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FULL-WAVE THEORY BASED DEVELOPMENT OF MM-WAVE CIRCUIT MODELS FOR MICROSTRIP OPEN END, GAP, STEP, BEND AND TEE

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ABSTRACT

Millimeter-wave discontinuity circuit models have been developed on the base of systematic full-wave data generated by a rigorous numerical approach. The applied physics - related and topology - sensitive modeling concept is new and extends previous quasi-static descriptions into dynamic ones including parasitic wave coupling and package resonances.

INTRODUCTION

The MIC and MMIC discontinuity models used today in state-of-the-art CAD tools are quasi-static or magnetic wall approximations, see for example R.K. Hoffmann's overview /1/, which are unable to describe full-wave coupling effects or interaction with a shielding package. From their very definition and method of derivation, existing analytical discontinuity models cannot take into account interaction with the circuit environment they are embedded in, but are treated as isolated structures. In the mm-wave region, our field-theory based investigations using full-wave hybrid-mode data /2/, /3/ have shown that package dimensions (not only cover height) and even the position of a structure within a package have to be considered for accurate modeling. Interaction with a package may be strong and is not negligible in the majority of cases. The same applies to coupling effects between components in a common package for which it is well known that they are different from those in an open circuit medium /4/. For this reason, we have developed a new physics-related and topology-sensitive modeling concept for (M)MIC structures and have successfully derived a variety of consistent results demonstrating the validity of this concept.

THEORY AND CONCEPT

The equivalent circuit models developed provide an extension of the commonly used analytic circuit descriptions by inclusion of the dominant dynamic full-wave mechanisms. In particular, this includes excitation of the main parasitic LSM_0 package mode at the discontinuities. At the same time, this provides a relatively simple but reasonably accurate description of coupling to the package field and indirectly, to other discontinuities. The outlined extension of models is achieved by transformer interconnections of the quasi-static model portion with transmission line representations of the dominant parasitic LSM_0 package mode. The results obtained confirm again that this mode is the dominant cause of dynamic coupling in (M)MICs as already outlined in /5/, /4/.

It has been found and is understandable from the vertical electric field of the LSM_0 mode, that the electrical characteristics of this dominant package mode can be assumed to be nearly independent of the specific metallization pattern on the substrate, that means independent of the type of discontinuity under investigation. As outlined, for the dynamic equivalent circuit models developed the LSM_0 package mode is described by suitable transmission line sections. Analytical approximate expressions for the transmission line characteristics of the LSM_0 package mode have been derived from wave guide theory using an effective dielectric constant $\varepsilon_{stat.}$ which depends on the substrate height h and the cover heigh H, see eq. (1). W_s is the width of the mm-wave package used. W_s and H have to be assumed reasonably small as in circuit applications such that higher order parasitic modes are negligible (extension to include these is possible in our concept).

$$\varepsilon_{eff}(LSM_0) = \varepsilon_{stat.}(1-(\frac{f_c}{f})^2) \quad \text{with}$$

$$f_c = \frac{c_0}{2W_s\cdot\sqrt{\varepsilon_{stat.}}} \quad \text{and}$$

$$\varepsilon_{stat.} = \frac{\varepsilon_r\cdot H\cdot h}{\varepsilon_r\cdot H + h}, \tag{1}$$

$$Z_L(LSM_0) = \frac{H+h}{W_s}\cdot\frac{Z_0}{\sqrt{\varepsilon_{stat.}}}\cdot\frac{1}{\sqrt{1-(f_c/f)^2}}$$

$$(Z_0 = 120\pi\,\Omega,\ c_0 = 2.9979\cdot 10^8\,\text{m/s}).$$

While the LSM_0 package mode is not noticeably dependent on the microstrip type conductor pattern, the coupling between the fundamental microstrip mode and the parasitic LSM_0 mode in the package is different for each specific type of microstrip discontinuity. The strength of coupling between the fundamental microstrip mode and the LSM_0 package mode depends on the degree of disturbance of the field distribution of the fundamental microstrip mode at a disontinuity. For example, it is obvious that for microstrip step discontinuities of nearly equal strip width in the limit case of a through line no parasitic mode is excited at all.

