Coupling of Electromagnetic Time-Domain Simulators with DSP/Subgridding Techniques for the Adaptive Modeling of Wireless Packaging Structures

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Abstract: The modeling of packaged modules that involve irregular metal shapes and lossy, dispersive materials requires design algorithms that combine the computational efficiency with the numerical accuracy over wide frequency bands. This paper presents the formulation of a hybrid FDTD method integrating a quasi-static subgridding algorithm and employing digital predictors. Three techniques of DSP-based digital predictors are used to calculate the S-parameters of highly complicated structures (RF-MEMS) and their performances are evaluated in terms of computational economies and accuracy.

1. Introduction

Significant attention is being currently devoted to the modeling and optimization of packaged modules (e.g. Flip-Chip, LTCC Multilayer Packages) used in Wireless communication and WLAN applications. Most of these structures involve laminated lossy dielectrics that are separated by metal planes with finite conductivity and thickness and sometimes with irregular shapes due to the existence of interconnects such as viaholes and wirebonds. Thus, there is a need for a design algorithm that combines the computational efficiency with the accuracy of electromagnetic simulations using real metal and dielectric properties. The finite-difference time-domain (FDTD) scheme is one of the most powerful and versatile techniques used for numerical simulations, since it provides accurate solutions of the Maxwell's equations for wide frequency ranges while avoiding oversimplifying approximations. Nevertheless, the addition of complex metal shapes (antennas, multilayer passives) and realistic material characteristics (metal finite conductivity and thickness) into simulations leads to very computationally intensive FDTD simulations. To alleviate this problem, there is a need for the hybridization of FDTD with a technique that can provide accurate modeling of skin depth-related effects without requiring a very dense grid.

First, DSP-based digital predictors are presented to deal with the time-domain modeling of a highly complex structure such as an RF-MEMS tuner that requires hundreds of thousands of time steps to reach convergent results. Prony's method and two Autoregressive models (covariance method and forward-backward method) are evaluated for this particular structure, and computational economies and accuracy are discussed in terms of mode order, decimating factor, and the size of sample train.

The second part of this paper presents the conceptualization of FDTD integration with a quasi-static field analysis algorithm. The technique involves using a static field solver to determine the potential over the lossy/metal surfaces (e.g. a ground plane in a packaged microsystem). The solution from the field solver is then used to calculate an effective resistivity, which is then inserted in the time-domain solver as an initial condition to account for field variations over the surface. The fine grid used by the static field solver displays clearly the areas of the fastest field variation, and then the FDTD solver can take advantage of that by incorporating some form of an "a-priori determined" subgridding, where areas of low field variation can be simulated with a much coarser grid.

2. Digital Signal Processing Predictors for highly resonant structures

The finite-difference domain (FDTD) method has been widely applied to the simulation of complex structures. It records the time-domain response at selected observation points of the FDTD grid and FFT algorithm is applied to transform the results to frequency domain. The satisfactory accuracy in the frequency domain results can be achieved by running a large number of time steps, but this can be a serious computational burden. Many approaches have been proposed to circumvent this problem and each technique has different operational characteristics. In this paper, three techniques are used for the calculation of quality factors and S-parameters, and their computational economies and accuracy are evaluated for an RF-MEMS tuner that is a good example of highly complicated resonant structures. The common feature of all these approaches is that they have been widely used in DSP and aim in decreasing the computational time for the late transient period of simulation by replacing mesh-wide finite-differences with simple algebraic equations at the probe positions only.

The first investigated predictor is Prony's method. This technique models sampled data as a linear combination of complex exponentials [1] and consists of multi-step procedures: 1.Perform an AR (Autoregressive) fit, 2.Root the AR coefficients for complex exponential parameters, 3.Filter the Roots, 4.Least-Squares' Fit for complex Amplitude Parameters, 5.Create the Final model with Signal Thresholding. The major problem of Prony's method is the model order (p) selection that determines the quality of the spectral resolution and the appearance of spurious modes [1]. As noted in [3], model order can be determined by Akaike Information Criterion (AIC) and the Minimum Description Length (MDL).

