Modeling and Optimization of RF-MEMS Reconfigurable Tuners with Computationally Efficient Time-Domain Techniques

Nathan Bushyager[1], Krista Lange[2], Manos Tentzeris[1], and John Papapolymerou[1]

[1]Georgia Institute of Technology, Atlanta, GA 30332
[2]Raytheon Company, Tucson AZ, 85734

***Abstract* — Modern RF-MEMS device design is difficult due to the lack of tools capable of simulating highly integrated structures. This paper presents methods in which the FDTD technique can be used to model a reconfigurable RF-MEMS tuner. A new method of modeling a conductor intersecting a cell is presented. In addition, code parallelization and variable gridding are used to simulate the tuner and decrease execution time by two orders of magnitude. Results of simulation and measurement for the tuner are presented.**

I. Introduction

RF-MEMS device design is a difficult and challenging task. Current research efforts are focusing on both the design of RF-MEMS themselves as well as circuits consisting of several RF-MEMS elements. As the devices themselves are under study, no firm design rules exist for their integration into circuits. Several different techniques have been employed to design these devices, with varying degrees of success. This paper suggests a time-domain simulation method that models the entire MEMS circuit in one simulation.

One popular design technique is to simulate the MEMS devices in a full-wave electromagnetic simulator. These simulators can characterize MEMS structures very well, but cannot be scaled to model the entire circuit. The results of the MEMS simulation can be used in a microwave circuit simulator to determine the interaction of the microwave circuit with the MEMS device. This technique often fails to consider the parasitics and coupling effects caused by the close proximity of the elements, which may lead to simulation results that do not match measurement results. This can increase the cost and time required for designing a MEMS circuit.

The finite-difference time-domain (FDTD) electromagnetic modeling technique has been shown to give very accurate simulation results for a variety of structures [1]. However, the smallest feature of the device being modeled limits the size of structures that can be simulated in FDTD. RF-MEMS devices are built on membranes that can have very fine features. When these elements are combined into circuits containing large connecting structures, the resulting grid can grow beyond the capability of most computers. Several techniques can be applied to an FDTD implementation to reduce the grid size while maintaining required accuracy.

FDTD is a robust technique that can be modified in many ways to increase computational efficiency. Three of these are parallelization [2], the addition of a variable grid [3], and the use of DSP-based spectral estimators [1]. The simulator is still limited, however, by the need to model the small cell size of MEMS devices. A method is presented in this paper that allows the modeling of metals that intersect an FDTD cell, removing this restriction.

The above-mentioned techniques are used in this paper to model a double stub '2-bit x 2-bit' RF-MEMS tuner [4]. This tuner uses 4 MEMS switches to control capacitive stubs. The switches are controlled independently to provide a total of 16 impedances that can be matched. The advanced modeling techniques are applied to this structure to provide an accurate prediction of measurement results. In the future this technique can be used to determine the results of structure modifications and to provide the basis for design rules of these structures.

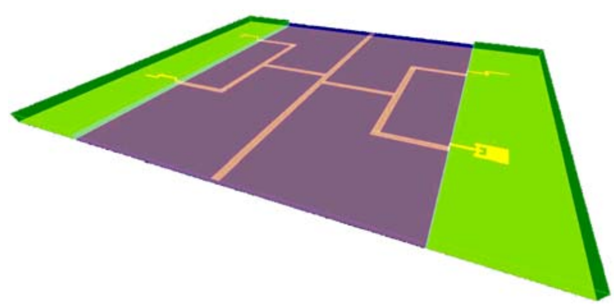

Fig. 1. Diagram of simulated '2-bit x 2bit' RF-MEMS tuner

II. Background – '2-Bit x 2Bit' RF-MEMS Tuner

The key benefits of RF-MEMS switches are their low power requirements and low insertion loss while maintaining compatibility with conventional semiconductor processing techniques. The design goal behind the simulated RF-MEMS tuner is to match many impedances over a wide band. This is accomplished through the use of MEMS capacitive switches to connect the stubs of a double stub tuner to a bank of fixed capacitors.

A diagram of the design structure is presented in Fig. 1. The dual stub configuration is commonly used to match impedances over a wide band. Each stub is terminated with a T junction into two one-port capacitors. Effectively, these capacitors add in parallel. By modifying the capacitance of each individual capacitor, the total capacitance seen by the stub can be varied.

