Full-Wave Analysis of 3D Metallization Structures Using a Spectral Domain Technique

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ABSTRACT

A full-wave method for the investigation of microstrip- and coplanar-structures including 3d metallization structures is presented. Spectral domain analysis method is used to calculate the S-parameters of unshielded microwave components containing bond-wires and air-bridges. The general formulation and the procedure of the method are described. The application of the theory is given by a comparison of measured and calculated results for a spiral inductor.

INTRODUCTION

Spectral domain analysis (SDA) technique [1, 2] and the basically equivalent space-domain integral technique [3, 4] are well-known in literature. These full-wave analysis methods using roof-top functions as expansion functions for the surface current density have proved to be flexible tools for the calculation of arbitrary shaped planar passive microwave structures. Due to the implementation of FFT-algorithm and iterative methods, efficient S-parameter calculations of complex planar circuits have become possible [5]. These methods can take into account effects of multilayer structures as well as losses due to surface waves, radiation and non-ideal strip and backside metallization (if existing). But in general both methods only can handle structures with planar metallizations.

Recently two hybrid methods [2, 3] have been introduced to overcome this major drawback of integral equation methods applied to coplanar structures. In [2] some 3d geometries are handled by first generating an S-parameter representation of the planar structure. Afterwards the third dimension is included into the calculation by applying suitable air-bridge descriptions in the sense of a hybrid method. In a very similar approach in [3] the frequency equivalent circuit of the planar discontinuity without the air-bridge is derived using SDA method. Then, the circuit is modified by using a quasi-static lumped element model of the air-bridge. Both formulations are looking for the third dimension of the structure under consideration only in the sense of a segmentation approach. Air-bridges at internal ports cannot be included into the calculation procedure.

THEORY

In this paper air-bridges and bond-wires are included in a full-wave analysis using the spectral domain technique. Electromagnetic effects due to electric currents in horizontal and vertical direction are considered in the approach. This is done by formulating the dyadic Green's function for currents in horizontal and vertical direction. For coplanar structures magnetic planar surface current densities can be used to restore the electric fields in the slots. The dyadic function is formulated either for an open or shielded structure, so antenna problems can be handled very easily. For an arbitrary current distribution the solution for the electric field is

$$\vec{E}(\vec{r}) = \iiint\limits_V \overleftrightarrow{G}_{E,J}(\vec{r},\vec{r}_0)\,\vec{J}(\vec{r}_0)\,dV_0. \qquad (1)$$

Incorporation of impressed current source distributions (matched sources) exciting electromagnetic fields, equivalent to the incoming field of an scattering problem, leads to an excitation problem. A reaction of the system has to compensate the portion of the source field tangential to or in the metallization. Result is a Fredholm integral equation. Introduction of rooftop functions as expansion functions for the planar surface current density leads to a discretization procedure (Fig.1). As shown in Fig.1 volume currents in vertical direction represent an bond-wire structure with horizontal cross-sectional area equal to one cell. A local mesh refinement can be used to reduce the diameter of this part of the bridge. It is important to note that the vertical directed parts of the bridge are characterized by a volume formulation. This is in contrast to the conventional surface formulation for the horizontal directed parts of the structure. Next step

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is the discretization of the electric fields tangential to or in the metallization in the sense of the well-known Galerkin procedure. This step projects the Fredholm integral equation onto a system of linear equations

$$\begin{pmatrix} \overleftrightarrow{Z}_{S,S} & \overleftrightarrow{Z}_{S,u} & \overleftrightarrow{Z}_{S,z} \\ \overleftrightarrow{Z}_{u,S} & \overleftrightarrow{Z}_{u,u} & \overleftrightarrow{Z}_{u,z} \\ \overleftrightarrow{Z}_{z,S} & \overleftrightarrow{Z}_{z,u} & \overleftrightarrow{Z}_{z,z} \end{pmatrix} \begin{pmatrix} \vec{J}_S \\ \vec{J}_u \\ \vec{J}_z \end{pmatrix} = \begin{pmatrix} \vec{V}_{S,S} \\ \vec{V}_{u,S} \\ \vec{V}_{z,S} \end{pmatrix}. \quad (2)$$

After solving this system with iterative methods like the conjugate gradient method or the Lanczos algorithm, which is better suited to handle multiport problems, S-parameter extraction can be done. In order to reduce computation time a modified FFT algorithm is used to fill the $\overleftrightarrow{Z}$-Matrix and during the matrix-vector multiplication needed once or twice each iteration step [5]. Because of this techniques matrix fill time becomes small compared to the whole solution time per frequency point.

The method described here is well suited to handle 3d microstrip structures as well as coplanar structures. In [6] a completely different method to calculate S-parameters of 3d coplanar type circuits has been introduced. This different method is a very efficient one for coplanar structures but is not able to handle microstrip structures. Because of this restriction the method presented here is given for an application to microstrip type circuits only.

