Optical requirements and modelling of coupling devices for the SAFARI instrument on SPICA

N Trappe[1], J.R.Gao[2], D. Glowacka[3], D. Goldie[3], D. Griffin[4], P. Khosropanah[2], P. Mauskopf[5], D. Morozov[5], A. Murphy[1], C. O'Sullivan[1], M. Ridder[2], S. Withington[3]

[1]NUIM, National University of Ireland Maynooth
[2]SRON Space Research Organization of the Netherlands
[3]University of Cambridge
[4]Rutherford Appleton Laboratory
[5]University of Cardiff

***Abstract*— The next generation of space missions targeting far-infrared bands will require large-format arrays of extremely low-noise detectors. The development of Transition Edge Sensors (TES) array technology seems to be a viable solution for future mm-wave to Far-Infrared (FIR) space applications where low noise and high sensitivity is required. In this paper we concentrate on a key element for a high sensitivity TES detector array, that of the optical coupling between the incoming electromagnetic field and the phonon system of the suspended membrane. An intermediate solution between free space coupling and a single moded horn is where over-moded light pipes are used to concentrate energy onto multi-moded absorbers. We present a comparison of modelling techniques to analyse the optical efficiency of such light pipes and their interaction with the front end optics and detector cavity.**

I. INTRODUCTION

This paper describes the optical coupling requirements of high sensitivity transition edge superconducting (TES) detectors using low thermal conductance silicon nitride (SiN) mechanical supports for future space missions. Silicon nitride thermal isolation was originally developed for ground-based and balloon-borne mm-wave instruments (SuZIE, BOOMERANG, BOLOCAM, BLAST), and later adapted for use in the PLANCK-HFI [1] and HERSCHEL-SPIRE [2] instruments, as well as in all of the current ground-based and balloon-borne instruments such as SCUBA2 and CLOVER. The rapid development over the last decade of TES technology has increased its technology readiness level, and has paved the way for use on future space missions such as SAFARI SPICA. While it is technically feasible to manufacture single TESs having the required sensitivity of 10^{-19} $\mathrm{WHz}^{-1/2}$ it is challenging to create an ultra-low-noise TES technology that can be engineered into complete imaging arrays, with the required optical packing and uniformity of performance.

A key element of a high sensitivity TES detector is the optical coupling between the incoming electromagnetic field and the phonon system of the suspended membrane. In CMB B-mode experiments there is a desire to use corrugated horns to couple the telescope optics to waveguide, and then to use a microstrip probe and termination resistor to couple the power in the waveguide mode to the membrane of the TES. In far-infrared applications free space absorbers are used on the TES membrane to couple the telescope optics to the detector directly. Both of these schemes have advantages and disadvantages, and there is even an intermediate situation where over-moded light pipes are used to concentrate energy onto multi-moded absorbers an option that is investigated in this paper. In developing high sensitivity TES detectors it is important to optimize the optical coupler mechanism for future proposed mm-wave to FIR missions to maximize sensitivity. A range of antenna designs applicable to these instruments are investigated and a review of the analysis tools available to carry out performance predictions accurately and efficiently are looked at. Due to the generic nature of the analysis, specific adaptations would be required for specific instrument deigns in the future but the overarching principle of the analysis of these structures is valid.

In high sensitivity TES detector technology the ability to control the electromagnetic and thermo-mechanical environment around the detector is desirable. Because the detector responsivity is proportional to the inverse of the NEP (Noise Equivalent Power) squared these detectors and their associated wiring and SQUID amplifiers must be shielded from disturbances such as stray light and horn antennas achieve this directionality noise limitation requirement. Alternative refractive element designs may also be applicable but we concentrate on a feed horn option which includes the advantages of very good control of beam pattern and side lobes, good rejection of stray light and broad bandwidths being possible with multiple EM waveguide modes being able to propagate within the structure. Of course this scheme comes at the cost of a relatively high mass and volume. For FIR applications, optical coupling to TES detectors can be achieved using a metal film absorber, possibly patterned into a mesh structure to achieve the necessary free space impedance. The minimum radius of the metal film absorber is approximately equal to the wavelength of observation, either as a pixel in a filled array or as an absorber in a cavity behind a concentrating horn. An advantage to using horns is that the absorber dimensions can be much smaller than the separation between pixels allowing space between pixels for the thermally isolating legs as well as a supporting frame and pixel wiring.

