FULL WAVE MODELING OF ELECTRICALLY WIDE MICROSTRIP OPEN END DISCONTINUITIES VIA A DETERMINISTIC SPECTRAL DOMAIN METHOD

James McLean, Hao Ling, and Tatsuo Itoh

Department of Electrical and Computer Engineering
The University of Texas at Austin, Austin, Texas 78712

ABSTRACT

A fullwave analysis of microstrip open-end discontinuities in an open environment is presented. The analysis differs from previous work [1,2,3] in that it includes the effects of both longitudinal and transverse current on the strip and mode conversion near the open end. The effects of space wave and surface wave radiation are included by making use of the exact spectral domain Green's function. The inclusion of transverse current in the analysis allows the analysis to be extended to electrically wide strips. Results of the calculation of the complex reflection coefficient are presented for both narrow and wide strips.

INTRODUCTION

Microstrip open-end discontinuities in open environments have been analyzed previously by James and Henderson [1], Jackson and Pozar [2], Katehi and Alexopolous [3],and Yang and Alexopolous [4]. James and Henderson developed a variational expression for the complex end admittance of the open-end termination by making use of a quasi-TEM assumption. The other three analyses used a more rigorous source formulation based on the fundamental mode of a uniform microstrip. However, all four analyses include only the longitudinal current on the strip. Rigorous spectral domain analysis of uniform microstrip shows that the transverse current can be appreciable even on electrically narrow strips. Therefore the effects of the transverse current should be included in the analysis. This study includes the effects of both longitudinal and transverse currents and incorporates the proper edge conditions for each component of the current at the edges of the strip and the open end of the strip.

METHOD

The computational method consists of two parts. In the first part the conventional spectral domain method [5,6,7,8] is used to compute the propagation constant and the longitudinal and transverse currents for the fundamental mode on an infinitely long open microstrip. The source current to be used in the second part of the method is then given by:

$$J_z^{source}(x,z) = \sum_{m=1}^{M} a_m J_{zm}(x)\exp(-j\beta z)$$

$$J_x^{source}(x,z) = \sum_{n=1}^{N} b_n J_{xn}(x)\exp(-j\beta z)$$

The functions J_{zm} and J_{xn} are the Maxwellian basis functions defined in [8] and [9]. They include the proper edge condition for the longitudinal and transverse current at the edges of the microstrip. The constants $a_1 \ldots a_M$, $b_1 \ldots b_N$ and β, the propagation constant are determined in the spectral domain analysis.

In the second part of the method, the microstrip is divided into two overlapping regions, a uniform region far away from the open end and a perturbed region near the open end as in [1,2,3,10] . In the uniform region the current is assumed to consist of only the fundamental mode. This will be true if the higher order modes are either leaky or evanescent. The current in the uniform region is represented by the source function and a reflected wave with an unknown amplitude, Γ.

$$J_z^{uniform}(x,z) = \sum_{m=1}^{M} a_m J_{zm}(x)(\exp(-j\beta z) - \Gamma\exp(+j\beta z))$$

$$J_x^{uniform}(x,z) = \sum_{n=1}^{N} b_n J_{xn}(x)(\exp(-j\beta z) + \Gamma\exp(+j\beta z))$$

The longitudinal dependance of the current in the perturbed region near the open end is augmented with piecewise linear (rooftop) subsectional basis functions which are defined in [10]. The piecewise linear functions allow a reasonable approximation to the edge condition for the both the transverse and the longitudinal currents at the open end. The transverse dependance of the current in the perturbed region is represented with Maxwellian basis functions with variable coefficients. This takes into account mode conversion in the perturbed region. Therefore, the current in the perturbed region is given by

CH2848-0/90/0000-1155$01.00 © 1990 IEEE

$$J_z^{perturbed}(x,z) = \sum_{k=1}^{K} J_{zk}(x) \sum_{p=1}^{P} c_{pk} F_p(z) + J_z^{uniform}(x,z)$$

$$J_x^{perturbed}(x,z) = \sum_{l=1}^{L} J_{xl}(x) \sum_{q=1}^{Q} d_{ql} F_q(z) + J_x^{uniform}(x,z)$$

where $F_p(z)$ and $F_q(x)$ are piecewise linear subsectional basis functions.

