AN ACCURATE CHARACTERIZATION OF OPEN MICROSTRIP DISCONTINUITIES INCLUDING RADIATION LOSSES

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Abstract-An accurate full-wave analysis of a variety of open microstrip discontinuities and circuit elements has been performed. The technique has been employed to characterize microstrip corners, steps, and matching sections. A two-dimensional application of Method of Moments is utilized to solve Pocklington's Integral equation in the space domain. The analysis accurately accounts for dispersion, space wave, and surface wave radiation. Scattering parameters are obtained for the circuit element or discontinuity by using transmission line theory.

INTRODUCTION

The accurate characterization of passive microstrip elements and discontinuities is critical to the development of increasingly higher frequency MIC and MMIC circuits. Additionally, when microstrip circuits are combined with monolithic antenna elements, as in a phased array, the understanding of the electromagnetic interactions between circuit and antenna elements is crucial.

Previously, open microstrip discontinuities have been analyzed primarily by quasi-static methods [1], [2] or by equivalent waveguide models [3], [4]. Quasi-static techniques yield models with no frequency dependence, while equivalent waveguide models contain limited information on dispersion. Neither technique accounts for space and surface wave radiation, and they are therefore restricted to lower frequencies where these effects are not significant.

Consequently, the study of microstrip elements at higher frequencies requires a rigorous full electromagnetic analysis which accounts for radiation and all substrate effects. The full-wave analysis of open microstrip structures printed on a single layer has been performed by Katehi [5], and Jackson and Pozar [6]. However, the work performed assumed electrically thin elements, and was restricted to simple structures such as open-ends or gaps. The full-wave analysis presented here is a rigorous extension of [5] to more complex elements which form the building blocks to many multi-port microstrip networks. The following approach requires a solution to the integral equation relating the electromagnetic fields to the current on the microstrip. On the plane of the microstrip discontinuity, both current components are expanded into finite series.

Two dimensional Method of Moments and Galerkin's procedure are then utilized. This technique allows the characterization of a wide range of planar microstrip elements. In addition, the method is applicable to the study of antenna elements.

This formulation has been shown to accurately characterize microstrip corners, steps, stubs, and simple impedance matching sections. Numerical results are shown in this paper for typical two-port discontinuities, and a comparison is made to *Touchstone* [1].

ANALYSIS

The open microstrip geometry is shown in figure 1. Pocklington's integral equation relates the electric field to the current on the microstrip. Both directions of current (J_x, J_y) on the plane of the microstrip conductor are considered allowing the analysis of a wide range of planar microstrip elements. The electric field on the plane of the microstrip conductor $(z = 0)$ is

$$\begin{aligned} E_x(x,y,0) = \int_{s'} [& \; G_{xx}(x,y;x',y') \; j^x(x',y') \\ + & \; G_{xy}(x,y;x',y') \; j^y(x',y')] dx'dy' \\ E_y(x,y,0) = \int_{s'} [& \; G_{yx}(x,y;x',y') \; j^x(x',y') \\ + & \; G_{yy}(x,y;x',y') \; j^y(x',y')] dx'dy' \end{aligned} \quad (1)$$

where the expressions $G_{ij}(x,y;x',y')$ are components of the dyadic green's function for a Hertzian dipole above a grounded dielectric substrate [7],[8].

Two-dimensional Method of Moments is utilized. The two unknown current components are expanded into finite series of unknown amplitudes multiplied by known basis functions. The basis functions chosen are rooftop functions which allow for sinusoidal variation in the longitudinal direction and for constant variation in the transverse direction according to

$$J_x = \sum_{n=1}^{N+1} \sum_{m=1}^{M+1} I_{nm}^x j_{nm}^x(x',y') \quad (2)$$

$$J_y = \sum_{n=1}^{N+1} \sum_{m=1}^{M+1} I_{nm}^y j_{nm}^y(x',y') \quad (3)$$

[1] *Touchstone* is a microwave CAD software package available from EESOF

$$j^x_{n,m}(x',y') = [f_n(x')g_m(y')] \quad (4)$$

$$j^y_{n,m}(x',y') = [g_n(x')f_m(y')] \quad (5)$$

with

$$f_n(x') = \begin{cases} \frac{\sin k(x_{n+1}-x')}{\sin kl_x} & x_n \leq x' \leq x_{n+1} \\ \frac{\sin k(x'-x_{n-1})}{\sin kl_x} & x_{n-1} \leq x' \leq x_n \end{cases} \quad (6)$$

and

$$g_m(y') = \{ 1 \quad y_{m-1} \leq y' \leq y_{m+1} \quad (7)$$

In equations (6) and (7) $l_x = x_{n+1} - x_n$, and k is a parameter which is equal to the wavenumber in the dielectric.

