A Parameter Extraction Technique for MM/FEM Analysis of Multilayered RF Passives Using TRL Calibration

Ke-Li Wu, *Senior Member, IEEE*, Yan Ding, and Da-Gang Fang, *Fellow, IEEE*

***Abstract*—This letter introduces a new efficient S-parameter extraction technique by exploiting through-reflection-line calibration. The technique will facilitate the modeling of multilayered RF passives using the hybrid mode matching and finite element method. With the proposed technique, a passive component is viewed as a series of cascaded transmission line discontinuities along the direction that is perpendicular to the layer surfaces. In order to handle arbitrary layout pattern of conductors, finite element method is used to determine a sufficient number of eigen modes. Two practical numerical examples are given to show the effectiveness and validation of the proposed technique.**

***Index Terms*—Embedded passives, low temperature co-fired ceramics (LTCC), modal matching (MM), multilayer circuits, through-reflection-line (TRL) calibration.**

I. Introduction

THE ANALYSIS of multilayered RF and microwave passive circuits is a continuing research theme in the field. With the increase of demands on integration of various passive components and circuits, more and more efforts have been paid to developing new methodologies with more practical considerations, such as finite conductor thickness [1]. The classic 2.5-D numerical techniques, such as method of moment, exhibit ineffectiveness in dealing with the problems where conductor thickness must be taken into account. Besides, many other numerical methods, such as finite element method (FEM) and finite-differences time-domain (FDTD) method are also widely used. Nevertheless, whichever the method is used, if any part of the circuit conductor layout is altered for design purpose, the whole circuit needs to be re-simulated.

Modal matching (MM) is an effective technique for handling irregular circuit problems where the discontinuities are cascaded in one direction. FEM can be used in conjunction with MM for finding a sufficient number of eigen modes across each discontinuity. MM thus can decompose the original three-dimensional (3-D) problem into a series of segregated junction scattering problems. The solutions for each of the junction scattering problems are then combined through the cascading procedure of the general scattering matrix (GSM).

For a multilayer RF circuit, the circuit structure can be viewed as a series of horizontally or vertically cascaded discontinuities. In spite of the convenience of the horizontally cascaded scheme, there are at least four attractive features for vertically cascaded scheme from analysis point of view.

1) For a layered RF passive circuit, when the structure is divided vertically, each of conductor layers and the substrate layers can be viewed as a section of uniform transmission line. Therefore, only real eigen modes need to be sought if the dielectric constant of each layer is a constant.
2) The conductor layout can be arbitrary as long as its eigen modes can be found by certain means.
3) Vertically cascaded scheme can effectively save the simulation time in the sense that only the GSM for those discontinuities where the conductor geometry is changed need to be reanalyzed.
4) It is convenient to deal with the finite conductor thickness since a conductor layer with finite thickness can be easily treated as a section of transmission line.

Although the hybrid MM/FEM method has the above mentioned advantages in analyzing layered passive RF circuits, a practical consideration has to be given to how to extract the S-parameters defined at the device ports, which are defined in the direction from strip lines to the ground. In this letter, the through-reflection-line (TRL) calibration technique is used in conjunction with MM/FEM to extract the S-parameters, for the first time. Two practical examples are given to show the validation and the promising features of the proposed technique.

II. Vertically Cascaded Modal Analysis Scheme

As shown in Fig. 1, the key issue in the vertically cascaded scheme is how to extract the S-parameters defined at the device ports. Since the whole circuit structure is viewed as a serial transmission line discontinuities in vertical direction with bottom end short circuited (the ground plane), the S-parameters obtained by the standard MM are defined at the test ports. We need to convert the S-parameters defined at the test ports to the S-parameters defined at the device ports. Instead of using the transverse resonant technique [2] to extract the S-parameters at the device ports, by which an expensive frequency sweep

Manuscript received December 12, 2003; revised April 10, 2004. This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region under Grant 2150326 CUHK 4371/02E and the Natural Science Foundation of China under Project Contract 60171017. The review of this letter was arranged by Associate Editor A. Stelzer.

K.-L. Wu is with the Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong (e-mail: klwu@ee.cuhk.edu.hk).

Y. Ding is with the Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong and also with Nanjing University of Science and Technology, Nanjing, China.

D.-G. Fang is with Nanjing University of Science and Technology, Nanjing, China.

