Full-Wave Modal Analysis of NRD Guide T-Junction

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***Abstract*—A full-wave analysis is made for a nonradiative dielectric (NRD) guide T-junction. It is developed on the basis of a mode-matching scheme combined with a cascading procedure that allows formulating generalized admittance and generalized scattering matrices. Results obtained by this technique are compared with HFSS results and they are found in an excellent agreement. Our calculations indicate a strong coupling that may take place between LSE and LSM modes among ports of the junction.**

***Index Terms*—Generalized scattering matrix, mode-matching method, NRD guide, T-junction.**

I. Introduction

MILLIMETER-WAVE technology holds the key for future broadband systems. It consists of planar and/or nonplanar building blocks including various waveguides. The nonradiative dielectric (NRD) guide [1] has been recognized as the one of the most attractive structures due to its unmatched properties such as radiationless and low-loss transmission as well as potentially low cost. Recently, a hybrid integration technology has been proposed and it offers the possibility of combining advantages of planar circuit and NRD-guide platforms, and at the same time overcoming their drawbacks [2], [3]. To date, design aspects and modeling results have well been documented for planar circuits. However, limited modeling work has been reported for basic NRD structures such as T-junction, which are critical in the design of NRD-related circuits and devices.

In this work, a NRD T-junction is studied by a mode-matching approach coupled with a cascading procedure. This scheme allows the formulation of a generalized S-matrix derived from a generalized admittance matrix, thereby leading to a very accurate and efficient algorithm. Since the present analysis technique for NRD-guide T-junction is not necessarily restricted to its standard geometrical form, a much more complicated shape of T-junction can be considered that leads to a more generalized T-junction.

II. Theory

A generalized three-port NRD-guide junction is represented in Fig. 1. The cross section of each NRD port is defined with height a and width b. The white square region defined by a coordinate (v, y, u) may be in the form of any NRD circuit. Then, electromagnetic fields can be expressed for each port as

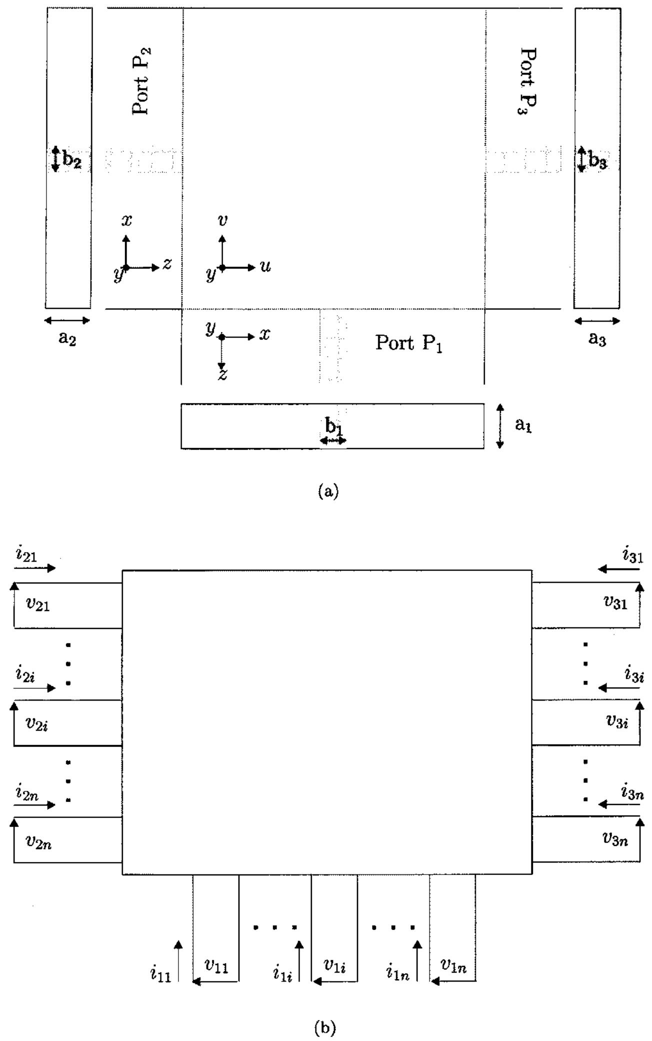

Fig. 1. Generalized three-port NRD junction. (a) Top and cross-sectional views for each port. (b) Its equivalent circuit.