RESULTS

In the numerical results shown here, the considered microstrip discontinuities are printed on a $635\mu m$ Al_2O_3 substrate ($\varepsilon_r = 9.8$) with a conductor width of $625\mu m$ or $635\mu m$. The characteristic impedance of such lines is approximately 50Ω. Fig.2 shows the first structure under consideration. It is a simple test structure, an interconnection of two microstrip lines by a bond-wire. The gap width is $g = 635\mu m$ and the bridge height is $h = 200\mu m$. The S-parameters of this structure are plotted in Fig.3. The SDA results (symbols $\times, +$) are compared to those calculated with the finite-difference time-domain method [7]. A good agreement between both methods, especially in the phase curves, is obtained. In a next step we looked for the influence of the bridge height and the gap width on the S-parameters of the same structure. This investigations are very similar to those in [8]. Fig.4 shows the influence of the bridge height varying from $h = 25\mu m$ up to $h = 250\mu m$. As expected the magnitude of the reflection coefficient S_{11} increases when increasing the bridge height. The next figure (Fig.5) shows the influence of the gap width, varying from one time the strip width up to four times the strip width. Again the magnitude of the reflection coefficient S_{11} increases according to the gap width. In order to compare the SDA results with measured results a spiral inductor (Fig.6) has been built and measured. The spiral inductor contains two turns separated by a gap of $s = 312.5\mu m$. The bridge height is $h = 315.5\mu m$ and the bridge length is $l = 3.125mm$. This structure was first introduced by [9]. The large geometrical dimensions have been chosen, because it was intended to have all the resonant phenomena of the component in a frequency range, that allows to verify the simulation by measurements. The strip width was discretized with four elements which results in a total number of $N_U = 1305$ unknowns. Fig.7 demonstrates the excellent agreement of the analysis and measured results. Even the phase response which has been a critical aspect in nearly all other calculation methods is predicted with a high accuracy by the SDA method.

CONCLUSION

In conclusion, the modified SDA method described here is a powerful tool to calculate 3d microwave structures. It is possible to look for the influence of parameter variations as well as coupling effects and losses due to non-ideal metallization or radiation within complex structures by application of this method.

REFERENCES

[1] R. W. Jackson, "Full-wave, finite element analysis of irregular microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, pp. 81-89, January 1989.

[2] R. Brömme and R. H. Jansen, "Systematic investigation of coplanar waveguide MIC/MMIC structures using a unified strip/slot 3d electromagnetic simulator," in *1991 IEEE MTT-S Digest*, (Boston, USA), 1991, pp. 1081-1084.

[3] N. I. Dib, P. B. Katehi, and G. E. Ponchak, "Analysis of shielded CPW discontinuities with air-bridges," in *1991 IEEE MTT-S Digest*, (Boston, USA), 1991, pp. 469-472.

[4] A. Skriverik and J. R. Mosig, "Equivalent circuits of microstrip discontinuities including radiation effects," in *1989 IEEE MTT-S Digest*, (Long Beach, USA), 1989, pp. 1147-1150.

[5] T. Becks, G. Gronau, and I. Wolff, "Efficient S-parameter calculation of multiport planar structures with the spectral domain analysis method," in *1991 IEEE MTT-S Int. Microwave Symp. Digest*, (Boston, USA), 1991, pp. 353-356.

[6] T. Becks and I. Wolff, "Calculation of three-dimensional passive structures including bond-wires, via-holes and air-bridges using the spectral domain analysis method," in *21th European Microwave Conf. Proc.*, (Stuttgart, FRG), 1991, pp. 571-576.

[7] M. Rittweger, Private communication.

[8] A. Christ and H. L. Hartnagel, "Three-dimensional finite-difference method for the analysis of microwave-device embedding," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 688-696, August 1987.

[9] M. Rittweger and I. Wolff, "Analysis of complex passive (M)MIC-components using the finite-difference time-domain approach," in *1990 IEEE MTT-S Digest*, (Dallas, USA), 1990, pp. 1147-1150.

FIGURES

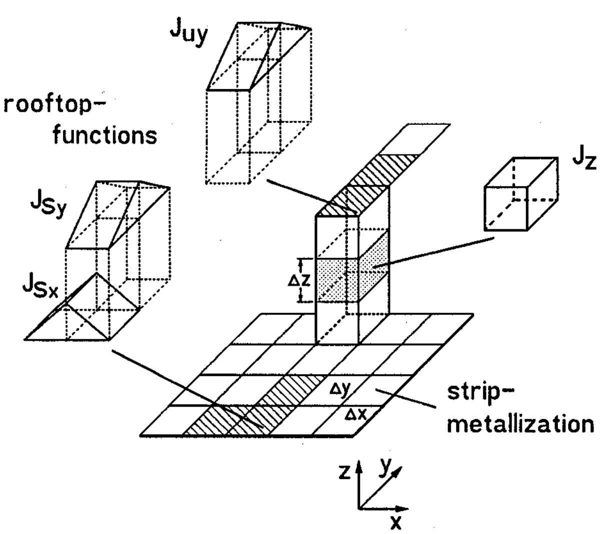

Fig.1: Current-discretization procedure for a bond-wire structure with horizontal cross-sectional area equal to one cell.

