A RIGOROUS DISPERSIVE CHARACTERIZATION OF MICROSTRIP CROSS AND TEE JUNCTIONS †

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Abstract– A full-wave spectral-domain analysis is applied to the characterization of multi-port microstrip discontinuities. This approach employs the moment method to find the currents in the microstrip circuits and subsequently, the scattering parameters of the junctions. In this approach, all the physical effects are considered, including radiation and surface waves. The numerical results for a tee and a cross junction are presented and agree well with the quasi-static values at low frequencies. The S parameters of a tee junction are further compared against the measured results with excellent agreement. The utilization of a shaped T-junction as a broad-band equal-power divider is also discussed.

I. Introduction:

The full-wave analysis which deals with microstrip discontinuities in an open geometry has been applied to a variety of problems. This approach based on the moment method solution of an exact integral equation involves the computation of a continuous plane wave spectrum such that the effects of radiation, surface waves and the higher-order modes are included. This full-wave analysis has been applied to microstrip open-ends and gaps [1-3], steps [4], and bends [5-7].

From the review of the past work, one finds the full wave analysis up to now is limited to two-port structures. In this paper, a full-wave analysis up to four ports is presented. The spectral domain dyadic Green's functions are adopted in electric-field integral equations (EFIE) to handle double-layer substrate problems. Both longitudinal and transverse current components on the microstrip are taken into account and are the solution of the method of moments. In Section II, the method of moments formulation of the EFIE is briefly outlined. Mode expansion utilizing the combination of semi-infinite line modes on transmission lines and piecewise sinusoidal basis functions on the vicinity of the discontinuity are also discussed. In Section III, numerical results of the scattering parameters of various microstrip discontinuities such as basic tee and cross junctions as well as a shaped T-junction are discussed and compared with available measurements and quasi-static results.

II. Analysis:

Microstrip discontinuities can be looked upon, from a circuit point of view, as N transmission lines (N ports) jointed in a common region. The modeling involves finding the current distribution not only in the junction region but also in the N semi-infinite microstrip transmission lines. The approach to solve the problem is based on the moment method solution of the exact integral equations.

A generic four-port microstrip discontinuity is presented in Fig. 1. Four semi-infinite microstrip transmission lines which extend to $\pm\infty$ in x or y direction are jointed in a common block (dash line box in Fig. 1). The widths of these four transmission lines are not necessary the same. The planar configuration of the microstrip discontinuity inside the common block is a state of the art to design the desired performance of this junction in a specified frequency range.

For microstrip junction problems, the concept of a module can be used. A module encloses the region at or near the junction where higher order modes are generated. The region otherwise consists of purely uniform transmission lines. The currents inside the module are expanded in terms of piecewise sinusoidal basis functions, while the currents outside the module are uniform transmission line currents (semi-infinite mode SIM).

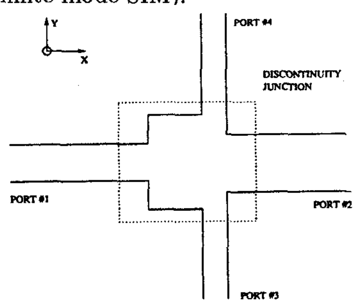

Fig. 1 A generic structure of a four port microstrip discontinuity

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If a local coordinate system is used at each line and the excitation is in the n^{th} port, then away from the junctions, the current in the n^{th} port, with longitudinal component oriented in x direction, is

$$J_x^{T_n} = \left(e^{-j\zeta_n\beta_n x_n} - \Gamma_n\, e^{j\zeta_n\beta_n x_n}\right) f_n(y_n), \tag{1}$$

while the current in the p^{th} port in x direction, with $p \neq n$, is

$$J_x^{T_p} = -\frac{\zeta_p}{\zeta_n}\Gamma_p\, e^{-j\zeta_p\beta_p x_p} f_p(y_p). \tag{2}$$

In addition, the current in the q^{th} port in y direction is

$$J_y^{T_q} = -\frac{\zeta_q}{\zeta_n}\Gamma_q\, e^{-j\zeta_q\beta_q y_q} f_q(x_q). \tag{3}$$

ζ_k is a sign index function of k^{th} port.

$$\zeta_k = \begin{cases} +1 & ;\ k^{th} \text{ line extends to } +\infty \text{ in } x \text{ or } y \text{ direction} \\ -1 & ;\ k^{th} \text{ line extends to } -\infty \text{ in } x \text{ or } y \text{ direction} \end{cases} \tag{4}$$

where k could be p, q or n. f_k and β_k are the pre-calculated current transverse dependence and the propagation constant on the k^{th} microstrip transmission line, respectively. It is noted that, in terms of scattering parameters, Γ_k is S_{kn}. This aspect describes a unique feature of the approach.