These series are substituted into Pocklington's Integral equation (1), and Galerkin's method is applied to enforce the boundary condition on the microstrip conducting strip. The inner products

$$\langle E_x, j^x(x,y)\rangle \quad (8)$$

$$\langle E_y, j^y(x,y)\rangle \quad (9)$$

which represent the weighted average of the electric field on the surface of the conducting strip are set to zero. The resulting system of linear equations can be written in matrix form as

$$\begin{bmatrix} Z_{XX} & Z_{XY} \\ Z_{YX} & Z_{YY} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (10)$$

where $Z_{ij}(i = x,y : j = x,y)$ represent blocks of the impedance matrix, I_i is the vector of unknown x and y current amplitudes, and V_j is the excitation vector which is identically zero everywhere except at the position of the source. After the matrix inversion is performed, the current amplitudes on the feeding lines are known. If only the fundamental microstrip mode is present, the current forms a uniform standing wave. For the case of a two-port discontinuity, the even and odd excitation technique is employed to determine the 2-port scattering parameters through transmission line theory.

RESULTS AND DISCUSSION

To accurately calculate scattering parameters, the current must form a uniform standing wave pattern away from the discontinuity being measured. At and near the discontinuity, power is launched into space and surface waves, and higher order microstrip modes are present. Additionally, at high frequencies (or more specifically electrically thick substrates) higher order modes have been observed on the microstrip line away from the discontinuity. The presence of these higher order modes complicates the analysis. Nevertheless, for practical applications it is desirable to choose dimensions and dielectric permittivity so that only the fundamental microstrip mode propagates away from the discontinuity. In this case, the scattering parameters are easily computed from the current standing wave patterns.

