

# Accurate Consideration of Ohmic Losses in Passive Waveguide Circuits for Microwave and Millimeter-wave Applications

M. Taroncher\*, J. Hueso\*, S. Cogollos\*, B. Gimeno<sup>†</sup>, A. Vidal\*, V.E. Boria\* and M. Guglielmi<sup>‡</sup>

\* Dpto. Comunicaciones, Universidad Politécnica de Valencia,

Camino de Vera s/n, E-46022 Valencia, SPAIN, Email: vboria@dcom.upv.es

<sup>†</sup> Dpto. Física Aplicada - ICMUV, Universidad de Valencia,

C/ Dr. Moliner 50, E-46100 Burjassot (Valencia), SPAIN, Email:benito.gimeno@uv.es

<sup>‡</sup> European Space Research and Technology Centre, Noordwijk, The Netherlands

**Abstract**—The accurate consideration of all ohmic losses effects in waveguide devices is rigorously studied in this paper. For such purposes, a full-wave CAD tool based exclusively on modal methods is originally proposed. Proceeding in this efficient way, losses are precisely considered in all common components of such complex devices, i.e. planar junctions, uniform lines and multi-port circuits implemented in waveguide technology. For verification purposes, we have successfully compared our results for an LMDS filter, an H-plane T-junction and a manifold diplexer with experimental and numerical results.

**Index Terms**—Losses, Waveguide components, Waveguide junctions, Multiport circuits, Diplexers and multiplexers.

## I. INTRODUCTION

Waveguide multi-port and planar junctions are the key building block of many waveguide structures (e.g. filters, diplexers and multiplexers, couplers, power dividers and combiners, and orthomode transducers) present in many wireless and space-based systems operating at ever increasing frequencies. At high frequencies (microwave and millimetre-wave bands), losses effects are more pronounced and can severely distort the electrical response of such waveguide devices. This means that, for design purposes, the conventional approach of neglecting losses or considering them as a small-effect phenomena is no longer valid. Therefore, the rigorous prediction of all ohmic losses effects affecting such passive waveguide devices is becoming more and more necessary.

The effect of losses in microwave waveguides and cavities has been under consideration in the technical literature during the last decades. Losses in hollow waveguides have been typically solved by means of the classical perturbation method [1], and more recently by means of an original analytical technique [2]. With regard to the precise analysis of multi-port lossy junctions, a new technique has been presented in [3]. In the other hand, many efforts have been traditionally devoted to the accurate consideration of losses at planar junctions. For instance, the well-known mode-matching procedure and a novel integral equation technique have been lately proposed in [4] and [5], respectively. Even though the losses effects in all key building blocks of waveguide devices have already been studied separately, to the authors knowledge, rigorous simulated results for such lossy passive devices including all elements (uniform lines, waveguide planar and multi-port junctions) can not be found in the available literature.

Therefore, this paper presents a novel analysis method for the fast and rigorous consideration of all metal losses effects in waveguide devices, which can be easily integrated within CAD tools for design purposes. This new method is based on modal techniques previously developed by the authors ([3] and [5]) for considering losses at each basic block of the considered circuits. The Theory section fully describes the admittance matrix representations of lossy planar discontinuities, lossy waveguides and lossy multi-port junctions, which can be easily combined giving place to very accurate and efficient CAD tools of passive waveguide devices considering all losses effects. Next, in the Results section, the new method is successfully validated by comparing our results with experimental measurements of an LMDS filter and a real H-plane T-junction. Finally, we show our simulated results for a lossy H-plane diplexer operating at 11-12 GHz, which are compared with numerical data provided by a finite-elements commercial software. In order to prove the numerical efficiency of this new technique, CPU times are presented for all the examples considered.

## II. THEORY

In this section we detail the theoretical contents of the new technique proposed for the accurate consideration of losses in rectangular waveguide devices. The objective is to derive a generalized admittance matrix formulation, which includes all ohmic losses effects in such real devices.

To solve this problem we propose to follow a segmentation procedure, which consists on decomposing the lossy device into several steps: the cubic junctions, the waveguide sections and the discontinuities between them. The multi-aperture junction and the waveguide section lengths can be characterized by a generalized admittance matrix representation, as explained in [3]. Next, a very efficient integral equation technique developed in [5] is followed to obtain the multimode admittance matrix representation of planar lossy junctions between rectangular waveguides. Finally, all the generalized admittance matrices can be connected in order to obtain a global equivalent network of the whole structure.

### A. Metal Losses in Multi-port Junctions

The lossless central cubic junction of a multi-port structure can be characterized in terms of a generalized admittance

matrix as follows

$$I_m^{(\delta)} = Y_{m,n}^{(\delta,\gamma)} V_n^{(\gamma)} \quad (1)$$

where  $I_m^{(\delta)}$  and  $V_n^{(\gamma)}$  are, respectively, the modal currents and voltages at the waveguide access ports of the cubic junction, and  $Y_{m,n}^{(\delta,\gamma)}$  terms represent the admittance matrix elements, whose completely analytical expressions are detailed in [6].

For considering the losses effect in port  $(\delta)$  due to the presence of a finite conductivity metallic wall on it, we first enforce the Leontovich impedance boundary condition satisfied by the tangential fields at a good conductor plane

$$\mathbf{E}_t^{(\delta)}(\mathbf{r}) \approx Z_s \mathbf{J}_s^{(\delta)}(\mathbf{r}) = Z_s (\hat{n} \times \mathbf{H}_t^{(\delta)}(\mathbf{r})) \quad (2)$$

where  $\mathbf{E}_t^{(\delta)}$  and  $\mathbf{H}_t^{(\delta)}$  are, respectively, the transverse electric and magnetic fields at the good conductor plane on port  $(\delta)$ ,  $\mathbf{J}_s^{(\delta)}$  is the surface current density and  $Z_s$  is the well-known surface impedance  $Z_s = (1 + j)\sqrt{\frac{\omega\mu}{2\sigma}}$ .