A further parameter of significant influence on the excitation of the parasitic LSM_0 package mode is the position of the microstrip structures in the package. The coupling between the fundamental microstrip mode and the LSM_0 package mode is strong for microstrip discontinuities in the middle between the lateral side walls of the package. If the position of a microstrip discontinuity is near the lateral side walls, the coupling to the fundamental microstrip mode decreases due to the decreasing of the electric field of the package mode near the walls. The strength of the coupling between the fundamental microstrip mode and the LSM_0 package mode determines the value of the transformer ratios for transformer interconnections used in the dynamic equivalent circuit models. Accordingly, analytic expression for these transformer ratios can be calculated from the scalar product of the electric fields of the modes which couple in the package cross-section A:

$$N \sim \iint_A 1/A\ \vec{E}_{strip}\cdot\vec{E}_{LSM0}\,dA \tag{2}$$

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The results obtained by now for open end, gap, step, bend and T-junction show clearly that in the development of accurate CAD models for mm-wave (M)MIC structures the physical circuit environment has to be considered, i.e. a deembedding problem including excitation, package, feed strips and relative location has to be solved. In addition, they show that the modeling approach developed ban be extended to complex situations in a straight forward manner. Therefore, the approach presented here is considered by the authors to have some impact for improved mm-wave circuit design.

Illustration of the physical mechanisms and the concept outlined so far is best provided by means of an example. In Fig. 1a, a microstrip gap configuration is shown in a package with the strips excited by impressed current density sources I_{01} and I_{02}. The rigorous full-wave analysis of this configuration using a previously published approach /2/, /3/ provides the wave amplitudes for the fundamental microstrip modes and the LSM_0/LSM_0' package modes associated with different excitations.

The respective equivalent full-wave circuit description is shown in Fig. 1b with the transformers describing coupling to the package field. LSM_0' is the package mode slightly perturbed by the presence of the strips.

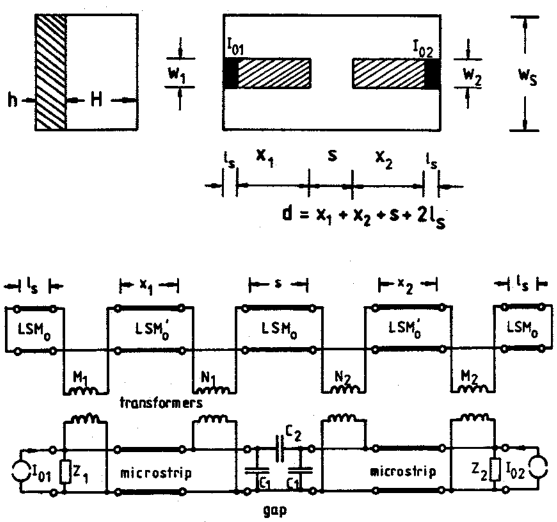

Fig. 1 Microstrip gap discontinuity with feed lines and current sources (a) and associated dynamic circuit model (b) describing the total electromagnetic situation for deembedding of model parameters

In Fig. 1 transformers N_1 and N_2 consider the excitation of the parasitic LSM_0 mode at the gap discontinuity. Transformers M_1 and M_2 take care of the LSM_0' mode excitation by the impressed current sources I_{01} and I_{02}. The microstrip configuration in Fig. 1 represents a very simple microstrip circuit showing four locations where package modes are excited. However, this single configuration makes clear that an extension of the described dynamic modeling concept to more complex situations is feasible in a straight forward manner. It should be noted that the inclusion of the dominant parasitic mode reveals the generic discontinuity structures as 2N-ports if N is the number of feed strips. This is shown in Fig. 2 for the gap discontinuity. Based on this, the terminations of the package field can be handled easily by circuit type interconnections, see Fig. 3, without going back to field-theory analysis.

The developed dynamic discontinuity models also allow the description of loss effects if the package mode is suppressed by absorber material. In this case the ideal short circuits of the LSM_0 mode transmission line sections in the equivalent circuit model of Fig. 3 representing the electric end walls of the package have to be exchanged against resistive terminations. For full suppression of the package mode the absorbed power ratio results from the characteristic impedance of the LSM_0 mode and the transformer ratios.