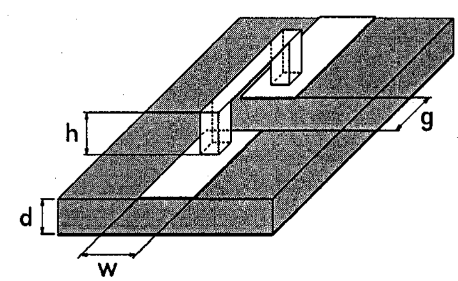

Fig.2: Schematic view on the interconnection of two microstrip lines by a bond-wire.
Parameters: $\varepsilon_r = 9.8$, $d = 635\mu m$, $w = 635\mu m$, $g = 635\mu m$, and $h = 200\mu m$.

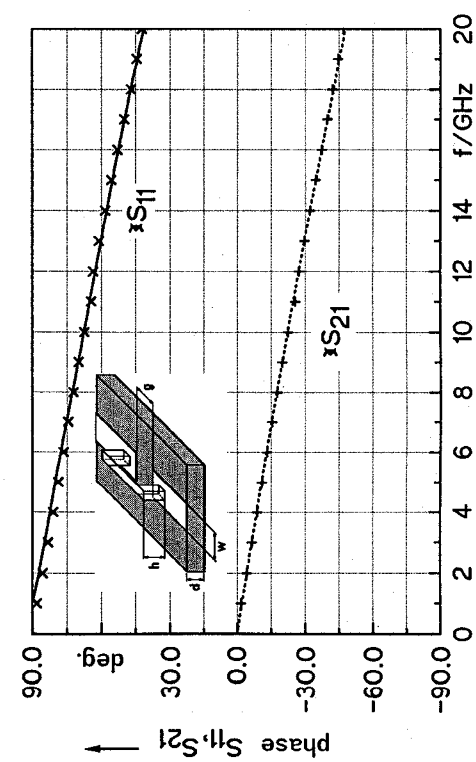

Fig.3: S-parameters for the interconnection of two microstrip lines by a bond-wire. Geometrie and material parameters in Fig.2. SDA results (symbols ×, +), FDTD results (lines —, - - -).

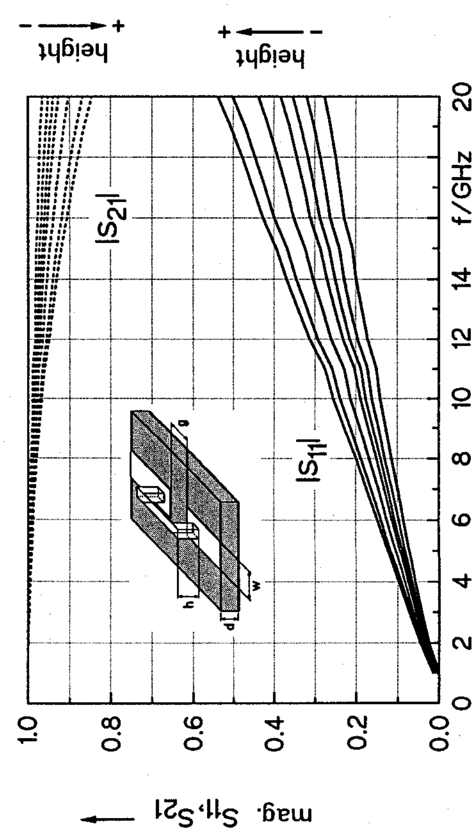

Fig.4: S-parameters of the structure of Fig.2 for different bridge heights, $h = 25, 50, 75, 100, 150, 200, 250\mu m$.

