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MILLIMETER-WAVE PROFILED CORRUGATED HORNS FOR THE QUAD COSMIC BACKGROUND POLARIZATION EXPERIMENT

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Abstract

In this paper we report on the design and validation process for the profiled corrugated horn antennas, which feed the bolometer array of a cosmology experiment known as QUaD located at the South Pole. This is a cosmic background radiation polarization project, which demands precise knowledge and control of the optical coupling to the signal in order to map the feeble E- and B-polarization mode structure. The system will operate in two millimeter wavelength bands at 100 and 150 GHz. The imaging horn array collects the incoming signal via on-axis front-end optics and a Cassegrain telescope, with a cold stop in front of the array to terminate side-lobe structure at an edge taper of –20dB. The corrugated horn design process was undertaken using in-house analytical software tools, based on modal scattering, specially developed for millimeter -wave profiled horn antennas. An important part of the instrument development was the validation of the horn design, in particular to verify low edge taper levels and the required well-defined band edges. Suitable feed horn designs were measured and were found to be in excellent agreement with theoretical predictions.

Key Words: profiled corrugated horn antennas, polarization, CMB.

1. Introduction

Profiled corrugated horns operating in the millimeter and sub-millimeter wavebands have been developed for various cosmological missions optimised for the detection of the cosmic microwave background (CMB) radiation, whose flux peaks in the mid millimeter-waveband [1-3]. QUaD is a CMB polarization experiment with an imaging array of horn antennas feeding hypersensitive bolometers [4]. In similar CMB experiments, such as PLANCK-HFI [5], so called flared-profiled designs have been developed that guarantee very low side-lobe levels but at the expense of a relatively large horn aperture compared with the beam waist size [1,6]. This is rather inefficient for mapping as a close packed array format is desirable with an optimised ratio of waist to horn aperture area. Therefore, optimisation of the QUaD array for high efficiency mapping is achieved through relaxing the edge taper requirements and terminating the unwanted resulting side-lobe response at a cold stop in front of the array. This also allows the upper edge of the frequency bands to be defined by filters mounted at the front of each horn, which otherwise would inevitably tend to generate a higher level of extended side-lobe structure but which is now truncated by the presence of the cold stop. Thus the more complex back-to-back horn feed filter structure used in PLANCK, for example, is avoided [1]. Note also that a corrugated waveguide filter, connecting each horn to the bolometer cavity at the back, determines the lower band-edge.

NUI Maynooth's modelling software (*SCATTER2*) [2,3], based on a rigorous electromagnetic mode matching technique, was used to develop designs for the QUaD 100 GHz and 150 GHz single-moded corrugated feed horns [2,3,7]. These horns have to produce well-controlled beams that satisfy strict criteria with regard to cross-polarization and side-lobe levels. The horns must transmit both orthogonal polarizations with well-matched beam patterns in the far field. The aim of this paper is to report on the QUaD [8-10] horn design and validation process. In section 2 we summarise the main features of the instrument of relevance to this paper. In section 3 the definition of the profiled corrugated horns is presented along with test measurements of the system to validate the design process. In section 4 the bandwidth characteristics of the horns are described while in Section 5 the effects of the filter at the horn aperture on the beam patterns is discussed. Finally in the conclusions we discuss any outstanding issues arising from the design procedure.

2. The Instrument

The cosmic microwave background (CMB) has proven to be an invaluable tool for cosmologists working to constrain fundamental cosmological parameters. In particular, the low-level ($\Delta T/T$ □ 10^{-5}) temperature fluctuations first detected by COBE (Cosmic Background Explorer) in 1992 have provided a rigorous test of cosmological models. However, it has become increasingly clear that temperature anisotropy measurements alone cannot distinguish between all competing models. Knowledge of the even fainter (by factors of 10 to 100) polarization characteristics will be needed to unambiguously determine the fundamental cosmological parameters. The polarization signal was recently detected by the DASI (Degree Angular Scale Interferometer), WMAP (Wilkinson Microwave Anisotropy Probe) and CBI (Cosmic Background Imager) experiments [11-13]. The CMB is predicted to exhibit two forms of polarization structure, so called *E*- and *B*-modes, each encoding important cosmological information. The latest generation of CMB experiments aims to map these polarization fluctuation structures on a wide range of angular scales. QUaD is one such experiment.

