CHARACTERIZING WAVEGUIDE T-JUNCTIONS BY THREE PLANE MODE-MATCHING TECHNIQUES

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ABSTRACT

A rigorous method for the solution of rectangular waveguide T-junction problems is presented. The method characterizes the waveguide discontinuity three times when the side-arm of the T-junction is terminated in a short circuit with three different lengths, and hence is called the Three Plane Mode-Matching Technique (TP-MMT). Computed and measured data on both E-plane and H-plane T-junctions are compared, showing an excellent agreement, of both magnitudes and phases of the scattering matrix elements.

I. INTRODUCTION

Waveguide T-junctions play an important role in designing microwave circuits, such as multiplexers used in modern communication systems [1,2,3,4], and power dividers [5]. Modeling waveguide T-junctions is an old problem. Initially, equivalent circuits were derived based on electrostatic approximations [6]. These approximations do not give accurate results, and are limited to very narrow frequency bands. Their accuracy can not satisfy the requirements for many applications. In recent years, Finite Element Method (FEM) and Boundary Element Method (BEM) were applied to solve this problem and gave very good results [7]. However, these methods require large computing efforts.

Mode-matching techniques have been used in the past for the successful solution of a wide range of waveguide discontinuity problems. For mode matching to be valid, the geometry of the configuration must have proper boundaries to allow the division of the structure into regions, expansions of the fields in terms of natural modes in each region, then the infinite set of mode-matching equations can be truncated to a finite set and solved numerically. If the field representation in any region can not be expanded in terms of natural modes, mode matching will be obviously invalid [8]. Unfortunately, waveguide T-junctions have a region (Region 4 in Fig. 1a) where the fields cannot be expanded in terms of natural modes.

One approach, introduced in the late 1960's [9], uses equivalent-circuit concepts applied to waveguide modes. This method calculates the admittance matrix of the T-junction by successively placing short circuits exactly at two of the three openings of the T-junction (i.e. at the thin lines in Fig. 1a), yielding three one ports of shorted uniform waveguides. The same strategy is used in [4,5] to compute the scattering matrix of the T-junction.

This paper uses the mode-matching technique directly, by modifying the configuration to avoid the field defective regions. The method modifies the configuration by placing a short circuit on the side arm of the T-junction, some distance away from the discontinuity. The scattering matrix of the resulting two-port network is then computed rigorously by mode matching. By repeating the same process with three different positions of the short circuit on the side arm, the three-port scattering matrix of the T-junction can be extracted. Since the solution is obtained by using mode matching three times, the method proposed will be called Three Plane Mode-Matching Technique (TPMMT).

The computed results using the TPMMT were verified by experimental measurements and excellent agreement was obtained for both the magnitudes and phases of all the scattering matrix elements of both E- and H-

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plane T-junctions.

II. THREE PLANE MODE-MATCHING TECHNIQUE (TPMMT)

1. Three Plane Measurement Method

A waveguide T-junction is modeled by a three-port network as shown in Fig. 2a. We developed a method, called three plane measurement method, to measure the scattering parameters of this three-port network by a network analyzer. The method can be described as follows. a) Connect three short circuits, (one at a time), with reflection coefficient $e^{j\theta_i}(i = 1,2,3)$ to one of the three ports (port 3). b) Measure the S-parameters of each of the resulting two-port networks $[S_{mi}], i = 1,2,3$, (port 1 to port 2) by a network analyzer (Fig. 2b). Let these two port parameters be:

$$[S_{mi}] = \begin{bmatrix} S_{m11i} & S_{m12i} \\ S_{m21i} & S_{m22i} \end{bmatrix}, \qquad i = 1,2,3 \qquad (1)$$

c) Calculate the S-parameters of the three-port network from the three measured two-port network S-parameters. Assuming the three-port network S-parameters are

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \qquad (2)$$

Then, the relationship between $[S]$ and $[S_{mi}]$ can be easily derived.

$$S_{m11i} = S_{11} + \frac{S_{31}^2 e^{j\theta_i}}{1 - S_{33}e^{j\theta_i}}, \qquad i = 1,2,3 \qquad (3-1)$$

$$S_{m21i} = S_{21} + \frac{S_{31}^2 e^{j\theta_i}}{1 - S_{33}e^{j\theta_i}}, \qquad i = 1,2,3 \qquad (3-2)$$