We present an analysis of two areas of interest related to optically coupling TES detectors. Initially we outline the analysis tools available to model the highly over moded horn structure (both of cylindrical and rectangular waveguide geometry) and then the analysis of the cavity where the detector and absorber are located behind the horn coupler.

Two main analysis tools were applied to the problem of analyzing a multimode horn operating at THz frequencies. These were the commercially available packages CST and HFSS and a developed mode matching technique based on a technique of propagating waveguide modes developed originally by Olver 1994 [3]. This mode matching technique can be used to accurately predict radiation characteristics of smooth-walled and corrugated waveguides and horn antennas regardless of the length, profile and opening angle. The technique is based on a scattering matrix description of the propagation within the waveguide and horn, and includes full modal scattering at discontinuities in the structure. The technique was originally developed by Alvin Wexler in the 1960's [4] with further developments made by Masterman and Clarricoats in the 1970's [5]. The technique is developed a software package SCATTER applicable to model waveguides and horn antennas with cylindrical symmetry before we developed an equivalent version for rectangular waveguides which use a different basis set of modes.

In the scattering matrix technique a conical or profiled horn structure is regarded as a sequence of cylindrical waveguide segments with the radius stepping between the top and bottom of the corrugation slots. A smooth-walled profile on the other hand is approximated by a series of cylindrical monotonically increasing radii giving a stair like profile. The natural modes of propagation for each segment of the guide and horn are the TE and TM modes of a uniform cylindrical or rectangular waveguide. Assuming there is a sudden change in the guide radius at the interface between two segments, the power carried by the individual incident modes is scattered between the backward propagating reflected modes in the first guide segment and the forward propagating modes in the second guide segment. The so called mode matching technique, to determine the scattering matrix describing the step, is based on matching the total transverse field in the two guides at the junction, so that the total complex power is conserved for incident modes from both directions and Maxwell's equations are satisfied with the usual boundary conditions applied to the fields at the conducting walls. Track must also be kept of the evanescent modes in the guide as these can propagate as far as the next step in the profile for short segments. The technique therefore involves determining the transmission and reflection coefficients at the discontinuities between the waveguide sections. Modal propagation within each waveguide section is taken into account using the usual phase delay term which is mode dependent as the guide wavelength depends on the mode. The relationship between the input and output mode coefficients for each junction between sections is described by a scattering matrix. Modal propagation between junctions can be expressed as a diagonal matrix whose elements describe the phase evolution of the modes. The matrices are then cascaded section by section to obtain an overall scattering matrix for the horn structure.

II. RESULTS

This waveguide mode matching technique is commonly applied to single moded horns. At Maynooth we have also applied this code to the successful analysis of multimoded horns such as those used on the Planck HFI instrument. For the SPICA SAFARI mission an extension needed to be added to model the SAFARI pixel. Firstly we expanded the cylindrical modal analysis to rectangular waveguide modes. Also the analysis of an integrating cavity was added to the standard horn analysis and finally we also introduce a technique to model the absorbing material in a cavity, representative of the absorbing material tantalum to be used in the SAFARI mission for the TES detectors. We outline a few examples of this mode matching technique development and also outline the remaining issues to be fully investigated.

The SCATTER code (mode matching technique) has been extensively used and tested to model corrugated horns particularly single mode corrugated horns for various CMB and submillimetre projects such as PLANCK (HFI), QUAD, HIFI for Herschel Observatory, and ALMA. In single mode operation many examples exist with excellent agreement achieved between theoretical predictions made with SCATTER and precise experimental measurements. Due to the heritage of the research group at Maynooth the application of SCATTER to smooth walled geometries has been less extensively applied and therefore before application to the smooth walled geometries (such as the proposed SAFARI designs) more verification of this code is required especially as smooth geometries would have larger currents influencing radiation characteristics at the horn aperture. A number of related validation tests were carried out and are described below. Once this exercise has been carried out the SCATTER code can be applied with confidence to smooth walled optical couplers to be used in SAFARI illustrated below in figure 1.

