ADAPTIVE MODELING AND DESIGN OF PACKAGING MICROSYSTEMS AND MEMS FOR WIRELESS COMMUNICATION MODULES

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ABSTRACT

This paper deals with some of the most important issues in modern packaging design and simulation of structures for use in wireless communications systems. The focus of the discussion is on the integration of novel complex device parameters, specifically the inclusion of MEMS devices and solid-state circuit elements, and on the mathematically correct implementation of the lossy material parameters. Also, guidelines for algorithm parallelization and spectral estimation provide significantly reduced simulation and design cycle time for wireless microsystems.

INTRODUCTION

Traditional packaging systems are used for both mechanical and thermal stability as well as to connect circuit elements. Modern systems are constantly being miniaturized and the role of the package is being refined. Instead of simply connecting the element to the rest of the circuit, the package can be used as a part of it. Multilayer circuit technologies and advances in semiconductor processing are providing the ability to implement a large number of components in the package itself. The possibilities that this opens for circuit design are limitless, however, this presents many difficulties for the designer.

In these modern packaging systems components are placed in very close proximity, and interaction between these elements is virtually guaranteed. Microwave circuit simulators are not designed for these topologies, as all of the possible configuration combinations have not been identified. As such, it is necessary to turn to full-wave electromagnetic simulators, which have shown excellent accuracy for a variety of structures in the past. However, problem sizes on the order of entire modules are often beyond the computational resources of most simulator/computer combinations. In order to create effective simulators for these structures, CAD tools and modeling techniques are needed that can simulate large structures in an efficient, broadband, and accurate way. The FDTD and MRTD time domain simulators meet all of these criteria. The MRTD technique, due to its time- and space-adaptive mesh, also offers considerable improvement in both accuracy and simulation duration. With the application of wavelets, MRTD can increase accuracy at material interfaces, and model more efficiently time-varying boundary positions. The task then becomes the incorporation of more complex circuit and system elements and effects in the electromagnetic model. This paper will discuss the effects of the addition of microelectromechanical systems(MEMS) and active device (solid-state semiconductor) modeling and loss characteristics to an electromagnetic simulator. The interference and crosstalk between circuit connections that can occur in high-frequency systems will also be examined, along with methods for reducing the time needed for simulation; specifically, the technique of FDTD parallelization and a method for spectral estimation.

COUPLING EM/MECHANICAL OR EM/SOLID-STATE EQUATIONS

With the miniaturization of semiconductor devices, packaged microsystems are becoming more complex. Using semiconductor processes, both traditional active devices such as transistors and novel devices such as MEMS can be fabricated. Standard time-domain simulators cannot be employed to model these devices due to their large size and hybrid nature. In order to simulate these devices, and model their interaction with surrounding circuit elements, simulators must be developed that accurately represent the effects of these circuit elements on the surrounding circuit.

Incorporating either active semiconductor devices or MEMS into time-domain simulations involves the creation of a model for the device that is able to both model all of the involved phenomena (motion, semiconductor, and electromagnetic), preferably in the time-domain, and then creating an interface for the models. Models have been investigated for both of these device types [1-3]. A model of a MEMS variable capacitor is shown in Fig. 1. The force applied to the movable plate, or MEMS membrane, can be calculated using the field information from theelectromagnetic simulator, which can then be used to determine the updated plate separation.

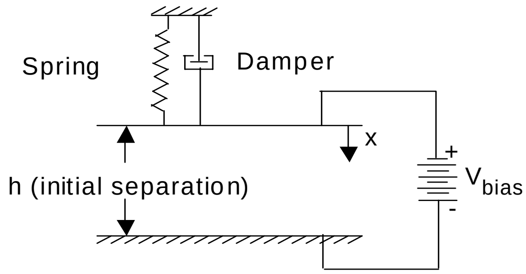

Fig. 1: Model of MEMS capacitor

Equation (1) is the discretized form of the mechanical equation coupled with the bias voltage (V_{bias}) effects, where x is the plate position (measured from the resting position), m is the mass of the plate, k is the spring constant, b is the damping coefficient, and Δt is the time step.