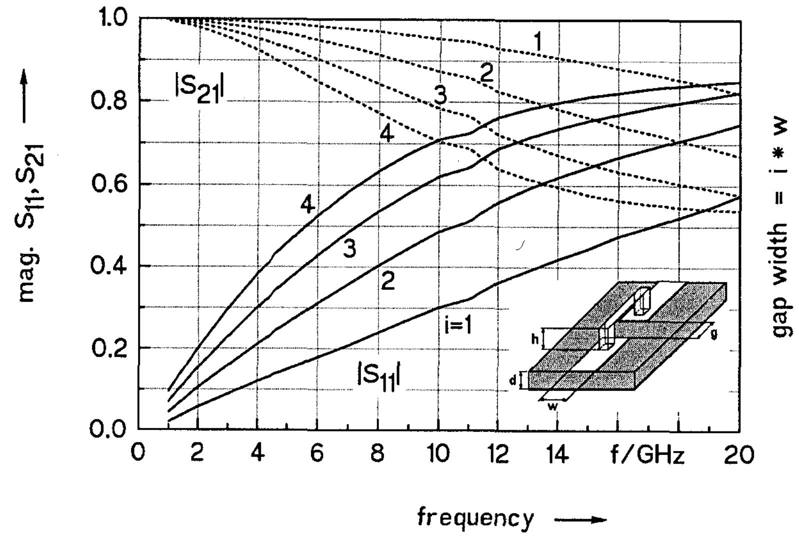

Fig.5: S-parameters of the structure of Fig.2 for different gap widths, $g = w$, $2w$, $3w$, $4w$.

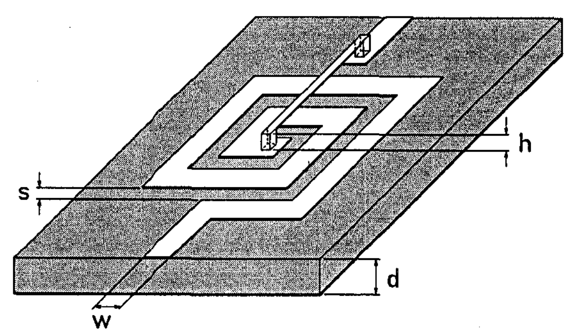

Fig.6: Schematic view on the rectangular spiral inductor. Parameters: $\varepsilon_r = 9.8$, $d = 635\mu m$, $w = 625\mu m$, $s = 312.5\mu m$, and $h = 317.5\mu m$.

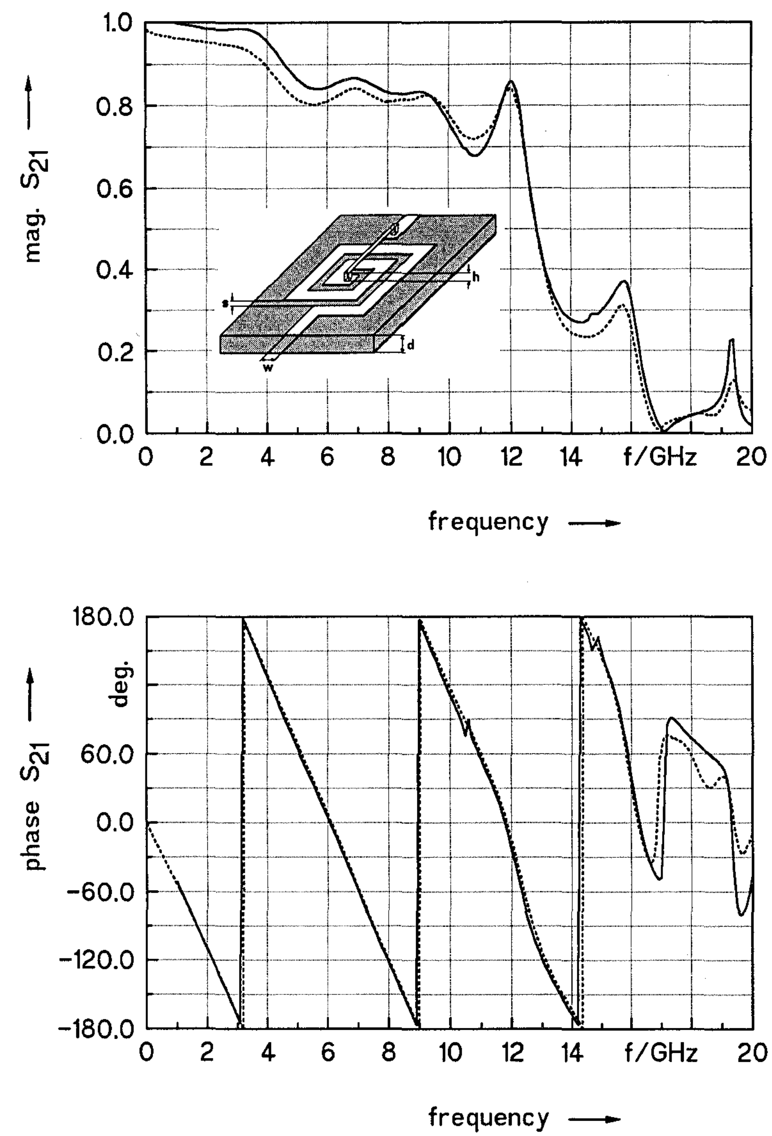

Fig.7: Transmission coefficient S_{21} of the structure of Fig.6. (—) calculated, (---) measured.
Top: Magnitude of S_{21}
Bottom: Phase of S_{21}