Evaluation of low-cost manufacture techniques in the design of multi-port waveguide junctions

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Abstract

A new tool for the rigorous and efficient design of compensated multi-port waveguide junctions, considering the mechanization effects due to low-cost manufacture techniques, is presented. Several new designs for different H- and E-plane components, present in modern microwave and millimetre-wave equipment, are proposed taking into account the introduction of rounded corners in the rectangular waveguide access ports of the considered device. The new implemented tool permits to evaluate the potential degradation of the wide-band performance of such components prior to their fabrication, thus achieving an optimal design. All the presented results have been successfully validated by comparing the obtained simulated data with the results provided by a commercial software based on the finite-element method.

Keywords: Multi-port waveguide junctions, low-cost mechanization effects, full-wave methods.

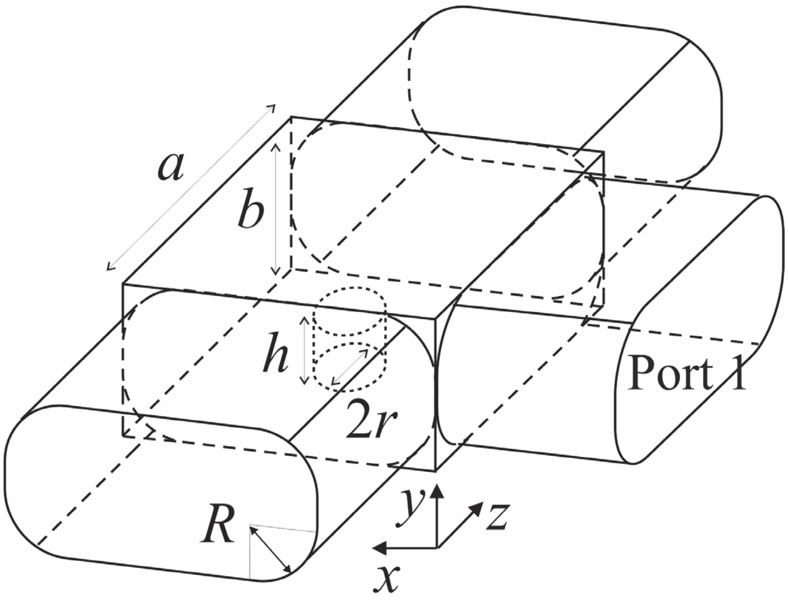
1. Introduction

Wide-band multi-port rectangular waveguide junctions are a topic of high interest in the field of modern microwave and millimetre-wave equipment, and they have been intensively investigated in the recent years [1–3]. They play an increasingly important role in the design of a great variety of microwave and millimeter-wave devices, such as power dividers/combiners [4–6], directional couplers [7], E-plane T-junctions [8, 9], double-ridge waveguide power dividers [10], waveguide bends and magic-T junctions [3, 11]. Traditionally, the usable bandwidth of these multi-port junctions has been optimized by compensating the structure using metallic insets, such as square prisms, pyramid tuning stubs, and cylindrical posts [12–15].

Moreover, it is usual to resort to low-cost waveguide device fabrication techniques, such as milling, in order to manufacture these optimized components. A common drawback of such previous techniques is the introduction of rounded corners in the cross-section of the waveguide access ports of the cited junctions, thus deteriorating the expected electrical response of the designed device and, therefore, limiting its desired wide-band performance [2]. Nevertheless, if computer-aided design (CAD) tools could accurately consider these undesired manufacture effects in the analysis stage, it would be possible to compensate them and achieve optimum electrical designs of such components easily implementable via low-cost fabrication techniques.

In this work, a novel full-wave CAD tool is proposed for the accurate and efficient design of compensated H-plane and E-plane multi-port waveguide junctions, taking into account the mechanization effects introduced by the low-cost production methods aforementioned. On the one hand, the proposed CAD tool allows the microwave designer to predict the electrical performance of the final manufactured device as a function of the radius of the considered rounded corners. On the other hand, it also enables to compensate for the degradation introduced in the frequency response of the device by redesigning the junction (i.e. modifying the position and/or the dimensions of the matching elements of the component) in order to achieve an optimum broadband operation.

In order to fully validate the presented CAD tool, new designs for a great variety of key components present in



■ **Figure 1.** H-plane T-junction compensated with a partial-height cylindrical metallic post.

many communication satellite subsystems are provided. In these devices, the effect of the rounded corners is considered, and partial-height cylindrical metallic posts, as well as matching irises, are used as matching elements. The first examples consist of new designs concerning compensated H- and E-plane right-angled bends and T-junctions. A more complex five-port device, specifically a compensated turnstile junction, considering these mechanization effects is also reported. For instance, an H-plane T-junction compensated with a partial-height cylindrical metallic post of radius r and height h has been depicted in Fig. 1. Note that rounded corners of radius R have been introduced in the waveguide access ports to take into account the mechanization effects due to the use of low-cost production techniques. Furthermore, it is important to note that, if rectangular waveguide E-plane components are going to be considered, the optimization of the frequency response of the designed junction usually requires the insertion of a matching iris in the E-plane arm of the structure [3].

Finally, it is worth mentioning that this work provides, for the first time to the authors' knowledge, a rigorous combination of 2-D and 3-D Boundary Integral-Resonant Mode Expansion (BI-RME) techniques [2, 16, 17] for the efficient analysis and design of compensated multi-port waveguide junctions considering mechanization effects. In this respect, note that the novelty of this work lies on the fact that previous works of the authors did not considered the presence of rounded corners in the analyzed multi-port junctions (i.e. [3, 14, 18]) or did not deal with the design of compensated multi-port junctions using the 3-D BI-RME technique (i.e. [2]). As a consequence, the work developed in this work, not only constitutes a noteworthy extension of authors' previous contributions, but also provides a novel and very efficient CAD tool aiming at improving the relative bandwidth of a great variety of compensated waveguide junctions considering mechanization effects.