QUaD is a ground-based high-resolution instrument (up to $l \approx 2500$, corresponding to a resolution of 4.3 arcmin) designed to map CMB polarization and to measure the *E*-mode and *B*-mode polarization power spectra [14]. It will operate for two years and begin observations in 2005. QUaD comprises a bolometric array receiver on a 2.6-m Cassegrain telescope [4]. The focal plane contains 31 pairs of orthogonal polarization-sensitive bolometers (PSBs), structures that were developed for the PLANCK satellite mission [15,16]. 12 of the PSB pairs will operate at 100 GHz, the remaining 19 at 150 GHz. Frequency bands are defined by a waveguide high-pass cut-off at the low end and by a metal-mesh low-pass filter at the high end [17]. Simultaneous observations in bands around the two frequencies, and optimised for atmospheric transmission, will allow spectral discrimination between CMB and foreground signals. Each pair of PSBs is located within a single feed and differenced to give a measure of the Q and U Stokes parameters in the coordinate frame of the instrument. The name of the project, QUaD, in fact signifies Quest at DASI, a collaboration which resulted from the siting of QUEST (the Q and U Extra-galactic Submillimetre Telescope) on the DASI (Degree Angular Scale Interferometer) mount at the South Pole.

The corrugated horn and waveguide feeds that couple radiation from the telescope to the PSBs need to have good beam symmetry and low sidelobe levels over the required bandwidth. CMB polarization measurements require not only a significant increase in sensitivity over earlier experiments but also a better understanding and control of systematic effects particularly those that contribute to the polarised signal. It is important that the feed horns preserve the polarization orientation of the incoming fields. In this paper we investigate the design and testing of the QUaD corrugated feeds. Suitable feed designs were found for both frequencies and the horns have been manufactured by TK Ltd. (UK). The 100 GHz beam profiles and band edges were measured at the NUI Maynooth test range and were found to be in excellent agreement with the theoretical predictions as will be discussed in Sections 3 and 4. Further tests were made at Stanford, in particular, again for validation of the band edges and reported in section 4.

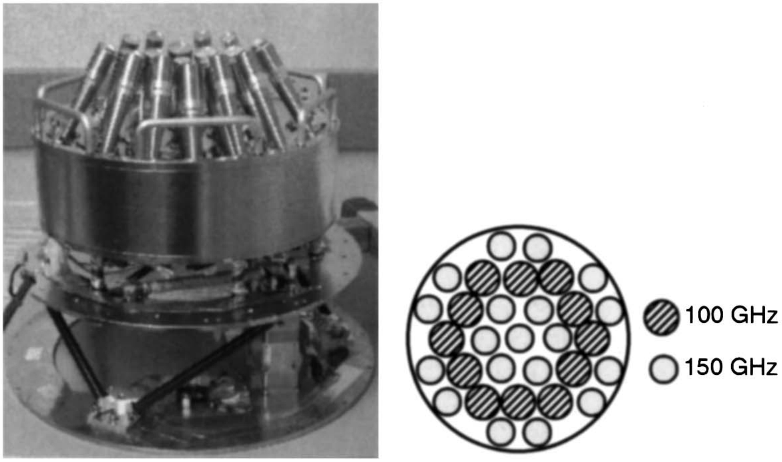

Figure 1. The QUaD focal plane showing the feed horns in a close-packed array.

3. Horn Profile Design

3.1 Profiled Design

A corrugated horn design was chosen as such horns produce symmetric beams with low side-lobe levels. The horn details are essentially then determined by the required beam characteristics, bandwidth and the limited volume available at the imaging plane inside the cryostat. The horns were required to illuminate a cold stop with an edge taper ideally approaching –20dB. This cold stop is placed at an image of the entrance pupil of the telescope, coincident with the secondary mirror of the on-axis Cassegrain system, with the clipped horn beams terminated on the cold surface at angles greater than 12.3 ° (or an *F*-number of 2.3). Regular conical corrugated horns, which meet the QUaD requirements, would be too long to fit into the cryogenic fridge and so a profiled design is necessary. Furthermore efficient use of the field of view of the telescope implies optimised sampling and profiled horns, by having the waist close to the horn aperture, provide a close packed array format possibility with a relatively low level of under-sampling.

Profiled corrugated horns, as pioneered by Clarricoats [7,18], are defined by *r*, the horn profile radius as a function of *z*, the distance from the horn throat given by:

$$r(z) = b + (a - b)\left[\frac{z}{L}(1 - A) + A\sin^2\left(\frac{\pi z}{2L}\right)\right],$$

where *a* is the horn aperture radius, *b* is the waveguide radius feeding the horn, *L* is the axial length of the horn and *A* is the profile parameter. For example, by setting $A = 0.7$ the shortest horns with side lobe levels no higher than –20dB can be achieved. The details of the 100 GHz and 150 GHz designs are summarised in figure 2 and table 1. The horn profiles are chosen so that both the 100 GHz and 150 GHz horns have approximately the same length. A scattering matrix technique using the *SCATTER2* mode matching software developed at NUIM and reported in [2,3] was used to model the far field beam patterns of the horns (see figure 3). The edge taper at the telescope (i.e. at a far field angle of 12.3 °) for the 100 GHz horn is slightly above that prescribed at –19.4 dB while for 150 GHz it is in fact –23.6 dB, which is better than the nominal –20 dB required by the QUaD experiment. These levels refer to single frequency predictions at 100 GHz and 150 GHz rather than over the full bandwidths, as will be discussed in section3.3.