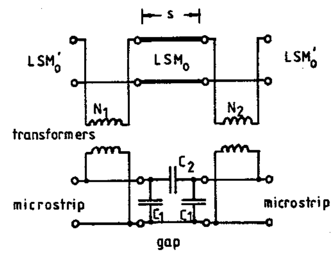

Fig. 2 Equivalent circuit for the gap discontinuity as a 4-port

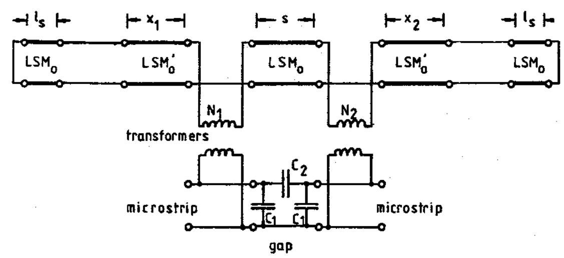

Fig. 3 Equivalent circuit for the gap discontinuity as a 2-port including the package effects

In the cases of microstrip open end, gap and step discontinuities the LSM_0/LSM_0' mode package fields are excited and described by an essentially unidirectional coupling mechanism. The dynamic equivalent circuit models for these microstrip discontinuities have been tested successfully agains numerically generated full-wave data. In contrast to these cases, the microstrip 90°-bend and T-junction discontinuities are associated with feed lines of orthogonal directions. The wave propagation on these feed lines implies excitation in two orthogonal directions therefore. For these cases, two orthogonal parasitic LSM_0 mode transmission lines have been considered to represent the bidirectional LSM_0 mode excitation in the package. The equivalent circuit model for a microstrip T-junction configuration incl. sources and feed lines is shown in Fig. 4 and contains 6 transformers to represent the coupling between the fundamental microstrip modes on the three feed lines and the three parasitic LSM_0' modes. In addition transformer N4 has been introduced to include the dependency between the parasitic LSM_0 modes of orthogonal directions (bidirectional excitation).

In which way the discontinuity equivalent circuit models developed here describe an extension of the quasistatic region of validity is explained from a field-theoretical point of view for the simplest case of the open end:

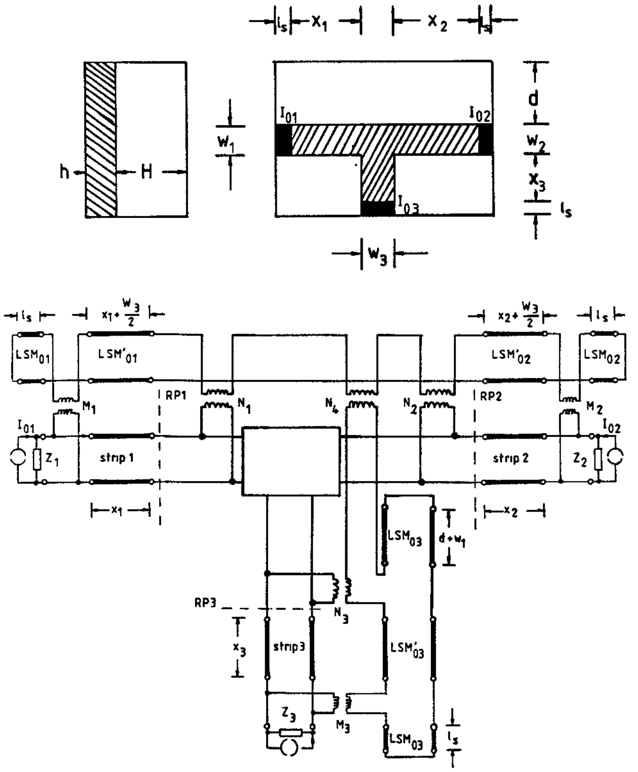

Fig. 4 Microstrip T-junction configuration (a) and associated dynamic equivalent circuit model (b)

For all frequencies, the total field results from a superpositon of LSM and LSE modes. In the quasi-static range of operation, the stray field of the open end is mainly determined by a superposition of LSE modes but contains a respective small LSM portion implicitly. The LSE modes dominate and represent a capacitve load for the microstrip. This effect is considered in the equivalent circuit model by a quasi-static open end length Δl. All higher modes are far below cut-off. Therefore, this quasi-static discontinuity description is valid for increasing frequencies also, as long as the below cut-off condition is met sufficiently well.

If the LSM_0 mode is approaching cut-off or is above cut-off, the package field is mainly described by its LSM_0 content. All effects of the LSE modes can be described by the quasi-static effective open end length further on, since the LSE modes are still below cut-off, assuming a reasonably small cover height H.