Next, we must expand the tangential electric  $\mathbf{E}_t^{(\delta)}$  and magnetic  $\mathbf{H}_t^{(\delta)}$  fields at the waveguide port  $(\delta)$  in terms of the normalized modal vector functions of the rectangular waveguide access port  $(\delta)$ . And then, remembering that  $\mathbf{h}_n^{(\delta)} = \hat{n} \times \mathbf{e}_n^{(\delta)}$ , it can be easily concluded that

$$V_n^{(\delta)} = -Z_s I_n^{(\delta)} \quad (3)$$

which means that all the modes considered in the access port  $(\delta)$  of the generalized admittance matrix representation of the cubic junction must be loaded with the surface impedance, thus considering in a rigorous way the losses effect in such port  $(\delta)$  due to the presence of a finite conductivity metallic wall on it.

### B. Metal Losses in Planar Waveguide Junctions

For the accurate consideration of metal losses in any planar waveguide junction, a very efficient method based on an integral equation technique has been properly updated. This technique leads to a multimodal representation of lossy discontinuities in terms of a generalized admittance matrix. A remarkable contribution of this method is the distinction made between accessible and localized modes: accessible modes are those used to connect transitions, while localized modes are only used to describe the fields in the junction (the number of localized modes is always greater than the number of accessible ones). The efficiency of the method lies in the fact that the dimensions of the derived generalized admittance matrix depends only on the number of accesible modes considered. The theory of the proposed method starts from enforcing the continuity of the electric field in the planar junction. After some mathematical manipulations, it is possible to obtain the following integral equation for the electric field  $\mathbf{e}_n^{(\delta)}$ :

$$\begin{aligned} \mathbf{e}_n^{(1)}(\mathbf{s}) = & (1 - \xi(\mathbf{s}))Z_s \mathbf{M}_n^{(1)}(\mathbf{s}) \\ & + \iint_{CS(1)} \mathbf{M}_n^{(1)}(\mathbf{s}') \cdot \mathbf{K}^{(1)}(\mathbf{s}, \mathbf{s}') ds' \\ & + \iint_{CS(2)} \mathbf{M}_n^{(2)}(\mathbf{s}') \cdot \mathbf{K}^{(2)}(\mathbf{s}, \mathbf{s}') ds' \end{aligned} \quad (4)$$

$$\begin{aligned} \xi(\mathbf{s})\mathbf{e}_n^{(2)}(\mathbf{s}) = & (1 - \xi(\mathbf{s}))Z_s \mathbf{M}_n^{(2)}(\mathbf{s}) \\ & + \iint_{CS(1)} \mathbf{M}_n^{(2)}(\mathbf{s}') \cdot \mathbf{K}^{(1)}(\mathbf{s}, \mathbf{s}') ds' \\ & + \iint_{CS(2)} \mathbf{M}_n^{(2)}(\mathbf{s}') \cdot \mathbf{K}^{(2)}(\mathbf{s}, \mathbf{s}') ds' \end{aligned} \quad (5)$$

where  $\mathbf{M}_n^{(\delta)}(\mathbf{s}')$  are the unknown vector functions and  $\mathbf{K}^{(\delta)}(\mathbf{s}, \mathbf{s}')$  are the kernels of the integral equations (see [5]). The integral equation is efficiently solved through Galerkin's procedure after decomposing  $\mathbf{K}^{(\delta)}(\mathbf{s}, \mathbf{s}')$  into a static (frequency independent) and a dynamic term.

Finally, proceeding in this way, the admittance matrix elements of the lossy junction can be easily computed as:

$$Y_{m,n}^{(\delta,\gamma)} = \iint_{CS(\delta)} \mathbf{M}_n^{(\gamma)}(\mathbf{s}') \cdot \mathbf{e}_m^{(\delta)}(\mathbf{s}') ds' \quad (6)$$

Once each lossy block has been fully characterized, all the generalized admittance matrices are efficiently connected, thus obtaining a global equivalent network. Making use of this method, it is possible to predict all losses effects in passive waveguide devices composed of cascaded waveguides interconnected with planar or multi-port junctions.

## III. RESULTS

In order to verify the new theory just described above, we have compared the losses effects predicted by this model with numerical data provided by Ansoft HFSS v.10.0 and experimental measurements. In this study, for comparative purposes, our simulation tool and the commercial software have been both run on a Pentium IV platform at 2.8 GHz with 1 GB RAM.

### A. LMDS Filter at 28 GHz

First, for evaluating the lossy Y-IE formulation for planar junctions, we have studied all losses effects in a 4-pole inductive and symmetric filter used at the input front-end of an LMDS receiver operating in the Ka-Band. For verification purposes, a prototype of such filter has been manufactured (see Fig. 1) employing an aluminum alloy of conductivity equal to  $1.2 \cdot 10^7$  S/m.

In Fig. 2, we can see a detailed view of the LMDS filter insertion losses. This figure includes the simulated results using

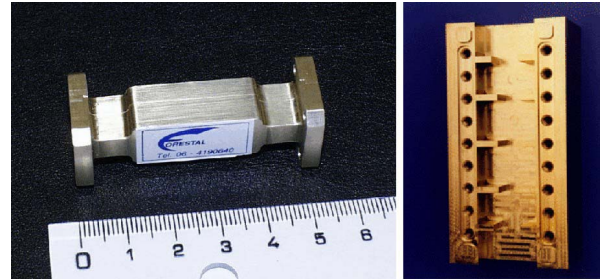


Fig. 1. Photographs of a 4-pole symmetric LMDS filter in WR-28 ( $a = 7.112$  mm,  $b = 3.556$  mm), where the inductive coupling irises have equal length (2.5 mm) and widths 4.939 mm, 3.799 mm and 3.578 mm, and the cavities have equal width (8.636 mm) and lengths 4.696 mm and 5.555 mm.