2. Full-wave analysis of multi-port waveguide junctions considering mechanization effects

The implemented full-wave CAD tool is mainly based on the BI-RME method. In particular, the 2-D BI-RME method is applied to obtain both the modal chart and the expressions of the vector modal functions of a rectangular waveguide with rounded corners of radius R. To this aim, the rigorous technique detailed in [2, 16] has been followed. This multimodal technique has been combined with the 3-D BI-RME method [17], which yields a generalized admittance matrix (GAM) of arbitrarily shaped cavities, to finally provide a wide-band electromagnetic characterization of the whole structure.

To illustrate this concept in more detail, we start by considering the compensated H-plane T-junction depicted in Fig. 1. In order to analyze this component, the 3-D BI-RME method can be first employed to derive the GAM of the central boxed cavity, which has been loaded with a partial-height cylindrical metallic post, and considering N standard rectangular waveguide access ports of dimensions a and b (N=3 in Fig. 1). The elements of the GAM can be obtained as:

$$Y = \frac{1}{jk\eta} Y^A + \frac{jk}{\eta} Y^B + \frac{jk^3}{\eta} \sum_{i=1}^{M} \frac{y^{(i)} y_T^{(i)}}{\kappa_i^2 - k^2}$$

where k is the wavenumber; η is the wave impedance; matrices Y^A and Y^B are real, symmetric and frequency-independent; κ_i represent the resonant wavenumbers of the short-circuited boxed cavity, and vectors $y^{(i)}$ are related to the eigenvectors associated to κ_i (see [17] for more details on this formulation).

Once the central boxed cavity has been characterized, the next step consists of analyzing the planar waveguide junctions found in the component. On the one hand, several planar junctions between a rectangular waveguide (i.e. a face of the central boxed cavity) and an arbitrarily shaped waveguide (i.e. rectangular waveguide with rounded corners) need to be analyzed in order to achieve a full-wave characterization of H-plane components, as the H-plane T-junction shown in Fig. 1. On the other hand, E-plane components manufactured by means of low-cost production techniques, present planar junctions between arbitrarily shaped waveguides (i.e. rectangular waveguides with rounded corners), which can be found in the E-plane arm of the structure. For instance, an E-plane T-junction with rounded corners in all the rectangular waveguide access ports has been depicted in Fig. 2 (the different building blocks of such E-plane T-junction have been disassembled for the sake of clarity). Note that, as a consequence of the insertion of a matching iris in the E-plane arm of the junction, several discontinuities between arbitrary waveguides can be observed in the cited E-plane arm.

With the aim of characterizing the different planar junctions of the analysed components, the efficient integral equation technique described in [19] has been implemented, which provides a full-wave characterization of the discontinuity in terms of an equivalent generalized impedance matrix (GIM). In order to derive such GIM, the coupling coefficients between the modal sets of the waveguides involved in the considered junction need to be first calculated. Note that, as this computation always involves a standard rectangular waveguide in the case of H-plane components, the procedure detailed in [20] can be implemented with the aim of achieving an efficient software tool. However, since the design of E-plane components force the appearance of planar junctions between arbitrarily shaped waveguides (see Fig. 2), the technique described in [20] cannot be longer used directly, and a new strategy is required to efficiently compute the aforementioned modal coupling coefficients.

This work provides a rigorous combination of 2-D and 3-D Boundary Integral-Resonant Mode Expansion (BI-RME) techniques for the efficient analysis and design of compensated multi-port waveguide junctions considering mechanization effects.

Such strategy starts from expressing the vector modal functions $e^{(A)}$ of the arbitrarily shaped waveguides in terms of the vector mode functions $e^{(R)}$ of their corresponding external rectangular contours:

$$e_p^{(A)} = \sum_{q=1}^{\infty} \gamma_{p,q}^{(A,R)} \, e_q^{(R)}$$

where the auxiliary coupling coefficients $\gamma_{p,q}^{(A,R)}$ can be readily computed by using the method explained in [20]:

$$\gamma_{p,q}^{(A,R)} = \int_{S_A} e_p^{(A)} \cdot e_q^{(R)} \, dS$$

The desired modal coupling coefficient $\Gamma_{m,n}$ between the m-th vector mode function of the arbitrarily shaped waveguide A_1 (bigger waveguide whose external rectangular contour is denoted by R_1) and the n-th vector mode function of the arbitrarily shaped waveguide A_2 (smaller waveguide whose external rectangular contour is denoted by R_2) can be now derived in the following form:

$$\Gamma_{m,n} = \int_{S_{A_2}} e_m^{(A_1)} \cdot e_n^{(A_2)} dS = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \gamma_{m,i}^{(A_1,R_1)} \gamma_{n,j}^{(A_2,R_2)} \int_{S_{R_2}} e_i^{(R_1)} \cdot e_j^{(R_2)} dS$$

Note that the last surface integral in the previous equation involves vector mode functions related to standard rectangular waveguides and, therefore, it can be analytically computed. Moreover, the authors have verified that only 150-200 terms are typically needed to achieve convergent results in the previous two-fold summation, provided that 20-30 accessible modes are considered in the equivalent multimodal network.

