# A NEW FULL-WAVE INTEGRAL EQUATION METHOD FOR THE ANALYSIS OF COPLANAR STRIP CIRCUIT USING THE MIXED-POTENTIALS EIGENFUNCTION EXPANSION TECHNIQUE

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## Abstract

The theoretic results obtained by the new full-wave integral equation formulation using the mixed-potentials eigenfunction expansion technique are presented. In contrast to what commonly known in the literatures the new formulation can analyze a three-dimensional coplanar strip discontinuity structure on a finite-width substrate. In the case of the reduced structure analyzed by the new method the theoretic results for a microstrip discontinuity problem are validated by comparing them with those obtained by the SDA(Spectral-Domain Approach) incorporated by the LINMIC+™.

## I. Introduction

Packaging an MMIC chip or multichip module normally requires good electric shielding to prevent inter-module or chip-to-chip electromagnetic interferences and radiations. A few methods have been well known for MMIC packaging, e.g. placing a chip or multichip module in a metal box or the use of multilayer thin-film/thick-film technology[1]. In these packaging schemes the MMIC chip or multichip module can be quite far from the idealized assumptions that most full-wave three-dimensional coplanar strip simulators[2,3,4,5,6] have made so far. One category of the 3-D simulators assumes that the substrate(s), either in the form of a single layer or the stratified layers, be extended to infinite[2,3,4]. The other one, however, often assumes that the substrate(s) be extended to the edges of the side walls of the electric enclosure[5,6]. Thus the proximity effects as suggested in [7] are often neglected. These proximity effects can take place within the chip[7] or between interface with other thin-film circuitry[1].

Besides the proximity effects on the dominant mode of propagation in MMIC or hybrid MIC environment[8], the higher-order modes excited at higher frequencies are quite different from those obtained by assuming uniform dielectric layers[9]. Therefore the existence of the non-uniform dielectric layer in MMIC subsystem module can't be neglected.

The aim of this paper is to present a new full-wave three-dimensional integral equation method that can solve a class of the problems concerning the proximity effects embedded in a generic structure shown in Fig.1, which consists of two layers of substrates of heights $h_1$ and $h_2$ resembling the multilayer thin-film/thick-film technology, a non-uniform dielectric layer of height $h_3$ containing various types of dielectric materials, the air

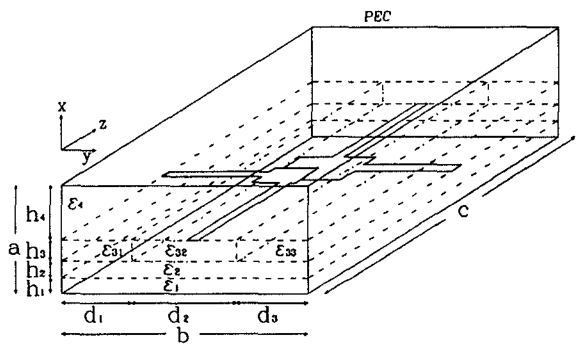


Fig.1 A generic planar transmission line circuit on layered and non-layered substrates.

LINMIC+ is a trademark of Jansen Microwaves, Inc.

region of height $h_4$, and two layers of metalization of arbitrary shape. The metalization is assumed to be infinitely thin and of infinite conductivity.

Section II briefly describes the new integral equation method. Followed by a validity check against the SDA(Spectral-Domain-Approach) in Section III, Section IV presents the theoretic data for a microstrip step discontinuity problem considering the proximity effects caused by the finite-width substrate as shown in Fig.2. Section V concludes the paper.

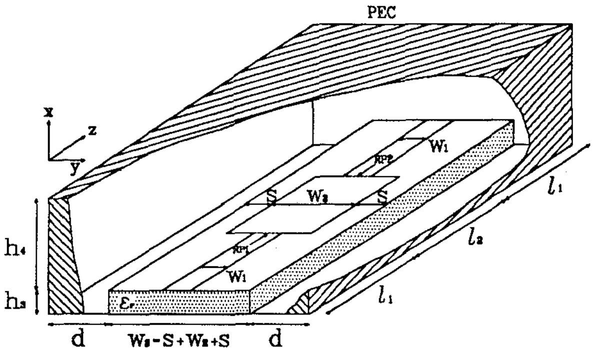


Fig.2 The reduced configuration of Fig.1 to illustrate one application of the new formulation for microstrip step discontinuity problem considering the proximity effects. The structural parameters are $h_1=h_2=0.0$, $h_3=0.635$mm, $h_4=6.35$mm, $\epsilon_r=10.2$, $w_1=0.61$mm, $w_2=1.83$mm, $l_1=l_2=3.5$mm, $w_s+2d=6.0$mm, s:variable.