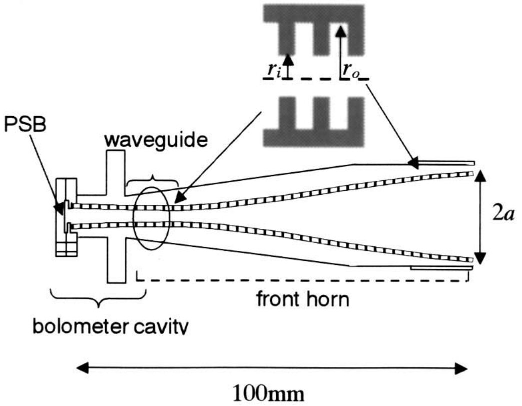

Figure 2. The QUaD profiled corrugated horns showing the bolometer cavity

Horn Type Profiled	Horn Dimensions (mm)	-20 dB beam edge	Band Edge (GHz)
(150 GHz)	a=7, L_{TOT}=102.25	11.6°	126.5
(100GHz)	a =10.5, L_{TOT} =100.5	12.4°	78

Table 1. Summary of the QUaD horn design parameters.

3.2 Beam Pattern Measurements

The 100 GHz QUaD horn beam patterns were experimentally verified at NUI Maynooth to check the simulations. Far field measurements were made using the experimental set-up shown schematically in figure 3 (a). To measure the far field radiation pattern the test horn was positioned so that the axis of rotation of the rotary table was centred on the phase centre of the horn. Eccosorb was placed around the experimental set-up to prevent unwanted reflections. A chopping reference signal is applied to both the Gunn oscillator power supply and the lock-in amplifier for improved signal to noise. The signal from the lock-in amplifier is transferred to a computer via an A/D converter with a large dynamic range. The usable range of the system is limited to about 50dB by the noise from the detector. The *E*-plane far field beam was measured at 100 GHz, 92 GHz and 105.5 GHz (see figure 3). In most cases there is remarkable agreement between the *SCATTER2* predictions and the experimental data even at the -35 dB level.

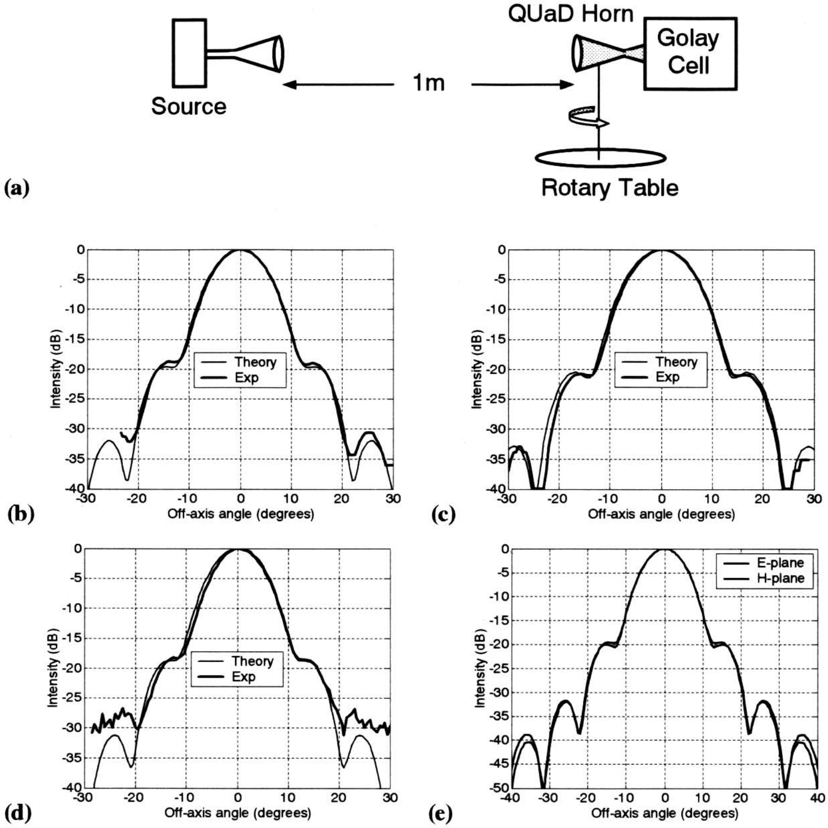

Figure 3. Measurements of the 100 GHz QUaD horns at NUI Maynooth. (a) QUaD feed horn on the antenna test range and theoretical and measured *E*-plane beam patterns at (b) 100 GHz, (c) 92 GHz, (d) 105.5 GHz. (e) shows the beam pattern predicted for the 150 GHz horn

