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EFFICIENT ANALYSIS AND DESIGN OF COMPENSATED TURNSTILE JUNCTIONS USING ADVANCED MODAL TECHNIQUES

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Abstract—In this work, the efficient analysis and design of optimised turnstile junctions showing low reflection coefficient is investigated. For this purpose, a rigorous multimodal analysis of compensated junctions is developed, which is based on the computationally efficient 3-D Boundary Integral-Resonant Mode Expansion (3-D BI-RME) technique. The electrical performance of the standard

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turnstile junction has been drastically improved by compensating this microwave component using piled-up partial-height cylindrical metallic posts placed on the base of the junction. Moreover, the authors demonstrate that improved designs can be derived by compensating the turnstile junction using one single cylindrical post, which is easier to manufacture than a piled-up post, and it is a more robust element to confront high-power effects. This novel Computer-Aided Design (CAD) tool has been verified through excellent comparisons between the obtained results and those provided by the technical literature, and also by a well-known commercial finite-element method software.

1. INTRODUCTION

The turnstile junction is a five-port microwave network with unique applications in many passive waveguide devices that operate at microwave and millimeter-wave frequencies, such as orthomode transducers, four-way power dividers, circulators, diplexers and multiplexers, and equipment for measuring the degree of ellipticity of waves [1, 2]. In spite of the important properties that the turnstile junction shows, few contributions in the technical literature are focused on its accurate multimodal analysis.

Over the last years, modern wideband telecommunications systems are increasingly demanding higher transmission bitrates, which has led to extend the usable frequency range of a great variety of microwave devices, such as right-angled bends, T-junctions, magic T junctions and turnstile junctions, by employing different compensation techniques [3–6]. With regard to the compensation of turnstile junctions, in [2] a metallic square prism is employed to enable a broadband operation of the presented turnstile junction, in [7] a metallic pyramid is placed on the base of a turnstile junction to achieve a wider operation bandwidth for the designed orthomode transducer, and in [8] a double-cylindrical structure is used to improve the electrical performance of the designed turnstile junction.

In all compensated cases, a commercial finite-element or finite-integration method software was used to optimise the electrical performance of the turnstile junctions. If an efficient full-wave CAD tool had been used to design these junctions, a drastical reduction of memory and CPU-time requirements would have been achieved in the design process. Therefore, refined designs of turnstile junctions with improved electrical response could be potentially derived.

Apart from using commercial software based on segmentation techniques for the accurate modeling of multiport waveguide junctions, their full-wave analysis can also be performed using the mode-matching method combined with different techniques such as the Fourier Transform, the Moment Method or the Multiple Cavity Modeling [9–13]. In this work, we propose to use a more advanced modal technique, i.e., the 3-D Boundary Integral-Resonant Mode Expansion (3-D BI-RME) method [14], for the efficient and optimized design of compensated turnstile junctions.

The compensation technique considered in this paper, which is based on the introduction of an N-step partial-height cylindrical metallic post placed on the base of the structure (see Fig. 1), aims to extend the usable frequency range of the junction thus achieving a low reflection coefficient in a wider operation band. Moreover, a novel contribution of this paper is that we demonstrate that the electrical performance of the turnstile junction can be further improved by using a simpler compensating element, i.e., a single cylindrical post. This post is easier to manufacture than a piled-up structure, it is a more robust element to face high-power effects and it presents lower losses than more complex N-step posts.

This work is, in fact, an extension of the contribution presented in [5], where several compensated multiport junctions involving only rectangular waveguide access ports were designed. In that contribution, the electrical performance of a great variety of multiport rectangular waveguide junctions (up to 4 access ports) was optimised

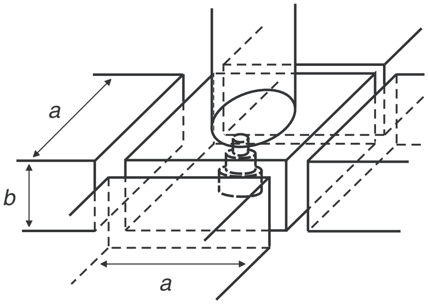

Figure 1. Turnstile junction with a circular waveguide input port and four rectangular waveguide output ports whose transversal dimensions are $a \times b$. The turnstile junction is compensated using an N-step partial-height cylindrical metallic post.