Digital Object Identifier 10.1109/LMWC.2004.832083

is needed for every single frequency simulation, we propose to use the TRL calibration technique [3] to do the conversion in a general way. The TRL calibration technique has been widely used for removing the discontinuities between the test ports to a given set of reference planes in experiments. It has also been successfully used in the parameter extraction in MoM [4]. Introducing the TRL calibration technique in modal analysis can greatly enlarge the scope where the modal analysis is competent.

In the proposed scheme the entire circuit structure to be analyzed is divided into a sequence of slices. Each slice represents a piece of transmission line, which is probably comprised of more than one inner conductor. A two-dimensional (2-D) eigen-value problem is first solved to obtain a sufficient number of eigen modes of each slice using FEM. With the eigen TE and TM modes found by Lanczos method, plus all the possible TEM modes solved using Incomplete Cholesky conjugate gradient (ICCG) algorithm, the standard modal analysis is used to find the GSM of each junction between two slices. The overall S-parameters at the computational test ports defined at the ends of extended coaxial transmission lines are obtained by cascading all the GSM of each junction. The details of the combined MM/FEM method can be found in [5].

In order to extract the S-parameters defined down the strip lines at the device ports, the required numerical TRL calibration standards also need to be analyzed. For a two-port device, three standards, namely a through line, two open lines and a section of quarter wavelength strip line at the center frequency, as shown in Fig. 2, must be analyzed. The analysis for those standards is the same as that of the model for the device under test (DUT). In the proposed scheme, the top conductor lid does not necessarily exist. For a device with multiple ports, multiport TRL scheme in [6] can be used. The side walls shown in Fig. 1 are necessary for modal analysis. From the practical point of view, the influence of the side walls can be ignored if they are far enough away from the device under test (DUT).

Similar to the device measurement, the analysis for the calibration standards only needs to conduct once if the port condition of DUT does not change in a design process.

III. Numerical Examples

In this letter, two numerical examples are given to show the validation of the proposed method. Example 1 is a three-layer spiral inductor and example 2 is a four-layer capacitor. They are commonly used in embedded LTCC passive designs. The dielectric constant of the substrate is chosen to be 7.8 and the total size of the shielded box is $4.2 \times 3 \times 0.86$ mm^3. Figs. 3(a) and 4(a) show the perspective 3-D view of the model for MM/FEM analysis of the spiral inductor and the capacitor, respectively.

The models for MM/FEM analysis of inductor and capacitor, as well as the designed TRL calibration standards, are simulated by the MM/FEM analysis and Ansoft's HFSS. The obtained responses are further processed by the TRL calibration technique to get the S-parameters defined at the device ports. In order to show the validation of the proposed scheme, a direct calculation of the S-parameters defined at the device ports are also carried out using the HFSS. Figs. 3 and 4 show the comparison among the results from the three different models, where "MA +TRL" refers to the results obtained by the MM/FEM analysis with TRL calibration; "HFSS+TRL" refers to the results by the HFSS analysis of the model for the MM/FEM analysis with TRL calibration; and "HFSS" refers to the results of a direct HFSS analysis with the ports defined at the device ports. Excellent agreement among the results can be observed. The computing time of this method for one complete simulation is

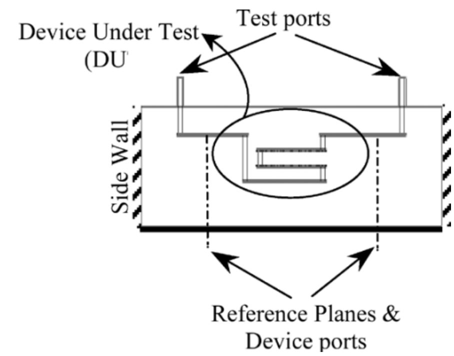

Fig. 1. Side view of the model for modal analysis for a multilayered passive circuit and the definitions of test ports and device ports.

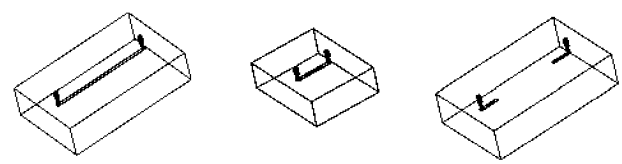

Fig. 2. Perspective view of TRL calibration standards.