The spectral domain equations describing the discontinuity are [9]:

$$\tilde{Z}_{zz}(\alpha,\beta)\tilde{J}_z(\alpha,\beta) + \tilde{Z}_{zx}(\alpha,\beta)\tilde{J}_x(\alpha,\beta) = \tilde{E}_z(\alpha,\beta)$$

$$\tilde{Z}_{xz}(\alpha,\beta)\tilde{J}_z(\alpha,\beta) + \tilde{Z}_{xx}(\alpha,\beta)\tilde{J}_x(\alpha,\beta) = \tilde{E}_x(\alpha,\beta)$$

where $\tilde{Z}_{zz} \ldots \tilde{Z}_{xx}$ are the components of the spectral domain dyadic Green's function, $\tilde{J}_z$ is the Fourier transform of the total longitudinal current, $\tilde{J}_x$ is the Fourier transform of the total transverse current, $\tilde{E}_z$ is the Fourier transform of the z-directed electric field at the dielectric interface, and $\tilde{E}_x$ is the x-directed electric field at the dielectric inteface.

The set of coupled algebraic equations is tested in the spectral domain to generate a system of linear equations for the $PK + LQ + 1$ unknowns, $c_{11} \ldots c_{PK}$,$d_{11} \ldots d_{QL}$, and Γ. Because of the method used to test the equations, the resultant linear system is over-determined and is therefore solved via a least squares method. Γ is the complex reflection coefficient for the fundamental mode. From $c_{11} \ldots c_{PK}$,$d_{11} \ldots d_{QL}$, and Γ, the current over the entire strip can be determined.

RESULTS

In Figures 1 and 2, the longitudinal (z-directed) current and the transverse (x-directed) current on an open circuited microstrip line are plotted to show the edge conditions for a typical case. The characteristics are as follows:

- Relative dielectric constant, ϵ_R : 12.8
- Substrate height, $h = .300$ mm
- Strip width, $w = .600$ mm
- Frequency = 4.00 GHz

It can be seen that the piecewise linear functions allow the edge conditions at the open end for both the transverse current and the longitudinal current to be accurately modeled.

In order to verify the method as much as possible the results were compared with existing data and calculations. Figures 3 and 4 show the magnitude and phase of the reflection coefficent for an open circuit discontinuity with the following characteristics:

- Relative dielectric constant, ϵ_R : 9.9
- Substrate height, $h = .635$ mm
- Strip width, $w = .600$ mm

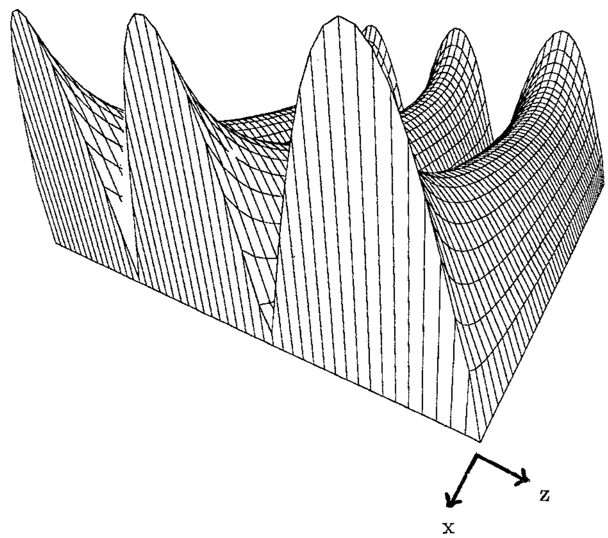

Figure 1
Magnitude of the longitudinal (z-directed) current on the strip

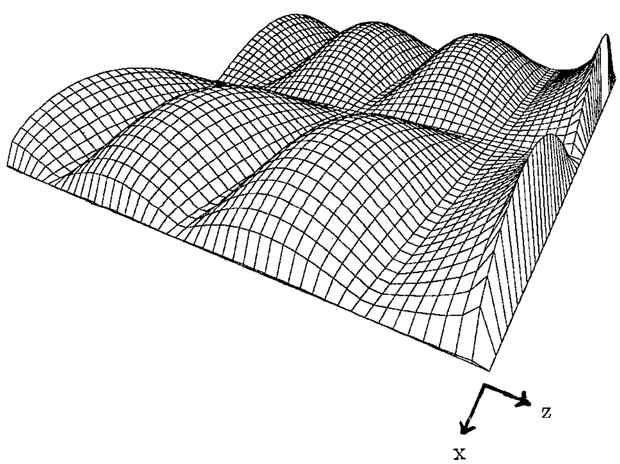

Figure 2
Magnitude of the transverse (x-directed) current on the strip

This line is very narrow electrically; at 20 GHz the line is still only 0.04 free-space wavelengths wide. Therefore the inclusion of the transverse current makes no discernable difference in the reflection coefficient value. The phase agrees well with the measured data in [11] (the magnitude was not presented in[11]) and with calculated data in [12], [13], and [4].

