RADIATION LOSS FROM OPEN COPLANAR WAVEGUIDE DISCONTINUITIES

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Abstract-Coplanar waveguide is becoming the dominant planar transmission line structure at millimeter-wave frequencies. In this paper, radiation losses are investigated for open coplanar waveguide discontinuities by the Space Domain Integral Equation Technique. Results are presented for CPW open-end and stub discontinuities.

INTRODUCTION

Coplanar Waveguide (CPW) is rapidly becoming the dominant transmission line structure in millimeter-wave circuit design due to its many appealing properties. In the past, microstrip was the primary structure for hybrid and monolithic design, because it was an established and relatively well understood technology. Although a large body of published data and CAD software pertaining to microstrip has existed for many years, the models available for open coplanar waveguide are primarily quasi-static[1]. Nonetheless, despite this scarcity of reliable circuit models, CPW is attractive at higher frequencies for several reasons. These include the ability to wafer probe, and the ease in connecting shunt lumped elements or devices. These two advantages arise because both conducting surfaces are on the top plane of the CPW structure, and there is no need for via connections. Furthermore, the characteristic impedance and phase velocity are less dependent on the substrate height and more dependent on the dimensions in the plane of the conducting surface. This relative independence to substrate height may also result in lower radiation loss. When the CPW lines are not enclosed in a metallic package radiation will occur. This is the case for monolithic antenna array CPW feeding networks. Mechanical considerations put a lower limit on the physical thickness of integrated circuit substrates, and in the case of microstrip it is difficult to avoid excessive loss when operating above 100 GHz, because the substrate height is electrically large [2]. Nevertheless, with coplanar waveguide the fields are concentrated in the slots, dimensions which are limited only by photolithographic techniques. This allows a greater degree of flexibility in coplanar waveguide design at high frequencies. Unfortunately, there is little data available concerning the radiation loss from CPW discontinuities [3]; therefore, there are few guidelines for low loss, high frequency CPW design.

In this paper, the radiation loss from CPW discontinuities will be studied with the Space Domain Integral Equation (SDIE) technique. This technique has previously demonstrated versatility and accuracy in analyzing microstrip discontinuities at high frequencies [4]. The integral equation is formulated in terms of the equivalent magnetic current for the electric field in the slot apertures. This is in contrast to the fullwave technique presented in [5], where an integral equation in terms of the electric current on the conducting surfaces is used. That technique is more appropriate for CPW problems having finite size ground planes. Radiation losses will be provided for CPW open-end and stub discontinuities, and a suggestion for an improved stub design will be given.

THEORY

The conventional coplanar waveguide structure is given in Figure 1. The substrate is lossless with thickness h, and the conducting surfaces have zero ohmic losses. The two slot apertures have width W and are separated by spacing S. With the equivalence principle, the CPW slots can be covered by a conductor and the electric field in the slots may be represented by equivalent magnetic [6] currents given by

$$\bar{M}^a = \hat{n} \times \bar{E}^a \quad z > 0 \tag{1}$$
$$\bar{M}^b = \hat{n} \times \bar{E}^b \quad z < 0 \tag{2}$$

To ensure that the tangential electric field is continuous through the slot region, the magnetic currents must be related according to

$$\bar{M}^a = -\bar{M}^b \quad . \tag{3}$$

The magnetic fields must also be continuous through the slot region resulting in the expression

$$\hat{n} \times \left[\bar{H}(\bar{M}^a) + \bar{H}(\bar{M}^b)\right] = \hat{n} \times \bar{H}^i \tag{4}$$

where $\bar{H}(\bar{M}^a)$ and $\bar{H}(\bar{M}^b)$ are the magnetic fields due to the equivalent magnetic currents in regions a and b respectively, and $\bar{H}^i$ is the incident magnetic field on the aperture. The magnetic fields may be expressed in terms of the magnetic currents through an integral equation

$$\bar{H}^{a,b} = \int\int_{S'} [k_i^2 \bar{\bar{I}} + \overline{\nabla\nabla}] \cdot \bar{\bar{G}}_{mi}(\bar{r}/\bar{r}') \cdot \overline{M}_i(\bar{r}')\, ds' \quad (i = a, b) \tag{5}$$

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where k_i and $\overline{\overline{G}}_{mi}(\overline{r}/\overline{r}')$ are the wavenumbers and dyadic Green's function in regions a and b, respectively. The Green's function appropriate for the open CPW problem contains Sommerfeld integrals [7] which have been evaluated by a real-axis integration given in [8].