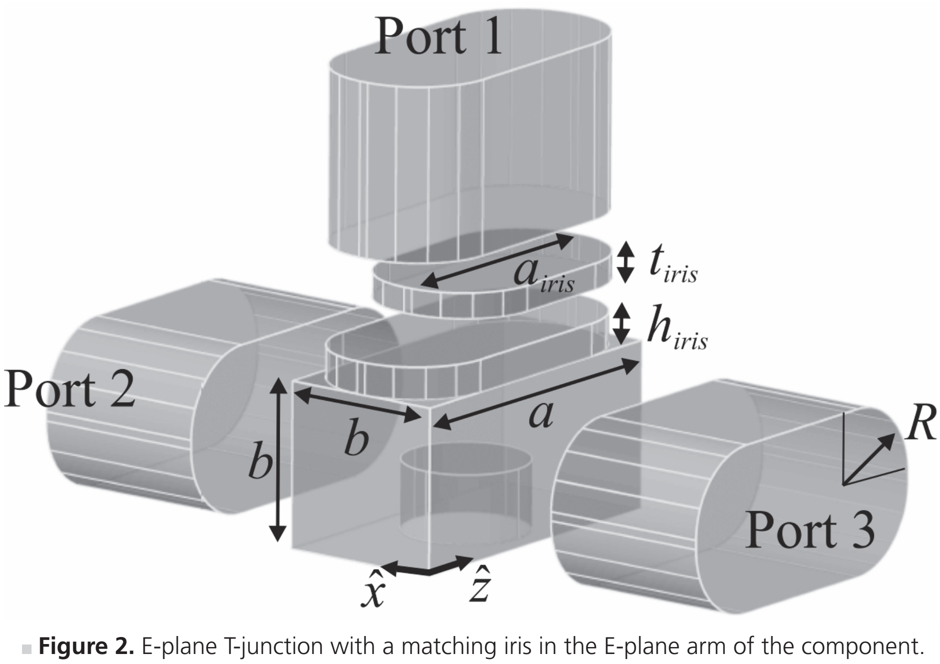


Figure 2. E-plane T-junction with a matching iris in the E-plane arm of the component.

Finally, all the obtained matrices (generalized impedance and admittance matrices) are properly connected to provide the electrical performance of the complete device. To this aim, it is worth mentioning that, for the sake of improving even more the computational efficiency of the implemented tool, an equivalent hybrid immittance matrix is derived for the characterization of the whole structure enabling only one matrix inversion per frequency point, and thus significantly reducing the overall CPU effort.

3. Design of multi-port waveguide junctions considering mechanization effects

In this section, we present new designs concerning compensated H- and E-plane right-angled bends and T-junctions, taking into account the mechanization effects introduced by the low-cost production of such components. The design of a more complex five-port device of a great technological interest, i.e. a compensated turnstile junction, is also discussed. In all cases, the obtained simulated results have been successfully validated using the numerical data provided by a commercial finite-element method software. With the aim of achieving convergent results for all the new designs presented in this work, we have required to use 25 accessible modes in each waveguide port and 275 resonant modes in the boxed cavity. In addition, the authors have verified that convergence properties of the method are not dependent on the post and rectangular cavity dimensions. Furthermore, for design purposes, the authors have followed the practical design procedures detailed in [21] to achieve an optimal electrical performance.

3.1. Design of compensated H-plane right-angled bends

A compensated H-plane right-angled bend is a two-port device that can be readily obtained starting from the three-port component depicted in Fig. 1, after short-circuiting the port placed at $z = a$. Next, Fig. 3 shows the variation of the electrical performance of a new designed compensated H-plane right-angled bend considering the presence of rounded corners of radius R in the two waveguide access ports. It is important to note that the curve $R=0$ stands for the case in which standard rectangular waveguides are considered and, therefore, the mechanization effect is not present. Besides, it is worth mentioning that the electrical performance of this new design with $R=0$ has been drastically improved with respect to the frequency response originally presented in [3] (see the blue dashed curve in Fig. 3).

In this case, the bend is implemented in WR-90 standard waveguide ($a=22.86$ mm, $b=10.16$ mm), the radius and height of the compensating post are $r=0.5$ mm and $h=8.75$ mm, respectively, and its relative position within the rectangular cavity (according to the axis system depicted in Fig. 1) is given by $x_0 = z_0 = 15.5$ mm. Moreover, a very good agreement is observed between the obtained results and the numerical data provided by a finite-element method (FEM) commercial software.

It is possible to observe in Fig 3 that the return losses of the bend deteriorates as the radius of the considered rounded corners increases. Lower values of the radius (e.g. $R=1$ or $R=2$ mm) do not change significantly the frequency response of the device. However, when higher values of the radius are considered (e.g. $R=4$ or $R=5$ mm),