The basis function of the module is chosen as a piecewise sinusoidal (PWS) function in the longitudinal direction (the direction of current flow) and a pulse function in the transverse direction. Mathematically, the current inside the module can be expressed as

$$J^{module} = \left[\sum_{n=1}^{N} I_x^n g_x^n(x) h_y^n(y)\right]\hat{x} + \left[\sum_{m=1}^{M} I_y^m h_x^m(x) g_y^m(y)\right]\hat{y} \tag{5}$$

The closed form of the Fourier transform of the basis function can be found.

A nearly Galerkin method is applied to transform the integral equations into a matrix equation. Inside the module, the testing functions are in the same form as the current basis functions. The testing function for the semi-infinite line, which is chosen as a piecewise sinusoidal function in direction of current flow and with the same transverse dependence as the transmission line current, is applied adjacent to the module. Finally, the matrix equation is in the form of

$$\begin{bmatrix} [Z_{nn'}^{xx}] & [Z_{mn'}^{xy}] & [Z_{T_{1,2}n'}^{xx}] & [Z_{T_{3,4}n'}^{xy}] \\ [Z_{nm'}^{yx}] & [Z_{mm'}^{yy}] & [Z_{T_{1,2}m'}^{yx}] & [Z_{T_{3,4}m'}^{yy}] \\ [Z_{nT'_{1,2}}^{xx}] & [Z_{mT'_{1,2}}^{xy}] & [Z_{T_{1,2}T'_{1,2}}^{xx}] & [Z_{T_{3,4}T'_{1,2}}^{xy}] \\ [Z_{nT'_{3,4}}^{yx}] & [Z_{mT'_{3,4}}^{yy}] & [Z_{T_{1,2}T'_{3,4}}^{yx}] & [Z_{T_{3,4}T'_{3,4}}^{yy}] \end{bmatrix} \cdot \begin{bmatrix} [I_x^n] \\ [I_y^m] \\ [\Gamma_x^{1,2}] \\ [\Gamma_y^{3,4}] \end{bmatrix} = \begin{bmatrix} [V_{in}^{n'}] \\ [V_{in}^{m'}] \\ [V_{in}^{T'_{1,2}}] \\ [V_{in}^{T'_{3,4}}] \end{bmatrix} \tag{6}$$

Each element in the submatrices of $[Z]$ and $[V_{in}]$ is the reaction between the basis function and the testing function and is in the form of a double integration in a spectral domain. The superscripts in $[Z]$ indicate the orientations of the corresponding testing and basis functions; and the subscripts represent their locations. For instance,

$$Z_{nm'}^{yx} = \frac{1}{r_0}\iint \tilde{G}_{yx}(k_x,k_y) X_x^n(k_x) Y_x^n(k_y) X_y^{m'}(k_x) Y_y^{m'}(k_y)\, dk_x dk_y \tag{7}$$

is the reaction between the basis function I_x^n (current in the x direction), with the testing function $I_y^{m'}$ (current in the y direction). $[V_{in}]$ is in the same mathematical form as [Z] except that the basis function is the semi-infinite mode of the incident wave.

III. Results and Discussions:

In this research, several microstrip discontinuities are analyzed by the method described above. The data generated by TOUCHSTONE version 1.7 , which are essentially quasi-static results, are also presented for comparison.