According to the fact that the LSM_0 mode is dominating in the package field, the coupling between the fundamental microstrip mode and the LSM_0 package mode has to be considered, as described by the new dynamic equivalent circuit model. Fig. 5 shows the ranges of validity for the quasi static mode portion (effective open end length Δl) and the LSM_0 mode portion of the dynamic equivalent circuit model (transformer ratio N) which have been merged in our concept to a unified description.

Summarizing these remarks on the theoretical background of our concept, it should be transparent by now that the developed modeling approach allows

a) to deembed discontinuity and component behaviour from performance data obtained in a packaged configuration (measured

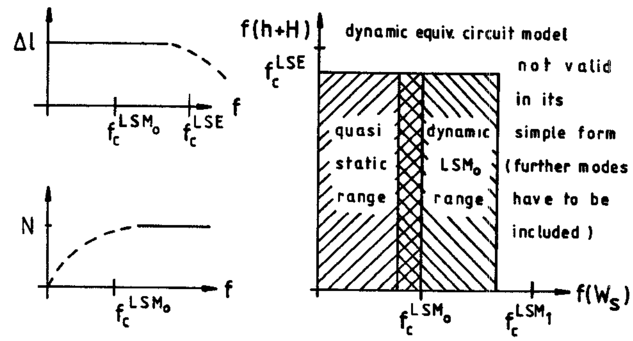

Fig. 5 Validity range of the dynamic equivalent circuit models explained for the open end

or numerically computed) using circuit descriptions with elements expressed in analytical form, or

b) to model microstrip structures under inclusion of their interaction with a package and of their mutal coupling via the common interaction with the field of the dominant package mode.

SOME RESULTS

To demonstrate the influence of the position of a discontinuity in a package, full-wave results for the open end configuration as a function of its position within the cross-section of a package have been generated and compared to the results predicted by the dynamic equivalent circuit model. The lateral position of the microstrip in the package is determined by parameter Y_m, the strip mid distance from the left hand lateral shielding wall.

The strip width assumed is 100 μm on a 100 μm GaAs substrate and the width W_s of the package is 3.1 mm. The open end configurations have been analyzed at 80 GHz. The predicted transformer ratios have been multiplied by a correction factor F_N to achieve an optimum fit between the full-wave results and the equivalent circuit data. Table 1 shows the optimized transformer ratios, the predicted transformer ratios following eq. (2) and the correction factors for 5 different positions of the open end discontinuity.

Y_m	N_{opt}	$N_{predicted}$	F_N
1.6 mm	0.144	0.149	1.038
1.2 mm	0.133	0.140	1.055
1.0 mm	0.118	0.108	1.076
0.6 mm	0.077	0.050	1.110
0.4 mm	0.051	0.059	1.157

Table 1 Optimized transformer ratio, predicted transformer ratio and correction factor for 5 different positions of an open end discontinuity in the cross-section of a package.

The microstrip-to-LSM_0 mode coupling is strong for strips in the middle of the cross section of the package and decreases for strip positions approaching the lateral side walls. This coupling phenomenon is reflected in the determination of the transformer ratios from the scalar product given in equation (2). The correction factor F_N required for an accurate fit with the full-wave numerical data is near $F_N = 1$ and, therefore, plays only the role of a fine-tuning parameter.

As another example, Fig. 6 shows magnitude and phase for S_{11} and S_{12} of a symmetric gap configuration of 100 μm strip width and 100 μm height, the package width is 3.1 mm and the frequency of analysis is 55 GHz. The comparison between the S-parameters generated by the equivalent circuit model and the full-wave results shows good accuracy of the equivalent circuit model description of the gap discontinuity. The result of a quasi-static analysis is also shown in Fig. 6. The dynamic equivalent circuit model is able to predict the resonance behaviour at a package length of 3.2 mm and agrees with the full-wave results.