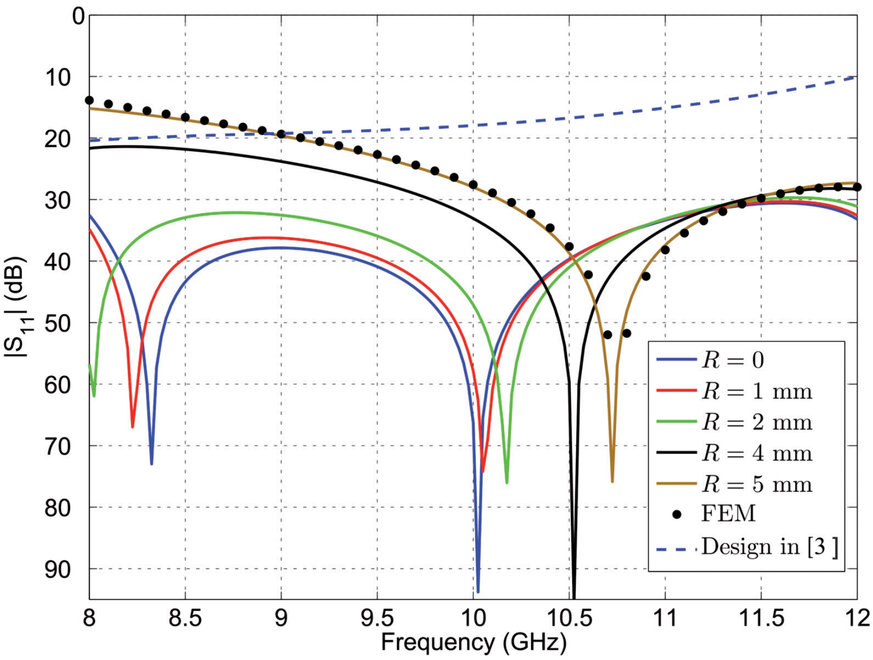


Figure 3. Return losses of a compensated H-plane right-angled bend. Rounded corners of radius R have been considered in the waveguide access ports.

the usable bandwidth of the device and its overall electrical performance are seriously affected. In these cases, it is possible to compensate for this degradation by re-designing the compensating post using the proposed CAD tool. As it is represented in Fig. 4 using solid curves, an optimized electrical performance of the final manufactured device has been provided. The new dimensions and relative positions of the post have been inserted in the figure. Finally, it is important to mention that the simulated results presented in this section were computed in just 0.02 seconds per frequency point (Intel Core i3@3.1 GHz - 4 GB RAM), thus demonstrating the high computational efficiency of the developed tool.

3.2. Design of compensated H-plane T-junctions

A new design concerning compensated H-plane T-junctions (see Fig. 1), considering the introduction of rounded corners of radius *R* in all the rectangular waveguide access ports, is discussed in this section. The electrical performance of this component, which is widely used in modern diplexers and multiplexers, is investigated in Fig. 5.

The T-junction has been implemented in standard WR-75 waveguide ($a=19.05$ mm, $b=9.525$ mm), the radius of the compensating post is $r=0.454$ mm, its height is $h=8.8$ mm, and its relative position is $x_0=a/2$, $z_0=11.525$ mm. It is important to note that, with respect to the previous results presented in [14], this new design (case for $R=0$) has significantly improved the return losses of the component.

With this design we conclude that, neither the wideband operation of the T-junction nor its overall electrical performance, are significantly affected by the introduction of the rounded corners and, therefore, further optimizations of the component are not required in this case. In fact, note that, even for higher values of the radius (e.g. $R=4.5$ mm), the usable bandwidth of the device under -20 dB remains almost invariable (observing only a frequency shift). Finally, regarding the computational efficiency of the implemented CAD tool, the complete analysis of the T-junction only took 0.03 seconds per frequency point.

3.3. Design of compensated turnstile junctions

A turnstile junction is a five-port microwave network composed of four rectangular waveguide ports and one circular waveguide port (see the inset of Fig. 6). This component, which is a key element in modern orthomode transducers, can be obtained starting from the structure shown in Fig. 1, by adding a fourth rectangular port at $x=a$, and an input circular waveguide port at $y=b$[18].

The electrical performance of a compensated turnstile junction (circular waveguide of radius 1.26 mm) implemented in WR-10 rectangular waveguide ($a=2.54$ mm, $b=a/2$), and considering the rounded corners effect in all the rectangular waveguide ports, is shown in Fig. 6. In contrast to the previous analyzed components, where a single cylindrical post was used as a compensating stub, this device is compensated using five piled-up cylindrical posts located in a centered position. The radii (in mm) of the piled-up cylindrical posts used in the design are (from bottom to top): $r_1=0.84$, $r_2=0.4$, $r_3=0.23$, $r_4=0.18$, $r_5=0.15$. The heights (in mm) are: $h_1=0.29$, $h_2=0.31$, $h_3=0.2$, $h_4=0.3$, $h_5=1.75$.

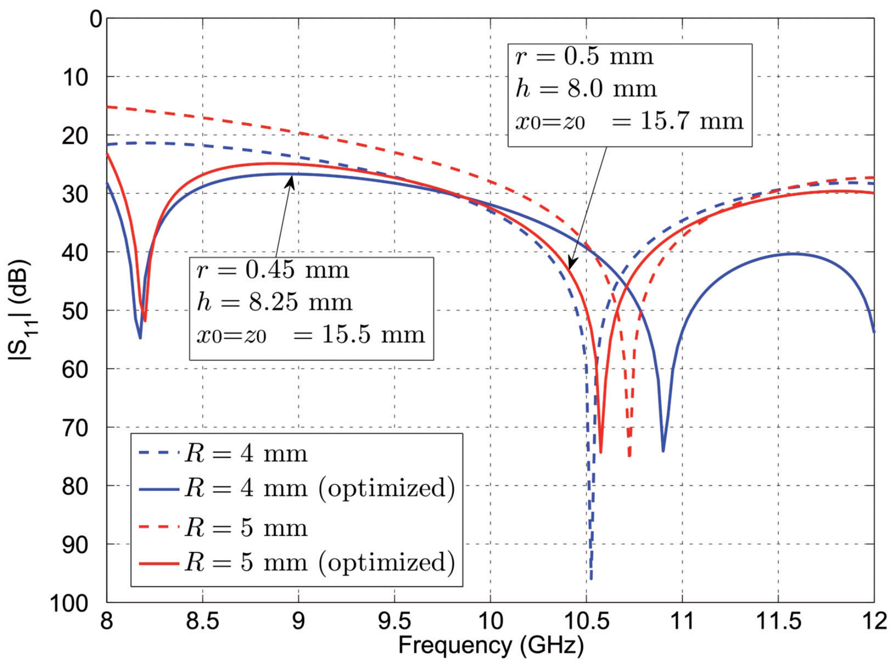


Figure 4. Return losses of a compensated H-plane right-angled bend. The matching post has been re-designed to compensate for the degradation introduced by the rounded corners.