## II. Method of Analysis: A Full-Wave Integral Equation Using Mixed-Potential Eigenfunction Expansion Technique [8]

The dyadic Green's function derived for the generic structure as shown in Fig.1 is similar to those reported in [8] except that the latter assumes a propagating factor $e^{\gamma z}$ for an uniform waveguide extending into $z=\pm\infty$. The electromagnetic field components in the various regions of Fig.1 are expressed by the Hertzian potentials satisfying the Helmholtz equations:

$$E^{(s)}=\nabla x \nabla x \pi_e^{(s)} - j\omega\mu \nabla x \pi_h^{(s)} \quad (1)$$
$$H^{(s)}=j\omega\epsilon \nabla x \pi_e^{(s)} + \nabla x \nabla x \pi_h^{(s)} \quad (2)$$

where s=1,2,4 for layered(uniform) dielectric regions, and s=3 for the non-layered (non-uniform) dielectric region. In the layered regions, the TE-to-x and TM-to-x Hertzian potentials are applied. In the non-layered region(s), the TE-to-y and TM-to-y Hertzian potentials are used. These Hertzian potentials, either x-directed or y-directed, constitute the mixed-potential formulation of the present method.

Followed by obtaining the y-directed and z-directed eigenfunctions for the layered and non-layered regions, respectively, we match the boundary conditions at the various dielectric interfaces. Here the unknown coefficients associated with the various regions can be eliminated by the biorthogonality relations.

Finally, by matching the boundary conditions imposed by the two metalizing layers at $x=h_1+h_2$ and $x=h_1+h_2+h_3$, respectively, a dyadic Green's function is obtained.

The unknown metal strip surface currents are discretized by roof-top functions. Galerkin's procedure is invoked to solve the integral equation for the unknown surface currents corresponding to various sets of excitations impressed at the interface ports. Once the various sets of solutions for the unknown surface currents are obtained the scattering-parameters can be extracted from these data.

## III. Validity Check Against the SDA

This section will compare the results obtained by our new formulation described in Section II with the de facto industry standard LINMIC+™ employing the SDA(Spectral-Domain-Approach). By setting the parameters $h_1$ and $h_2$ equal to zero in our new 3-D program, the corresponding reduced structure is shown in Fig.2. Next we increase the substrate width $w_s$ to such an extent that it separates from the side walls by a very small amount d, where d=0.0006mm in our comparative study. The distance d is kept small enough such that the small gap will have only negligible effect on the field distribution of the microstrip step discontinuity problem illustrated in Fig.2, where two 50Ω microstrip lines of width $w_1$ are connected to the input and output ports. A wider microstrip of width $w_2$ is inserted between the input and output ports. Throughout the paper $w_1$ and $w_2$ are kept constant, i.e. $w_1=0.61$mm and $w_2=1.83$ mm.

When applying the LINMIC+, the SDA

program will automatically assume that d=0. Fig.3 plots the magnitudes of transmission($S_{21}$) and reflection($S_{11}$) coefficients versus frequency by varying substrate widths. Note that

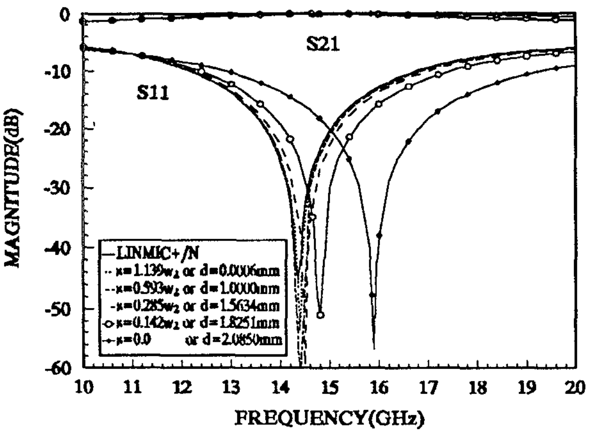


Fig.3 The theoretic results for the magnitude of transmission($S_{21}$) and reflection($S_{11}$) coefficients of the microstrip step discontinuity problem shown in Fig.2. When s=1.139$w_2$ or d=0.0006 mm, no proximity effects exist. As s is reduced further, the proximity effects become significant.

s denotes the distance between the edge of the wider microstrip and the edge of the substrate. Since the electric enclosure has fixed dimensions when referring to Fig.2, the bigger the s is, the smaller the d is. For example s=1.139$w_2$, d=0.0006 mm ($d \neq 0$). Fig.4 plots the respective phase informations of Fig.3. The SDA data obtained by the LINMIC$^+$

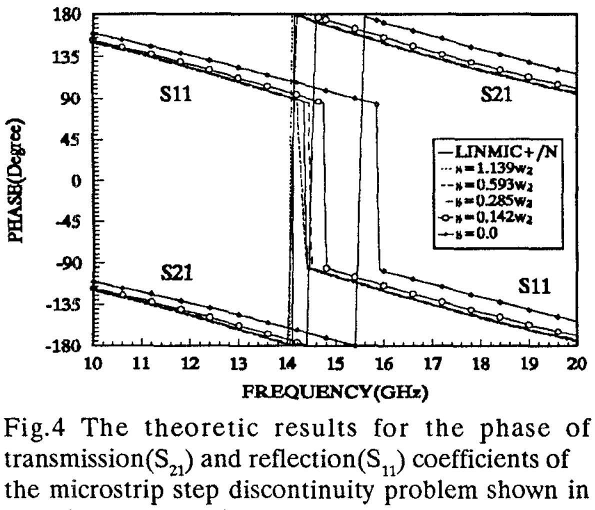


Fig.4 The theoretic results for the phase of transmission($S_{21}$) and reflection($S_{11}$) coefficients of the microstrip step discontinuity problem shown in Fig.2. When s=1.139$w_2$ or d=0.0006 mm, no proximity effects exist. As s is reduced further, the proximity effects become significant.