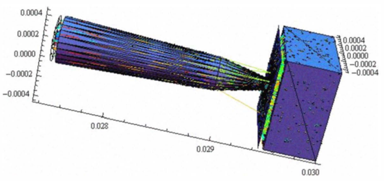

Figure 1 A 3D CAD model of the proposed SAFARI horn and cavity modelled in Optica to use ray tracing as a first order technique to model the leakage through the 50μm gap located at the horn plate in front of the cavity.

The finite element technique utilised by commercial packages such as CST[6] (Computer Software Tool©) or HFSS[7] to such large electrical structures is computationally unfeasible. These packages propagate modes independently and so if *n* modes are propagating (typically $n \approx 100$) such packages would need to be ran *n times* in series making this approach impossible. Mode matching is therefore the ideal tool to apply to SAFARI horn and cavity geometries.

Next we analyse the cavity effects and the absorber sitting in a cavity. The farfield plots illustrated in figure 2 below are calculated at 5 THz for a 2mm smooth walled conical horn with an input waveguide diameter of 100μm and an exit aperture of 445μm.

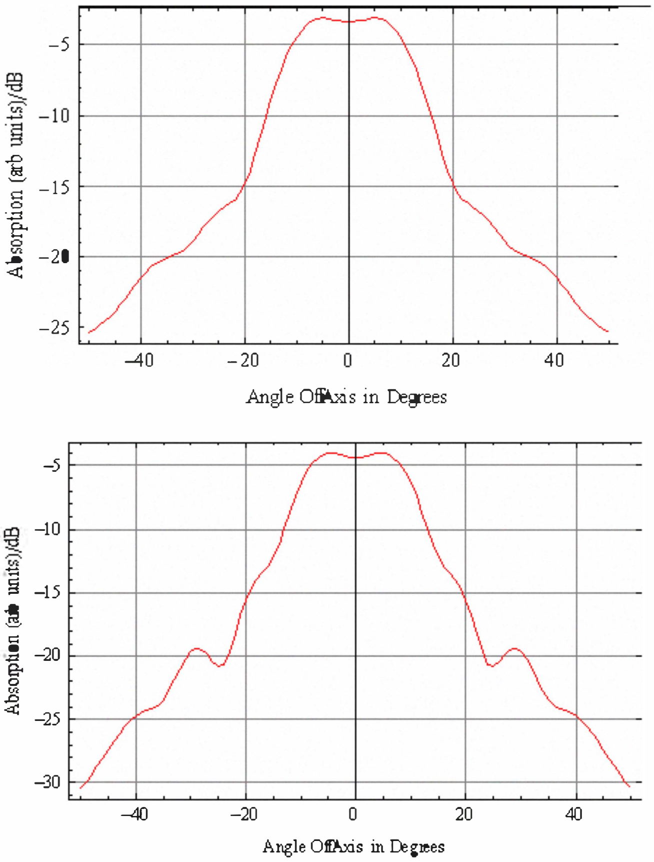

Figure 2: Comparison of patterns for case of black body excitation of the waveguide feeding the horn and the case with a lossy dielectric absorber in the cavity.

Knowledge of the true eigenfields (particular combinations of waveguide modes) are determined by the eigenvectors of [S11]†* [S11], and represent those fields that are reflected completely and those that are partially absorbed when a resistive sheet is placed in the integrating cavity behind the horn as illustrated in figure 1. Such eigenfields are propagated to the farfield (figure 2) for two cases. We synthesize the reception pattern by adding in quadrature the far field patterns of those eigenfields which suffer some absorption (figure 1). The individual eigenfields on the sky can be written as a coherent sum of the farfield patterns of waveguide mode patterns using the mode coefficients derived from the eigenvectors of [S11]† [S11], (i.e. the component wave guide modes which make up the basis set for the description).