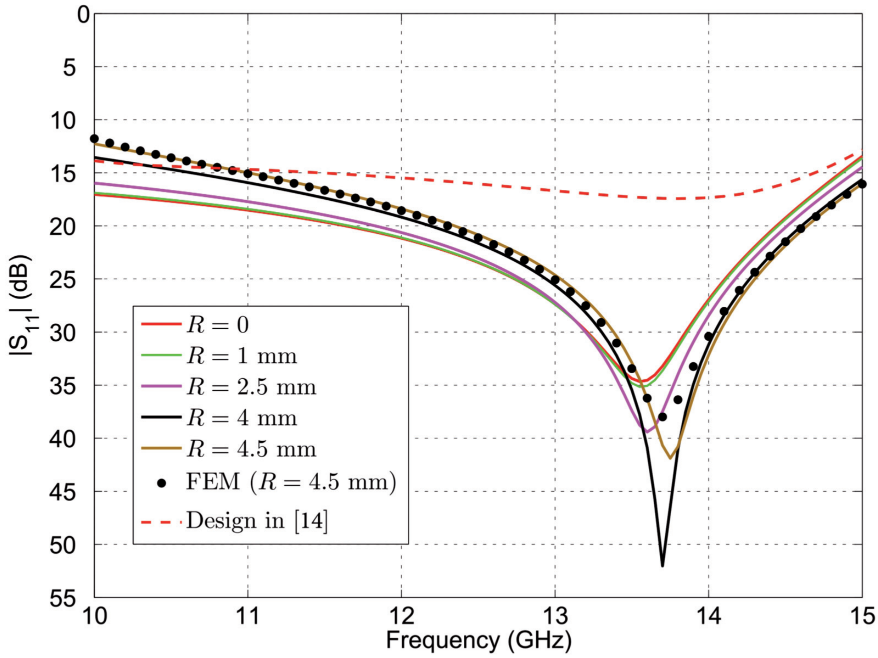


Figure 5. Electrical performance of a compensated H-plane T-junction in terms of the radius R of the considered rounded corners.

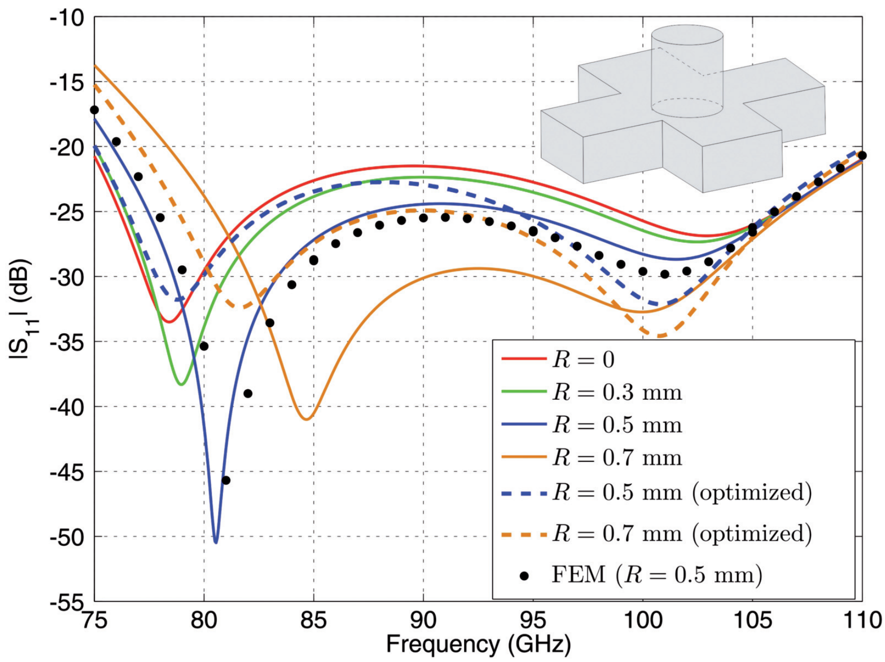
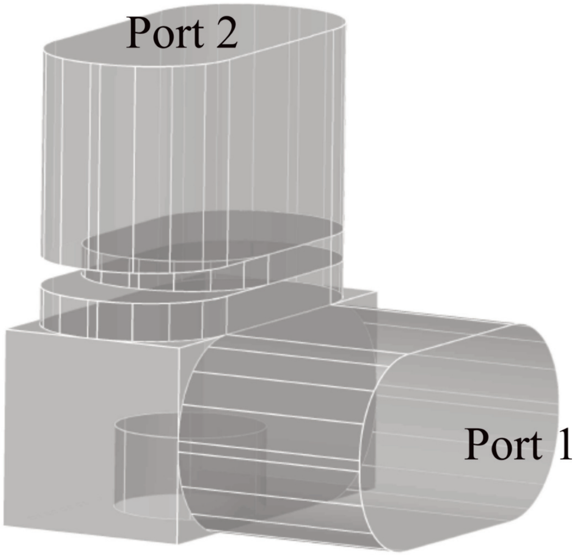


Figure 6. Return losses of a compensated turnstile junction as a function of the radius R of the introduced rounded corners.