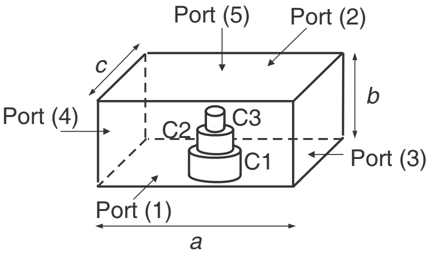

Figure 2. Basic building block: Five-port rectangular waveguide junction compensated with an N-step partial-height cylindrical metallic post of radii r_i and heights h_i ($i = 1, 2, 3$, since $N = 3$ in this figure).

following the same compensation technique stated before. In this work, we extend the theory presented in [5] to permit the full-wave analysis of five-port waveguide junctions, including also a circular waveguide access port and piled-up metallic posts.

2. THEORY

The turnstile junction shown in Fig. 1 can be analysed using the 3-D BI-RME method, which is a multimodal analysis technique for the wideband electromagnetic characterization of microwave components with arbitrary 3-D geometry. This method is very efficient from a computational point of view, and provides the generalised admittance matrix of the structure in the following form (see [14] for more details):

$$\mathbf{Y} = \frac{1}{jk\eta}\mathbf{Y}^{\mathrm{A}} + \frac{jk}{\eta}\mathbf{Y}^{\mathrm{B}} + \frac{jk^3}{\eta}\mathbf{Y}^{\mathrm{C}}, \quad k \le 2\pi f_{\max}\sqrt{\mu\epsilon} \tag{1}$$

where k is the wavenumber, η is the wave impedance, and the matrices $\mathbf{Y}^{\mathrm{A}}$, $\mathbf{Y}^{\mathrm{B}}$ and $\mathbf{Y}^{\mathrm{C}}$ are detailed in [5].

2.1. Multimodal Analysis of Compensated Waveguide Junctions

The analysis of the turnstile junction starts from the electromagnetic characterization of the basic building block depicted in Fig. 2 using the 3-D BI-RME method. This basic building block consists of a five-port rectangular waveguide junction, compensated with an N-step partial-height cylindrical metallic post of different radii and heights placed on the base of the structure (in Fig. 2 we have piled-up 3 cylinders: C1, C2 and C3). Moreover, we have to choose $c = a$ in Fig. 2 in order to represent the turnstile junction. The efficient characterization of this basic building block is performed following the procedure described in [5], which allows us to obtain a wideband generalised admittance matrix of this component.

Once the basic building block has been modeled, the full-wave analysis of the turnstile junction is completed by connecting a circular waveguide to the square waveguide port (5) represented in Fig. 2. The electromagnetic characterization of the planar junction between a circular and a rectangular waveguide has been carried out by implementing the integral equation technique described in [15]. This method provides a generalised impedance matrix representation of the planar junction under study, and has been typically used to analyse planar junctions between different waveguides. Finally, the two generalised matrices provided by the multimodal methods are properly connected through an efficient circuital theory, thus obtaining a full-wave representation of the turnstile junction.

The implemented integral equation technique is based on the calculation of the modal coupling coefficients between the two waveguides involved in the planar junction so, in our case, we need first to obtain the modal chart of a circular waveguide. To this aim, in this work we follow a new procedure based on expressing the radial variation of the modal solutions in terms of sinusoidal functions [16]. Proceeding in this way, the CPU-effort related to the calculation of the modal coupling coefficients is reduced, since we do not need to evaluate the more cumbersome Bessel functions that appear in the classical formulation.

2.2. Modal Chart of a Circular Waveguide

The vector mode functions of a circular waveguide can be obtained by solving the well-known Helmholtz equation:

$$\left(\nabla_t^2 + k_{t,m}^2\right) \Psi_m(\rho, \phi) = 0 \tag{2}$$

where $k_{t,m}$ is the cutoff wavenumber related to the m-th mode of the waveguide, and $\Psi_m(\rho, \phi) = R(\rho)\psi(\phi)$ represents the corresponding scalar potential function, which satisfies the Dirichlet or the Neumann boundary condition. Next, after expanding the Laplacian operator in cylindrical coordinates, it is easy to obtain the following differential equation with respect to the radial coordinate ρ:

$$\left(\frac{d^2}{d\rho^2} + \frac{1}{\rho}\frac{d}{d\rho} - \frac{s^2}{\rho^2}\right) R(\rho) = -k_{t,m}^2 R(\rho) \tag{3}$$

where s represents the modal index related to the azimuthal coordinate. The previous equation can be solved numerically using the Method of Moments by expanding the unknown radial function $R(\rho)$ in terms of an appropriate set of N_ρ basis functions of sinusoidal variation [16].