The first farfield in figure 2 is for an ideal blackbody integrating cavity where all modes are equally excited. The second farfield plot illustrates the calculated farfield when the true nature of the cavity is included. It can be seen that there is some difference in the patterns at low levels due to not modes being truly excited when the geometry of the cavity and absorber are included.

We have developed a technique to include the absorbing material placed in an integrating cavity where the sheet resistance may be altered to see what fraction of the incident power is absorbed with multiple reflections within the cavity. The mode matching code with the inclusion of a resistive sheet description of an absorbing layer was applied to a multimoded SAFARI-like type geometry. A cross section of the cavity geometry implemented in the mode matching technique is shown below in figure 3. The sheet resistance of the absorber is set to $Z_0/2$. The bandwidth of is taken from 30 to 70μm. The absorber diameter is 75μm, about 1.5 times the central wavelength.

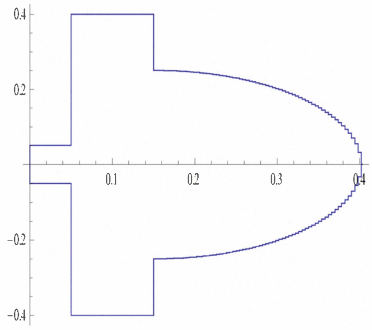

Figure 3, representative cavity geometry implemented in the mode matching code.

The number of true modes propagating in the waveguide structure feeding the cavity (without an absorber) n is initially calculated using the singular values of the S_{11} scatter matrix for the system. We calculate the power absorbed by the absorber by measuring the power reflected (from the S_{11} scatter matrix) from the waveguide when unity power is launched into the cavity in each propagating mode in the waveguide. Without the absorber present all power is reflected from the cavity structure. When the absorber is then introduced to the model we see the large drop in reflected power indicating that that most power incident on the cavity is absorbed after multiple reflections within the structure from which the effective number of modes coupled to the cavity can be estimated. The cavity structure in the model requires a waveguide input section to insure no evanescent modes are present at the input aperture.

Presented in figure 4 is a plot of the number of modes propagating in the cavity structure in red and the efficiency of the absorption over the band is also plotted in blue (which yields the effective number of modes propagating n_{eff}). This efficiency represents the fraction of the total modal power propagating towards the cavity in the waveguide that is successfully coupled to the absorber which on average over the band is roughly 85%.

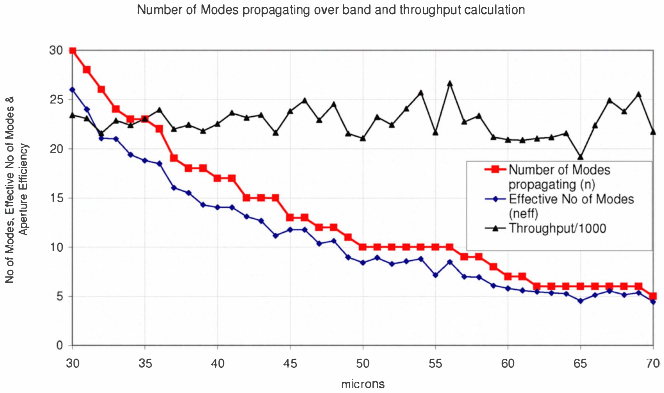

Figure 4: Plot of the total number of modes propagating in the cavity structure illustrated in figure 3 for the SAFARI short wavelength band. The effective number of modes plot represents the fraction of this total modal power successfully coupled to the absorber placed in the cavity illustrating high levels of absorption.

III. CONCLUSIONS

In this paper we have outlined the techniques applied to model the complete SAFARI pixel where the sensitive TES detectors will be housed including a horn integrating cavity and absorber. Using a mode matching approach it is possible to model all components in an efficient manner and predict beam patterns and optical efficiency in a computationally straight forward manner.

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