ELECTROMAGNETIC MODELLING OF RF MEMS STRUCTURES

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ABSTRACT

Micro-electro-mechanical-systems are expected to play a central role in the extremely rapidly expanding area of wireless communications, as they are suited for a number of applications ranging from mobile phones to satellite and terrestrial broadband communications. The design of RF MEMS however require sophisticated modeling techniques because of their complicated 3-D geometries with critical aspect ratios and strong inhomogeneities, in such a way that only electromagnetic-based techniques can provide reliable characterizations of their performances. This paper presents a brief, far from being exhaustive, survey of the main EM modelling techniques currently employed for the accurate modelling of MEMS structures. It should be stressed that this research area is still under development: no numerical method can be seen as the optimum one, each exhibiting advantages and disadvantages over the others. For this reason, hybrid approaches combining the advantages of different methods are of special interest. Practical examples of MEMS structures are presented and discussed.

INTRODUCTION

A micro-electro-mechanical-system (MEMS) is a miniature device or an array of devices combining electrical and mechanical components, fabricated with IC batch-processing techniques. By leveraging existing state-of-the-art integrated circuit (IC) fabrication technologies, MEMS technology exhibits many advantages indigenous to IC technologies such as cost, size and weight reduction. These advantageous characteristics have positioned MEMS as a winning technology in many application areas, including accelerometers, pressure sensors, micro-optics, and ink-jet nozzles. In this paper we are concerned with radio frequency (RF) applications of MEMS specifically with wireless communications. As is well known, this area is expanding at an incredible pace for applications ranging from mobile phones to satellite and terrestrial broadband communications, and RF MEMS technologies are going to be central to many parts of this expansion. New developments in satellite communications as well as advances in the area of millimeter-wave multimedia services require high performance components, and RF MEMS can fulfill that need by providing critical reductions in power consumption and signal loss, thereby extending battery life or reducing weight.

The building block element of RF MEMS technology is the switch. RF MEMS switches are specifically designed to operate up to mm-wave frequencies (0.1 to 100 GHz). A moving bridge is employed to achieve a short or an open circuit in an RF transmission-line. The forces required for the mechanical movement can be obtained using electrostatic, magneto-static, piezoelectric or thermal designs. To date, only electrostatic-type switches have been demonstrated at 1-100 GHz with high reliability.

The design of a MEMS device is a complex task that involves both electrical and mechanical optimisation steps. The geometry of such a device, in fact, must satisfy technological constraints while achieving good reliability and very high electrical performances. To obtain these results, several commercial software, specifically designed for RF MEMS development, are appearing in the market. Generally, these environments perform a full device analysis concerning the mechanical and thermal aspects but are lacking in the electrical modelling, usually based on lumped equivalent circuits. Because of the high integration levels and the high frequencies involved, in fact, fullwave CAD tools based on the rigorous solution of Maxwell's equations, become indispensable in order to account for phenomena such as electromagnetic (EM) coupling, cross-talk, package interaction, etc. To this end, various EM methods, based on integral or differential approaches, either in time or frequency domains, have been developed and presented in the literature.

A brief survey of such techniques, focused on the most popular ones, is presented in this paper. Because of the stringent requirements in terms of accuracy, on the one hand, and the compatibility with the computational resources available, on the other, none of the basic methods can be regarded as the optimum one. As a consequence, hybrid methods are being developed with the aim of combining advantages of different numerical techniques. Although still preliminary, the results appearing in the literature look very promising in the capability of accurately predicting the EM behavior of MEMS devices with a reasonable numerical effort.

BASIC METHODS FOR THE EM MODELLING OF MEMS DEVICES

An in-depth discussion on numerical methods for the EM modelling of microwave structures is outside the scope of this paper. We would rather simply mention those techniques that have been considered more promising and attractive with specific reference to MEMS devices and present and discuss some of the results that have been achieved.

The EM modelling of such a device could in principle be performed using any full-wave method for microwave 3D structures. The task, however, is made quite hard because of the presence of various dielectric materials, many geometrical details with very high aspect ratios, metal and dielectric losses. Moreover, the presence of moving parts constitute a specific challenge that only time-domain methods can effectively cope with. Among those, one of the most effective is the Finite Difference Time Domain (FDTD) method [1]. The method is based on the direct solution of Maxwell's time-dependent curl equations. Time and space are discretized according to the Yee's algorithm [1]: in particular, the space is divided into a finite number of elementary cells used for the mapping of electric and magnetic fields. The time solution is obtained by an iterative scheme which evaluates the electric and magnetic field components at alternate half-time steps. Since its first formulation by Yee [1] in 1966, a huge number of extensions and enhancements have been developed over the years, so that the method is nowadays one of the most popular ones since it allows complex electromagnetic structures with arbitrary geometries to be modelled with great flexibility. Moreover, lumped, both linear and non-linear, devices can simultaneously be taken into consideration in the Lumped-Element formulation (LE-FDTD) [2]. The main disadvantage of the FDTD method lies in the need for a growing memory and computational time when critical "aspect-ratios" are present. To increase its efficiency several algorithms, such as for example the Short Open Calibration procedure [3] or the system identification technique [4] have been developed. Figure 1 shows a comparison between the experimental results reported by Muldavin and Rebeiz on a shunt MEMS switch [5] and two FDTD simulations, using a mesh of 30x100x80 cells. The adoption of the calibration procedure allows a considerable improvement of the accuracy (more than 5 dB at 22 GHz in Fig. 1a). The frequency shift between the theoretical and experimental responses in the down-state is due to the surface roughness of the oxide layer underneath the bridge. This has the effect of lowering the bridge capacitance in the down state thus increasing the resonant frequency of the switch. In spite of such discrepancy the above results confirm the suitability of the FDTD method for the fullwave analysis of MEMS devices. Another, though less popular, time domain method is the transmission line matrix (TLM) method, developed and first published in 1971 by Johns and Beurle and emerged as a powerful method for computer modeling of electromagnetic fields [6],[7]. It is a space discretizing method in which the evolution of the discretized electromagnetic field is modeled by wave pulses propagating on a mesh of transmission lines and scattered at the mesh nodes. The TLM method exhibits an excellent numerical stability and is also suitable for modelling lossy, dispersive and nonlinear media.