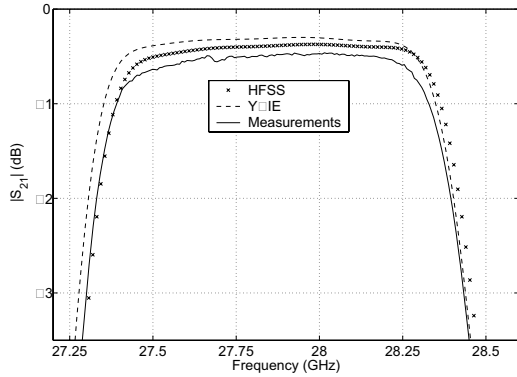


Fig. 2. Detailed view of the insertion losses of the LMDS filter considering the conductivity value of the aluminum alloy. Comparisons with HFSS data and experimental measurements.

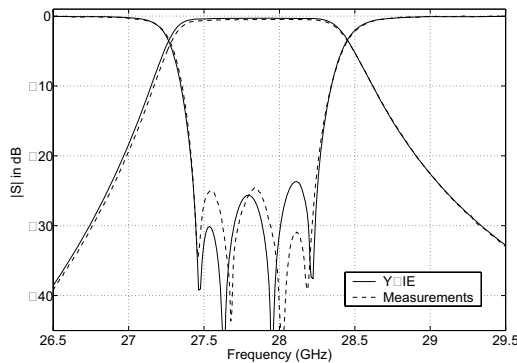


Fig. 3. Magnitude of the  $S$ -parameters of the LMDS filter considering the conductivity value of the aluminum alloy. Comparison with experimental measurements.

the Y-IE formulation and HFSS considering the conductivity value of the employed aluminum alloy, as well as a comparison with the experimental measurements of the prototype. As it can be seen, our results agree well with those given by the commercial software. However, the two simulated results are slightly different from measurements, which can be attributed to several reasons. First, the real conductivity of a material can be altered from its nominal value due to environment temperature and humidity. Besides, additional insertion losses can be introduced by each specific manufacturing technique. Finally, conductivity values are typically provided at zero frequency. However, at higher frequencies (microwaves and millimeter-waves), such values can be affected by the surface properties, since the induced electrical current flows in smaller layers. To alleviate such small differences, or even for predicting conductivity values for unknown materials, we can make use of our accurate simulation tool in order to find an equivalent conductivity which allows to recover experimental results.

The complete reflection and transmission responses of this LMDS filter are shown in Fig. 3. To compute these results, our simulation tool only takes 14 min. for 250 frequency points (3.4 s per frequency value), whereas HFSS requires about 140 min.

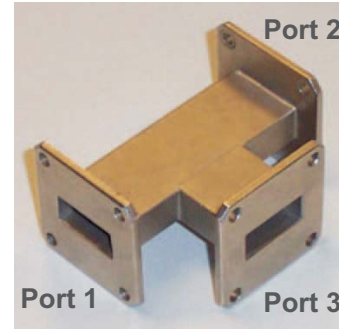


Fig. 4. H-plane T junction in WR-75 ( $a = 19.05$  mm and  $b = 9.525$  mm) with waveguide access ports ( $l_1 = l_2 = 6.03$  mm and  $l_3 = 15.00$  mm).

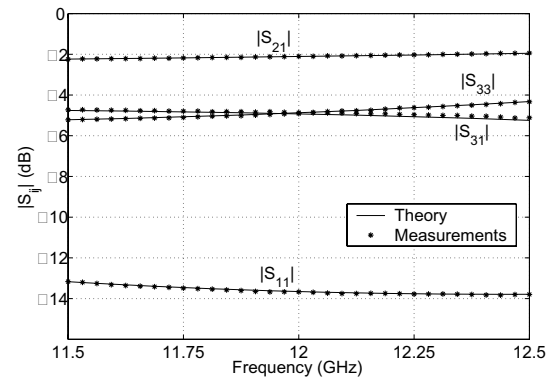


Fig. 5. Magnitude of the  $S$  parameters for the lossy H-plane T-junction in WR-75. Comparison with experimental results.

### B. H-plane T-junction

Next, making use of the lossy admittance formulation of multi-port junctions, we have fully characterized a real H-plane T-junction including its typical waveguide access ports (see Fig. 4). To solve this problem, we have connected the generalized admittance matrices of the internal 3-port junction and of the 3 waveguide sections, which have been computed including all losses effects with our method. In Fig. 5, we successfully compare our results for the whole set of  $S$  parameters with experimental measurements of a real prototype made of silver and, as it can be seen, an excellent agreement between both sets of results has been achieved. To recover these accurate results our method required to consider 30 modes at each waveguide access port and an equivalent conductivity of  $\sigma = 10^5$  S/m. The complete simulation of this real example only took 23 s for 51 frequency points.

### C. H-plane Manifold Diplexer

Finally, the combination of both methods has been successfully applied to the accurate analysis of the losses on a manifold diplexer in H-plane configuration, which is a common solution in satellite high-power applications. The H-plane manifold diplexer analyzed was originally designed in [7] and its structure is represented in Fig. 6.