3.3 Broadband response

The broadband E-plane beam patterns in Figure 4 were computed by adding in quadrature the beam patterns (each normalised in total power) at 5 uniformly spaced spot frequencies across the two bands. It was assumed that the edge frequencies only contributed half of their power to the overall sum (trapezoidal rule for numerical integration). The broadband edge taper at the telescope was found to be –16 dB and –19 dB (a deterioration over the numbers quoted above for the centre of band frequencies because of the long-wavelength contributions). QUaD is a polarization sensitive experiment and therefore like in PLANCK minimised cross-polarization levels are desirable, as high levels reduce sensitivity. The cross-polarization levels are low across the QUaD 100 GHz and 150 GHz bands as is illustrated in figure 4. The maximum cross-polarization level in the broadband beam is at the -42dB level at both 100 and 150 GHz.

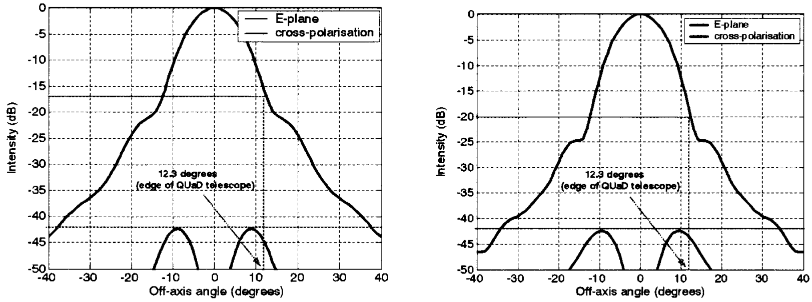

Figure 4. Broadband far field and cross-polarization patterns at the cold stop for the QUaD 100 GHz and 150GHz horn antennas.

4. Waveguide Filter Definition

4.1 Definition process

Low-pass metal mesh filters mounted at the front of each horn antenna define the upper edge of the frequency bands. The lower edge is determined by the waveguide connecting each horn to a bolometer cavity at the back. The detailed characteristics of the corrugations in the waveguide filter as well as the transition from deep ($\approx$ 0.35 λ) to shallower corrugations (≈ 0.25 λ) in the horn throat determine the single mode bandwidth of these corrugated horns, including the precise band edges and any low frequency leakage. Based on previous experience, it was decided to begin the transition at the horn throat and extend it over about 30 corrugations to ensure a sharp band edge [19]. The required low frequency band edge of the 100 GHz horns is 78 GHz, and is 126 GHz for the 150 GHz horns (see Figure 5).

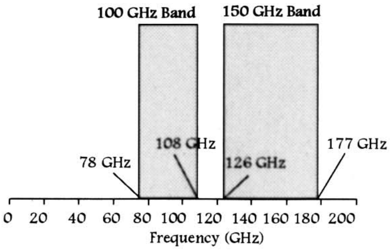

Figure 5. QUaD 100 GHz and 150 GHz frequency bands.

Two methods can be used to model the frequency response of the waveguide filters. An approximate hybrid mode model [3, 18], where an average surface impedance is assumed for the corrugated guide, can be used, since there are several corrugations per wavelength. With this approach it is straightforward to predict the dominant HE_{11} mode cut-offs in terms of the waveguide radius and slot depths [18]. The more accurate scattering matrix technique using the *SCATTER2* software was then used to predict the precise behaviour of the filter and also to predict the leakage of unwanted modes of various azimuthal orders (0,1, & 2). The mode matching technique allowed the design to be fine-tuned in order to obtain a sharp band edge at the required frequency.

Below the dominant HE_{11} mode band edge the transmission power levels predicted by the scattering matrix technique are in some cases unreliable because of numerical instabilities. However, the range of frequencies over which the EH_{11} mode causes out of band power leakage is still accurately predicted. This mode propagating in the waveguide filter becomes evanescent in the horn flare and so does not transmit power efficiently to the horn aperture. Leakage of the E_{01} mode is also predicted, although being a surface mode similar to the EH_{11} mode, it too can be expected to have negligible power at the horn aperture. An important part of the measurements of the horn frequency response is the verification that the EH_{11} and E_{01} leakage levels are indeed insignificant.

In general it was found that the process of designing the waveguide filter to obtain the required band edges is an iterative one with not just the waveguide but also the transition sections at both ends of the waveguide having an impact. The waveguide filter corrugations, defined in terms of inner and outer waveguide radii (to the top and bottom of a slot), were set to $r_i = 0.713$ mm & 1.15 mm and $r_o = 1.423$ mm & 2.29 mm, respectively for the 150 GHz and 100 GHz waveguide filters ($r_o - r_i$ equivalent to a corrugation depth of 0.355 λ).