As in the previous discussed components, a degradation of the electrical response is observed as the radius of the rounded corners increases. In particular, note that the usable bandwidth below -20 dB decreases for R=0.5 mm and R=0.7 mm. Nevertheless, it is possible to compensate for this undesired effect by re-designing the height of the top piled-up cylindrical post used to compensate the junction, as it is shown in the same Fig. 6 (dashed curves). Thanks to this new optimization, the usable bandwidth below -20 dB for the case R=0.5 mm is equal to the one achieved for the case R=0, while maintaining a good average return losses. Regarding the optimized case for R=0.7 mm, the relative bandwidth below -20 dB has been increased in a 1.5% with respect to the original design. The new height of the top piled-up post used in these two new designs is h_5=2.03 mm. With regard to the computational efficiency, it is important to point up that the accurate analysis of this multiport junction needed 0.9 seconds per frequency point.



■ **Figure 7.** Compensated E-plane right-angled bend with rounded corners in the rectangular waveguides of the component.

In view of the results provided by the optimized design of the analyzed H-plane multi-port waveguide junctions, it is possible to conclude a useful design guideline to estimate the maximum radius allowed for a certain electrical performance. The wide-band degradation of the designed devices is sensitive to the ratio R/b. On the one hand, we have observed that when such ratio is lower than 0.25, the usable bandwidth of the device remains almost invariable and no further optimizations are required. On the other hand, when higher values of the ratio are considered, especially for $R/b>0.5$, an important degradation of the electrical response may be observed, and new optimized designs

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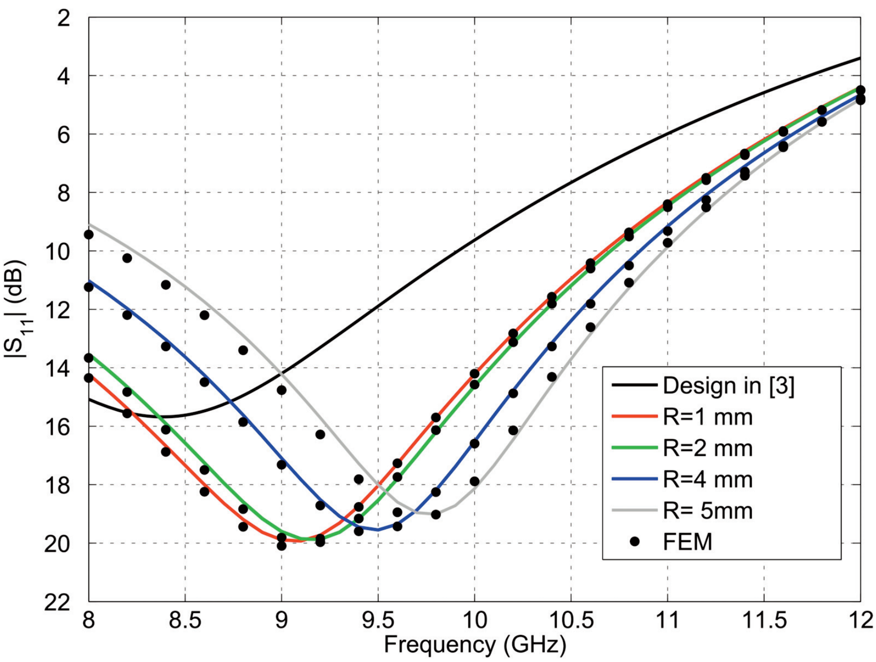
could be necessary. In this worst case, we have concluded that it may be possible to recover a relative bandwidth under -20 dB similar to the one obtained for the case $R=0$, as we have verified, for instance, in the case of H-plane bends. Even in the case of more complex structures (such as turnstile junctions), an optimized response can be designed obtaining an improved relative bandwidth.

3.4. Design of compensated E-plane right-angled bends

Next, we proceed to validate the proposed tool by analyzing a compensated E-plane right-angled bend implemented in WR-90 waveguide, as the one represented in Fig. 7.

A cylindrical metallic post with radius $r=3.75$ mm, height $h=3.08$ mm, and relative position $x_0=6.31$ *mm*, $z_0=11.48$ mm (according to the axis system depicted in Fig. 2) has been used to compensate the junction. In addition, a matching iris has been inserted into the component to optimize its broad-band operation. The dimensions of the iris, referred to the notation indicated in Fig. 2, are: $a_{iris}=20.32$ mm, $t_{iris}=2.15$ mm, and $h_{iris}=8.1$ mm. Moreover, the rectangular waveguides present in the component have been perturbed by introducing rounded corners of radius R.

The electrical performance of the designed E-plane bend, as a function of the radius R of the rounded corners, is



■ **Figure 8.** Return losses of a compensated E-plane right-angled bend as a function of the radius R of the rounded corners.

