Rectangular to Large Diameter Conical Corrugated Waveguide Converter Based on Stacked Rings

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***Abstract*—This paper considers the design and manufacture, using stacked rings, of a standard corrugated antenna for the WM-380 band for use as a converter from a WM-380 rectangular aperture to a large diameter conical corrugated waveguide. In-house mode matching software is utilised for the design and three prototypes manufactured using stacked rings. The level of agreement of the stacked ring prototypes with the design predictions for the return loss and HE$_{11}$ modal coupling is measured and found to demonstrate high levels of agreement.**

***Index Terms*—mode matching, antenna, measurement**

I. Introduction

A modular set of compact circular corrugated wave-guiding components based on stacked rings technology has been demonstrated to yield broadband and low loss performance when compared to standard rectangular waveguides [1]. This low loss performance is attributed primarily to the propagation of the HE$_{11}$ mode inside of circular corrugated waveguides. In order to combine this technology with a vector network analyser it is necessary to transition from the standard rectangular waveguide to the large corrugated conical waveguide. This can be accomplished using a step transition to a smooth conical waveguide, followed by a transition to a corrugated waveguide with a subsequent flare out to the desired diameter.

As the goal is to couple power into a straight waveguide section it is also assumed that for optimum performance the phase radius of curvature should be maximised. As such, both a linear and a sine-squared flare profile are considered, and their performance examined as a function of total length / number of ring elements. This considers the benefit of the larger phase radius of curvature yielded by the profiled flare versus the greater conversion to higher order modes.

Ultimately, this work considers the applicability of in-house mode matching code for the design of such a three stage converter, and most importantly examines the reliability of the stacked rings technology at producing the design predictions yielded by simulation.

II. Design Procedure

Mode matching is an efficient technique for the electromagnetic simulation of waveguide structures. The basis of the technique lies in the assumption that the field power distribution of a waveguide can be described as the sum in quadrature of the waveguide TE and TM modes. Consequently, one may propagate a field through a uniform segment of constant dimension by considering the propagation of the supported component modes individually, before recombining the modes to provide the resulting field. This yields a fast and computationally non-intensive performance when compared with standard finite element alternatives. The work reported on in this paper made use of the SCATTER mode matching code developed at Maynooth University [2] [3].

The S$_{21}$ matrix for a given design is calculated using SCATTER and the aperture field constructed by considering the complex field distribution of the individual modes. This allows for the coupling coefficient, η, between the converter's aperture field E_{A} and the desired field distribution E to be calculated (see equation 1).

$$\eta = \frac{\langle E_{\mathrm{A}}|E\rangle}{\sqrt{\langle E_{\mathrm{A}}|E_{\mathrm{A}}\rangle\,\langle E|E\rangle}} \tag{1}$$

The creation of the converter geometry was further integrated into the code so as to allow for a series of parametric sweeps to be considered. Inside of a single parametric sweep the appropriate geometry was created, the corresponding scattering matrices and aperture field calculated, and the coupling to the desired field established. The following outlines the results of this analysis.

The goal of the final design is to allow for low loss transmission through a sealed conical corrugated waveguide network, 5 mm in diameter, initially fed by a standard rectangular WM-380 aperture. The design of the convertor was separated into three steps, and the coupling to a flat phase HE$_{11}$ mode adopted as the appropriate metric. These steps included:

- the transition from the rectangular to a smooth circular waveguide,
- the transition from a smooth to a corrugated waveguide and the excitation of a balanced hybrid mode, and
- the expanding of the corrugated waveguide diameter to that specified and transition into the straight section.

Given the compatibility with the stacked rings methodology a two step transition from the rectangular to a smooth circular waveguide was selected. The transition was designed to minimise the impedance mismatch between the fundamental rectangular TE$_{10}$ and the circular TE$_{11}$ mode. A first step in accomplishing this involved matching the guide wavelengths of the relevant modes, see equations 2, 3 and 4 where λ_c refers to the cut on wavelength of a mode and $p\prime_{mn}$ refers to the roots of the bessel function. To further assist in accomplishing this the inner radius of the conical guide remained a free variable through this process.