$$x^{n+1} = 2x^{n}\left(\frac{2m - k\Delta t^{2}}{2m + b\Delta t}\right) + x^{n-1}\left(\frac{b\Delta t - 2m}{b\Delta t + 2m}\right) + \frac{2\Delta t^{2}\varepsilon_{\circ} A V_{bias}^{\ 2}}{(2m + b\Delta t)(x^{n} - h)^{2}} \qquad (1)$$

The modeling of MEMS devices requires an electromagnetic simulator that can model moving metal boundaries and determine the force placed on these boundaries by the electromagnetic fields. The complexity of the mechanical simulator depends on the type of motion of the MEMS device itself. It has been shown [1,2] that for simple 1-D membrane motion, which can approximate the motion in many variable capacitors and switches, the combination is fairly straightforward, and there are several methods that can be used to represent the position of the plate in the electromagnetic simulator. Likewise, the addition of semiconductor devices into the FDTD grid requires a method in which electromagnetic fields within cells can interact with these complicated materials. Time-domain semiconductors utilizing hydrodynamic carrier motion have been employed in the past [1,3].

The methods that are used to simulate a moving boundary depend on the simulation technique used. The FDTD and MRTD methods, while similar, provide different opportunities for representing moving boundaries. The FDTD method can do this using either a very fine grid [2], where the PEC boundary conditions are applied at the closest area to the metal, or a variable grid, where the grid is reformulated local to the metal [4]. The MRTD technique provides a natural method for representing PEC. The time- and space-adaptive grid can be used to represent the position of the metal up to any desired degree of accuracy [1,2]. Semiconductor devices can be modeled using carrier fluid-flow equations [1,3] in time domain form. The motion of the carriers depends on and can alter the fields in the semiconductor device.

The other challenging characteristic of combining two simulations is the difference in time steps. In the mechanical simulation, several (possibly hundreds or thousands) of time steps will pass in the electromagnetic simulation before each time step in the mechanical simulator. The opposite is true in the semiconductor device simulator. The time step for the carrier simulation is significantly smaller than the time step for the electromagnetic simulator. Therefore, dividing the large electromagnetic simulator time step into smaller time steps of appropriate size for the semiconductor simulator and interpolating may produce a numerically correct excitation (Fig.2).

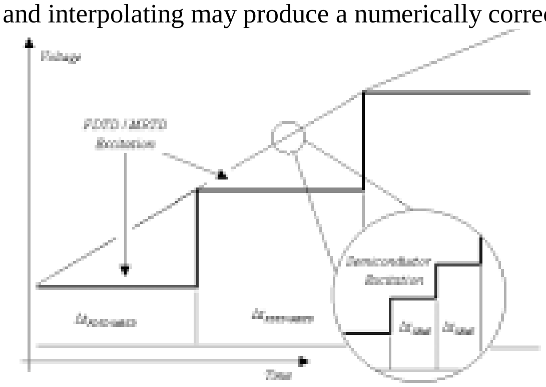

Fig. 2: Semiconductor excitation interpolation

LOSS CHARACTERISTICS

Another characteristic of RF packaging structures that must be taken into account in order to gain an accurate view of device behavior is the loss characteristics of real materials. Neglecting lossy material parameters in simulations can cause a large discrepancy between measured and simulated results. There are several methods for including these parameters in FDTD and MRTD models, including the surface impedance boundary condition (SIBC), which is useful for determining the scattered field from an RF structure, but the technique of interest is the discretization of Maxwell's equations with the inclusion of loss characteristics. This method allows for the probing of fields inside the structure, and determining the RF behavior of structures that may be embedded due to a multilayer process (e.g., LTCC).