The magnitude of the reflection coefficient for an open-circuited microstrip line of width $.1\lambda_0$ on a substrate with a relative dielectric constant of 12.8 is shown in Figure 5. In the same figure the magnitude of the reflection coefficient is shown calculated including only longitudinal current on the strip as in [2]. It can be seen that for narrow lines such as this one the inclusion of the transverse current makes little difference in the magnitude of the reflection coefficient for small values of $\frac{d}{\lambda_0}$. However near the cutoff of the first TE surface wave, it is seen that the magnitude of the reflection coefficient displays a more pronounced trough and peak. This seems reasonable because the transverse current tends to store energy (as opposed to radiating) thereby increasing the frequency sensitivity of the reflection coefficient.

Also in Figure 5, the magnitude of the reflection coefficient for an open-circuited microstrip line of width $.15\lambda_0$ on a substrate with a relative dielectric constant of 12.8 is shown. It can be seen that the wider line has a more pronounced resonance at the cuton of the first TE surface wave mode. This is because the transverse current tends not to radiate but instead to store energy at the open-end.

CONCLUSIONS

Electrically wide microstrip open-circuit terminations have been analyzed using a deterministic spectral domain method. It has been shown that the the transverse current in the microstrip has a significant effect on the reflection coefficient especially near the cutoff frequencies of surface wave modes.

ACKNOWLEDGEMENTS

This work was supported in part by the Office of Naval Research under ONR grant N00014-89-J-1006 and by the Texas Advanced Technology Program.