The simulated reflection and transmission coefficients of this lossy (considering first  $\sigma = 10^6$  S/m) H-plane manifold

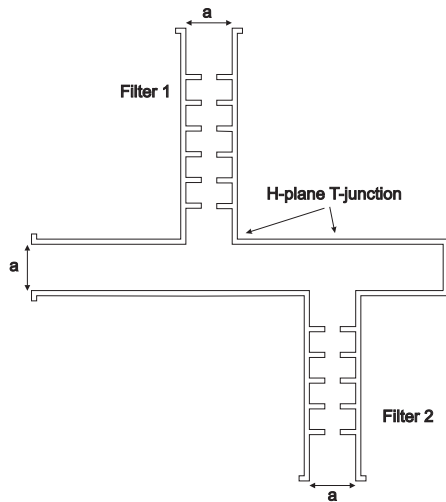


Fig. 6. H-plane manifold diplexer in WR-75 ( $a = 19.05$  mm and  $b = 9.525$  mm). Dimensions in [7].

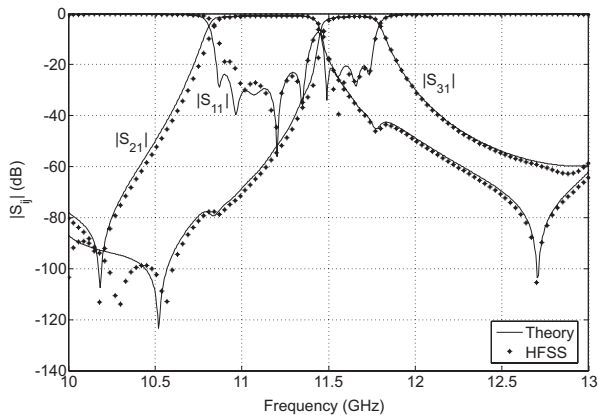


Fig. 7. Magnitude of the  $S$  parameters of a lossy ( $\sigma = 10^6$  S/m) H-plane manifold diplexer. Comparison with HFSS.

diplexer are successfully compared with the HFSS results in Fig. 7. In Fig. 8 we have represented the magnitude of the  $S_{21}$  and  $S_{31}$  parameters for several conductivity values, i.e. for  $\sigma = \infty$  (without losses), for  $\sigma = 5.8 \cdot 10^7$  S/m (a typical value for Copper, which is a standard waveguide material) and for  $\sigma = 10^6$  S/m (very high losses). A very good agreement between the losses effects predicted by our technique and the HFSS data can be observed. To compute these results, the IE-based analysis method has required 40 accessible modes, 300 basis functions and 400 kernel elements, and 40 modes has been used in the analysis of the H-plane T-junctions. The complete simulation of the electrical response of this device, due to the complexity of the structure, has required a total computational effort of 69.8 min. (41.5 s per frequency point), whereas the HFSS needed around one full day.

#### IV. CONCLUSION

In this paper we have presented a novel analysis method for the fast and rigorous consideration of all ohmic losses effects

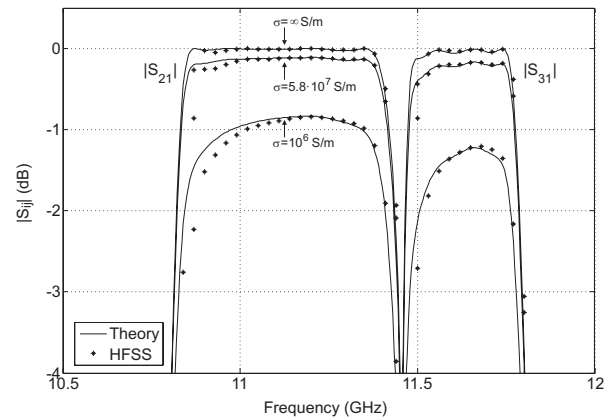


Fig. 8. Magnitude of the transmission parameter of the H-plane manifold diplexer for several conductivity values. Comparison with HFSS.

in waveguide devices. This new procedure is completely based on modal techniques for considering losses at each basic element of the circuit (i.e. planar junctions, uniform lines and multi-port apertures in waveguide technology). The generalized admittance matrices of each lossy key building block have been connected in a very efficient way. Comparison with experimental measurements and results provided by a commercial simulator are included, thus confirming that the novel formulation derived is very accurate. CPU times have also revealed that the novel analysis method proposed is very efficient, and therefore it could be integrated within presently available CAD tools for design purposes considering losses.

#### ACKNOWLEDGMENT

The authors wish to acknowledge the economic support of Ministerio de Educación y Ciencia, Spanish Government, through the Research Project TEC2004/04313-C02.

#### REFERENCES

- [1] C. A. Balanis, *Advanced Engineering Electromagnetics*. New York: John Wiley & Sons, 1989.
- [2] M. Mattes and J. R. Mosig, "Calculation of ohmic losses in waveguide based components using an analytical technique," in *Proc. 7th Int. Symp. on Recent Advances in Microwave Technology*, Málaga, Dec. 1999, pp. 529–532.
- [3] M. Taroncher, S. Cogollos, V. E. Boria, B. Gimeno, A. Vidal, J. Hueso, and I. Hidalgo, "On the rigorous calculation of all ohmic in rectangular waveguide multi-port junctions," in *IEEE MTT-S Int. Microw. Symp. Digest*, Long Beach, June 2005, pp. 71–74.
- [4] D. Trincherio, R. Tascone, P. Savi, and R. Orta, "Metal loss effect in the analysis of waveguide discontinuities," in *Proc. ICEAA Int. Conf. on Electromagnetic in Advanced Applications*, Torino, Sept. 1997, pp. 411–414.
- [5] J. Hueso, S. Cogollos, B. Gimeno, V. E. Boria, A. Vidal, M. Taroncher, H. Esteban, and M. Guglielmi, "Accurate consideration of metal losses in planar waveguide junctions using an efficient integral equation technique," in *IEEE MTT-S Int. Microw. Symp. Digest*, Fort Worth, June 2004, pp. 1411–1414.
- [6] V. Boria, S. Cogollos, H. Esteban, M. Guglielmi, and B. Gimeno, "Efficient analysis of a cubic junction of rectangular waveguides using the admittance-matrix representation," *IEE Proc. Microw. Antennas Propag.*, vol. 147, no. 6, pp. 417–422, Dec. 2000.
- [7] M. Guglielmi, "Simple CAD procedure for microwave filters and multiplexers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 7, pp. 1347–1352, July 1994.