The discretization of Maxwell's equations is essentially the same for lossless and lossy materials. The only difference is the inclusion of the conductivity in the current term that accounts for the electrical loss mechanisms [5]. The standard central differencing scheme is followed, and the resulting expression is easily implemented in the existing FDTD algorithm, with only minor changes to the coefficients used. These coefficients are easily modified in an existing code, and add only a small overhead in memory requirements. The resulting expression is shown in (2).

$$E_x\Big|_{i-.5,j,k}^{n+1} = \left(\frac{1-\frac{\sigma\Delta t}{2\varepsilon}}{1+\frac{\sigma\Delta t}{2\varepsilon}}\right) E_x\Big|_{i-.5,j,k}^{n} + \left(\frac{\frac{\Delta t}{\varepsilon}}{1+\frac{\sigma\Delta t}{2\varepsilon}}\right)\left(\frac{H_z\big|_{i-.5,j+.5,k}^{n+.5} - H_z\big|_{i-.5,j-.5,k}^{n+.5}}{\Delta y} - \frac{H_y\big|_{i-.5,j,k+.5}^{n+.5} - H_y\big|_{i-.5,j,k-.5}^{n+.5}}{\Delta z}\right) \quad (2)$$

This technique can be easily extended to MRTD, to allow for memory and processing savings, as well as increasing accuracy at material boundaries. Similarly, MRTD can be used to allow for nonuniform loss characteristic distributions as it can be configured to provide for variations in conductivity across a problem space.

CROSSTALK BETWEEN INTERCONNECTS

Having discussed the addition of active device models to the simulator, the next area for investigation is the effect that the increasing complexity has on circuit operation and interaction. In order to ensure correct operation of a packaging structure, we must take into account the interaction and interference that results from the close proximity of components in the package. The modeling of coupling between interconnects is another issue that must be considered when designing three-dimensional circuits for RF applications. Coplanar Waveguide (CPW), Finite Ground Coplanar (FGC), and Thin-Film Microstrip (TFMS) are all common choices for interconnecting multilayer circuits embedded in polyimide and fabricated on Silicon [6,7]. Fig. 3 below shows field plots of closely spaced TFMS lines embedded in polyimide layers on a silicon substrate for use in wireless communications systems. The simulator can also be used to develop practical design rules for closely spaced interconnects.

Fig. 3a: Electric field distribution

Fig. 3b: Magnetic field distribution

Fig. 3: Field Distributions for TFMS lines embedded in polyimide on Silicon

PARALLELIZATION

A significant amount of research has been performed into the parallelization of the FDTD algorithm in order to reduce computation time for larger problem spaces. FDTD is relatively easy to parallelize because the field updates depend only on the previous values of updated field and the values of the surrounding points, and is known as a nearest-neighbor problem. This allows the FDTD grid to be easily split and the subgrids processed separately. The data that then needs to be passed between the processes is limited to the field values on the borders of these subgrids. Codes employing this technique have been shown to run on a wide variety of parallel supercomputers. It has been shown [8] that a nearly linear speedup can be achieved using a Linux Beowulf cluster for this type of application.

SPECTRAL ESTIMATION

One of the major difficulties of modeling resonant structures, such as inductors and capacitors, is the large number of time steps required for the simulation to converge. This can be prohibitive in many cases of high-Q devices that require hundreds of thousands or millions of time steps to accurately simulate. In order to reduce the time needed for simulation, many spectral estimation techniques have been developed [5] that use the resonant nature of the structure and an exponential expansion to predict future time steps. Variations on this approach allow the spectral properties of the signal to be calculated directly. In this way, the number of time steps needed for a simulation can be greatly reduced. Combined with FDTD or MRTD, spectral estimation techniques can provide a very powerful tool for the multifrequency calculation of quality factors Q.

CONCLUSIONS

This paper discusses some of the salient issues in current RF microsystem and packaging design, including the simulation of active semiconductor and MEMS devices, and the modeling of loss mechanisms with full-wave time-domain electromagnetic simulators. Also discussed are techniques for reducing the overall computation time for the system-level simulations that modern miniaturized RF modules require.

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