Where θ_i is the phase of ith short. The reciprocity and the symmetry properties of the T-junction have been used in equation (3). These are:

$$S_{13}^2 = S_{31}^2 = S_{23}^2 = S_{32}^2 \qquad (4-1)$$

$$S_{12} = S_{21} \qquad (4-2)$$

$$S_{11} = S_{22} \qquad (4-3)$$

and

$$S_{m11i} = S_{m22i} \qquad (5-1)$$

$$S_{m12i} = S_{m21i} \qquad (5-2)$$

Solving equation (3-1), S_{11}, S_{33} and S_{31}^2 can be obtained, and then substituting S_{33} and S_{31}^2 into equation (3-2), S_{21} can be calculated.

2. T-Junction Modeling

Inspired by the three plane measurement method, three shorts (with different phases) are used to modify the T-junction configuration. Once the side-arm of the T-junction is shorted, region 3 and 4 are combined to form region B in Fig. 1b. This new region is considered as a uniform waveguide of cross section $(a \times b_i)$, different from the cross section of regions A and C $(a \times b)$, and length x, as shown in Fig. 1b. The problem is therefore reduced to a waveguide discontinuity problem of three waveguides: two infinite waveguides A and C of cross section $a \times b$, separated by a length x of waveguide B of cross section $a \times b_i$. The same procedure as three plane measurement method is used to obtain the S-parameters of the T-junction, except that the S-parameters of the three two-port networks are now computed by using mode-matching techniques instead of measurements by the net-

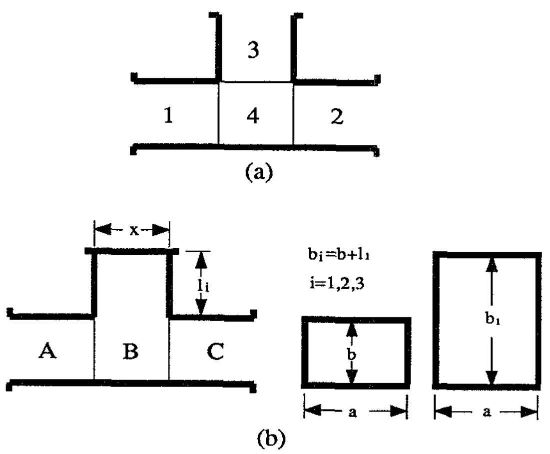

Fig. 1 The cross sections of T-junction and side-arm shorted T-junction

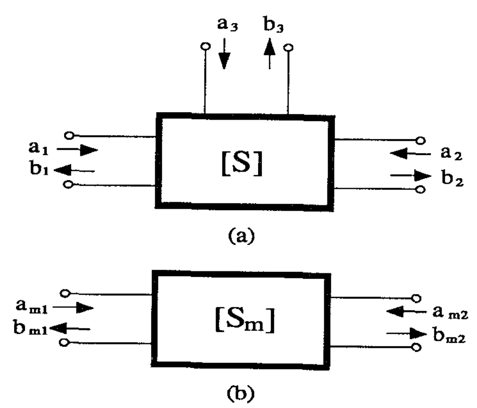

Fig. 2 Three-port & two-port networks

work analyzer.

III. COMPUTED AND MEASURED RESULTS

A computer program was developed to compute the S-parameters of both E-plane and H-plane rectangular waveguide T-junctions. Convergence of the solution was checked by increasing the number of modes used in the mode-matching. Six modes in each region were found to be sufficient for convergence of the S-parameters to within 0.5%.

Using three plane method, the best choice of lengths for the three shorts is to make the phase difference between each two of the three ±120°. Considering the higher order modes excited by the T-junction, a certain minimum distance from the mouth of the T to the short is necessary to avoid higher order mode interaction between the short reference plane and the T-junction. On the other hand, the longer the minimum distance is, the more the number of modes in region B is needed. As a compromise, it is found that (0.6-0.8)λ_g is the best choice, for the minimum short circuit distance.