# Efficient and Accurate Consideration of Ohmic Losses in Waveguide Diplexers and Multiplexers

M. Taroncher\*, J. Hueso\*, S. Cogollos\*, A. Vidal\*, V.E. Boria\* and B. Gimeno†

\* Dpto. Comunicaciones, Universidad Politécnica de Valencia,

Camino de Vera s/n, E-46022 Valencia, SPAIN, Email: vboria@ocom.upv.es

† Dpto. Física Aplicada - ICMUV, Universidad de Valencia,

C/ Dr. Moliner 50, E-46100 Burjassot (Valencia), SPAIN, Email:benito.gimeno@uv.es

**Abstract**—The accurate consideration of all ohmic losses effects in waveguide manifold diplexers and multiplexers is rigorously studied in this paper. For such purposes, a full-wave CAD tool based exclusively on modal methods is originally proposed. Proceeding in this very efficient way, losses are precisely considered in all common components of such complex devices, i.e. planar junctions, uniform lines and multi-port circuits implemented in waveguide technology. For verification purposes, we have successfully compared our results for a magic-T junction and a manifold diplexer with experimental and numerical results.

**Index Terms**—Losses, Waveguide components, Multipoint circuits, Diplexers and multiplexers.

## I. INTRODUCTION

Waveguide diplexers and multiplexers are widely used in satellite payloads [1], where the dissipated power (directly related to the losses of the structure) is a parameter of crucial relevance. Furthermore, modern satellite communication systems are increasingly using higher frequency bands, such as the millimeter-wave range, where losses effects are more pronounced and hazardous. Recently, novel topologies for different waveguide configurations of millimeter wave diplexers and multiplexers are being proposed (see e.g. [2]-[5]). Therefore, the rigorous prediction of all ohmic losses effects affecting such passive waveguide devices is becoming more and more necessary.

Many efforts have been traditionally devoted to the accurate consideration of losses at planar junctions (see [6] and related references). However, the ohmic losses in waveguide sections have been typically solved by means of classical perturbation techniques [7], which are only valid for propagating modes. This limitation has been recently overcome in [8], where the fast and accurate consideration of metal losses in waveguide multi-port junctions (i.e. H- and E-plane T-junctions) has also been extensively studied. Even though the losses effects in all key building blocks of waveguide diplexers and multiplexers have already been studied separately, to the authors knowledge, rigorous simulated results for such lossy passive devices can not be found in the available literature.

Therefore, this paper presents a novel analysis method for the fast and rigorous consideration of metal losses in waveguide diplexers and multiplexers, which can be easily

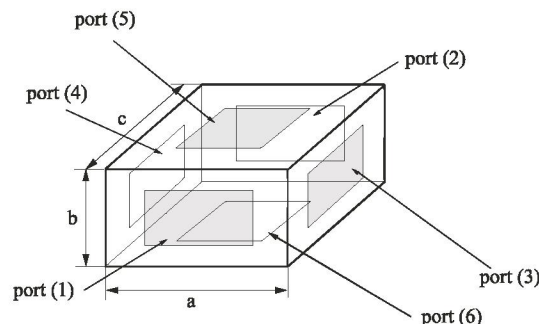


Fig. 1. Standard six-port waveguide junction.

integrated within CAD tools for design purposes. This new method is based on modal techniques previously developed by the authors ([6] and [8]) for considering losses at each basic block of the considered multiplexing circuits. The Theory section fully describes a new efficient way for connecting the generalized admittance matrices characterizing each lossy key building block. Next, this new procedure has been initially validated by comparing our results with experimental measurements of a real magic-T junction in WR-90 waveguides. Finally, we show our simulated results for a lossy H-plane diplexer operating at 11-12 GHz, which are successfully compared with numerical data provided by a finite-elements commercial software. In order to prove the numerical efficiency of this new technique, CPU times are presented for both examples.

## II. THEORY

In this section we detail the theoretical contents of the new technique proposed for the accurate consideration of losses in rectangular waveguide diplexers and multiplexers. The objective is to derive a generalized admittance matrix formulation, which includes all ohmic losses effects in such real devices.

To solve this problem we propose to follow a segmentation procedure, which consists on decomposing the lossy device into several steps: the cubic junctions, the waveguide sections and the discontinuities between them. The multi-aperture junction and the waveguide section

lengths can be characterized by a generalized admittance matrix representation, as explained in [8]. Next, a very efficient integral equation technique developed in [6] is followed to obtain the multimode admittance matrix representation of planar lossy junctions between rectangular waveguides. Finally, all the generalized admittance matrices can be connected in order to obtain a global equivalent network of the whole structure. Making use of this method, it is possible to predict all losses effects in passive waveguide devices composed of cascaded waveguides interconnected with planar or multi-port junctions.