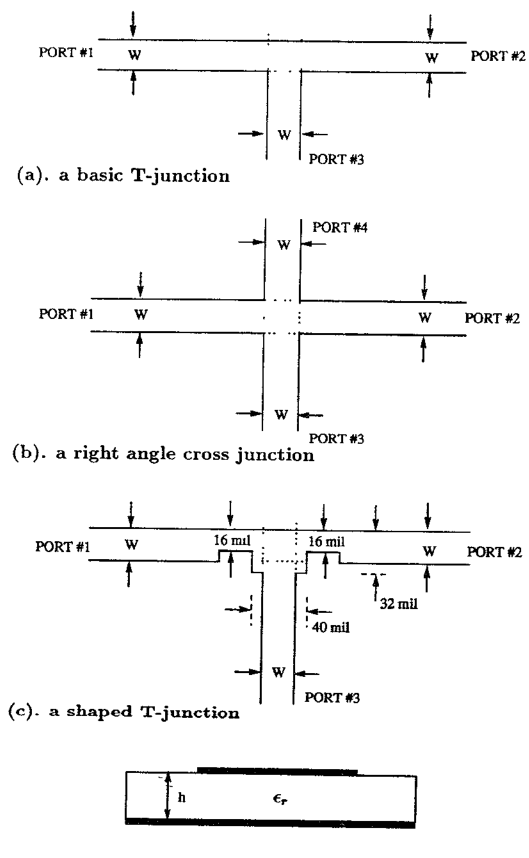

Fig. 2 Layout of a variety of junctions

A basic T-junction with three identical semi-infinite transmission lines is shown Fig. 2(a). The numerical results shown in Fig. 3 and 4 are converged within 0.2dB in magnitude and 2.5° in phase. The results of the magnitude of the scattering coefficients are compared against with measurements [8] and the quasi-static values (TOUCHSTONE data), and are shown in Fig. 3. It is seen that the present full-wave results are in excellent agreement with the measured data, but agree well only in the low frequency range with the TOUCHSTONE results. In the high frequency region, the unequal power transmitted on S21 and S31 observed in both theory and measurement is more significant than what TOUCHSTONE predicts. It is noted that the TOUCHSTONE results are from a quasi-static analysis, which are not as accurate at high frequencies. The full-wave results and the TOUCHSTONE results for the phase of $S33$ are also compared and are shown in Fig. 4. Good agreement is found below 10 GHz, but more than 45° discrepancy is found at 24 GHz in this particular case.

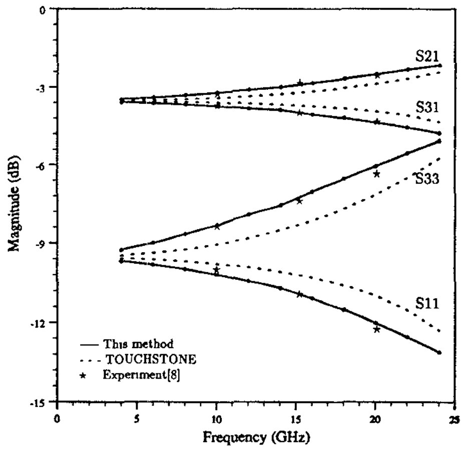

Fig. 3 Magnitude of S parameters of a basic T-junction ($\epsilon_r = 9.9$, $h = 25$ mil , $w = 24$ mil)

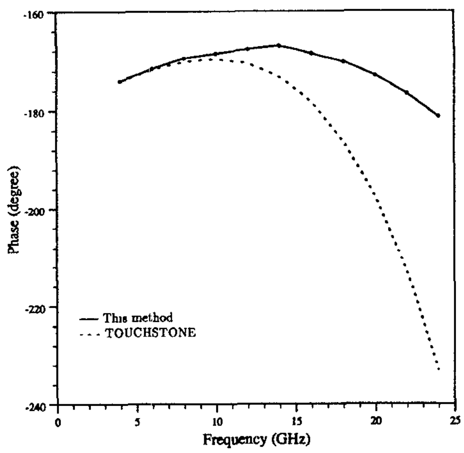

Fig. 4 Phase of $S33$ of a basic T-junction ($\epsilon_r = 9.9$, $h = 25$ mil , $w = 24$ mil)

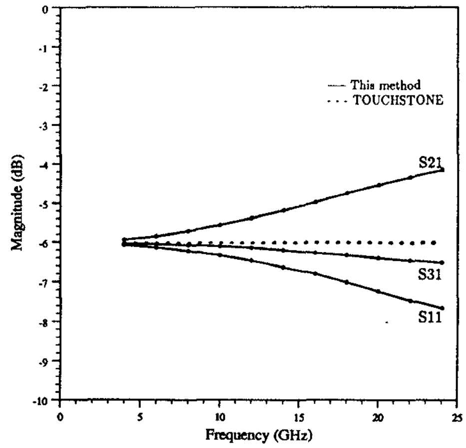

Fig. 5 Magnitude of S parameters of a right angle crossing junction ($\epsilon_r = 10.2$, $h = 25$ mil , $w = 24$ mil) Note that in TOUCHSTONE $|S11| \approx |S21| \approx |S31|$

A symmetrical cross junction is shown in Fig. 2(b), where two identical transmission lines are crossed at a right angle. With the same numerical convergence criteria as in a basic T-junction, the magnitudes of scattering coefficients are shown in Fig. 5. TOUCHSTONE predicts equal power distribution for a cròss junction in a wide frequency range; however, the results of this study indicate there is an unequal power distribution for the cross junction. The phenomenon of unequal power distribution is more significant for higher frequencies. From a distributed circuit point of view, this phenomenon is obvious since port II and port III are not symmetric and the current tends to go straight through the cross junction. For a quasi-static calculation, the cross junction is like two wires jointing together and in terms of the lumped circuit concept, the power distributed in each port is certainly identical.