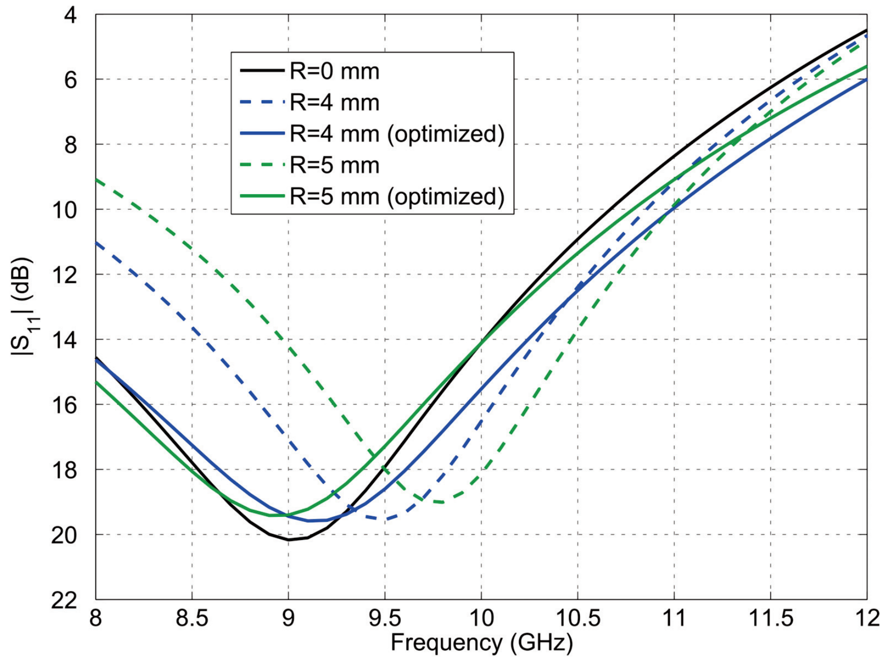


Figure 9. Return losses of the re-designed E-plane right-angled bend.

presented in Fig. 8, where the obtained simulated data is successfully compared to the results provided by a finite-element method software. The results related to the case $R=0$ (absence of rounded corners), which have not been included in such figure for the sake of clarity, are very close to the data obtained for the case $R=1$ mm. Furthermore, the return losses related to an authors' previous design concerning a compensated E-plane bend without rounded corners ($R=0$) are also included in Fig. 8 for comparison purposes (see the solid black curve) [3]. It is important to note, by comparing the cited black curve and the curve related to the case $R=1$ mm (whose results are very close to the case $R=0$), that an improved initial design (for the cited case of $R=0$) has been achieved in this new work.

In view of the obtained results, it is possible to conclude that the overall electrical performance of the device deteriorates as the radius of the rounded corners increases. The negative effect is noteworthy in the cases $R=4$ mm and $R=5$ mm. Nevertheless, even in these cases with stringent mechanical constraints, the broad-band operation of the low-cost manufactured E-plane bend can be almost restored by properly re-designing the junction. In this particular case, we propose to re-design the dimensions and the relative position of the compensating cylindrical post, and also the different dimensions related to the auxiliary iris. The return losses related to these new designs are shown in Fig. 9, where it is possible to observe that the overall electrical performance of the device has been almost restored (compared to the case $R=0$ that has been now included in the figure), when high values of rounded corners ($R=4$ and $R=5$ mm) are considered. The dimensions of the cylindrical post (its radius r, height h and relative position x_0 , z_0) and the dimensions that define the matching iris (its width a_{iris}, thickness t_{iris}, and height h_{iris}), related to such new designs, are collected in Table 1.

It is important to note that the electrical performance of the device is sensitive to the ratio R/b. In particular, when $R>b/4$, further optimizations may be needed in order to restore the broad-band operation of the component. Finally, it should be observed that the CPU time required for the computation of a complete frequency response (150 points) was only 28.7 s (Intel Core i3@3.1 GHz with 4 GB RAM), thus demonstrating the computational efficiency of the developed CAD tool (Ansys HFSS, the commercial tool based on FEM used for validation purposes, took about 1 min per frequency point).

Radius R	r (mm)	h (mm)	x_0 (mm)	z_0(mm)	a_{iris} (mm)	t_{iris} (mm)	h_{iris} (mm)
R=4 mm	3.75	3.05	6.4	11.43	21.15	2.79	7.8
R=5 mm	3.75	2.56	6.4	11.43	21.45	2.79	7.8

Table 1. New dimensions of the matching elements (post and iris) used in the re-design of the E-plane right-angled bend.

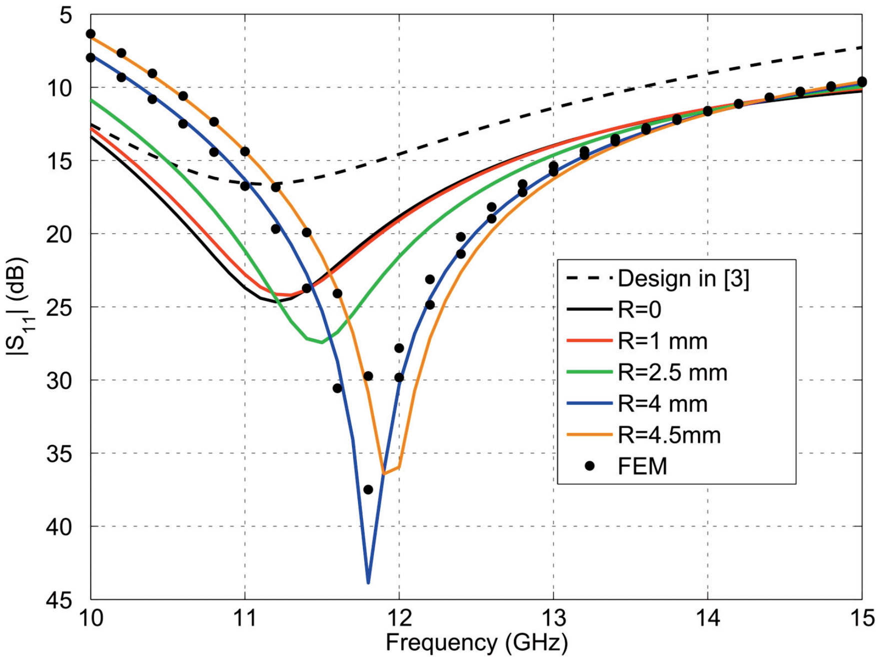


Figure 10. Return losses of a compensated E-plane T-junction as a function of the radius R of the rounded corners.

