quality patterns with cross polarizations of below -30 dB are obtained over a bandwidth of 120 GHz. In fact, a cross polarization level below -25 dB was maintained across a bandwidth of 170 GHz which is remarkably broad, considering that only a three-section horn is used. Clearly, the bandwidth can be further increased by increasing the number of horn sections and we are expecting the bandwidth to exceed 30% for a 4-section horn.

From Fig. 4, it can also be seen that our patterns are diffraction limited with a beamwidth that is dependent on frequency. This feature may or may not be desirable depending on the application. For example, a telescope feed is usually designed to have high beam efficiency which is indeed given by our patterns. If on the other hand, a broad-band horn is required then this can also be obtained by imposing a higher flare angle to the second section. A broad band horn must have a phase error $\Delta > 0.4$ where

$$\Delta = \frac{r}{\lambda} \tan \frac{\vartheta_0}{2}$$

Where r and ϑ_0 are respectively the horn section radius and semiflare angle. In our case, the third section phase error is $\Delta \sim 0.1$ which yields a diffraction limited horn.

Finally it is instructive to compare our pattern with those obtained by Granet et al. [11], who generated a wide-band high performance horn by optimizing a spline-horn profile (Fig. 5).

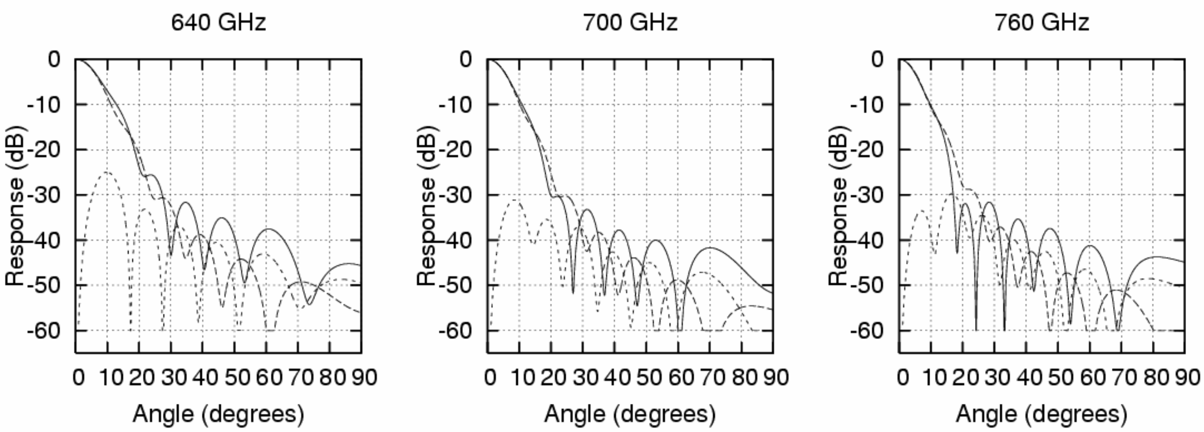


Figure 5: Radiation patterns of a 700 GHz spline horn computed using the method in [11].

The quality of the radiation pattern is similar in both cases with spline patterns being much less dependent on frequency and the three-sections pattern having better beam efficiency. The differences between the horns can clearly be seen by comparing their profiles given in Fig. 6. We would like to emphasize that the spline horn used 6-optimization radii while we only used three.

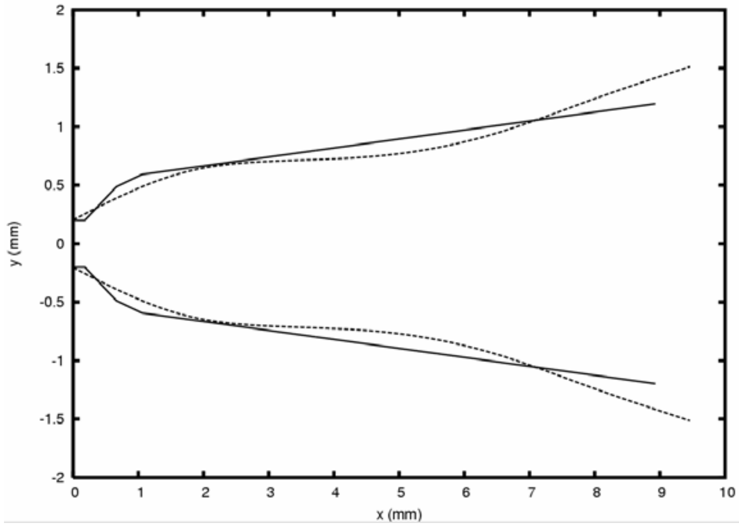


Figure 6: A comparison of the horn profiles for our 3-section horn and the horn reported in [11].