The Method of Moments[9] is applied by expanding the two-dimensional magnetic current by the summations of unknown coefficients (V_{nm}) and roof-top basis functions

$$M_x(x',y') = \sum_{n_x=1}^{N_x+1} \sum_{m_x=1}^{M_x+1} V^x_{nm}[f_{n_x}(x')g_{m_x}(y')] \quad (6)$$

$$M_y(x',y') = \sum_{n_y=1}^{N_y+1} \sum_{m_y=1}^{M_y+1} V^y_{nm}[f_{n_y}(y')g_{m_y}(x')] \quad (7)$$

where the functions f_n and g_m give the longitudinal and transverse dependence of the basis functions, respectively. The matrix equation is generated by the application of Galerkin's method to equation (5)

$$\left[Y^{\nu\mu}_{nm} \right] \left[V_{nm} \right] = \left[I_{\nu\mu} \right]. \quad (8)$$

In the above, $Y^{\nu\mu}_{nm}$ are elements of the admittance matrix, $I_{\nu\mu}$ is the excitation vector, and V_{nm} is the vector containing the amplitude coefficients for the magnetic current expansions. The excitation is provided by gap generators. The solution of this matrix equation provides the equivalent magnetic current and consequently the electric field in the slots. Transmission line theory is then utilized to characterize the CPW structure by scattering parameters from which radiation loss may be determined.

NUMERICAL EXAMPLES

Shown in Figure 2 is the normalized capacitive impedance for an open-end discontinuity excited by the coplanar waveguide mode. The results are compared to a fullwave shielded simulation [6] and are in good agreement considering the differences resulting from radiation loss in the open example, and shielding effects in the enclosed case. The open-end capacitive impedance is greater at smaller line spacings, and increases with increasing gap length eventually leveling off as the gap width becomes large. Similarly, the radiation loss from this discontinuity also increases with gap length as shown in Figure 3. In addition, the radiation loss increases with line spacing, because with the coplanar mode the electric fields in the slots are oppositely directed, and a greater degree of phase cancellation in the radiated fields is occurring for smaller spacings.

Two CPW stub geometries are shown in Figure 4, and their transmission parameter's are given in Figure 5. The straight stub has a resonance at about 22 GHz, while for the bent geometry the resonance is 1 GHz lower. The sharper resonance of the bent structure indicates low radiation loss. As shown in figure 6, the straight stub experiences severe loss which exceeds 25% of the input power. The parasitic radiation is high in this example because the electric fields in the two stub slots (or the equivalent magnetic current) are in the same direction and the slots are radiating in phase. In contrast, the electric field in the bent geometry is oppositely directed. It has been proposed [10] that a geometry having the stubs positioned between the coplanar lines would result in even lower loss.

CONCLUSIONS

The radiation properties of open coplanar waveguide discontinuities have been studied by the Space Domain Integral Equation Technique. At sub-millimeter wave frequencies, CPW technology offers greater design flexibility over microstrip, but lags in the availability of design tools. The method presented here can be used to develop high frequency circuit models. In addition, it can be used to realize low-loss designs, as was demonstrated by the improved tuning stub layout.

ACKNOWLEDGMENTS

This research was sponsored by the National Science Foundation (contract number ECS-8657951).

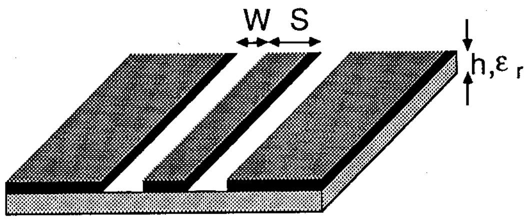

Figure 1: Coplanar Waveguide Structure

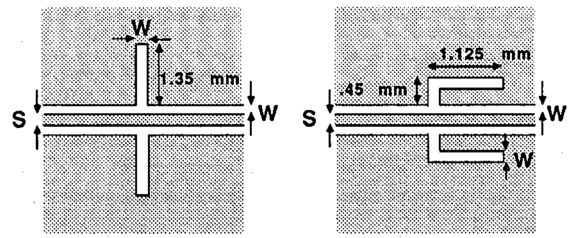

Figure 4: Coplanar Waveguide Stub Geometries ($W = .225mm, S = .45mm, h = .635mm, \epsilon_r = 9.9$)

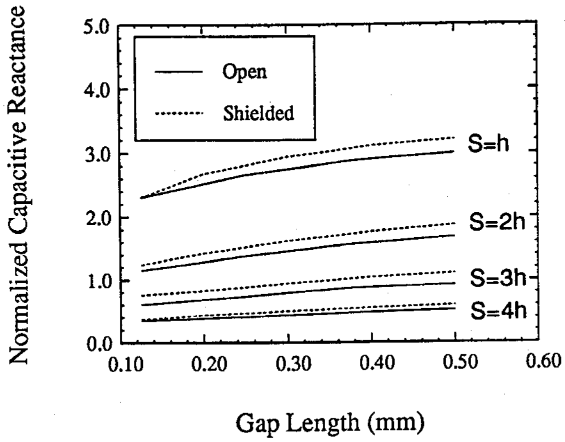

Figure 2: Normalized Capacitive Impedance at CPW open-end discontinuity ($W = .25mm, h = .5mm, \epsilon_r = 13.1$)