An important goal for the design was single moded HE_{11} operation over a 33% bandwidth. Figure 6 illustrates the total transmission predicted over the two relevant bands. All modes of azimuthal orders 0, 1 and 2 were included in these calculations. With the exception of some low frequency $n = 0$ leakage between 91 – 105 GHz (numerically unstable region), the 150 GHz horn responds to frequencies in the range 126 – 177 GHz before becoming multi-moded when the E_{02} mode starts to propagate. Similarly the design for the QUaD 100 GHz horn is single-moded between 78 GHz and 108 GHz (a 33% bandwidth). The $n = 0$ leakage between 58 GHz and 64 GHz is expected to be negligible because the mode is a surface mode and evanescent in the horn as noted above.

4.2 Bandwidth measurements

The band edge of the 100 GHz QUaD horn was measured using the set-up schematically shown in Figure 7 where the oscillator was operated in variable frequency mode (75 GHz –110 GHz). In the measurements taken, the on-axis gain was recorded as a function of frequency. A conical horn radiator attached to the Gunn oscillator source back illuminates the QUaD horn.

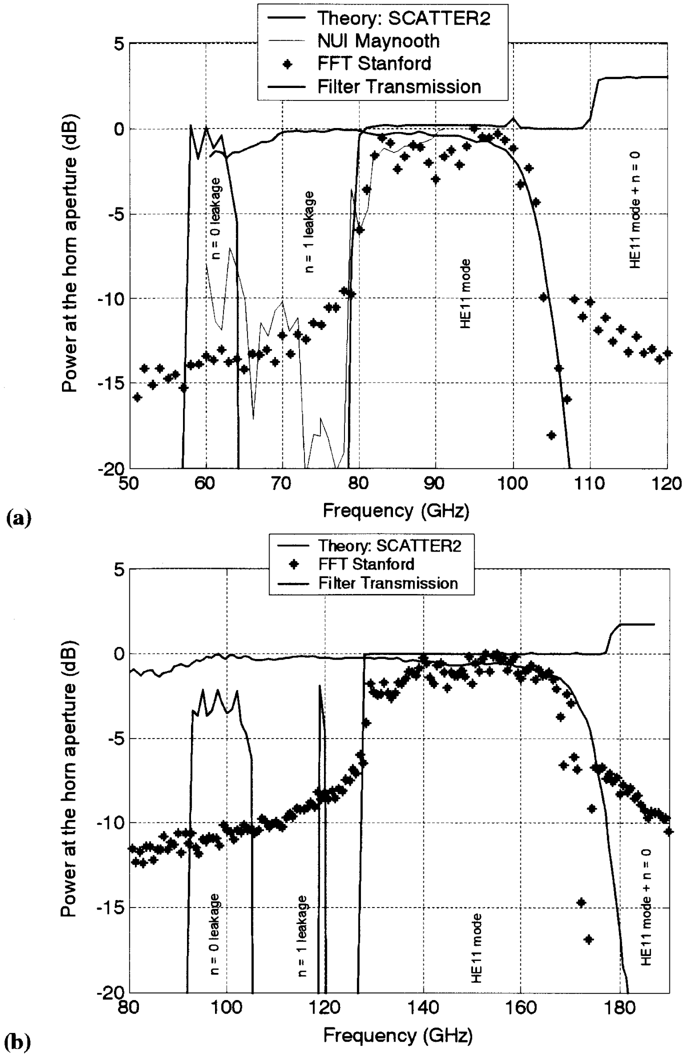

Figure 6. Measured and predicted total transmission for the (a) 100 GHz and (b) 150 GHz QUaD horns using the NUIM test range and the Stanford Fourier transform spectrometer.

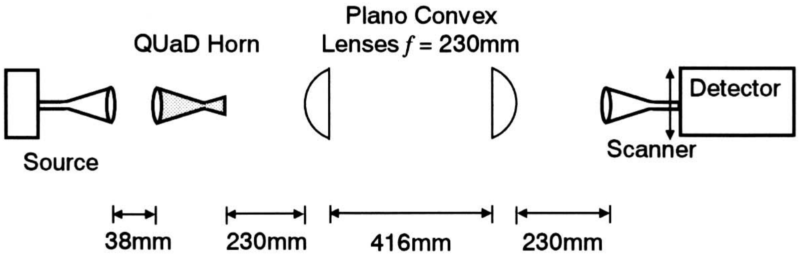

Figure 7. Schematic diagram (not to scale) of the experimental set -up in NUI Maynooth for measuring the band edge of the 100 GHz QUaD horn.

The predicted and measured HE_{11} band edge for the QUaD 100 GHz horn is shown in Figure 6 (a), which clearly indicates that the mode begins to propagate at 78 GHz. In order to ensure that there was no unexpected off-axis power being transmitted, beam patterns were also measured at regular frequency intervals below cut -off. In particular these measurements observed no unusual off-axis beam pattern behaviour in the predicted transmission region of the EH_{11} and E_{01} modes below the HE_{11} band edge. The *SCATTER2* software was also capable of computing far field beam patterns at all frequencies.