The lossless central cubic junction of the multi-port structure shown in Fig. 1 can be characterized in terms of a generalized admittance matrix representation

$$\mathbf{I} = \mathbf{Y} \cdot \mathbf{V} \quad (1)$$

where the matrix  $\mathbf{Y}$  contains the admittance elements, and column vectors  $\mathbf{V}$  and  $\mathbf{I}$  are composed of the modal voltage and current amplitudes, respectively, at the waveguide access ports of the cubic junction:

$$\mathbf{V} = \begin{bmatrix} V^{(1)} \\ \vdots \\ V^{(6)} \end{bmatrix} \quad \mathbf{I} = \begin{bmatrix} I^{(1)} \\ \vdots \\ I^{(6)} \end{bmatrix} \quad (2)$$

For considering the losses effect in port ( $\delta$ ) due to the presence of a finite conductivity metallic wall on it, we must load all the modes in that port with the surface impedance ( $Z_s = (1 + j)\sqrt{\frac{\omega\mu}{2\sigma}}$ ) as follows (see details in [8]),

$$V_n^{(\delta)} = -Z_s I_n^{(\delta)} \quad (3)$$

In order to obtain a reduced admittance matrix  $\mathbf{Y}_R$  from the admittance matrix of the standard cubic junction  $\mathbf{Y}$ , with the corresponding short-circuited waveguide access ports loaded with the surface impedance, first we rewrite (3) in matricial form as

$$\mathbf{A} \cdot \mathbf{V} = -\mathbf{Z}_s \cdot \mathbf{I} \quad (4)$$

where  $\mathbf{A}$  and  $\mathbf{Z}_s$  are, respectively, diagonal matrices with ones and  $Z_s$  values corresponding to the short-circuited ports of the cubic junction, and zero elements in both matrices for the access ports. For instance, when solving an H-plane T-junction, the short-circuiting condition must be applied to ports (4), (5) and (6) of the cubic waveguide junction (see Fig. 1), so the  $\mathbf{A}$  and  $\mathbf{Z}_s$  take the following expressions

$$\mathbf{A} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & 1 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \quad (5)$$

$$\mathbf{Z}_s = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & Z_s \cdot \mathbf{1} & & \\ & & & & Z_s \cdot \mathbf{1} & \\ & & & & & Z_s \cdot \mathbf{1} \end{bmatrix} \quad (6)$$

If we define a new matrix  $\mathbf{B}$ , being the sum of  $\mathbf{A}$  and  $\mathbf{B}$  equal to the unit matrix ( $\mathbf{A} + \mathbf{B} = \mathbf{U}$ ), we can write

$$\mathbf{I} = \mathbf{Y} \cdot \mathbf{V} = \mathbf{Y} \cdot \mathbf{A} \cdot \mathbf{V} + \mathbf{Y} \cdot \mathbf{B} \cdot \mathbf{V} \quad (7)$$

Substituting the load condition (4) in (7), and solving for the column vector  $\mathbf{I}$ , we obtain

$$\mathbf{I} = [\mathbf{U} + \mathbf{Y} \cdot \mathbf{Z}_s]^{-1} \cdot \mathbf{Y} \cdot \mathbf{B} \cdot \mathbf{V} \quad (8)$$

Multiplying both sides of (8) by  $\mathbf{B}$  we finally obtain

$$\mathbf{B} \cdot \mathbf{I} = \mathbf{B} \cdot [\mathbf{U} + \mathbf{Y} \cdot \mathbf{Z}_s]^{-1} \cdot \mathbf{Y} \cdot \mathbf{B} \cdot \mathbf{V} \quad (9)$$

where the matrix  $(\mathbf{B} \cdot [\mathbf{U} + \mathbf{Y} \cdot \mathbf{Z}_s]^{-1} \cdot \mathbf{Y})$  is the desired reduced matrix  $\mathbf{Y}_R$ , after discarding the neglecting blocks. So, proceeding in this way, we obtain the generalized admittance matrix representation of the lossy multi-aperture junction, which can be then effectively combined with the generalized admittance matrices of remaining lossy waveguide sections and planar junctions.

### III. RESULTS

In order to verify the new theory just described above, we have compared the losses effects predicted by this model with numerical data provided by Ansoft HFSS v.10.0 and experimental measurements. In this study, for comparative purposes, our simulation tool and the commercial software have been both run on a Pentium IV platform at 2.8 GHz with 1 GB RAM.

First, to validate the admittance matrix representations just derived, we have computed the scattering parameters of a Magic-T junction (see Fig. 2). A laboratory prototype of such junction is shown in Fig. 3. To solve this problem, we have connected the generalized admittance matrices of

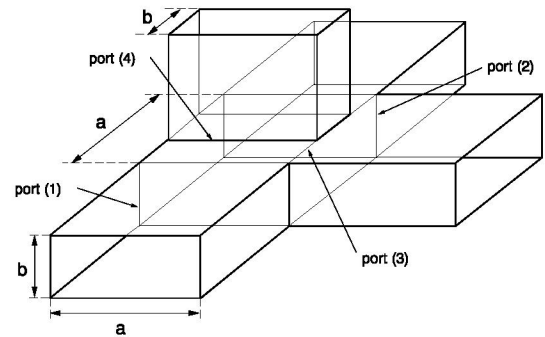


Fig. 2. Magic-T junction in WR-90 waveguide ( $a = 22.86$  mm and  $b = 10.16$  mm) with waveguide access ports ( $l_1 = l_2 = 33$  mm,  $l_3 = 27$  mm and  $l_4 = 26.84$  mm).

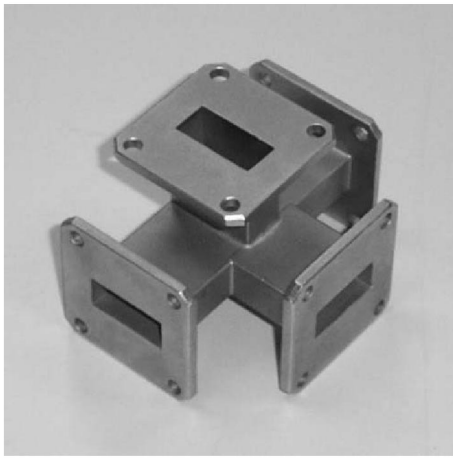


Fig. 3. Prototype of a magic-T junction in WR-90 waveguide.