Next, we proceed to validate the numerical accuracy of this modal technique. In Table 1, we present the cutoff wavenumbers of a circular waveguide of radius 1.0 m related to several $\mathrm{TE}^z_{s,3}$ modes (the modal index in the radial coordinate is 3). In our analysis, we have considered $N_\rho = 75$ terms in the expansion of the radial function $R(\rho)$. The obtained results are in excellent agreement with those provided by [17], thus fully validating this modal analysis method. In addition, it is important to note that the first 950 TE^z or TM^z modes are calculated in only 0.2 seconds in a PC-Pentium IV@2.55 GHz (512 MB of RAM memory).

Table 1. Cutoff wavenumber of several TE^z modes of a circular waveguide of radius 1.0 m.

Modal	Cutoff wavenumber: $\mathrm{TE}^z_{s,3}$ (rad/m)		
index s	**Ref. [17]**	$N_\rho = 75$	**Relative error (%)**
0	10.17346814	10.17346814	$1 \cdot 10^{-6}$
1	8.53632	8.53631637	$4 \cdot 10^{-5}$
2	9.96947	9.96946814	$2 \cdot 10^{-5}$
8	17.77401	17.77401237	$1 \cdot 10^{-5}$
5	13.98719	13.98718863	$1 \cdot 10^{-5}$
6	15.26818	15.26818146	$1 \cdot 10^{-5}$
7	16.52937	16.52936588	$2 \cdot 10^{-5}$
8	17.77401	17.77401237	$1 \cdot 10^{-5}$

3. RESULTS

In order to validate the developed CAD tool, we first consider an uncompensated turnstile junction. We present in Fig. 3 the S-parameters of such junction implemented in the standard WR-62 rectangular waveguide ($a = 15.799$ mm, $b = 7.8995$ mm) with a circular waveguide input port of radius 6.99 mm. The ports are numbered following the notation presented in Fig. 2, being the circular waveguide the access port number (5). The obtained results are compared with the ones presented in [11] and a very good agreement is found. We observe that the electrical performance of the uncompensated turnstile junction does not present a low reflection coefficient (S_{55} in the figure) and, therefore, the transmission to the coupled output rectangular ports (1) and (2) is not appropriate for practical applications.

Next, our aim is to improve the electrical performance of the turnstile junction and, to this purpose, we compensate the structure by adding an N-step partial-height cylindrical metallic post ($N = 3$, as in Fig. 1) placed on the base of the junction in a centered position in order to preserve the symmetry of the component. We have investigated first a compensating post with $N = 3$ piled-up cylinders since this structure has been widely used in the classical technical literature dealing with turnstile junctions (see [18], for instance). The dimensions of the compensating post, which have been optimized to achieve a broadband operation, are $r_1 = 3.5$ mm, $h_1 = 1.8$ mm, $r_2 = 2.5$ mm, $h_2 = 1.5$ mm, $r_3 = 1.2$ mm and $h_3 = 1.8$ mm. The S-parameters of the compensated junction are shown in Fig. 4. In this figure, we have also added the electrical response of the uncompensated junction. We observe in Fig. 4

that the electrical performance of the junction, which is successfully compared with the data provided by Ansoft HFSS v10.0 (a commercial finite-element method software), has been improved. Moreover, the simulation of the junction with $N = 3$ piled-up posts has consumed 1.05 seconds of CPU-time per frequency point, thus demonstrating that the developed tool is very efficient for design purposes (HFSS required 1.84 minutes per frequency point).

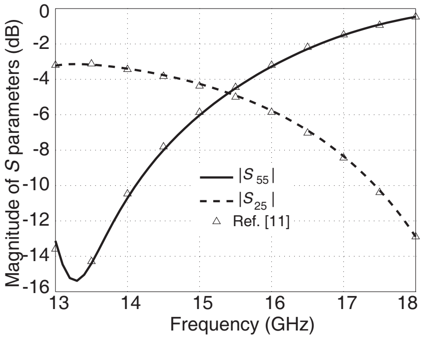

Figure 3. *S*-parameters of an uncompensated turnstile junction implemented in WR-62 rectangular waveguide with a circular waveguide of radius 6.99 mm.