$$\lambda_{\text{guide}} = \frac{\lambda_{\text{freespace}}}{\sqrt{1 - \left(\frac{\lambda_{\text{freespace}}}{\lambda_c}\right)^2}} \tag{2}$$

$$\lambda_c^{\text{rec}}(m,n) = \frac{2}{\sqrt{\left(\frac{m}{2}\right)^2 + \left(\frac{n}{2}\right)^2}} \tag{3}$$

$$\lambda_c^{\text{circ}}(m,n) = \frac{2\pi r}{p\prime_{mn}} \tag{4}$$

Additionally two non-standard rectangular step pieces were designed to minimise reflections while extending the spatial extent of the TE_{10} mode. Furthermore, to adhere to specified manufacturing constraints each successive rectangular step was constrained to be larger in all planes to that previous. A graphical representation of the final design can be seen in figure 1 and its performance in figure 2, which met the specified criteria of the return loss remaining below a value of -20 dB.

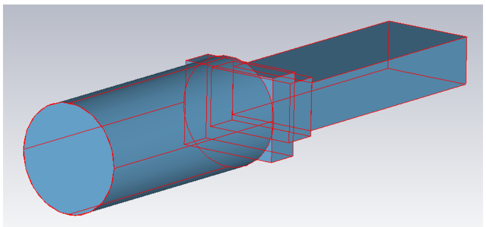


Fig. 1. Graphical representation of the two step rectangular to circular convertor section

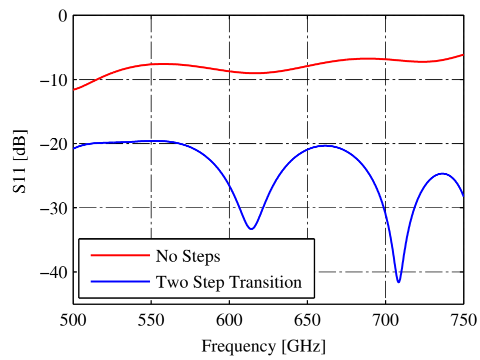


Fig. 2. The return loss from the rectangular to circular junction with and without the two step transition pieces

The smooth conical waveguide section was set a total axial length of 1 mm, corresponding to approximately two wavelengths, this further mitigates against the possibility of higher order modes being coupled into by the rectangular aperture.

The transition from this smooth to a corrugated waveguide focuses on matching the TE_{11} to an HE_{11} mode while minimising return loss and the excitation of the HE_{12} mode. As before the reflection coefficient ρ is best minimised by matching the guide wavelengths, see equation 5, although in this situation the two modes in question have different dependencies on frequency and so the aim becomes ensuring acceptable impedance values are achieved over the desired band. The slot depth of the corrugations and their profile must be chosen so as to avoid sharp variations in the guide wavelength and also not excite the HE_{12} mode, one possible procedure for achieving this is outlined in [4].

$$|\rho| = \frac{\lambda_{g2} - \lambda_{g1}}{\lambda_{g2} + \lambda_{g1}} \tag{5}$$

The third and final stage in the converter now expands the corrugated waveguide to the 5 mm diameter transmission corrugated guide, and forms a match with the corrugation parameters between the two. The primary strategy adopted was to attempt to maintain the HE_{11} content achieved thus far by minimising any further mode conversion. Essentially, a low flare angle linear taper should achieve this, however this would result in a non-flat phase radius of curvature which could impact on the coupling to the final straight section conical corrugated guide.

As such, the effect of adopting a sine-squared profile to flatten the phase front while supporting greater levels of mode conversion was examined. This profile is described in equation 6, where $a(z)$ refers to the diameter at a distance z along the axis of propagation, L the total axial length, and A the extent of the profile. A value of $A = 0$ reverts to a linear taper, while a value of $A = 1$ provides the most extreme sine-squared profile.

$$a(z) = a_1 + (a_2 - a_1)\left[\frac{z}{L}(1 - A) + A\sin^2\left(\frac{2\pi}{2L}\right)\right] \tag{6}$$

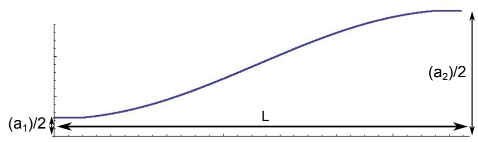


Fig. 3. An example of a smooth sine-squared profile as descriped by equation 6, A=1