An enlarged view of one of the capacitors that terminates the structure is presented in Fig. 2. The RF-MEMS switch can be used to provide either a low capacitance, where the membrane is in the up (off) position, or a high capacitance in the down (on) position. The switch capacitance adds in series to the capacitance of the stub. The tuner uses four tunable capacitive stubs, each with a different configuration, providing a total of sixteen configurations, and thus sixteen impedances, that can be matched.

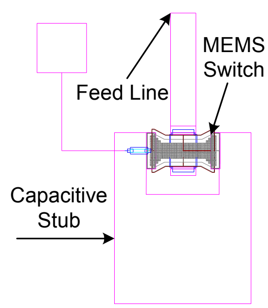

Fig. 2. RF-MEMS capacitive stub

III. FDTD MODIFICATIONS

The standard Yee-FDTD technique [1] can be used to simulate a wide variety of structures in an efficient and accurate way. The technique, however, can require large amounts of time and computational resources for large, finely detailed, resonant structures such as the tuner being analyzed in this paper. In order to simulate the tuner in a more reasonable amount of time, a parallelized code has been employed. In addition, the required computation resources can be decreased through the use of variable gridding, spectral estimation, and a novel technique that will be presented which allows the modeling of a metal that intersects a cell.

A. Parallelized FDTD

A significant quantity of research has been performed in the area of parallelizing FDTD [2]. FDTD is relatively easy to parallelize because it is a nearest-neighbor problem. FDTD field updates depend only on the previous value of the current points and the values at the surround points, or nearest-neighbors. This feature of FDTD enables codes to divide large problems into subgrids which can be distributed to various processors of multi-processor supercomputers. The only data that needs to be passed between processors is the field values on the borders of the subgrids. These codes have been shown to run on a wide variety of supercomputers as well as workstation clusters such as a Linux Beowulf cluster.

The tuner modeled in this paper was simulated using a parallel FDTD code running on eight, dual 500MHz Pentium III processor workstation class PCs. The code provides nearly linear speedup, extending the size of the structure that can be simulated.

B. Variable Gridding

The variable grid method used to model the tuner allows each dimension of the FDTD grid to be varied in a cell-by-cell fashion, independent of the other dimensions. The resulting grid can easily be applied to an FDTD code by representing Δx, Δy, and Δz as array variables. The resulting grid has increased resolution in the areas of fine structures while keeping the number of cells low. This method is used in the modeling of the tuner to provide high resolution in the area of the MEMS switch while allowing the use of large cells elsewhere. This method has been shown to give an acceptable level of error, however, the restrictions that it places on the grid are sometimes a matter of experiment.

C. Spectral Estimation

The tuner under study in this experiment contains four capacitive stubs. The fields that enter these elements resonate and require an extremely large number of time steps to settle. In order to determine the frequency domain parameters of the device, the simulation must normally be run until the fields inside the device run become negligibly small. In order to compensate for these requirements, techniques have been developed to determine the long-term response of these resonant structures from a limited set of initial data [1]. There are several of these techniques, which involve an expansion of the initial data set in the form of exponentials. These techniques have shown their ability to predict the results of high frequency circuits very accurately. The application of these techniques can be very difficult, due to the nature of choosing the data set needed to perform the estimation. In a case such as this tuner, an initial case can be used to determine the appropriate method of predicting, and future cases can be predicted with confidence.

D. Split-Cell Metal Intersection Modeling

One particular problem in modeling the tuner is the large size disparity between the capacitor plate spacing and the network feeding the capacitors. To compensate for this problem a technique was developed that models the effect of metal that passes through a cell. This technique is based on a contour modeling approach [5] and the variable gridding method [3].

The method presented in this paper is for a cell split by a metal perpendicular to the y axis. It is trivial to extend this technique into either other dimensions. It is also possible to extend this technique to determine the effect of a metal that is not parallel to one of the axes.