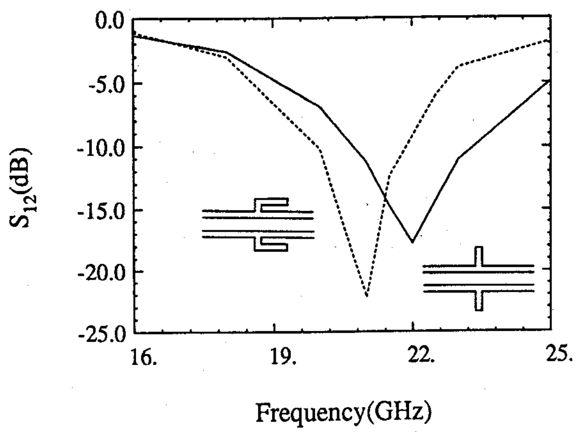

Figure 5: [S]-parameters of CPW stub elements ($W = .225mm, S = .45mm, h = .635mm, \epsilon_r = 9.9$)

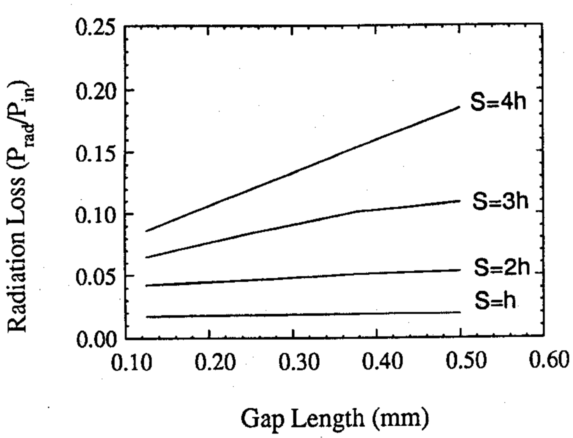

Figure 3: Radiation Loss at CPW open-end discontinuity ($W = .25mm, h = .5mm, \epsilon_r = 13.1$)

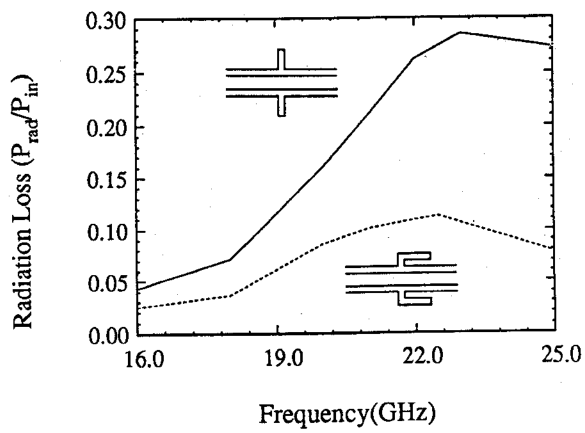

Figure 6: Radiation Loss of CPW stub elements ($W = .225mm, S = .45mm, h = .635mm, \epsilon_r = 9.9$)

References

[1] M. Naghed and I. G. Wolff, "A Three Dimensional Finite-Difference Calculation of Equivalent Capacitances of Coplanar Waveguide Discontinuities," *IEEE Microwave Symposium Digest*, pp. 1143-1146, May 1990.

[2] W. P. Harokopus, Jr. and P. B. Katehi, "Electromagnetic Coupling and Radiation Loss Considerations for Open Microstrip Discontinuities,"to appear in *IEEE Trans. Microwave Theory Tecniques*, March 1991.

[3] M. Drissi, V. Fouad Hanna, and J. Citerne, "Analysis of radiating end effects of symmetric and assymmetric coplanar waveguide using integral equations technique," *IEEE Microwave Symposium Digest*, pp. 791-794, June 1989.

[4] W. P. Harokopus, Jr. and P. B. Katehi, "Characterization of Open Microstrip Discontinuities on Multilayer Substrates Including Radiation Losses", *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-37, pp. 1964-1972, Dec. 89.

[5] R. W. Jackson, "Mode Conversion at Discontinuities in Finite-Width Conductor Backed Coplanar waveguide,"*IEEE Trans. Microwave Theory Tech.*, Vol. MTT-37, pp. 1582-1589, Oct. 89.

[6] N. I. Dib, P.B. Katehi, G.E. Ponchak, and R.N. Simons, "Modeling od Shielded CPW Discontinuities Using the Space Domain Integral Equation Method (SDIE),"accepted for publication in *Journal of Electromagnetic waves and Applications.*

[7] P.B. Katehi,"A Space Domain Integral Equation Approach in the Analysis of Dielectric-Covered slots," *Radio Science*, vol. 24, April 1989.

[8] P.B. Katehi and N. G. Alexopoulos, "Real Axis Integration of sommerfeld Integrals With Applications To Printed Circuit Antennas," *J. Math. Phys.*, vol. 24(3), Mar. 1983.

[9] R. F. Harrington, Field Computation By Moment Methods, Macmillan,N.Y. ,1968.

[10] N. I. Dib, P.B. Katehi, G.E. Ponchak, and R.N. Simons, "Coplanar Waveguide Discontinuities for P-I-N Diode Swithces and Filter Applications, " *IEEE Microwave Symposium Digest*, pp. , May 1990.