At this point the SCATTER mode matching software was used to conduct a trade-off analysis in assessing the benefit of supporting higher levels of mode conversion with a sine-squared profile in order to flatten the phase front. The standard metric of coupling to a flat phase HE_{11} mode was adopted, see equations 1 and 8.

$$E_{\text{HE}_{11}} = J_0(2.405\frac{r}{a})e^{i\frac{\pi r}{\lambda R}} \tag{7}$$

$$E_{\text{HE}_{11}}(R = \infty) = J_0(2.405\frac{r}{a}) \tag{8}$$

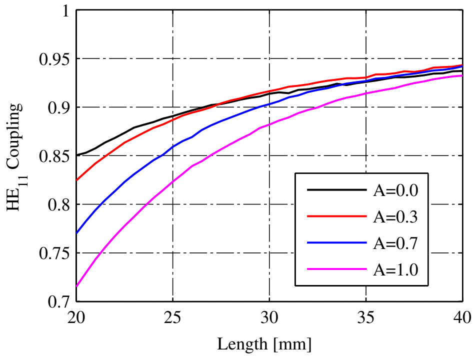


Fig. 4. Parameter sweep results describing the coupling of the convertor output to a flat phase HE$_{11}$ mode for varying profiles and lengths at the center of the WM-380 band (625 GHz).

The results of this trade-off analysis are displayed in figure 4 and examine the level of HE$_{11}$ coupling versus the total length and extent of the applied profile. One observes that the gain in flattening the phase front provided by the profiled designs is not sufficient to compensate for the higher levels of mode conversion induced along the length of the profile, for lengths of less than 28 mm. A minor profile, corresponding to a value of $A \leq 0.3$, appears beneficial for lengths greater than 28 mm, and a more significant profile defined by $A \leq 0.7$ for lengths greater than 34 mm. However, the increase in coupling efficiency is marginal, of the order of 0.01, and as such a linear design 28 mm in length was adopted for prototyping.

III. Prototype Manufacture & Characterisation

Three prototypes of this design were manufactured by SWISSto12 using their patented stacked rings technology [5], [6], where corrugations are built by alternately stacking two sets of metallic rings having the same external shape but different inner diameters and thickness inside a guiding pipe (see figure 5).

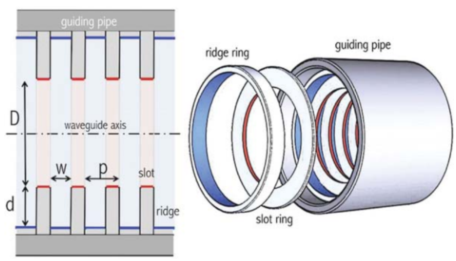


Fig. 5. A schematic view of the stacked ring process for the construction of corrugated structures.

A photograph of one of these converters is displayed in figure 6. The coupling to a flat phase HE$_{11}$ mode of the prototypes was determined by measuring the field distribution a known distance in front of the converter using a frequency extension module on a translation stage connected to a Vector Network Analyser (VNA), see figure 7.

(a) Manufactured converter WM-380 interface

(b) Manufactured converter 5 mm conical corrigated interface

Fig. 6. Front and rear views of a manufactured prototype.

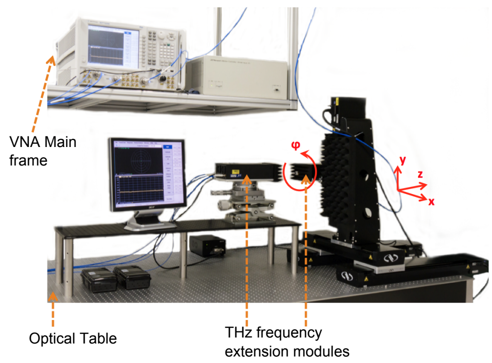
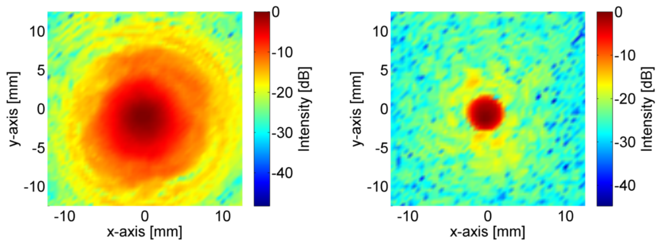


Fig. 7. VNA Lab setup



(a) Measurement plane 2.5 cm in front of converter aperture

(b) Converter aperture plane

Fig. 8. The field distribution as measured 2.5 cm in front of the converter and after back propagation to the aperture plane.