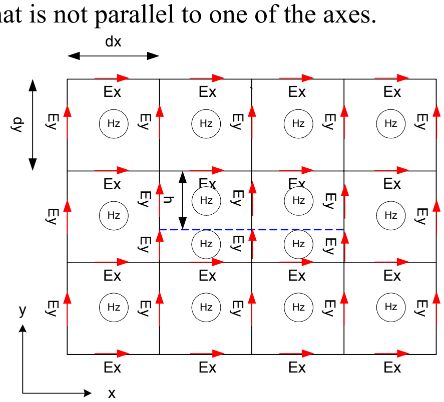

Fig. 3. Diagram of split cell modeling region illustrating field arrangement

A diagram that demonstrates this case is presented in Fig. 3. A y normal metal intersects a section of the grid. The cells that do not interface with the metal demonstrate a standard Yee-cell configuration. The cells intersected by the metal have been split. In this region, twice as many cells are needed to represent the structure. Only three extra field elements are needed by these cells, however, because the metal boundary condition requires that E_x, E_z, and H_y fields located on the metal are zero for all time.

The fields in the split cell region can be updated using standard FDTD update equations with a few minor modifications. The E_y equations located in the split cell region require no changes. It should be noted that at the edge of the update region the E_y field both above and below the metal use the same H_x and H_z fields in their update. The domain of the H fields in these areas is the entire length of the cell, however, so this does not present a problem. The Hx and Hz fields in the update region simply require the substitution of Δy in the update equation with the appropriate length for the split cell. In the region above the split, h (from Fig. 3) is used in place of Δy, and in the region below, Δy-h is used.

The only other fields to consider in the update are the fields surrounding the split cell region. In these areas Hx and Hz require special update equations. These equations can be derived using the Ampere's and Faraday's law in integral form derivation of the FDTD technique [1]. The H fields in these equations are determined using the equation:

$$\frac{\partial}{\partial t}\int_{S_1} \vec{B}\cdot d\vec{S}_1 = -\oint_{C_1} \vec{E}\cdot dl_1 \qquad (1)$$

In this equation S_1 represents the cell surface centered on the H field, and dl_1 represents the contour surrounding it that contains the E fields.

Using this equation to derive the update equation for the H_z field on the side of the split with the highest x value results in:

$$H_z\Big|^{n+1}_{i,j+1,k+\frac{1}{2}} = H_z\Big|^{n}_{i,j+1,k+\frac{1}{2}} + \left(\frac{\Delta t}{\mu}\right)\left[\frac{E_x\Big|^{n+\frac{1}{2}}_{i,j+\frac{3}{2},k+\frac{1}{2}} - E_x\Big|^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k+\frac{1}{2}}}{\Delta y} - \frac{E_y\Big|^{n+\frac{1}{2}}_{i+\frac{1}{2},j+1,k+\frac{1}{2}} - \left(E_{y,above}\Big|^{n+\frac{1}{2}}_{i-\frac{1}{2},j+1,k+\frac{1}{2}}\cdot h + E_{y,below}\Big|^{n+\frac{1}{2}}_{i-\frac{1}{2},j+1,k+\frac{1}{2}}(\Delta y - h)\right)}{\Delta x}\right] \qquad (2)$$

This technique has been applied to the modeling of one of the capacitive stubs used in the tuner. A graph of the comparison of the capacitance calculated using the split-cell technique to measurement is presented in Fig. 4. It can be seen in this graph that the technique matches the pattern of the measurement data with a fairly constant error vs. frequency. The error is most likely caused by the loss of the substrate, which is not accounted for in this FDTD simulator.

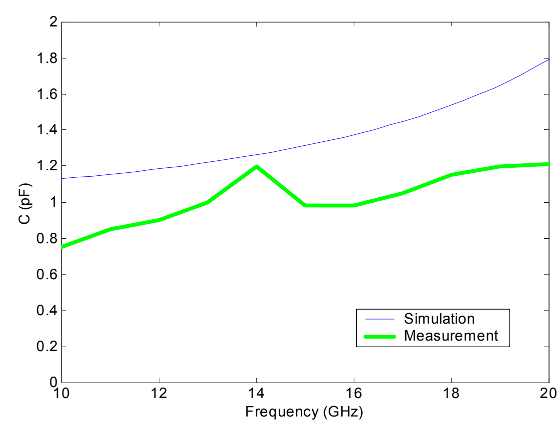

Fig. 4. Simulation vs. measurement for capacitive stub of Fig.2 using split-cell modeling

IV. Description of Test Device

A schematic of the device simulated is presented in Fig. 1. As stated previously this is a double stub tuner, with RF-MEMS switched capacitive stubs as termination. The central line is 13864 µm long. Each stub is fed by a 2870 µm line that splits into two 8012 µm lines. The substrate under the central portion of the grid is 254 µm thick alumina, with an ε_r of 9.8. The MEMS stubs are built on 525 µm thick silicon with an ε_r of 11.7. The feed lines are 254 µm wide in the alumina and 130 µm wide in the silicon [4].