For the case of the set-up shown in Figure 7 the oscillating nature of the on-axis gain above the HE_{11} band edge is due to variations in the coupling efficiency between the conical horn and the QUaD horn in the experimental back-to-back set-up and is also influenced by standing wave effects in this region.

The frequency responses of the QUaD 100 and 150 GHz horns were also measured using a Fourier transform spectrometer (FTS) at Stanford. The input signal was chopped at 10 Hz between 300K and a 77K cold load and detected using a polarization-sensitive bolometer fed by the horn under test with the low-pass mesh filters in place. The band edges were found to agree with those predicted at 78 GHz. The FTS bandwidth measurements are also presented in Figure 6. Standing w aves also appear to be present in the FTS system measurements, although these are not due to the presence of mesh filters.

5. Effects of Horn Aperture Filters

5.1 Computing effects of aperture filters

On QUaD a series of low-pass optical filters based on metal mesh technology developed at the University of Wales, Cardiff [17] are used to define the high frequency band edges. The filters are anti-reflection coated to minimise reflections and optimise transmission in band, and are arranged in a stack in front of the horn apertures being held in position by metal filter caps as illustrated in Figure 8. The edge frequency of each low-pass filter is tuned to avoid coincidence of harmonic leaks and have an in-band transmission close to unity. The filters produced by photolithography use polypropylene substrates onto which the thin metal layer is evaporated and a mask of the required grid pattern applied to the substrate surface. The filter stack transmissions are shown in figure 6.

The filter stacks are required to perform two roles: minimizing out-of-band thermal loading on the cryogenic system and defining the photometric bandwidth in conjunction with the waveguides. By careful tuning of the filters, these tasks are achieved whilst also maintaining high in-band transmission of the filter chain. As far as optical modelling is concerned we can consider that the filter substrate polypropylene (n = 1.49) effectively fills the filter cap. The filters were expected to cause some deterioration of beam quality off-axis for the optimised designs above and these effects were simulated and measured to ensure adequate performance, especially important for a CMB experiment like QUaD.

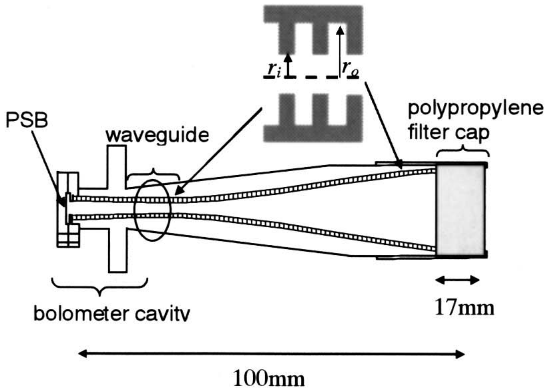

Figure 8. Final design of the QUaD horns with filters in place.

Thus, in order to ensure no significant off-axis deterioration of the beam due to the conducting filter caps, a set of measurements (Figure 9) on the QUaD 100 GHz horn were made with a filter cap (17 mm deep) in place and also filled with polypropylene dielectric to act as a physical model for the filter substrate (filters were not yet available). These "dummy" filters were not anti-reflection coated and therefore the additional reflection effects were included in the modal matching *SCATTER2* software (although the real filters are anti-reflection coated and will therefore have a more ideal behaviour). It was assumed for the simulations that the radiation is only affected by the filter polypropylene substrate and not the transmitting mesh filter itself. Predicted *E*- and *H*-plane far-field radiation patterns of the 100 GHz and 150 GHz QUaD horns are shown in Figure 9. The edge taper at the telescope aperture is now predicted to be somewhat worse than –20dB, which affects edge taper requirements but not spill over. The respective edge taper in the *E*- and *H*- far-field planes for the QUaD horns with the filters in place are –18 dB and –19.5 dB for the 100 GHz horns (-23.5 and –18.8 dB experimentally) and –15 dB and –23dB for the 150 GHz horns.

Measurements were also taken with an empty filter cap, which might be expected to be a closer representation of the actual horn pattern. The predicted beam in the *E*-plane is somewhat wider than the experimentally measured beam, whereas on the other hand in the *H*-plane the far-field beam patterns agree to –20 dB (Figure 9). The discrepancies may be due to the electromagnetic nature of the filter cap (for example the electrical contact is made by a sliding fit). But even in this non-ideal case the measured beams show acceptable distortion and demonstrate that real performance of the QUaD horns will not be adversely affected by the presence of the filter substrate at the front of the horns in terms of the edge taper and spill over.

The *broadband* edge tapers at the telescope were also computed and found to be –15 dB and –20 dB at 100 GHz and 150 GHz, respectively, assuming anti-reflection coated ideal performance filters (almost the same as the edge taper without the filters). The maximum cross-polarization level in the broadband beam is now at the -20dB and –23 dB level at 100 and 150 GHz, respectively, which is low, but significantly higher than when the filters were excluded.

