A 3-D Method of Moments for the Analysis of Real Life MMICs

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Abstract — **In this contribution we introduce a 3-D Method of Moments (MoM) approach, suitable for the analysis of real life monolithic circuits for microwaves/millimeter waves (MMIC). It shares the flexibility and the efficiency of the currently available spectral domain commercial simulators, while considering all metallizations to have finite thickness and finite conductivity. The method is successfully applied to Microelectromechanical (MEM) capacitive switch in the 1-50GHz frequency range.**

I. Introduction

The Method of Moments (MoM) applied to Spectral Domain (SD) integral equations is one of the most successful tools in the analysis of printed multilayer circuits. The quite large number of commercially available software packages exploiting this philosophy bears witness of such a success.

The most popular electromagnetic tools rely basically on the approach described in [1], adopting the efficiency-enhanced algorithm introduced in [2] and the method detailed in [3], allowing vias to be treated by means of constant vertical currents. The main limitation of these software packages is that, in principle, they are not able to rigorously handle thick lossy conductors, even if such a limitation is partially overcome by some sort of expedient. Surface impedances were used e.g. in [4] in order to include conductor losses, and metallizations with finite thickness are often modeled by means of boxes constituted by infinitely thin conductors or introducing a number of vias between parallel thin conductors.

In [5] we introduced a different point of view, leading to a 2-D general approach to the modeling of lossy planar structure that in [6] was also extended to include linear active effects and used to model millimeter wave FETs. In [7] a first 3-D formulation of this approach was proposed, by using the excitation scheme introduced in [8], namely the travelling-wave excitation, obtaining satisfactory results. However it is known that this kind of excitation suffers some limitations, mainly due to the need of considering waves impinging from infinity, and the resulting formulation lacks the flexibility needed for integration in a commercial software framework.

In this contribution a 3-D formulation is developed by the more conventional delta-gap excitation scheme [9], that is the one currently used by commercial software packages: by adopting this scheme we developed a general program including a simple editor that allows dealing with general topologies.

As a key example we report the simulation of a microelectromechanical (MEM) capacitive switch. This example has been chosen because, in spite of its simplicity — a simple lumped element equivalent circuit may well do the work— it is hardly addressed by the available approaches. In fact while the conventional MoM approaches are faced with their limitation in handling lossy metals with finite thickness, techniques relying on some space/time discretization — e.g. Finite Differences (FD), Transmission Line Method (TLM) etc — fail or simply become inefficient due to the aspect ratio of the involved geometrical dimensions.

II. Theory

According to the strategy adopted in [5] for 2-D structures, as a first step the dyadic Green's function (DGF) of the dielectric multilayer structure has to be calculated. This step is common to the standard MoM approaches, like [1]; however in the present approach the DGF has to relate the electric field in the dielectric stack to *volume* currents. As an additional difficulty, this representation has to be valid even in the source region: the issue is investigated in [10].

Consequently

$$\mathbf{E}(\mathbf{r}) = -\iiint_V d\mathbf{r}'\, \mathbf{Z}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}(\mathbf{r}') \qquad (1)$$

where V is the volume where currents are non vanishing, namely the conductors, and $\mathbf{Z}$ is the needed DGF. $\mathbf{Z}$ also includes dielectric losses by the usual definition of complex permittivities.

The very nature of volume currents is specified by imposing Ohm's law to be satisfied within the lossy conductors: this condition replaces the vanishing of the tangential electric fields, as used by standard SD MoM.

In order to obtain a deterministic integral equation, some kind of known excitation has to be imposed: in this paper we use the conventional delta-gap excitation scheme introduced in [9]. The whole structure is assumed to be enclosed between electric walls (however top and bottom covers may also be infinite dielectric layers) and at some point along the feeding lines a constant electric field, orthogonal to a virtual plane cutting the conducting line, is applied. Such a plane may be defined at an arbitrary position and along any of the three directions.

Hence the excitation field is:

$$\mathbf{E}_0(\mathbf{r}) = -\delta(v - v_0)\mathbf{u} \quad \text{if } \mathbf{r} \in \text{feeding line p} \qquad (2)$$

where $v = x$, y or z, and $\mathbf{u}$ is the direction normal to the defined plane. This is a unitary voltage generator applied at an arbitrary reference plane defining an accessible port p; usually, even if not necessarily, the plane coincides with one of the enclosing walls, so to have ground referenced quantities in the subsequent network calculations.

Summarizing, Ohm's law and the excitation condition (2) are applied to equation (1) providing the integral equation

$$\iiint_V d\mathbf{r}' \left[\mathbf{Z}(\mathbf{r},\mathbf{r}') + \rho(\mathbf{r})\mathbf{I}(\mathbf{r},\mathbf{r}')\right] \cdot \mathbf{J}(\mathbf{r}') = \delta(v - v_0) rect(p)\mathbf{u} \qquad (3)$$

where ρ is the metal resistivity, $\mathbf{I}$ is the identity operator, *rect*(p) is a function of unitary amplitude not vanishing only along the cross-section of the feeding line at port p. Equation (3) must be solved within the volume of the conductors.