3.5. Design of compensated E-plane T-junctions

E-plane T-junctions are extensively used as power dividers in modern diplexers and multiplexers [22, 23]. In this section, we present a new design of a compensated E-plane T-junction, considering rounded corners of radius R in the rectangular waveguides of the component (see Fig. 2). The T-junction has been implemented in WR-75 waveguide, using a cylindrical post whose dimensions are: $r=3.6$ mm, $h=3.96$ mm. In this case, the best performance has been found when the post is located in a centered position $x_0=b/2$, $z_0=a/2$. On the other hand, the dimensions of the matching iris are: $a_{iris}=15.12$ mm, $t_{iris}=1.45$ mm, and $h_{iris}=1.85$ mm. The electrical response of the T-junction, as a function of the radius R of the rounded corners, is shown in Fig. 10, where an excellent agreement with the data provided by the finite-element method software is again observed.

First of all, it should be noted that this new design has improved the electrical performance of the component (case for $R=0$) with respect to an authors' previous design presented in [3] (see the dashed black curve in Fig. 10). Moreover, in contrast to the outcome of the study about H-plane T-junctions performed in section 3.2, where the introduction of the rounded corners did not significantly affect to the electrical response of the device, the degradation of the overall frequency response is more evident in the present E-plane case (especially at low frequencies) for the cases $R=4$ mm and $R=4.5$ mm (note that, in such cases, the condition $R>b/4$ is not satisfied). As a consequence, a further optimization of the device is required in order to recover its wide-band performance, and the main goal is to find a new electrical response as close as possible to the one obtained for the case $R=0$.

The new obtained designs are shown in Fig. 11, where the achieved electrical performance is, indeed, very close to the one we have derived for the case $R=0$ (included in this case as a good reference curve). The new dimensions of the cylindrical post (located in a centered position) and the matching iris are shown in Table 2. The obtained results show that the developed CAD tool allows the microwave designer to accurately evaluate the final electrical response of the device prior to its manufacturing, and compensate the impact of the low-cost fabrication techniques by re-designing the dimensions of the matching elements (cylindrical post and iris). The CPU time required for the computation of a complete frequency response (150 points) was only 33.9 s (Ansys HFSS needed about 65 s per frequency point).

Radius R	r (mm)	h (mm)	a_{iris} (mm)	t_{iris} (mm)	h_{iris} (mm)
R=4 mm	3.78	4.08	15.17	1.25	2.74
R=4.5 mm	3.78	4.03	15.21	0.9	2.98

Table 2. New dimensions of the matching elements (post and iris) employed in the re-design of the E-plane T-junction.

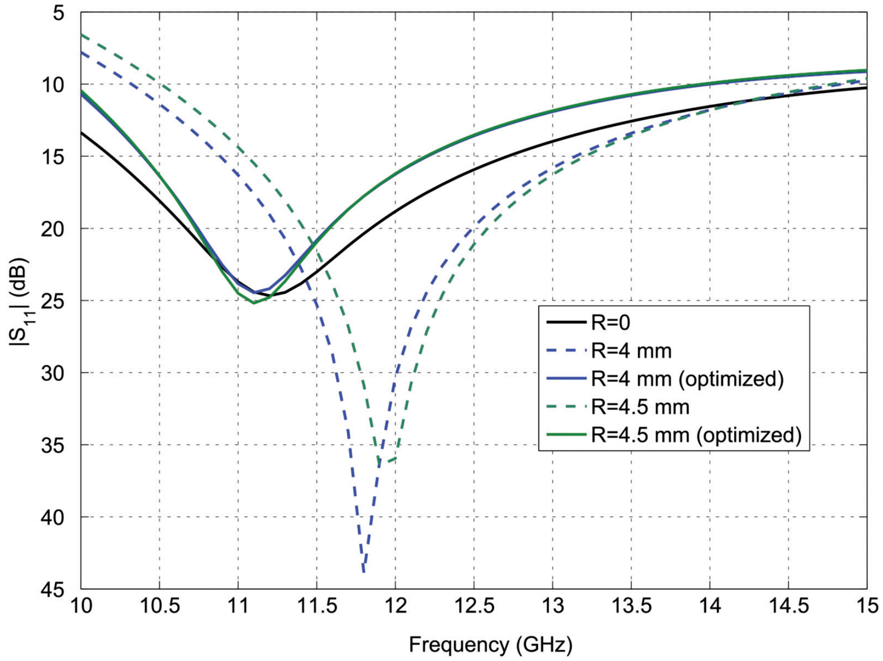


Figure 11. Return losses of the re-designed compensated E-plane T-junction.

Conclusion

A rigorous and very efficient CAD tool for the analysis and design of compensated H- and E-plane multi-port junctions, which takes into account the presence of rounded corners in the rectangular waveguides of the considered device, has been proposed. The developed tool is based on well-known full-wave methods which assure the accuracy of the provided results. Several new designs concerning different H- and E-plane components, such as right-angled bends, T-junctions and turnstile junctions, have been presented and discussed. The obtained results show that the implemented tool allows the designer to precisely predict the electrical performance of the device prior to its fabrication, and compensate the impact of the low-cost manufacture techniques by re-designing the matching elements considered in the device (i.e. cylindrical post and iris). Therefore, the wide-band performance of the analyzed device can be almost restored even though stringent mechanical effects are imposed. The presented numerical results have been successfully validated by comparison with simulated data provided by a commercial software based on the finite-element method.

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