Fig. 3 shows the computed results by TPMMT and the measured data by an HP8510B, including the magnitudes and the phases of a S-band E-plane T-junction

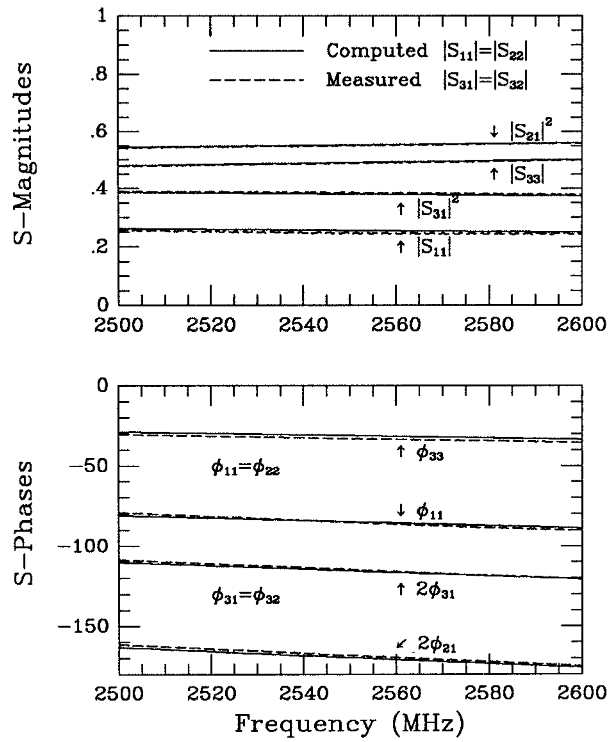

Fig. 3 S-band E-plane T-junction with a=2b=3.4", x=b=1.7"

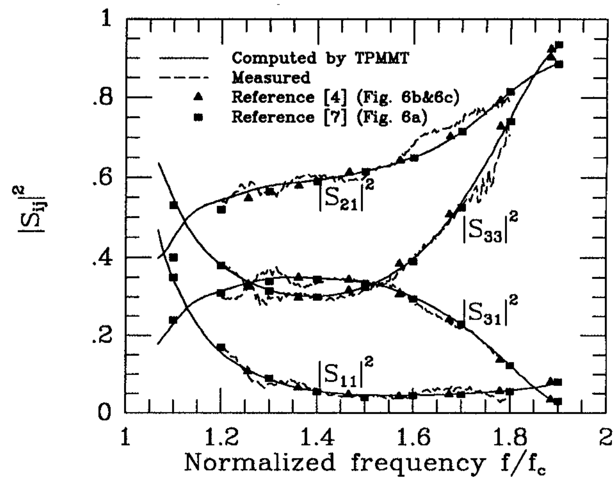

Fig. 4 H-plane T-junction with b=2a=x
For measurement, b=.9", a=.45"

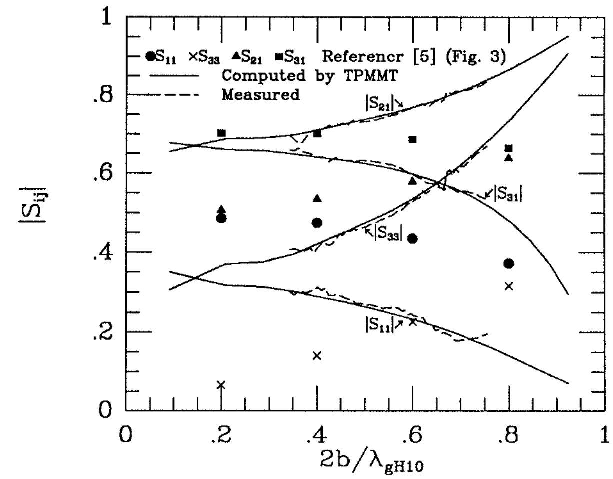

Fig. 5 E-plane T-junction with a=2b=2x
For measurement, a=3.4", b=1.7"

over the frequency band 2.5GHz to 2.6GHz. Agreement between computed and measured data is remarkable.

Fig. 4 compares, over the total waveguide frequency band, the S-parameters computed by TPMMT, measured by the HP8510, and published using other methods [4,7], for an H-plane T-junction. The results are in excellent agreement over the total waveguide frequency band.