$$\vec{E} = \sum_{n=1}^{N} v_n(z)\vec{e}_{nt} + \sum_{n=1}^{N} i_n(z)e_{nz}\vec{z} \tag{1}$$

$$\vec{H} = \sum_{n=1}^{N} i_n(z)\vec{h}_{nt} + \sum_{n=1}^{N} v_n(z)h_{nz}\vec{z} \tag{2}$$

where $\vec{e}_n$ and $\vec{h}_n$ are the normalized modal fields of LSE or LSM mode. In this way, equivalent modal voltage $v_n(z)$ and

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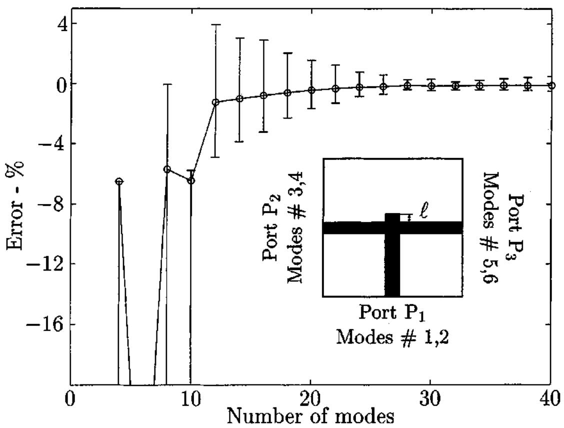


Fig. 2. Typical convergence behavior of a NRD T-junction at $f = 28$ GHz.

equivalent modal current $i_n(z)$ can be given in terms of incident and reflected waves [4]

$$v_n(z) = a_n e^{-\gamma z} + b_n e^{\gamma z} \tag{3}$$
$$i_n(z) = a_n e^{-\gamma z} - b_n e^{\gamma z}. \tag{4}$$

Since LSE and LSM modes are mutually orthogonal in power, the following relation should be verified:

$$\int_S (\vec{e}_m \wedge \vec{h}_n^*) \cdot \vec{z}\, dS = \lambda_n \delta_{mn} \tag{5}$$

and the equivalent modal current at port s is simply given by

$$i_{s,n}(z) = \frac{1}{\lambda_n^*} \int_S (\vec{e}_{s,n}^{\,*} \wedge \vec{H}) \cdot \vec{z}\, dS. \tag{6}$$

An equivalent circuit can be deduced and it is represented in Fig. 1(b) [5]. The admittance matrix is then defined by

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \tag{7}$$

where i_s and v_s are vectors of order n_s, Y_{sr} is a $(n_s \times n_r)$ matrix and $(s, r) \in \{1, 2, 3\}$

If all ports are short-circuited except port r by electric wall, all the equivalent modal voltages $v_{s,n}(z)$ are equal to zero except $v_{r,n}(z)$. Thus the sub-matrix admittance Y_{sr} is defined by

$$[i_s] = Y_{sr}[v_r]. \tag{8}$$

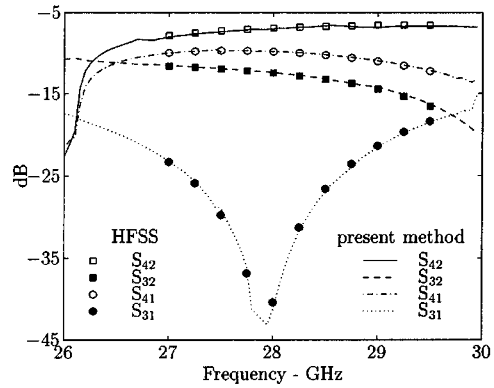
Following a procedure similar to that in [6], each sub-matrix admittance Y_{sr} can be calculated by using a mode matching technique combined with (6) as the definition of equivalent modal current where H is the total magnetic field on the electric wall at port s excited by port r. Therefore, a generalized S matrix is derived from its corresponding Y matrix through

$$S = (Id + Y)^{-1}(Id - Y) \tag{9}$$

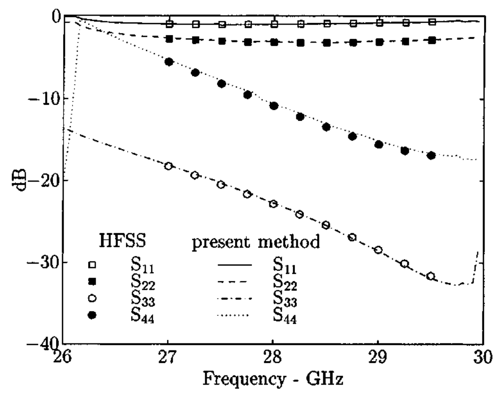
where Id is the identity matrix.