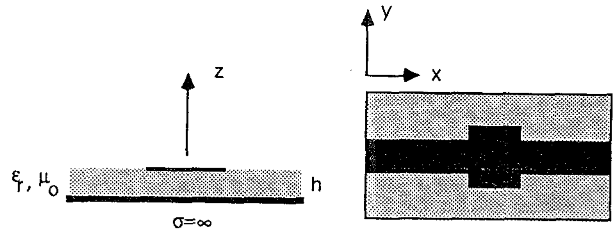

Figure 1: Open Microstrip Geometry

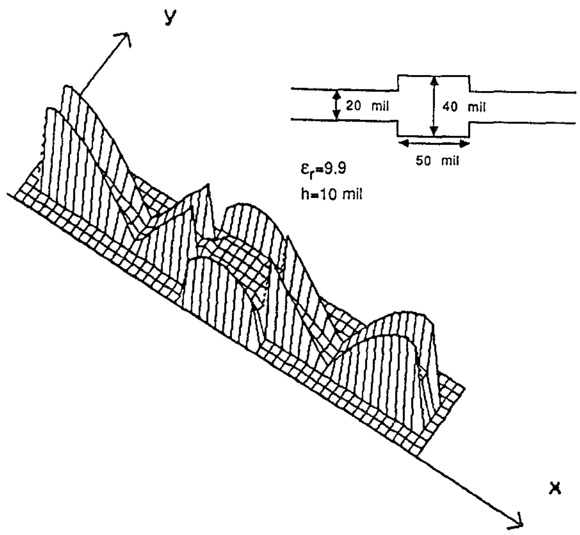

Figure 2: Longitudinal Current On Matching Section

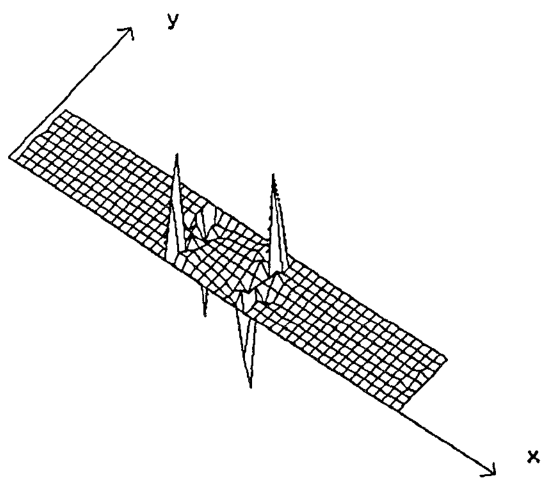

Figure 3: Transverse Current On Matching Section

For an impedance matching section on a 10 mil substrate of permittivity 9.9, the longitudinal and transverse current components are shown in Figures 2, and 3 for the even excitation case. As illustrated, the current forms a uniform standing wave pattern on the feeding lines of the discontinuity. The scattering parameters are easily determined and are compared to *Touchstone* with good agreement (Figure 4).

In Figure 5 the scattering parameters for a microstrip corner on a 20 mil substrate with a dielectric permittivity of 9.9 are shown to be in excellent agreement with *Touchstone* from 6-14 GHz (*Touchstone* model is valid to 14 GHz).

The final numerical example clearly shows the effect of space and surface wave losses on circuit performance. The two-port scattering parameters for an open ended tuning stub are examined. The stub has a quarter wave resonance at 41 GHz. The phase of the scattering parameters for the microstrip tuning stub are in good agreement with *Touchstone* (Figure 6). Nonetheless, the radiation and surface wave losses are quite large and become a dominate effect over this frequency range. Figure 7 shows the radiated power as a function of frequency.

Beyond 30 GHz, the radiated power increases sharply. The radiation losses can also be seen in the failure of our S_{11} to reach 1 (0 DB) as the *Touchstone* simulation does at the stubs resonance. The loss is due to space waves and the TM_0 surface wave. The TM_0 surface wave has a zero cutoff frequency in open microstrip.

Such an example shows that the accurate characterization of space and surface wave radiation losses is critical to MMIC design. In addition, other microstrip elements will be presented [9] which demonstrate radiation and substrate effects.

CONCLUSIONS

An accurate fullwave analysis of a variety of open microstrip discontinuities has been presented. Numerical results for the technique have demonstrated good agreement with the commercially available microwave software package *Touchstone* at lower frequencies. The presented technique accounts fully for radiation losses and all substrate effects, thus facilitating the development of more accurate high frequency circuit models.