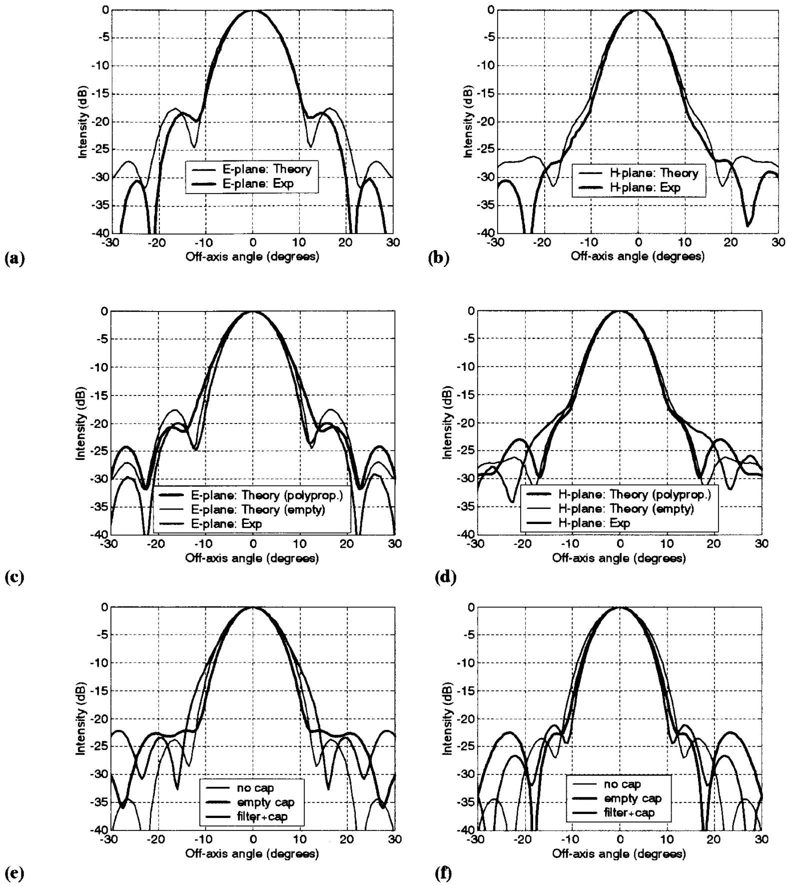

Figure 9. QUaD 100 GHz (empty filter cap) (a) E and (b) H-plane far field beam patterns. QUaD 100 GHz (polypropylene filled filter cap) (c) E and (d) H-plane far field beam patterns (the experimental data is compared to the theoretical predictions for the cases where the filter cap is empty (n=1) and filled with polypropylene (n= 1.49)). QUaD 150 GHz (e) E-plane and (f) H-plane predicted far field beam patterns at the cold stop for the cases without the filter, with an empty filter cap and with the real anti-reflection coated filters.

5.2 Phase centre

The phase centre [20] positions of the QUaD horns can be determined by optimising the on-axis gain of the telescope as a function of the distance between the horn aperture and the final focal plane. In the simulations it was found that by including the filters in front of the 100 GHz horn, the phase centre moves 4 mm towards the horn aperture, while the phase centre of the 150 GHz horn moves forward by 12 mm compared with the cases for a bare horn. However, in order to avoid shadowing the front of all the horns plus front-end filter configurations must lie on the same spherical surface. Thus, some defocusing, in terms of not having the phase centres coinciding with the telescope focus, is inevitable. The broadband phase centre of the 100 GHz horn is farther from the horn aperture (taken as the front of the filter cap) than the phase centre of the 150 GHz horn, as shown in Figure 10. It is clear from Figure 10 that the best position of the telescope focus is about 23.5 mm behind the horn apertures (taken as the front of the filter caps) of the 100 GHz and 150 GHz horns.

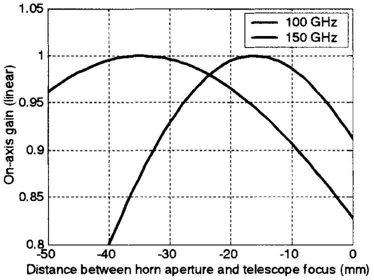

Figure 10. Broadband phase centre of the QUaD 100 GHz and 150 GHz horns where horn aperture refers to the *front* of the filter cap.