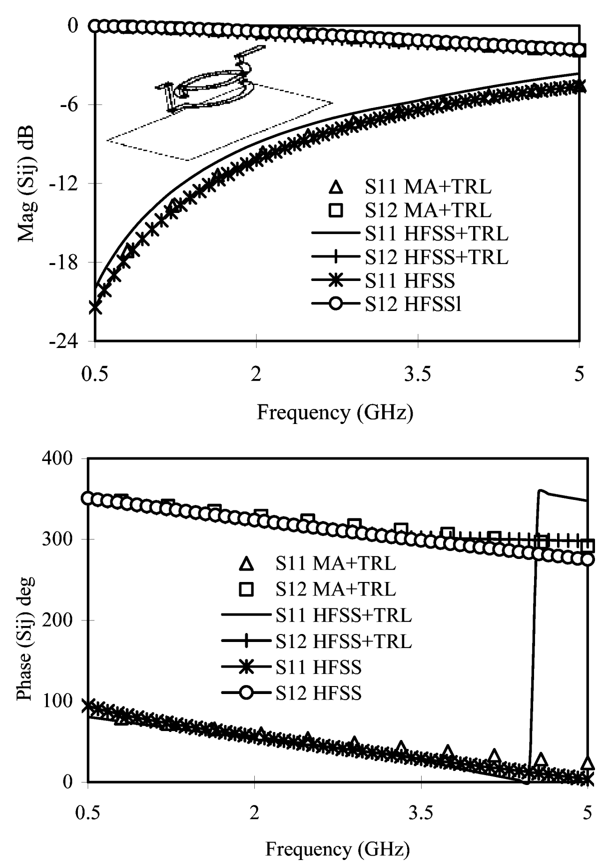

Fig. 3. S-parameters of a spiral inductor defined at the device ports.

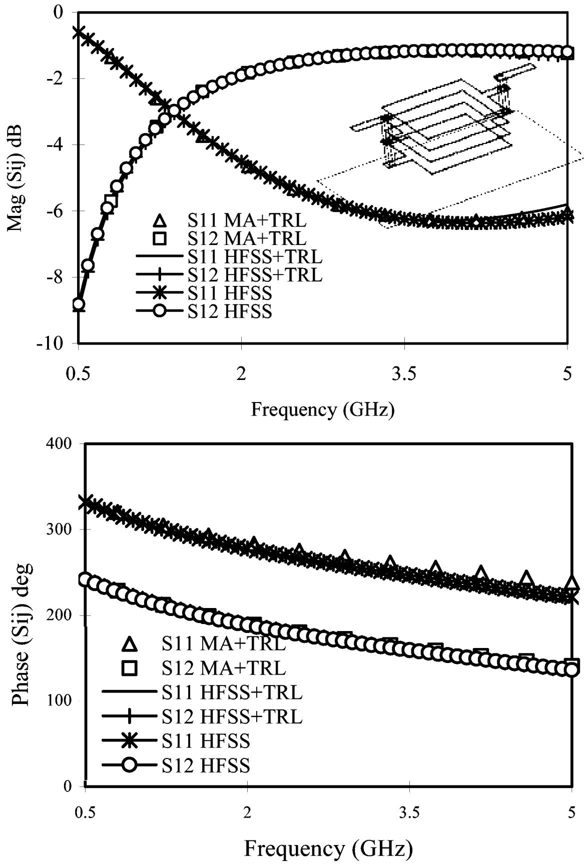

Fig. 4. S-parameters of a multilayer capacitor defined at the device ports.

in the same order as that of HFSS analysis. However, in a design or optimization process, for those layers where the conductors are not changed, the solutions of the eigen value problems and their associated GSMs can be reused. This will greatly reduce the computing time.

The factors that affect the accuracy of the MM/FEM analysis most have been well investigated in [7] and [8]. We use a similar spectral criterion for determining the number of the triangular elements in meshing process and the number of the TE/TM modes for each cascaded junction. The numbers of the modes on all the layers are very close since the outer electric boundaries are the same and the complexity of the inner circuits is about the same. In the two examples, the number of the modes on each layer is around 140. It is worth mentioning that for the two examples it takes about 2 min to find all the modes and about 30 s to calculate each frequency point on a 1.5-G CPU PC with memory of 512 Mb. A typical number of nodes for each layer is about 3000.

IV. Conclusion

A novel numerical scheme for multilayered RF passive circuits is proposed in the letter. The scheme combines the MM/FEM method and the traditional TRL calibration technique in an efficient way so that it can be easily used to handle the multilayered RF circuit structures with finite conductor thickness. The scheme is particularly efficient for a circuit optimization, in which only those altered conductor layers of a circuit need to be reanalyzed. The method can also be extended to analyzing many other types of microwave circuits in which the discontinuities can be viewed as a series of cascaded junctions in one direction.

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