A critical aspect of space-discretizing methods like TLM or finite-difference in time/frequency domain (FDTD, FDFD) methods occurs in the choice of proper absorbing conditions at the boundaries of the computational domain. These conditions must simulate either free-space or matched load conditions in guiding structures, over a wide frequency band and for arbitrary wave incidence.

Many popular frequency domain techniques are based on an integral formulation of the boundary value problem. Both Finite Element Method (FEM) and the Integral Equation methods (IE) belong to this category. As is known, in the FEM the boundary value problem is expressed in the form of an equivalent functional to be minimized and the spatial computational domain is discretized into a grid of "finite elements".

Figure 2 shows a comparison between experimental and theoretical results for a series MEMS switch fabricated and tested by the group led by Professor Guillon at the IRCOM in Limoges, France [8]. Theoretical results have been obtained both by the FEM and by a commercial MoM software. A good accuracy is shown by both methods.

IE methods are based on a formulation of the Maxwell's equations in the form of a surface integral equation based on either the Electric Field (EFIE) or the Mixed Potential (MPIE) formulation. The IE equation is then discretized using the Method of Moments. Such methods involve a considerable amount of preprocessing but possess a high numerical efficiency, since the computational domain is reduced to a two-dimensional one by exploiting the knowledge of the appropriate Green's function. IE-MoM methods have been implemented in a number of commercial software packages.

A specific 3-D technique that has been employed for the analysis of RF MEMS is the Generalized Transverse Resonance-Diffraction approach (GTRD) [9]. The derivation of the integral equation is somewhat similar to the Spectral Domain approach (SDA). In contrast to SDA, however, currents have to be volum rather than mere surface currents. Finite conductivity as well as finite thickness of the conductors are accounted for by imposing that Ohm's law be satisfied within the conductors. This additional condition provides an eigenvalue integration equation to be solved in source regions that becomes a deterministic one by selecting the ports as the sources. The integral equation is solved by a standard Method of Moments (MoM). Discontinuity effects due to the excitation are removed by a numerical calibration technique. As a frequency-domain technique, GTRD is limited to the linear regime and the computational time increases with the number of frequency points.

HYBRID METHODS

As mentioned above, space discretization methods, such as FDTD, TLM and FEM, have high flexibility but involve a large number of unknowns, while IE-MoM methods suffer from low flexibility but have reduced number of unknowns. As an alternative to the fundamental methods mentioned above, hybrid approaches can be adopted to exploit the advantages of different methods by creating more powerful tools capable to overcome the drawbacks of each method alone. A number of hybrid methods have been proposed in the literature for the modeling of complex microwave structures [10]. We refer here to a recent contribution specifically applied to MEMS structures [11].

Let us observe first that complex geometries possessing fine details and high aspect ratios, such as MEMS switches, must be finely discretized only in those regions containing small details, thus associated to rapid variations of the EM field distribution. A dense mesh would involve an unaffordable computational effort if adopted over the entire computational domain, including the large homogeneous parts of the structure. The TML-IE method has been proposed in [11] in order to combine the advantages of TLM with those of the IE method. The 3-D volume is segmented into sub-regions, where the most appropriate method between TLM and IE is applied.. Each physical object is enclosed into an imaginary box, where the TLM method is applied. The space outside the boxes is represented by means of an appropriate Green's function, the IE being formulated at the box boundaries.

In Fig.3 the results of the analysis of a CPW Shunt MEMS Switch using TLM, TLM-IE and GTRD methods are compared along with the experimental results. All methods are shown to yield equivalent accuracy, except TLM-IE and GTRD are much faster than conventional TLM.

CONCLUSIONS

A brief, far from being exhaustive, survey of the main EM modelling techniques currently employed for the accurate modelling of MEMS structures has been presented. No numerical method can be regarded as the optimum one, each exhibiting its own advantages and disadvantages over the others. For this reason, hybrid approaches ar being developed in order to exploit the advantages of different methods. Practical examples of MEMS structures have been presented and discussed.

