A FULL-WAVE ELECTROMAGNETIC MODEL OF CYLINDRICAL AND CONICAL VIA HOLE GROUNDS FOR USE IN INTERACTIVE MIC/MMIC DESIGN

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ABSTRACT

An approximate yet accurate 3D electromagnetic model of cylindrical and conical vias in microstrip is presented. The new model is formulated entirely in terms of the via physical parameters and has been verified against measured data to 40 GHz. Its extremely short execution times make it suitable for interactive CAD.

INTRODUCTION

There is little detailed information on the electrical characteristics of cylindrical via hole grounds in microstrip type transmission lines in the published technical literature. There is virtually nothing for conical via structures though via holes fabricated with conventional techniques are actually conical. One of the reasons for this is that vias have been avoided in MMICs unless about 10 years ago suitable technologies have been developed to produce vias with high aspect ratios and good yield. Another reason is that via hole analysis in a microstrip circuit medium is a 3D electromagnetic problem with the additional difficulty of mixed circular cylindrical and rectangular (strip) boundaries. Finally, via hole grounds are short circuits to a zero order approximation, however, with their multiple use in MMICs and at higher frequencies their accurate characterization in CAD has become important recently.

A brief survey of literature in which the via hole problem is addressed is given with the references listed here. Quantitative information relevant for design is given in refs. /1/, /2/ with results derived by the method of lines. Ref. /3/ is quite unspecific, but refers to some interesting early work by Owens. Ref. /4/ contains some measured results for through contacts in hybrid microstrip and, in addition, comparisons with theoretical results derived by the microstrip equivalent parallel plate waveguide concept. Ref. /5/ treats in detail the radiation and surface wave effects caused by via holes without discussing the basic electrical characteristics themselves, i.e. inductance and resistance. In the list of papers given here, then refs. /6/, /7/ and /8/ provide some details on the solution of the related problem of inductive posts in waveguide. The remaining papers up to ref. /14/ merely contain hints regarding the typical order of magnitude of via hole inductance and the effects in a circuit. Very recent work performed at Raytheon Research Division /15/, /16/ concentrated on the experimental evaluation of via hole grounds in GaAs substrates, their numerical analysis using commercial 3D electromagnetic simulators and the empirical derivation of a simple analytical model for cylindrical via holes in microstrip.

The development described here was performed end of 1989 as part of a MMIC design workstation project under contract with Plessey Research Caswell, UK, today GEC-Marconi Materials Technology, and is now open for public release. The goal was to derive a realistic, physics-based model that is efficient enough for interactive microwave CAD and allows to study in detail the electrical characteristics of vias as a function of the physical parameters. Since typical vias deviate quite drastically from the cylindrical shape, the inclusion of conical shapes was considered important. Indeed, as will be shown here, with a cylindrical approximation using the mean diameter the inductance of a conical via is quite seriously underestimated. The new model presented agrees well with published data, numerical and measured, for cylindrical through contacts and it is also in very good agreement with data measured for conical via hole grounds in GaAs. The full-wave 3D electromagnetic analysis of conical vias should be possible too by means of commercial finite element simulators, e.g. ref. /16/. However, the computation times associated with such simulators are estimated to be about 1000 times higher than for the approximate 3D model outlined here.

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MODELLING APPROACH

The basic via hole geometry as considered in this paper is shown in Fig. 1 together with the vertical discretization used to arrive at an approximate full-wave 3D analysis. The top of the via is sitting in a strip of width w and has the diameter d_{min}. The via hole bottom has the diameter d_{max} and sits in the ground plane metallization of the respective substrate of thickness h.

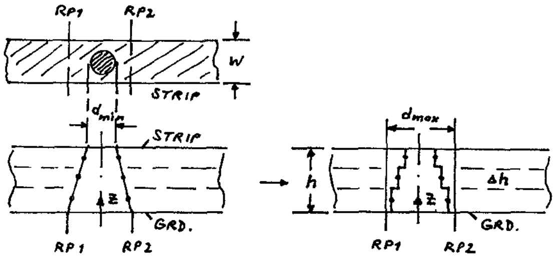

Fig. 1 Via hole geometry considered and vertical discretization used

The reference planes of the two-port formed by the via hole ground centered in a strip have been chosen to touch the circumference of the circular hole in the substrate bottom plane. By applying a non-ideal open circuit to one of the reference planes, the structure degenerates into a non-ideal short-circuited stub one-port. The vertical discretization of the conical via structure and its electromagnetic field in steps of Δh is made in such a way, that in each of the layers Δh the respective via section is considered cylindrical and the field is assumed z-independent. Thus, the total 3D field around the conical via structure is represented by a stepwise 2D field approximation in the vertical direction. Note, that in practice the strip or pad width w applied has to be reasonably large in order to ensure reliable alignment during backside processing /16/. Correspondingly, the chosen approximation can be assumed to be quite accurate, particularly since applied stepwise to the layers Δh under the strip, and the algorithmic steps in the developed model are as follows:

- describe each layer Δh by an equivalent parallel plate waveguide representation,
- use in each layer the respective effective via diameter d_{eff} as derived by Schulz with the method of lines /2/,
- modify the resulting effective cross-section slightly to arrive at an equivalent rectangular cross-section,
- formulate in each layer a mode-matching problem for the local effective cross-section (even and odd excitation),
- eliminate analytically the unknowns at the feed side by application of orthogonality of the layer functions,
- solve the small local system of equations by matrix inversion,
- generate for each layer a suitable representation for the field region between the reference planes,
- interface these representations to arrive at a total one, finally at the via S-parameters or an equivalent circuit, respectively.

Loss has been implemented into the model by a subsequent perturbation approach. The equations given in ref. /5/ for radiation into free space and in the form of surface waves have been implemented in order to produce warnings in cases where such effects become noticeable. The upper frequency of application of the model is restricted to the range in which only the fundamental strip mode is propagating, e.g. to about 100 GHz for a 200 μm GaAs substrate with w = 100 μm.

The analysis procedure developed is briefly illustrated below for the fundamental case of a single substrate layer with Δh = h. Fig. 2 indicates the effective parameters of the via hole ground in microstrip configuration for a via of diameter d as used by Schulz /2/ and the subsequent further rectangular shape modification made here. Fig. 2 also shows how the subregions I and II for the local effective cross-section are chosen in order to formulate the local mode-matching analysis procedure applied for the modelling.

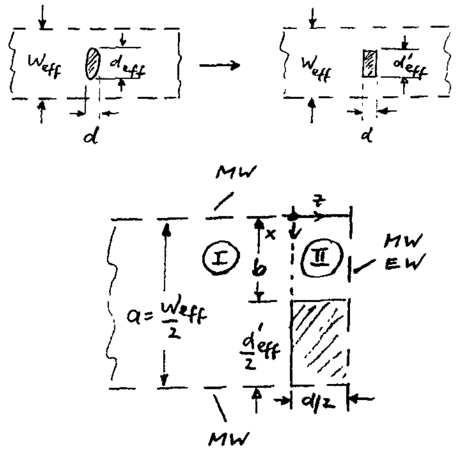

Fig. 2 Indication of subregions chosen for the via hole local mode-matching

It is assumed here that the considered vias are centered in the microstrip, so that for excitation with the fundamental strip mode the longitudinal symmetry plane of the configuration has the properties of a magnetic wall (MW). The second, transverse symmetry plane through the via structure behaves either like a magnetic wall (MW) or an electric wall (EW) depending on even or odd excitation, respectively, in the analysis procedure. The advantage obtained here is the reduction of the electromagnetic field region of interest to a quarter of its original size.

The partial electromagnetic fields in the subregions I and II of Fig. 2 are formulated in terms of orthonormal waveguide mode functions taking into account the boundary conditions explicitly, except for those in the front plane z=0 of the rectangular post representing the via. Formulating then the boundary and continuity equations for the transverse field components in z=0, eliminating analytically the mode amplitudes in region I by means of the prevailing orthogonality relations and rearranging yields the set of equations:

$$2\,\frac{T_{oi}}{Z_{Io}} = V_{IIi}\,\frac{1-r_{ie,o}}{1+r_{ie,o}}\cdot\frac{1}{Z_{IIi}}$$

$$+\sum_{k=1}^{K} V_{IIk}\cdot\sum_{\mu=o}^{M}\frac{T_{\mu i}T_{\mu k}}{Z_{I\mu}},\qquad i,k=1\ldots K,\quad M=\mathrm{INT}(K\tfrac{a}{b}),$$

$$\text{with}\qquad T_{\mu i} = h\cdot\int_{o}^{b} t_{I\mu}\cdot t_{IIi}\cdot dx. \qquad (1)$$

Here, $t_{I\mu}$ and t_{IIi} represent the orthonormal mode functions. $T_{\mu i}$ is the coupling integral linking the mode functions in subregion I with those in subregion II. T_{oi} relates to the excitation of the structure by the fundamental mode of the microstrip containing the via hole ground. The deterministic system of linear equations (1) written in terms of the mode amplitudes V_{IIi} of subregion II converges well already for only 5...7 terms (M=10 typically). The upper summation limits K and M are related in such a way that the relative convergence phenomenon is avoided. The series taken over the subscript μ can be presummarized before setting up the system (1) and is imaginary except for its first term $\mu=0$, independent of even or odd excitation. The quantities $Z_{I\mu}$ and Z_{IIi} denote mode impedances in the respective subregions, with $r_{ie,o}$ standing for the mode reflection coefficients in subregion II for the even and odd excitation case, respectively. Note, that only the diagonal terms of the set of equations (1) depend on $r_{ie,o}$ so that reconstruction of the equations for the even and odd case can be performed very efficiently. From the solution of eq. (1) the reflection coefficient of the fundamental microstrip mode interacting with the via structure can be derived as:

$$r_{oe,o} = -1 + \sum_{k=1}^{K} V_{IIk}\cdot T_{ok}$$

$$\text{with } e,o = \text{even, odd.} \qquad (2)$$

Besides the high numerical efficiency achieved with this formulation, it gives immediate physical insight since the series in eq. (2) directly describes the deviation of the via from ideal short circuit electrical behaviour (r=-1). The case of general excitation is derived by superposition of the even, odd results. For the analysis of conical via hole geometries, the outlined mathematical procedure is carried out for each of the layers h applied for the vertical discretization, see Fig. 1. The individual layer impedance contributions are then combined in the reference planes RP1, RP2 taking into account the different electrical lengths associated.

RESULTS

For cylindrical vias, the developed model gives accurate results already if just a single substrate layer $\Delta h = h$ is used, i.e. if no vertical discretization is performed at all. In that case, the obtained results are very close to those derived in Fig. 10.20b of Hoffmann's book /1/ by the method of lines (alumina substrate), as is shown in the table below for various strip widths and via diameters d(L/nH values).

	d/w	LNH This Paper	LNH Ref. /1/
w/h =0.5	0.20	0.0686	0.072
	0.50	0.0338	0.034
	0.80	0.0179	0.018
w/h =1.0	0.20	0.0534	0.055
	0.50	0.0202	0.021
	0.80	0.0074	0.008

For typical conical via hole grounds in MMICs, a vertical discretization in 3 steps, i.e. $\Delta h = h/3$, has been found sufficient in all cases investigated. For a 1% accuracy of the via inductance as compared to fully converged values, the number of unknowns in each layer Δh is typically less then M = 10. This explains the high numerical efficiency of the model resulting in analysis times of a small fraction of a second per frequency on a modern workstation. That the consideration of the actual conical shape of vias is important is demonstrated in Fig. 3, where the reflection coefficients of several via hole grounds in 200μm GaAs with d_{min} = 80 μm and d_{max} = 120...160 μm have been computed. The cylindrical approximation in Fig. 3 uses mean diameters of $d = (d_{min} + d_{max})/2$ = 100...120μm.

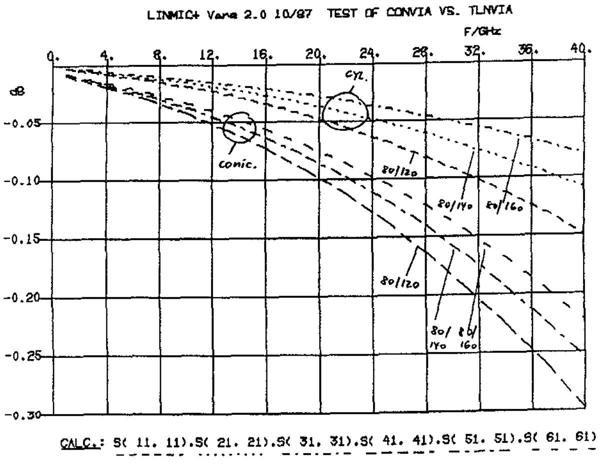

Fig. 3 Reflection coefficient of 3 different conical via shapes in the cylindrical approximation (cyl.) and with the conical geometry taken into account (conic.), $\Delta h = h/3$

As a further simulation example given here, Fig. 4 shows a comparison made by M.E. Goldfarb /15/, Raytheon, measured data against the model presented for a conical via hole in GaAs microstrip (h = 100μm, w = 166μm). The shape of the considered via structure was actually measured too. As can be seen in Fig. 4, the agreement between measured reflection and transmission and the prediction obtained by the model of this paper is excellent over the full range up to 40 GHz. Further verification results and more details regarding the 3D electromagnetic modelling approach will be given in the symposium presentation.

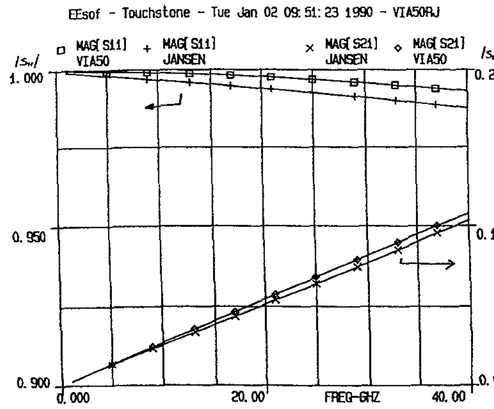

Fig. 4 Comparison between measured data and the model of this paper as provided by M.E. Goldfarb /15/

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