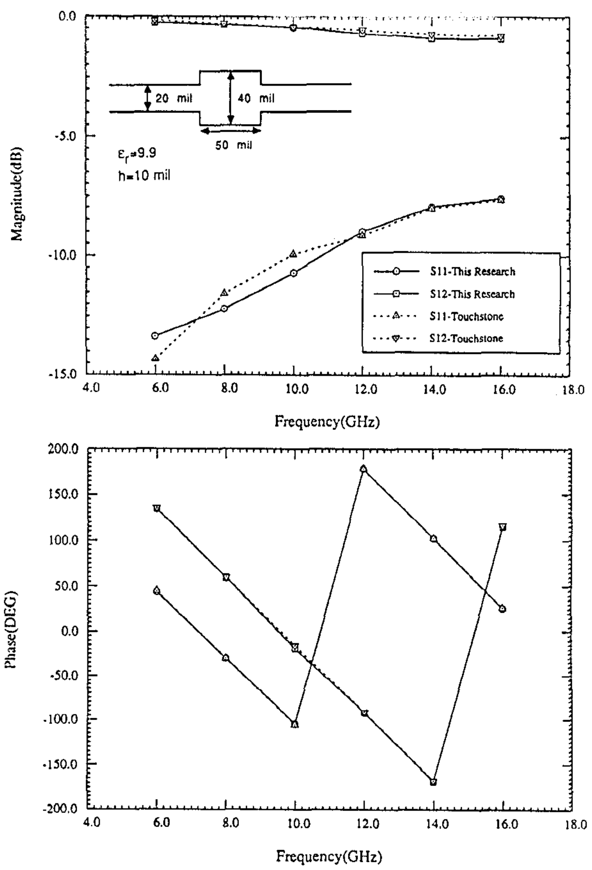

Figure 4: Scattering Parameters of Matching Section

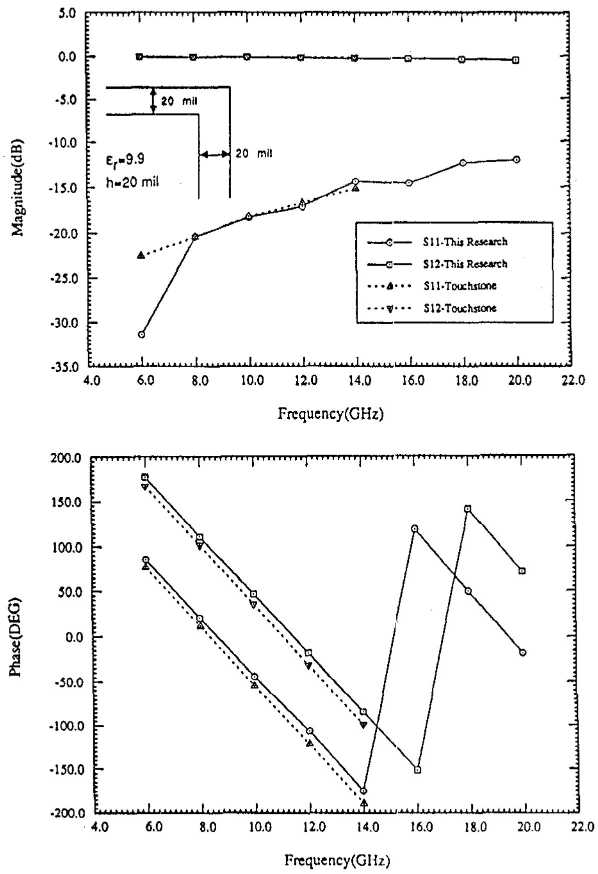

Figure 5: Scattering Parameters of Microstrip Corner

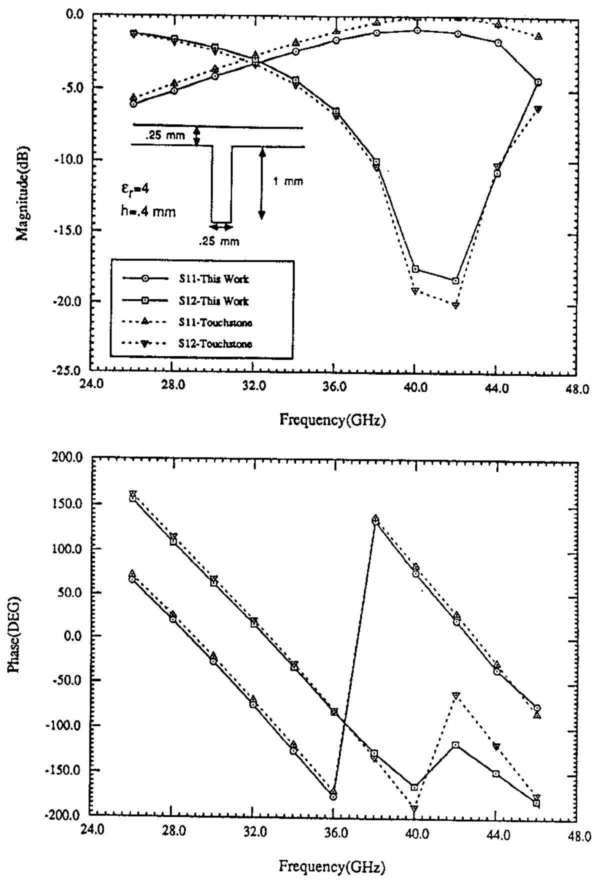

Figure 6: Scattering Parameters of Microstrip Stub

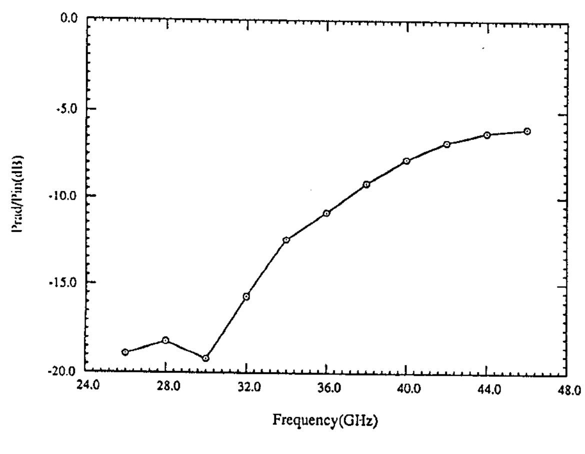

Figure 7: Power Radiated by Microstrip Stub

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