6. Conclusions

In this paper the design process for the profiled corrugated horn array on QUaD, determined by the need to meet the edge taper and band edge requirements of the CMB polarization experiment, was described. This paper validates the mode matching scattering matrix approach for corrugated waveguides through the comparison with experimental test data from a range of cases. Far field beam patterns of the 100 GHz horn, as shown in Figure 9, illustrate remarkable agreement between simulations and measurement. The scattering matrix model can also accurately predict the HE_{11} band edge, but evanescent modes below the fundamental mode cut-off cause numerical instabilities. The bandwidth properties of the 100 GHz QUaD horn were measured in the NUI Maynooth and Stanford test facilities and the predicted and measured HE_{11} band edges agree perfectly. The theoretical and experimental far field beam patterns of the horn give good agreement to approximately –20 dB for the case of the inclusion of a polypropylene filled filter cap on the horn, especially in the *H*-plane. The filter model assumed here is approximate and the real filters are anti-reflection coated. Nevertheless, one can conclude that in terms of the operation of QUaD placing the filters in front of the horns should not cause any significant deterioration in performance. Broadband simulations of the horn beam patterns and phase centres indicate that that there are no surprises and the horns essentially reach the basic specifications required.

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References

[1] B. Maffei *et al.,* "Shaped corrugated horns for Cosmic Microwave Background anisotropy measurements", Int. J. Infrared & Millimeter Waves, **21**, 2023, 2000

[2] R. Colgan, *Electromagnetic and Quasi-optical Modelling of Horn Antennas for Far-IR Space Applications*, Ph.D. thesis, NUI Maynooth 2001

[3] J.A. Murphy *et al.*, "Radiation patterns of multi-moded corrugated horns for far-IR space applications", Infrared Physics and Technology, **42**, 515, 2001

[4] S. Church *et al.*, “QUEST and DASI: A South-Pole CMB polarization experiment”, New Astron. Revs., **47**, 1083-1089, 2003

[5] J.M. Lamarre, *et al.,* “The High Frequency Instrument on PLANCK: Design and Performance”, Astro. Letters and Communications, **37**, 161-170, 2000

[6] E. Gleeson *et al.*, “Definition of the Multi-Mode Horns for the HFI Instrument on PLANCK”, *Proceedings of 25th ESA Antenna Workshop on Satellite Antenna Technology*, 609-615, ESTEC, Noordwijk, 2002.

[7] A. D. Olver *et al.*, *Microwave Horns and Feeds,* chapter 4, IEEE Press, New York, 1994.

[8] A. Rusholme *et al.*, “QUaD: A ground based millimeter-wave telescope for CMB polarization studies”, *Carnegie Observatories Astrophysics Series, Measuring and Modeling the Universe,* (ed. W. L. Freedman), **2**, 2003

[9] L. Piccirillo *et al.*, “QUaD-A 2.6-m mm-Wave Telescope for CMB Polarization Studies”, *Astrophysical Polarized Backgrounds AIP Conference Proceedings*, p159, **609**, 2002

[10] G. Cahill *et al.*, “The Quasi-Optical Design of the QUaD Telescope”, *Proceedings of the SPIE International Conference on Astronomical Instrumentation*, Glasgow, 2004

[11] E.M. Leitch *et al.*, “Measurement of Polarization with the Degree Angular Scale Interferometer”, Nature, **420**, pp. 763-771, 2002

[12] A. Kogut *et al.*, “First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature-Polarization Correlation”, Astrophysical Journal Supplement Series, **148**, pp. 161, 2003

[13] A.C.S. Readhead *et al.*, “Polarization Observations with the Cosmic Background Imager”, astro-ph/0409569

[14] M. Bowden *et al.,* “Scientific optimization of a ground-based CMB polarization experiment”, Monthly Notices of the Royal Astronomy Society, **349**, 321-335,2004

[15] W.C. Jones *et al.,* “A Polarization Sensitive Bolometric Receiver for Observations of the Cosmic Microwave Background”, in *Millimeter and Submillimeter Detectors for Astronomy, Phillips T. G. & Zmuidzinas J., eds., Proceedings of the SPIE*, **4855**, 227, 2003

[16] J.J. Bock, “Bolometers for Millimeter-wave Cosmology”, *Proceedings of the 2K1BC Workshop on Experimental Cosmology at Millimeter Wavelengths*, Breuil Cervinia, Italy, July 2001

[17] P.A.R. Ade *et al.*, “Filters, Dichroics, Beam Dividers and Fabry-Perot Plates for Ultra-low-background Far Infrared Instruments”,

Proceedings of the Second Workshop on New Concepts for Far-IR Submillimeter Space Astronomy, University of Maryland, 2002
[18] Clarricoats P.J.B. and Olver A.D., *Corrugated Horns for Microwave Antennas,* chapter 3, Peter Peregrinus, 1984.Clarricoats
[19] E. Gleeson *et al.*, "Corrugated Waveguide Band Edge Filters for CMB Experiments in the Far Infrared," *Infrared Physics and Technology*, (in press).
[20] E. Gleeson *et al.*, " 'Phase centres' of Far Infrared Multi-moded Horn Antennas", Int. J. Infrared & Millimeter Waves, **23**, No. 5, 711 – 730, 2002.