The measured complex field was analysed by propagating it back to the converter aperture using the complete diffraction integral of equation 9, where r is the propagation vector representing the distance between any point in the observation plane at z$_j$ and the input plane at z, (x,y,z$_i$) are the waveguide aperture plane coordinates, and (x′,y′,z$_j$) are the measurement plane coordinates. This procedure is outlined in detail in [7]. A comparative sample of the two field distributions can be seen in figure 8 for the centre of the WM-380 band (625 GHz).

$$u(x, y, z_i) = \frac{1}{2\pi} \int\int u(x\prime, y\prime, z_j) \frac{\partial}{\partial z} \left(\frac{\exp(ikr)}{r} \right) \mathrm{d}x\prime \mathrm{d}y\prime \tag{9}$$

The results of the measurements, as well as those of the mode matching simulations, are displayed in figure 9. While variation does exist between the three converter prototypes all measurements appear to follow the trend predicted by simulation. Further work is required in refining the measurement procedure, after which any variation in performance between the manufactured prototypes will be more carefully investigated.

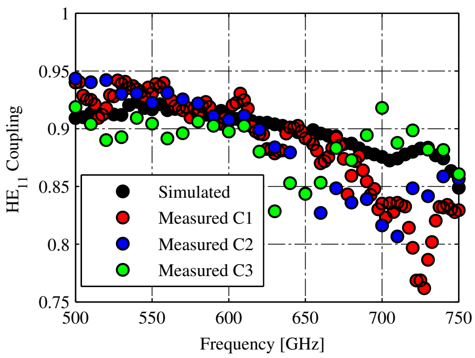


Fig. 9. The measured HE_{11} coupling of the three converter prototypes vs. that predicted by the mode matching simulations.

The return loss of the converters was also measured on the Vector Network Analyser by recording the S_{11} while allowing the converter to radiate to free-space. The results of these measurements were found to be in good agreement with the simulated predictions and can be seen in figure 10; to illustrate the level of variation between different manufactured prototypes the results for two converters are displayed.

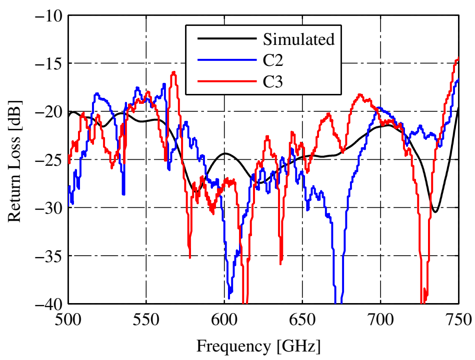


Fig. 10. The return loss as measured for two converters vs the simulated performance

IV. Conclusion

This work has considered the application of stacked rings technology for the manufacture of a WM-380 band corrugated antenna designed for the purpose of converting from the standard rectangular aperture to a large diameter (5 mm) corrugated waveguide.

The design procedure was outlined and some of the trade-off's to be considered in such a design explored, such as the potential benefit of applying a sine-squared profile to the flared section. As the goal was to develop a convertor to allow for low loss transmission through a waveguide network the coupling to a flat phase HE_{11} mode was adopted as the most appropriate metric, and a linear flared design 28 mm in length was ultimately selected for prototyping.

Three prototype converters were successfully manufactured using the stacked rings method of SWISSto12 and characterised using a vector network analyser. The return loss was demonstrated to follow the trend predicted by the mode matching simulations, with some variation existing between prototypes below the -20 dB level.

The HE_{11} performance was calculated by back propagating the measured complex field distribution to the aperture of the converter and the results were demonstrated to again follow the trend predicted by the design simulations. Further work is still to be conducted in evaluating the precision of the HE_{11} measurements. After which, future work will also examine the impact of improving the mechanical tolerances.

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