The problem for a basic junction is that the power transmission distributed in each port is usually restricted. For example, in a basic T-junction, there is always more power transmitted in port II than in port III, and the reflection coefficient increases as the frequency increases. In order to make the circuit design more flexible, modified or compensated discontinuities are usually used [9]. A shaped T-junction shown in Fig. 2(c) is an example of this modification. In the present full-wave analysis, the advantage of using piecewise sinusoidal basis functions can be seen in this particular application. By using piecewise sinusoidal basis functions inside the module, the shape of the junction can be quite flexible in the modeling. The design of a shaped T-junction shown in Fig. 2(c) is intended for equal-power transmission in ports II and III and small reflection coefficient at port III. If the difference of the transmitted power for ports II and III is required to be less than 0.5 dB,

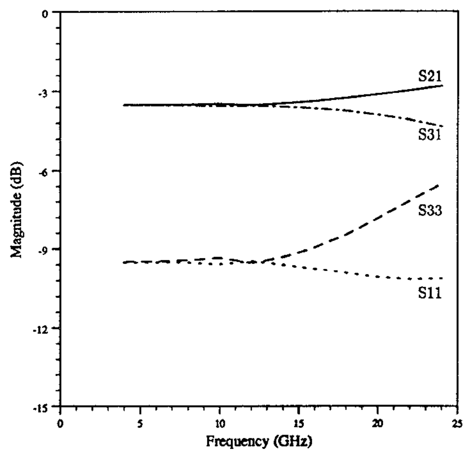

Fig. 6 Magnitude of S parameters of a shaped T-junction ($\epsilon_r = 10.2$, $h = 25$ mil , $w = 24$ mil)

the results in Fig. 6 show that equal power transmission is very broad band (from D.C. up to 16 GHz). In comparison, for a basic T-junction, equal power transmission only valid up to 6 GHz. Besides, $S33$ of a shaped T-Junction is usually a few dB lower than that of a basic T-junction.

IV. Conclusion:

A full wave analysis of a multi-port network is carried out by the moment method. It has the capability of analyzing four-port irregular shaped junctions. The results for a tee and a cross junctions are presented and found in good agreement with the quasi-static results at low frequencies. An example of using a shaped T-junction to improve the performance of a basic T-junction was given. This example also illustrated the flexibility and the CAD potential of the full-wave analysis presented in this paper. The computed results are further compared against the measured data for a tee junction. The comparison shows excellent agreement.

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References

[1] P.B. Katehi and N.G. Alexopoulos, "Frequency-dependent characteristics of microstrip discontinuities in millimeter wave integrated circuits," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-33, pp.1029-1035, Oct. 1985.

[2] R.W. Jackson and D. M. Pozar, "Full wave analysis of microstrip open-end and gap discontinuities," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-33, pp.1036-1042, Oct. 1985.

[3] H.Y. Yang, N.G. Alexopoulos and D.R. Jackson, "Microstrip open-end and gap discontinuities in a substrate-superstrate structure," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-37, pp.1542-1546, Oct. 1989.

[4] R.W. Jackson, "Full-wave, finite element analysis of irregular microstrip discontinuities," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-37, pp. 81-89, Jan. 1989.

[5] J.R. Mosig, "Arbitrarily shaped microstrip structures and their analysis with a mixed potential integral equation," IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-36, pp. 314-323, Feb. 1988.

[6] A. Skrivervik and J.R. Mosig, "Equivalent circuits of microstrip discontinuities including radiation effects," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 1147-1150.

[7] W.P. Harokopus and P.B. Katehi, "An accurate characterization of open microstrip discontinuities including radiation losses," 1989 IEEE MTT-S International Microwave Symposium Digest, pp. 231-234.

[8] I. Wolff, private communication

[9] M. Dydyk, "Master the T-junction and sharpen your MIC designs," Microwaves, pp.184-186, May 1977.