In order to efficiently simulate this structure the variable grid method was applied in each direction. The variable grid in the directions parallel to the surface of the substrates was used both to match the complex geometry of the MEMS stubs, and minimize the number of cells needed to cover the connecting lines. In the direction normal to the substrate surface, variable gridding was used to match the geometry and to provide fine cells in the region of the MEMS switch and thick cells in the bulk of the substrate. In the surface transverse directions the cells ranged in size from 52 to 22 µm, in the normal direction the cells ranged from 3 to 30 µm.

The structure was excited with a Gaussian derivative pulse in time, with a maximum frequency of 25GHz. Using the requirement that the maximum cell length be smaller that l/12 leads the maximum frequency restriction of approximately 480GHz. The variable gridding used in this simulation, however, led to the requirement that 25GHz be used to minimize dispersion.

V. Results

Simulations of the tuner were run in the case of every switch in the on position and every switch in the off position. The results of the simulation were used to determine the impedances that the tuner can match. The combined FDTD modifications employed in this simulation reduced the execution time by more than two orders of magnitude. A plot of the matched impedances, both simulation and measurement is presented in Fig. 5. The simulation results are within 10% of the measurement results. Error sources are most likely the lack of loss modeling in the FDTD code and fabrication and measurement tolerances.

It is interesting to note that in the case of the switches in the on position, a much more coarse grid was used because the small MEMS gap no longer existed. This had the effect of allowing the time step used for the simulation to be approximately an order of magnitude larger than the time step for the other case. As a result, the simulation time was reduced by an order of magnitude.

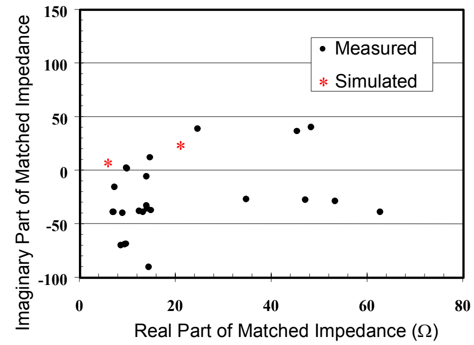

Fig. 5 Plot of measured and simulated matched impedances at 20GHz

VI. Conclusion

This paper presents the modeling of an RF-MEMS reconfigurable tuner using FDTD techniques designed to improve the efficiency and reduce the time needed to perform the simulation. These techniques provide the needed tools to simulate these large structures in a reasonable amount of time. They can be used as guidelines on simulating other complex high-speed reconfigurable circuits with finely detailed components. Further investigations in this area may involve the application of split cell modeling to more of these structures in order to further reduce the computational requirements.

Acknowledgement

The authors wish to acknowledge the support of the NSF CAREER Award, the Yamacraw Design Center, and the Georgia Tech Packaging Research Center.

References

[1] A. Taflove and S. Hagness, *Computational Electrodynmics: The Finite Difference Time Domain Method*, 2nd Ed., Norwood, MA. Artech House, 2000.

[2] G. A. Schiavone, I. Codreanu, R. Palaniappan, and P. Wahid, "FDTD speedups obtained in distributed computing on a Linux workstation cluster," *Proc of the 2000 IEEE Symposium on Antennas and Propagation*, pp. 1336-1339, Salt Lake City, UT.

[3] S.D. Gedney and F. Lansing "Explicit time-domain solution of Maxwell's equation using nonorthogonal and ununstructured grids" in *Computational Electrodynamics: The Finite Difference Time Domain Method,* A. Taflove, Ed. Norwood, MA: Artech House, 1995, ch 11.

[4] K. Lange, *A Dynamically Reconfigurable Impedance Tuner Using RF MEMS Technology*, M. Sc. Thesis, University of Arizona, May 2001.

[5] S. Dey and R. Mittra, "A locally-conformal finite-difference time-domain algorithm for modeling three-dimensional perfectly conducting objects," *Microwave and Guided Wave Letters*, vol. 7, pp. 273-275, Sept. 1997.