are plotted by continuous solid lines whereas the data obtained by the new formulation are plotted by the dotted lines for d=0.0006mm(or s=1.139$w_2$). The fact that all the plots having continuous solid lines and the dotted lines in Figs. 3 and 4 are almost indistinguishable validates our new formulation for being capable of obtaining accurate S-parameters.

We also proceed to compare the results obtained by the LINMIC$^+$ and the new formulation for a number of well-known benchmark structures assuming d is almost zero in the new formulation, e.g. a symmetric microstrip gap and a 90°-bend discontinuities [10]. In every case study, excellent agreements are obtained between two methods.

## IV. A Case Study Example: The Proximity Effects on the Microstrip Discontinuity Problem

As the validity of the new full-wave 3-D program has been established in Section III, we will discuss further the data reported in Figs. 3 and 4. When s is reduced from 1.139$w_2$ to 0.593$w_2$, 0.285$w_2$, 0.142$w_2$, and 0, d ranges from 0.0006mm to 1.0mm, 1.5634mm, 1.8251mm, 2.085mm, respectively. At one extreme case where s=0, the wider microstrip of width $w_2$ has its two edges coincide with the two substrate edges.

By using s as a controlling parameter, Fig.3 shows very good transmission characteristics of nearly 0dB loss between 14 GHz and 16 GHz, which are half wavelength frequencies of the wider microstrip. At these nearly zero-loss transmission frequencies the phases of the various circuits are nearly 180° as shown in Fig.4. Therefore, the first half wavelength frequency for 0dB-loss transmission can be expressed as

$$\beta_2 l_2 = 2\pi f l_2 / v_{g2} = \pi \qquad (3)$$

where $\beta_2$, $v_{g2}$, and $l_2$ correspond to the propagation constant, phase velocity, and the length of the wider microstrip of width $w_2$, respectively. Since the value of $l_2$ is fixed, the progressive change of locations of the valley points from left to right in $S_{11}$ plot of Fig.3 as s decreases implies that $v_{g2}$ increases. As a result, at a given frequency, $\beta_2$ should decrease as s decreases. Fig.5 plots the normalized propagation constant($\beta_2/k_0$) of the wider mic-

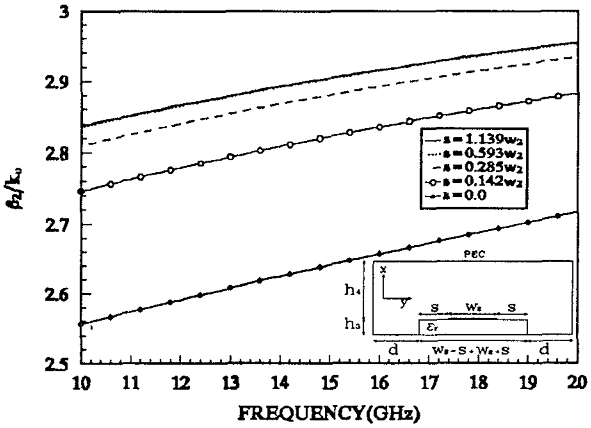


Fig.5 The normalized propagation constant ($\beta_2/k_0$) of the wider microstrip versus frequency. The structural parameters are $h_3$=0.635mm, $h_4$=6.35mm, $\epsilon_r$=10.2, $w_2$=1.83mm, $w_s+2d$=6.0mm, s:variable.

rostrip versus frequency. At a given frequency, the value of the normalized propagation constant decreases as expected when s decreases[8]. Note that the decreasing change in the normalized propagation constant of Fig.5 maps one-to-one to the incremental change of zero-loss transmission frequency as s decreases from $1.139w_2$ to 0. Thus the three-dimensional microstrip discontinuity problem considering the proximity effects is closely related to the propagation characteristics of the microstrip line obtained by rigorous full-wave analysis taking into account the effect of the finite-width substrate.

## V. Conclusion

A new full-wave three-dimensional CAD simulator has been described and validated by comparing its results with the respective data obtained by the rigorous de facto SDA program LINMIC+. The new space-domain integral equation formulation can analyze the coplanar strip circuits on layered and nonlayered substrates, which can be of finite substrate width. An example showing one of the many possible applications of the new integral equation is illustrated by a microstrip step discontinuity problem shown in Fig.2. The obtained scattering-parameters of the microstrip step discontinuity problem under various substrate widths are explained by relating them to the propagation characteristics of the wider microstrip in Fig.2.


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