Fig. 5 gives the performance of E-plane T-junction over the total waveguide frequency band. The results computed by TPMMT and measured are in agreement. However the data from [5] appears to have significant discrepancy.

Fig. 6 and Fig. 7 compare the S-parameters, including magnitudes and phases, obtained from TPMMT and from the equivalent circuits [6], for E-plane and H-plane T-junctions, respectively. Although the equivalent circuit model of Ref. [6] predicts the general trend of S-parameter frequency dependences, its accuracy is entirely inadequate for most modern applications, particularly in the high frequency range of the waveguide band.

IV. CONCLUSIONS

A rigorous method was presented to model rectangular waveguide T-junctions. The method is a combination of mode-matching techniques and three plane measurement method. The computed and measured results of magnitude and phase of the scattering matrix elements are in excellent agreement for both E-plane and H-plane T-junctions. The significance of TPMMT is not just in solving waveguide T-junction problems, it can be used to solve other problems which have field deficiency in some regions, such as right angle bends in waveguides, T-junction series, etc.

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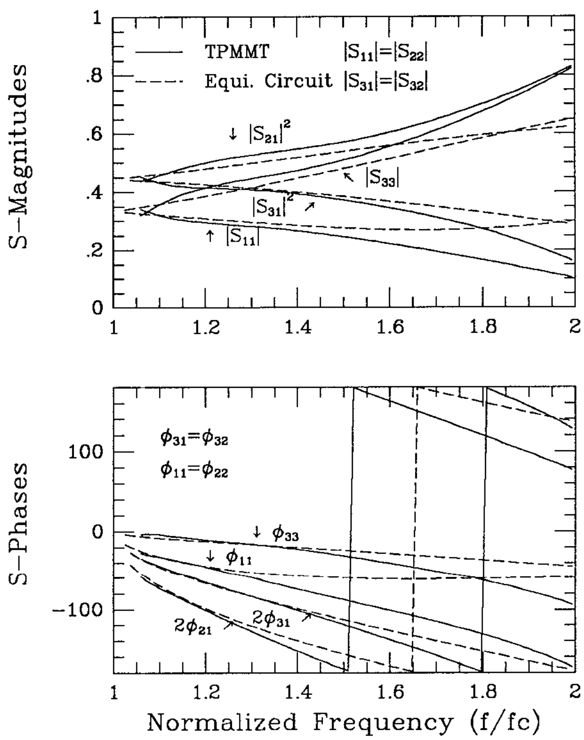

Fig. 6 Comparison between the results of TPMMT and equivalent circuit for E-plane T-junction with a=2b=2x

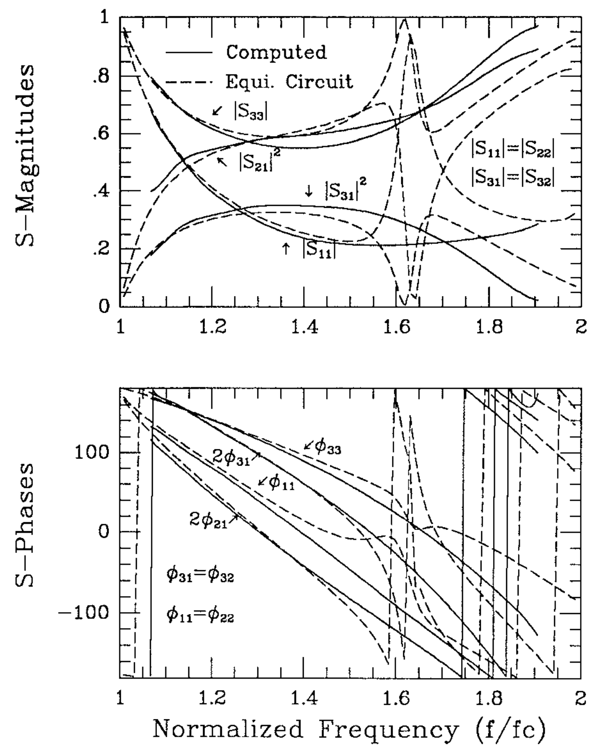

Fig. 7 Comparison between the results of TPMMT and equivalent circuit for H-plane T-junction with b=2a=x

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