III. Numerical Results

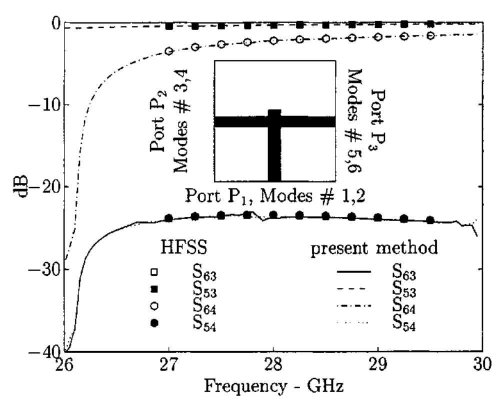
The developed algorithm is used to analyze a T-junction defined by $a_1 = a_2 = a_3 = 5$ mm, $b_1 = 3.75$ mm, $b_2 = b_3 = 3.556$ mm, $\epsilon_r = 2.56$ and $\ell = 2$ mm, where ℓ is the length of the open-end stub. Moreover, in our modeling, the transverse section of each port is terminated by metallic walls that are placed at 10 mm from the center of dielectric part. This length is found large enough to avoid field interference in 26 to 30 GHz frequency band. Under such a geometrical condition, two fundamental guided modes are present at each port, that is LSE_{10} mode and the LSM_{10} mode. Usually, the LSM fundamental mode is preferred in the design with its lowest loss properties [7]. Nevertheless, the LSE_{10} mode is known to have its cut-off frequency lower than its LSM counterpart, suggesting that modal coupling and power transfer between them may be inevitable in a discontinuity region such as T-junction. In our



(a)



(b)



(c)

Fig. 3. Calculated S-parameters with the present algorithm and HFSS package for a NRD T-junction. (a) Transmission characteristics from port 1 to port 2. (b) Reflection characteristics at ports 1 and 2. (c) Transmission characteristics from port 2 to port 3.

studies, modes numbered 1, 3, and 5 are LSE_{10} modes, and modes numbered 2, 4, and 6 are LSM_{10} ones.

Now, the first step is to check the convergence characteristics of this method with respect to the number of mode used in the algorithm. Since the structure is lossless, the following power error matrix can be defined:

$$E = Id - |SS^{t*}| \tag{10}$$

from which the average, maximum and minimum power errors are easily extracted. In this way, error-bar plots may be performed and numerical results for a typical example is shown in Fig. 2.

A large number of multi-port structures were studied, and it is found that 30 modes are a good tradeoff in view of the computational accuracy and efficiency. Note that this developed algorithm is much faster and more efficient for our modeling problems than its discretization-based counterparts such as the finite element method as used in the commercial package HFSS.

Results from this algorithm and HFSS are plotted together in Fig. 3, showing a very good agreement between the two different approaches. The symmetry of structure is respected and therefore the following results have been established:

$$|S_{42}| = |S_{62}| \tag{11}$$

$$|S_{32}| = |S_{52}| \tag{12}$$

$$|S_{41}| = |S_{61}| \tag{13}$$

$$|S_{61}| = |S_{51}|. \tag{14}$$

This example indicates that there is a strong coupling between LSE-3 mode (respectively, LSM-4 mode) at port P_2 and LSM-2 mode (respectively, LSE-1 mode) at port P_1. It can be expected that a complete mode transfer is realizable from LSE to LSM from port P_2 and P_3 to port P_1 if the T-junction geometry is adequately designed.

IV. Conclusion

A full-wave algorithm is developed for modeling the generalized NRD T-junction. It is based on a mode-matching method combined with a cascading procedure. Our results are well compared with HFSS results, also showing a strong coupling between LSE and LSM modes in the junction.

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