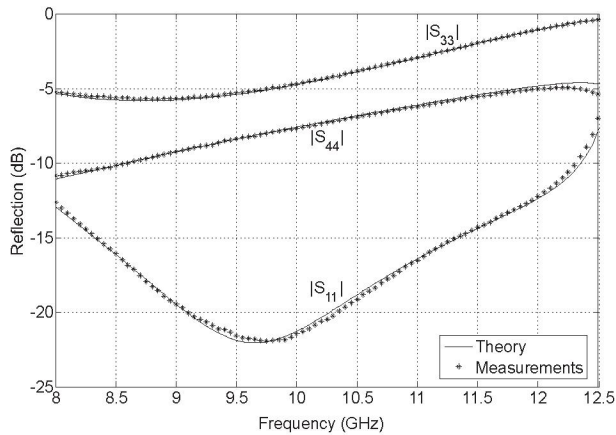


Fig. 4. Magnitude of the reflection coefficients ( $S_{11}$ ,  $S_{33}$  and  $S_{44}$ ) of a lossy Magic-T junction in WR-90. Comparison with experimental results.

the internal 4-port junction, of the step junction and of the 4 waveguide sections involved in this structure, which have been computed including all losses effects following our methods.

In Fig. 4 and Fig. 5, we successfully compare our results for the reflection and transmission parameters with experimental measurements of the real prototype and, as it can be seen, an excellent agreement between both sets of results has been achieved. In order to recover these accurate results, an equivalent conductivity of  $\sigma = 0.5 \cdot 10^7$  S/m was used. For this case, 60 modes have been required at each port of the cubic junction. The complete simulation of this real example only took 1.6 sec. per frequency point.

Next, the novel method has been successfully applied to the accurate analysis of the losses on a manifold diplexer in H-plane configuration, which is a common solution in satellite high-power applications. The H-plane manifold diplexer analyzed was originally designed in [9], and

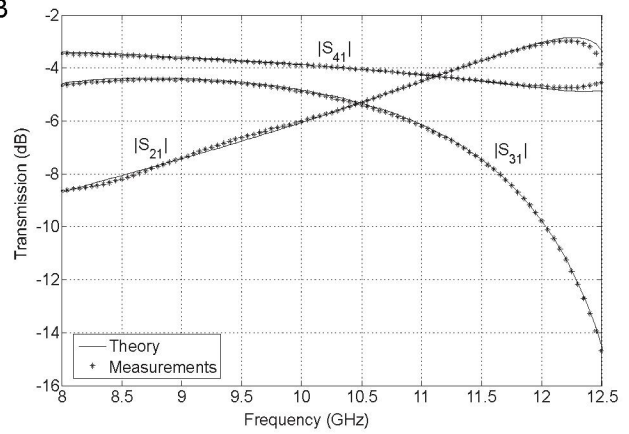


Fig. 5. Magnitude of the transmission coefficients ( $S_{21}$ ,  $S_{31}$  and  $S_{41}$ ) of a lossy Magic-T junction in WR-90. Comparison with experimental results.

consists of two inductive filters and a common waveguide where the filters are connected. This waveguide is short-circuited at one end with the common output located at the other end. The structure of this device is represented in Fig. 6.

The simulated reflection and transmission coefficients of this lossy (considering first  $\sigma = 10^6$  S/m) H-plane manifold diplexer are successfully compared with the HFSS results shown in Fig. 7. In Fig. 8 we have represented the magnitude of the  $S_{21}$  parameter for several conductivity values, i.e. for  $\sigma = \infty$  (without losses), for  $\sigma = 5.8 \cdot 10^7$  S/m (a typical value for Copper, which is a standard waveguide material) and for  $\sigma = 10^6$  S/m (very

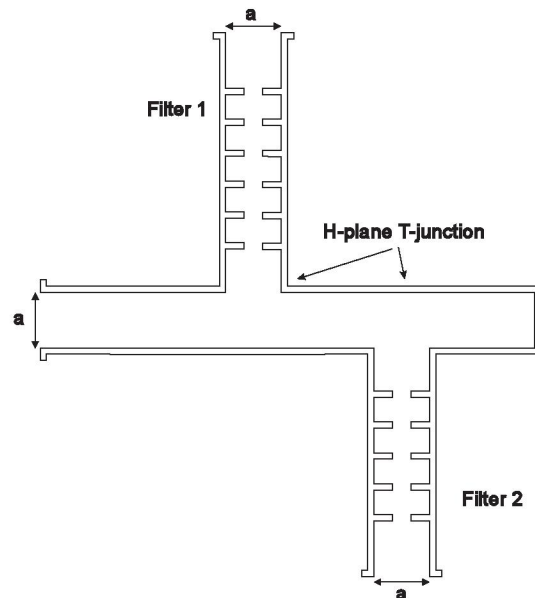


Fig. 6. H-plane manifold diplexer in WR-75 ( $a = 19.05$  mm and  $b = 9.525$  mm). Dimensions in [9].