To this aim, the MoM is applied to (3) expanding the unknown currents as

$$J_x(x,y,z) = \sum_{i=1}^{N_x-1}\sum_{j=1}^{N_y}\sum_{k=1}^{N_z} PWS(x, x_i, x_{i+1}) rect(y - y_j) rect(z - z_k)$$
$$J_y(x,y,z) = \sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{k=1}^{N_z} rect(x - x_i) rect(y - y_j) rect(z - z_k)$$
$$J_z(x,y,z) = \sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\sum_{k=1}^{N_z-1} rect(x - x_i) rect(y - y_j) PWS(z, z_k, z_{k+1}) \qquad (4)$$

where PWS(u,u_i,u_{i+1}) are asymmetrical piece-wise sinusoidal functions with argument k_o, the vacuum wave-number, and N_x, N_y and N_z are the number of subsection intervals.

Solution of (3) yields the complete current distribution over the thick lossy metals, as well as, by means of (1), the electric field distribution everywhere in the dielectric stack. By integrating the current distributions along the sections where the ports are defined, one obtains the network admittance (Y) parameters as

$$y_{ij} = I_i\Big|_{v_k = \begin{cases} 1 \text{ if } k=j \\ 0 \text{ otherwise} \end{cases}} \qquad k,i,j = 1 \ldots N$$

where N is the number of ports, I_i is the current at the i-th port, and v_k is the voltage generator at the k-th port.

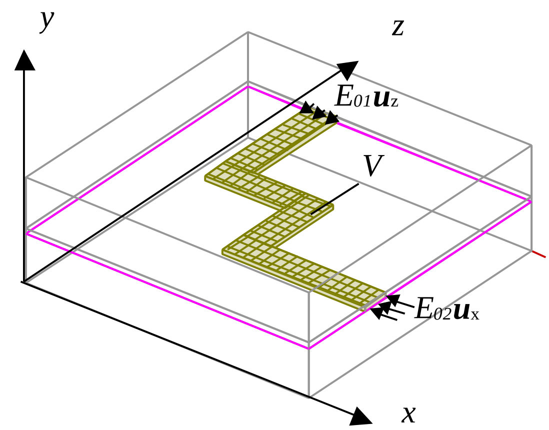

Fig. 1. 3-D structure involving finite thickness conductors, with delta-gap excitation

Defining the ports leads to a local discontinuity; such a discontinuity may sometimes model an actual discontinuity, encountered in the circuit being modeled; if this is not the case the discontinuity has to be evaluated and removed by means of one of the standard de-embedding algorithm. This issue is discussed in [11].

III. Results

By using the theory described in the previous section, a general-purpose program has been developed and used to successfully study several passive structures.

An interesting test-bed is the analysis of MEM devices, as the thickness and the conductivity of the metallizations may hardly be neglected; note that the working conditions encountered in the present example are rather common when modeling real MMICs.

A MEM capacitive switch [12] is depicted in fig. 2: it is shown in its not actuated ("on") position. In such a case the structure is similar to a bridge on a thick, lossy coplanar waveguide. As the bridge capacitance is relatively small, removing the port discontinuity by a correct de-embedding procedure is mandatory in this case. Figure 3 reports a comparison between the experimental results of [12] and the theoretical ones. No attempt was made to introduce radiation losses that are believed to play a role for the insertion loss in the higher frequency range.

The actuated ("off") position is the one that usually poses a major challenge to the FD and TLM methods: in this state an electrostatic potential snaps down the metallic membrane, now acting as a large shunt capacitance.

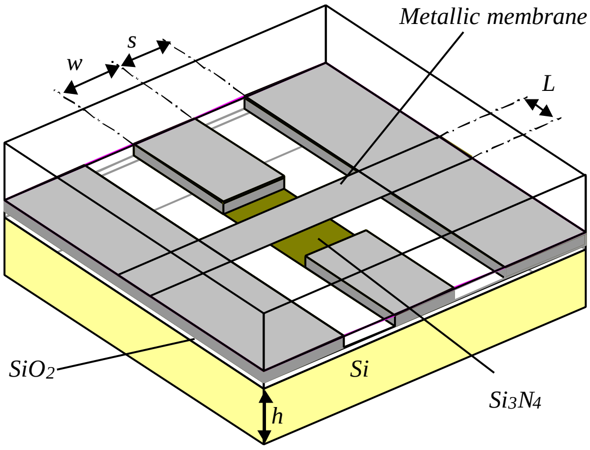

Fig. 2. Geometry of the MEM ("on" position): *w*=60 μm, *s*=45 μm, *L*=60 μm, h=300 μm; the aluminum metallization is 2.5 μm thick, while the metallic membrane is 0.5 μm thick; the switch electrode is 0.4 μm thick, covered by a 0.1 μm thin film of Si_3N_4 (ε_r=7.5). The switch is on the top of a 1 μm of a silicon dioxide insulating layer (ε_r=3.9). For the buffer ε_r=11.9, σ=0.01 S/m. The whole structure is 1030 μm long.