Finally, we present the computed return loss as a function of frequency for the three section horn (Fig. 7). As can be seen, the return loss is excellent (below -32 dB) across the operating bandwidth. The return loss shows less frequency dependence compared to a corrugated horn, since the return loss of a corrugated horn is determined by a $\sim \lambda/2$ deep groove at the horn throat.

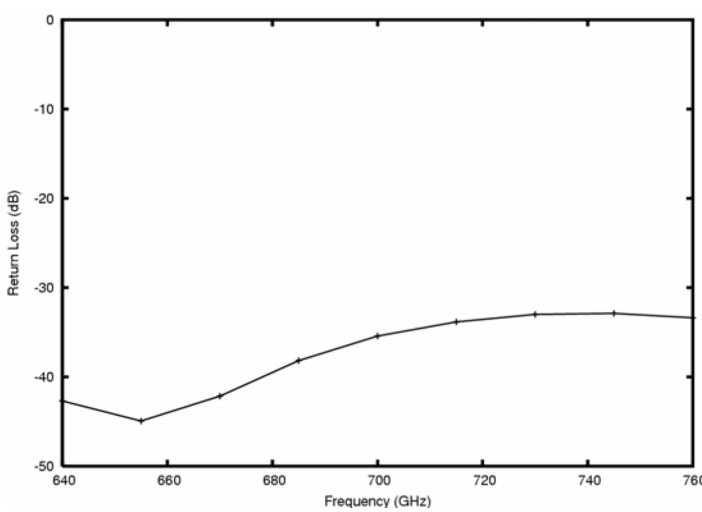


Figure 7: The computed return loss for the 3-section horn across the 640 to 760 GHz band.

4. Method of fabrication

Fabrication of smooth-walled horns is clearly easier than machining corrugated feeds. This becomes crucial at very high frequencies or one large arrays are required. For example, the focal plane arrays for millimetre or submillimetre wavelengths are now formed from horns that are fabricated individually. They are then mounted on metallic blocks that contain hundreds of detector channels. We are now proposing however to fabricate the whole array by drilling the horns into a block of aluminum using drill-bit tools that have the shape of the horn profile. Drilling the horns can be done using a standard mill and a high-speed steel tool. We have already fabricated a two-section 230 GHz Potter horn to test the precision of the method. Using the steel tool shown in Fig. 8, we drilled three horns using a mill into an aluminum block and then spit one of them into two halves in order to check the repeatability of the method and the accuracy of the surface finish.

Figure 8: The tool used for machining the two-section, 230 GHz horn.

Our measurements have shown that the surface finish and the accuracy near the flare discontinuities is sufficiently good to reproduce the theoretical predictions. Also, comparing the three horns that were fabricated using the same tool, did not reveal significant differences in the dimensions, although our measurements were accurate to within a micron.

5. Conclusion

We have presented a multi-section high performance horn design that has high beam circularity, low cross polarization and low sidelobe level. Each section is a smooth-walled conical horn with constant flare and no corrugations. The bandwidth of the horn depends on the number of sections but 25% useful bandwidth can be obtained at 700 GHz using only three sections. Synthesis of the horn geometry is done using the software package *hornsynth* which we have written for this purpose which combines a minimization package using a genetic algorithm and a horn analysis package using the modal matching method. Fabrication of this horn at millimetre wavelengths can be obtained by drilling using a tool that has the shape of the horn into a block of aluminum. Our first attempt using a steel tool which cost £75 has demonstrated that several horns can be fabricated with identical dimensions and sufficiently good machining tolerances. Increasing the bandwidth requires more sectioning which in turn requires more computing time but the same fabrication effort. At lower frequencies, our method can still be used but it may be easier to use machining by a programmable lathe rather than drilling by a mill. Testing the RF performance of the horn is in progress.

6. References

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