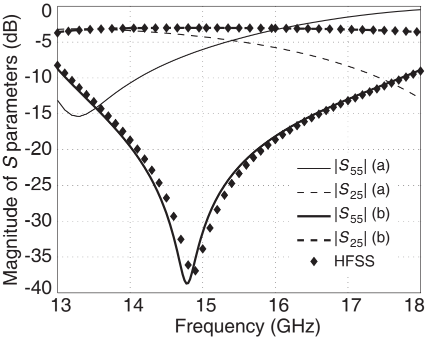

Figure 4. *S*-parameters of a turnstile junction: Uncompensated junction in (a) and compensated junction using piled-up cylindrical posts in (b).

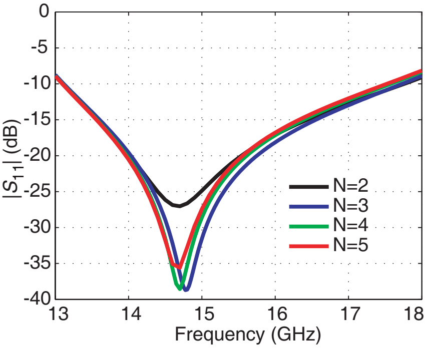

Figure 5. Influence of the number N of piled-up posts on the electrical response of the compensated turnstile junction.

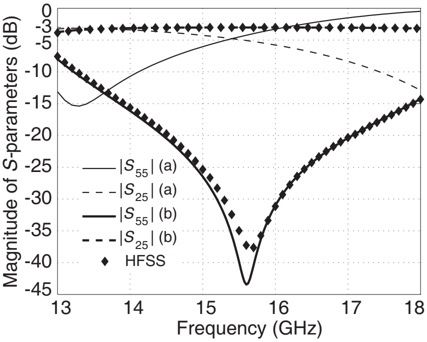

Figure 6. *S*-parameters of a turnstile junction: Uncompensated junction in (a) and compensated junction with only one cylindrical post in (b).

Next, in order to study the influence of the number N of piled-up cylindrical posts on the bandwidth of the junction, we have also investigated the electrical response for the following cases: $N = 2, 3, 4, 5$. To this aim, we start from the previous structure with $N = 3$ piled-up posts. Then, we have eliminated the upper post to consider the case in which $N = 2$ (a piled-up compensating post with $N = 2$ was proposed in [8]), and, afterwards, we have added the fourth and the fifth cylinders ($r_4 = 0.8\,\text{mm}$, $h_4 = 1.2\,\text{mm}$, $r_5 = 0.5\,\text{mm}$, $h_5 = 1.0\,\text{mm}$) to investigate the cases in which $N = 4$ and $N = 5$, respectively. We observe in Fig. 5 that the case in which $N = 3$ is the best one in terms of electrical response, when dealing with piled-up compensating posts. Moreover, the bandwidth of the junction is quite similar in all considered cases. The simulation of the structure with $N = 5$ piled-up posts required 3.6 seconds per frequency point.

Finally, the novel contribution of this paper lies in the fact that we have observed that the achieved electrical response for $N = 3$ posts can be further enhanced if we compensate the junction with only one cylindrical post of radius $r_1 = 3.5\,\text{mm}$ and height $h_1 = 3.0\,\text{mm}$. This single post is, in addition, easier to manufacture than a piled-up post, it is a more robust structure to confront high-power phenomena (multipactor and corona effects) and it presents lower losses than a piled-up post. The obtained results, which are presented in Fig. 6, show that the return loss parameter S_{55} has been minimized and the transmission to the coupled output rectangular ports ($S_{25} = S_{15}$) is around $-3\,\text{dB}$ in a wide frequency range of about 3 GHz. Moreover, the transmission to the uncoupled output ports (not represented in Fig. 6) is about $-170\,\text{dB}$ in the whole band. In Fig. 6 the obtained results are also compared with the data provided by HFSS and an excellent agreement is observed. The simulation of the junction has required 0.49 seconds of CPU-time per frequency point (HFSS needed 1.04 minutes per frequency point).

4. CONCLUSION

A rigorous technique for the efficient analysis and design of compensated turnstile junctions using partial-height cylindrical metallic posts has been presented. For the accurate and efficient design of this component, a full-wave analysis method based exclusively on advanced modal techniques has been employed. It has been also proved that the electrical performance of the turnstile junction can be improved by using a simpler compensating element, that is, one single cylindrical post.

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