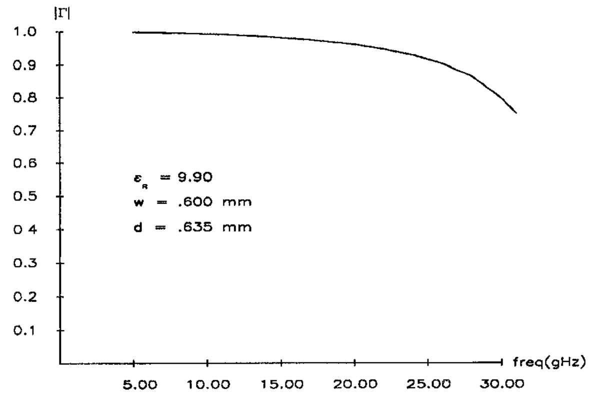

Figure 3
Magnitude of Reflection coefficient versus frequency

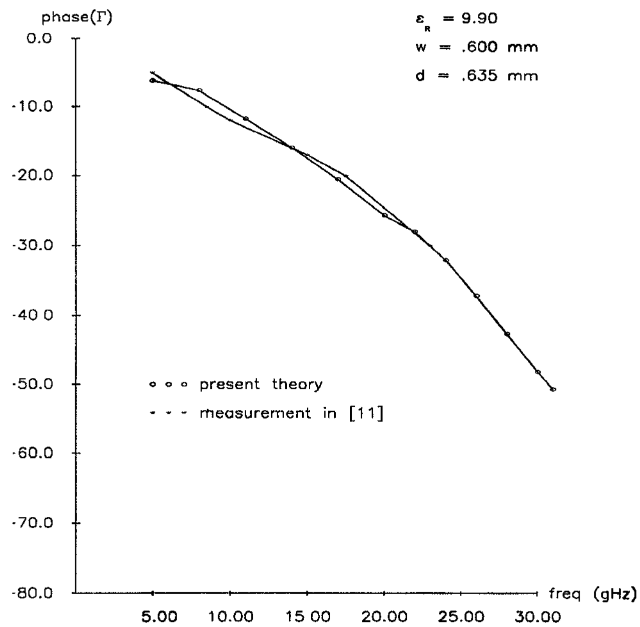

Figure 4
Phase of Reflection coefficient versus frequency

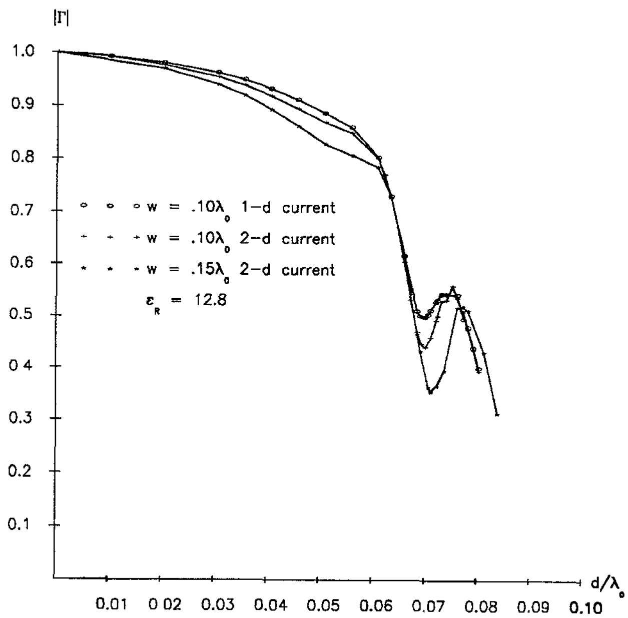

Figure 5
Magnitude of Reflection Coefficient versus $\frac{d}{\lambda_0}$

REFERENCES

1. J. R. James and A. Henderson, "High Frequency behavior of microstrip open-circuit terminations," *IEE J. Microwave Optics and Acoustics*, vol 3, pp. 205-211, September 1979.

2. R. W. Jackson and D. M. Pozar, "Full-Wave Analysis of Microstrip Open-End and Gap Discontinuities," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-33, no. 10, pp. 1036-1042, October 1985.

3. P. B. Katehi and N. G. Alexopoulos, "Frequency Dependant Characteristics of Microstrip Discontinuities in Millimeter-Wave Integrated Circuits," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-33, no. 10, pp. 1029-1035, October 1985.

4. H. Y. Yang, N. G. Alexopoulos, and D. R. Jackson "Microstrip Open-End and Gap Discontinuities in a Substrate-Superstrate Structure," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-37, no.10, pp. 1542-1546, October 1989.

5. T. Itoh and R. Mittra, "Spectral-Domain Approach for Calculating the Dispersion Characteristics of Microstrip Lines," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-21, pp. 496-499, July 1973.

6. T. Itoh, "Spectral Domain Immitance Approach for Dispersion Characteristics of Generalized Printed Transmission Lines," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-28, No 7, pp. 733-736, July 1980.

7. J. B. Knorr and A. Tufekciouglu, "Spectral-Domain Calculation of Microstrip Characteristic Impedance," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-23, No. 9, pp. 725-728, July 1975.

8. T. Itoh, Numerical Techniques for Microwave and Millimeter-Wave Passive Structures, John Wiley & Sons, New York, 1989.

9. S. Nam and T. Itoh, "Calculation of the Accurate Complex Resonant Frequency of an Open Microstrip Resonator using the Spectral Domain Method," *Journal Of Electromagnetic Wave and Applications*, Vol. 2, No. 7, pp. 635-651, 1988

10. J. Boukamp and R. H. Jansen , "The High Frequency Behaviour of Microstrip Open Ends in Microwave Integrated Circuits Including Energy Leakage," Proceedings of the 14th European Microwave Conferance, September 10-13, 1984, Liege, Belgium.

11. G. Gronau and Ingo Wolff, "A Simple Broad-Band Device De-Embedding Method Using an Automatic Network Analyzer with Time-Domain Option," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-37, No 3, pp. 479-483, 1989.

12. X. Zhang and K. Mei, "Time-domain Finite Difference Approach to the Calculation of the Frequency-Dependant Characteristics of Microstrip Discontinuities," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-36, No. 12, pp. 1775-1787, 1988.

13. N. H. L. Koster , R.H. Jansen, and Kirschning, "Accurate Model for Open End Effect of Microstrip Lines," *Electronics Letters*, 5th February 1981, No 3.