A thin film (0.1μm) of silicon nitride that prevents the upper membrane from sticking on the lower electrode, plays now a major role: discretizing the whole structure as required by standard FD and TLM methods may lead to inefficient or unstable solutions, due to the critical aspect ratio. Moreover the shunt capacitance, assuming large values (in the order of some pF), is responsible for long transient oscillations in time-domain methods.

Figure 4 shows a comparison between experimental and theoretical data for the return and insertion loss for the switch in the "off" state.

Obtaining the network parameters for both the “on” and “off” states required a few minutes per frequency point on a Pentium II 233 MHz processor.

V. Conclusion

A general 3-D MoM approach for the modeling of passive MMIC circuits involving thick lossy conductors has been introduced. Sharing several steps with MoM currently used by available commercial software packages, the algorithm is flexible and able to handle complex structures.

In order to validate the method, several structures have been analyzed. In this contribution we report as an example the simulation of a MEM capacitive switch in its "on" and "off" states.

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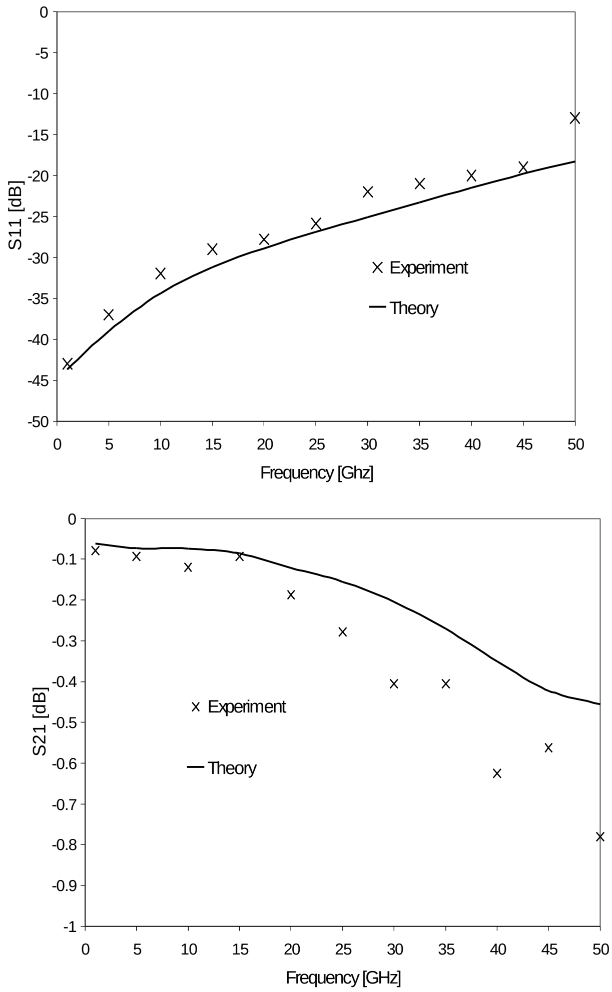

Fig. 3. Return loss and Insertion loss for the "on" state: comparison between theoretical and experimental data [12].

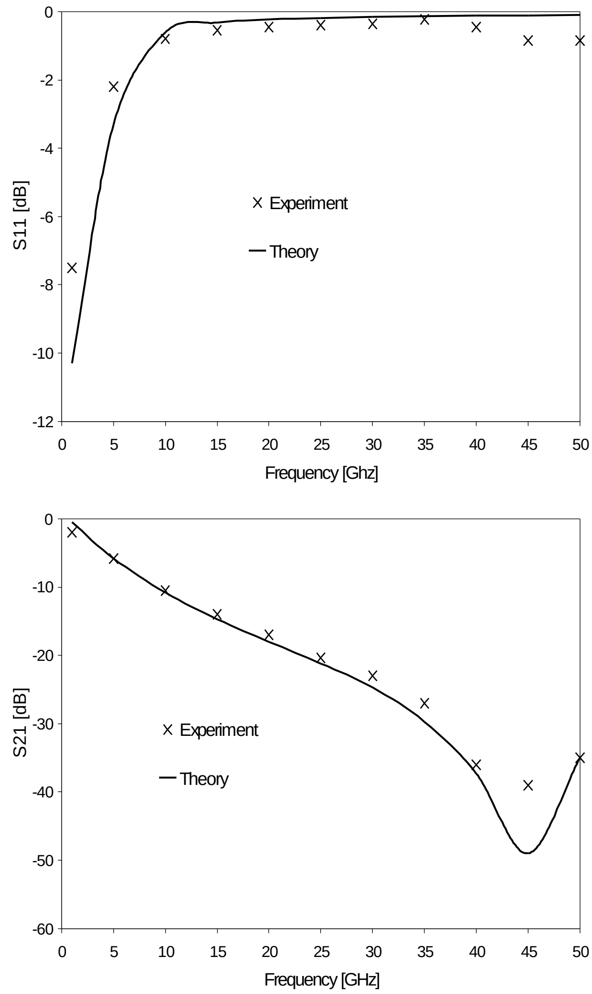

Fig. 4. Return loss and Insertion loss for the "off" state: comparison between theoretical and experimental data [12].