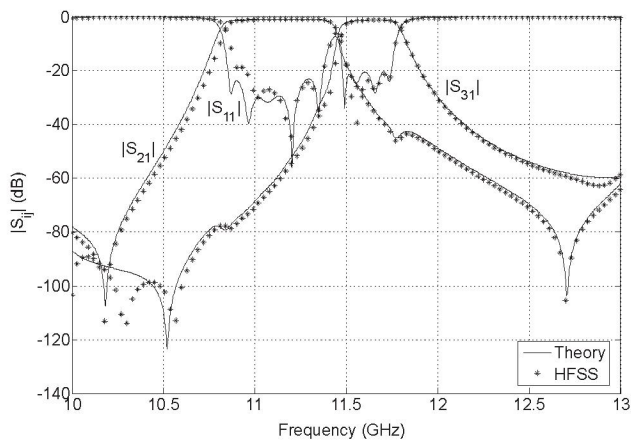


Fig. 7. Magnitude of the  $S$  parameters of a lossy ( $\sigma = 10^6$  S/m) H-plane manifold diplexer shown in Fig. 6. Comparison with HFSS.

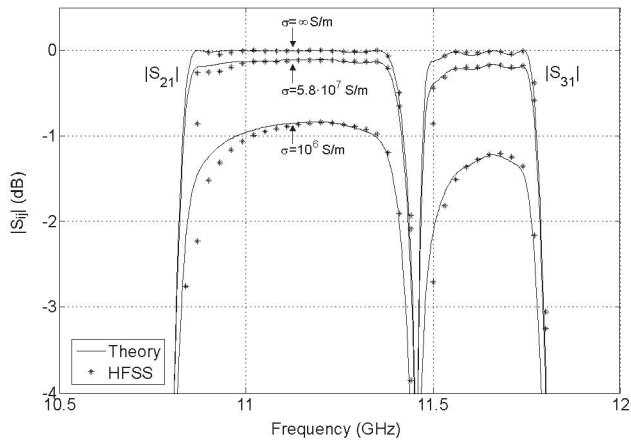


Fig. 8. Magnitude of the transmission parameter of the manifold diplexer shown in Fig. 6 for several conductivity values. Comparison with HFSS.

high losses). A very good agreement between the losses effects predicted by our technique and the HFSS data can be seen in Fig. 8, where an asymmetric behavior of dissipation losses for both channel filters is also observed. Such behavior, typically present in practical realizations of waveguide based components, can be attributed to the high degree of frequency dispersion related to such technology. Our full-wave CAD tool is successfully able to predict such behavior, since it accurately takes into account all real losses effects, and specifically those introduced by the coupling structures of the waveguide devices.

To compute the diplexer results, the IE-based analysis method has required 40 accessible modes, 300 basis functions and 400 kernel elements, and 40 modes has been used in the analysis of the H-plane T-junctions. The complete simulation of the electrical response of this device, due to the complexity of the structure, has required a total computational effort of 69.8 min. (41.5 sec. per frequency point), whereas the HFSS needed around one full day.

This substantial improvement on the numerical efficiency, preserving accuracy, is one of the most relevant advantages of the novel CAD tool proposed in this paper.

#### IV. CONCLUSION

In this paper we have presented a novel analysis method for the fast and rigorous consideration of all ohmic losses effects in waveguide manifold diplexers and multiplexers. This new procedure is completely based on modal techniques for considering losses at each basic element of the multiplexing circuit (i.e. planar junctions, uniform lines and multi-port apertures in waveguide technology). The generalized admittance matrices of each lossy key building block have been connected in a very efficient way. Comparison with experimental measurements and results provided by a commercial finite elements simulator are included, thus confirming that the novel formulation derived is very accurate. CPU times have also revealed that the novel analysis method proposed is very efficient, and therefore it could be integrated within presently available CAD tools for design purposes considering losses.

#### ACKNOWLEDGMENT

The authors wish to acknowledge the economic support of Ministerio de Educación y Ciencia, Spanish Government, through the coordinated Research Project TEC2004/04313-C02.

#### REFERENCES

- [1] J. Uher, J. Bornemann, and U. Rosenberg, *Waveguide Components for Antenna Feed Systems: Theory and CAD*. Norwood: Artech House, 1993.
- [2] A. Morini, T. Rozzi, and D. De Angelis, "A novel matched diplexer configuration in e-plane technology," in *IEEE MTT-S Int. Microw. Symp. Digest*, Atlanta, June 1993, pp. 1077–1080.
- [3] W. Menzel, F. Alessandri, A. Plattner, and J. Bornemann, "Planar integrated waveguide diplexer for low-loss millimeter-wave applications," in *Proc. 27th Eur. Microw. Conf.*, Jerusalem, Sept. 1997, pp. 676–680.
- [4] E. Offi and R. Vahldieck, "A novel compact millimeter wave diplexer," in *IEEE MTT-S Int. Microw. Symp. Digest*, Seattle, June 2002, pp. 377–380.
- [5] G. Tudosie, E. Offi, and R. Vahldieck, "Hybrid EM-simulator based optimization of microwave and millimeter wave diplexers and multiplexers," in *IEEE MTT-S Int. Microw. Symp. Digest*, Philadelphia, June 2003, pp. 1219–1222.
- [6] J. Hueso, S. Cogollos, B. Gimeno, V. E. Boria, A. Vidal, M. Taroncher, H. Esteban, and M. Guglielmi, "Accurate consideration of metal losses in planar waveguide junctions using an efficient integral equation technique," in *IEEE MTT-S Int. Microw. Symp. Digest*, Fort Worth, June 2004, pp. 1411–1414.
- [7] C. A. Balanis, *Advanced Engineering Electromagnetics*. New York: John Wiley & Sons, 1989.
- [8] M. Taroncher, S. Cogollos, V. E. Boria, B. Gimeno, A. Vidal, J. Hueso, and I. Hidalgo, "On the rigorous calculation of all ohmic in rectangular waveguide multi-port junctions," in *IEEE MTT-S Int. Microw. Symp. Digest*, Long Beach, June 2005, pp. 71–74.
- [9] M. Guglielmi, "Simple CAD procedure for microwave filters and multiplexers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, no. 7, pp. 1347–1352, July 1994.