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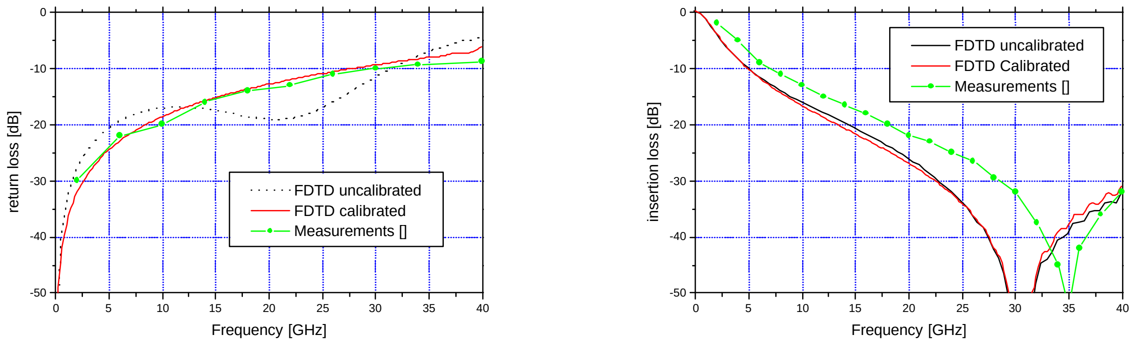
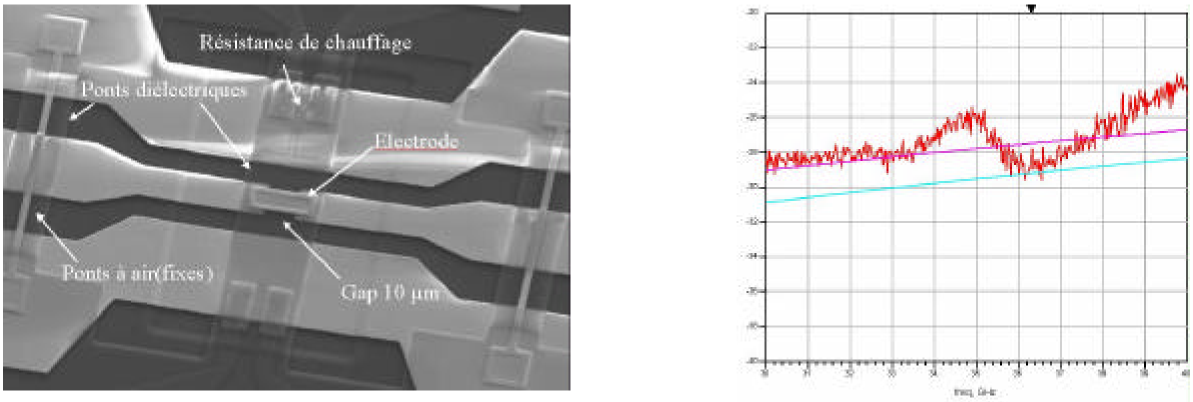


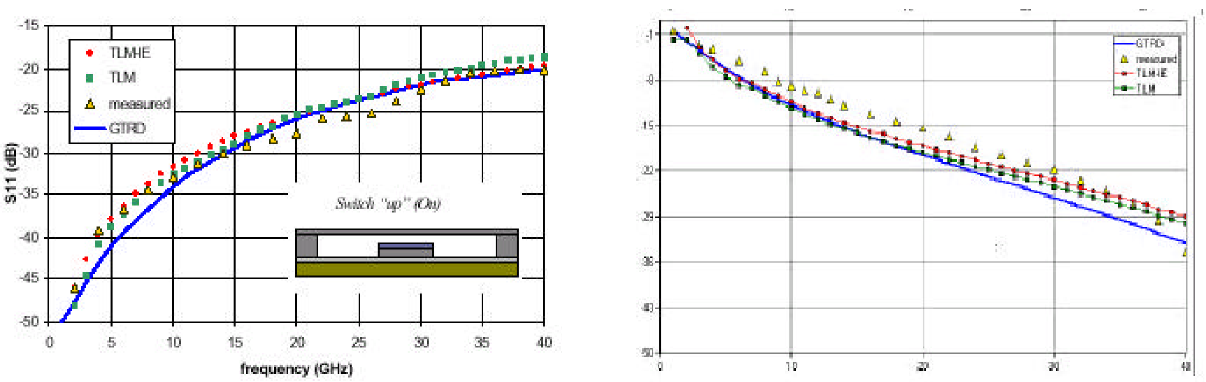
(a) (b)

Fig. 1. Comparison between experimental results on the MEMS switch in [9] with FDTD simulations: (a) return loss in the up-state. (b) insertion loss in the down-state.



(a) (b)

Fig.2. A MEMs series switch: a) photo of the structure; b) insertion loss in Off-state. Comparison among experimental (red), FEM (cyan) and Momentum (magenta) results.



(a) **(b)**

Fig.3. Comparison of TLM, TLM-IE and GTRD methods [11]: S_{11} (a) On-State and S_{21} (b) Off-state vs. Frequency (GHz).