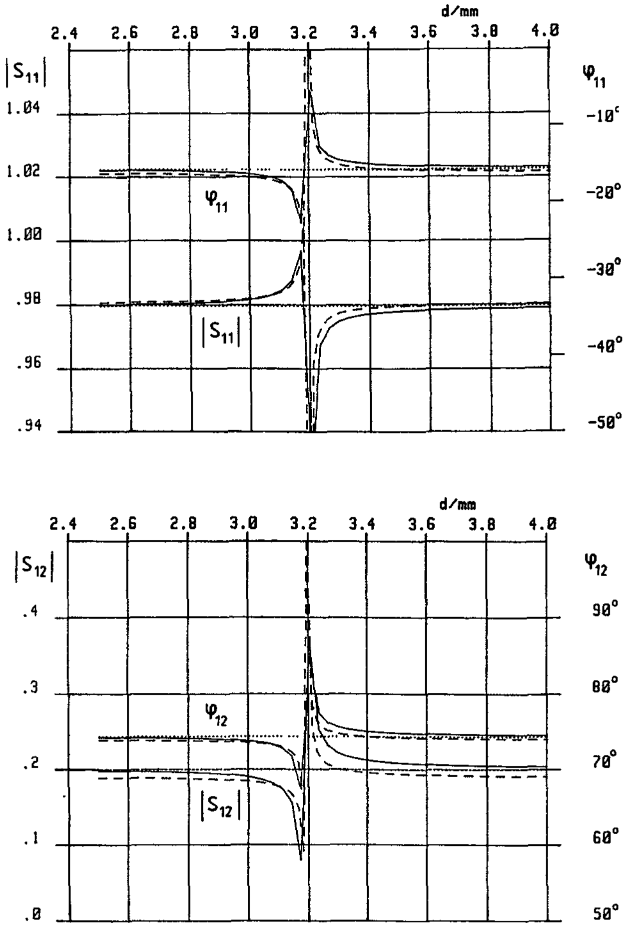

Fig. 6 Magnitude and phase of the scattering parameters of a symmetric microstrip gap configuration as a function of the package dimension d (see Fig. 1(a)), $W_s = 3.1$mm, $H = 0.5$mm and $W_1 = W_2 = s = 100$ μm, 100 μm GaAs substrate, f= 55 GHz.

Fig. 7 shows a further example, a 90°-bend discontinuity. The phase of the reflection coefficient on strip 1 at the reference plane of the discontinuity is shown as a function of the package length $d + x_1 + l_s + W_2$ (0.8 mm 2.8mm). Again the resonance behaviour here at a package dimension of d = 1.8 mm is predicted with good accuracy by the dynamic equivalent circuit model.

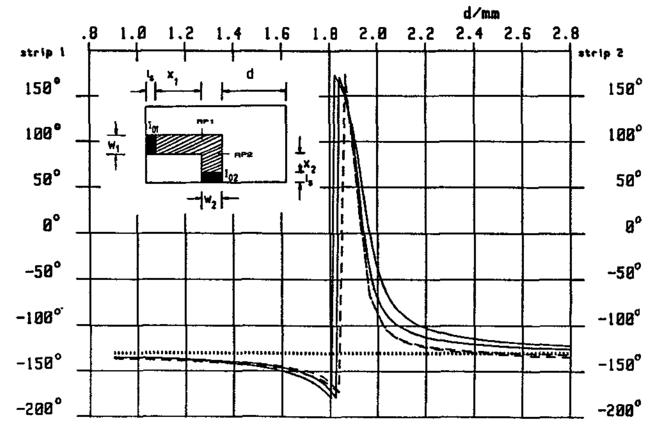

Fig.7 Phases of reflection coefficients in a bend configuration at 80 GHz as a function of the package length d, W_1 = 100 μm, W_2 = 40 μm (nonsymm. 90°-bend) for a 100 μm GaAs substrate, H = 200 μm, W_s = 1.9 mm.

CONCLUSION

The dynamic models developed for open end, gap, step, bend and T-junction are valid below and above cut-off of the dominant package mode. They allow to predict package resonances and their effect on component behaviour. The agreement with the respective field-theoretical simulations is good which verifies that our modeling approach indeed incorporates the dominant physical mechanism. The range of validity of the developed dynamic equivalent circuit models is restricted in the presented form to frequencies below the second LSM cut-off frequency. An extension of the equivalent circuit models by the inclusion of one or more parasitic modes appears feasible and would extend the range of validity of the presented discontinuity models further. Also, extension to a description of coupling between separate discontinuities seems feasible and is presently studied. The analytical details of the models described here will be given in a considerably extended paper on this topic.

ACKNOWLEDGEMENT

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