Secondly, linear predictors or autoregressive (AR) models are compared to Prony's method in terms of their prediction performance. Linear predictors are historically some of the most important speech analysis techniques and have been applied to many applications of FDTD algorithm. The basis is the source-filter model that is constrained to be an all-pole linear filter. This amounts to performing a linear prediction of the next sample as a weighted sum of past samples. In this paper, two techniques are used to estimate the AR parameters: (1) the covariance method and (2) the forward-backward method. The covariance method estimates the solution of $p \times p$ linear matix, which is Hermitian and positive semidefinite, by Cholesky decomposition [1]. The performance of this method is totally sensitive to the model order like Prony's method and the order of the model can be determined by Akaike Information Criterion (AIC) and the final prediction error technique [3]. Next, the forward-backward method includes estimating the solution of $p+1 \times p+1$ linear matix to get AR coefficients [1]. This technique is less sensive to model order and can be more accurate than the covariance method since it uses only time-data, not about covariances that are approximated with inaccurate functions of the known time signal.

3. Comparative evaluation of the predictors for a complex RF MEMS structure

The benchmark example for the performance of the FDTD predictors presented in this paper is a double tuner '2bit × 2bit' RF-MEMS shown Figure 7 [2]. This device is built on membranes to match numerous impedances over a wide frequency band, something that is accomplished through the use of MEMS capacitive switches to connect the stubs of a double stub tuner to a bank of fixed capacitors [2]. The standard Yee-FDTD Technique requires a prohibitive computational time for this type of large, finely detailed, resonant structures and the use of DSP based predictors could relieve this burden.

As the first test, Prony's method is applied to the tuner. Figure 1 displays the comparison between the waveform of the direct FDTD computation and the extrapolated waveform by FDTD plus Prony's model. This extrapolated waveform covers the period between 100,000-200,000 time steps with the sampling range of 100,000-130,000 time steps decimated by 100, and the order of Prony's method is 63. It is observed that the Prony's model produces very poor results for predicting the large amount of time-steps of transient waveforms for highly resonant structures. Figure 2 shows S-parameters of FDTD alone and FDTD plus Prony's model, and it can be seen that there is good agreement for the two sets of S-parameters. Both AR linear predictors are tested on the same data set of the tuner as Prony's method. For covariance method, 100,000-130,000 iterations decimated by 100 and the AR model order of 66 are used to predict over 200,000 time steps. Figure 3 shows both the computed voltage signature by direct FDTD and the predicted one by FDTD plus the covariance method. Compared S parameters are shown in Figure 4. Very good agreement in the results is observed for voltage signatures and frequency-domain data. Finally, the forward-backward method is applied to the tuner. The 80th-order predictor extends the data set over 200,000 by using 100,000-130,000 iterations and decimating factor is 50. The comparison of voltage signals at the observation point between FDTD and FDTD plus the forward-backward method is presented in Figure 5. Figure 6 presents S-parameters in the same way as the other cases. Although the performance of the forward-backward method is not better than the covariance method in terms of higher order, less decimating factor and more deviated matches, it can be realized that the forward-backward method is still an efficient predictor to generate accurate S-parameters results. Table 1 summarizes the numerical results of three DSP predictors. Mean-square error (MSE) at the last row of the table can be used to evaluate the performances of three techniques.

Predictor Techniques	Prony's Method	Covariance Method	Forward-Backward Method
Sampling Range	100,000 – 130,000	100,000 – 130,000	100,000 – 130,000
Sampling Rate	100	100	50
Model Order	63	66	80
MSE (Time Probe/S-parameter)	1.6751e-8 / 2.6776e-4	5.4863e-10 / 2.6721e-4	2.0178e-9 / 2.6725e-4

Table 1: Summary of numerical results

4. Subgridding with a hybrid static/dynamic finite-difference method

To achieve a computationally efficient subgrid, the dynamic finite-difference time-domain method was combined with a static field solver [4]. This static solver first simulates the structure over a very high-resolution grid, and then the dynamic simulation is performed over a coarse, lower resolution grid. The methods are coupled by the employment of correction factors determined by the analysis of the static fields.

One of the difficulties with the full-wave analysis of resonant structures is the need for very fine mesh sizes to accurately model small device features. The development of variable gridding methods [1] offers a way to alleviate this problem, but still doesn't resolve the difficulty of defining a priori the computationally optimized grid size. Researchers mainly rely on heuristic approaches to mesh generation, and the results often demonstrate inaccuracies in areas of very high field variation. The idea of the static solver is to eliminate this approach and provide evidential knowledge of field variations in the area of structure discontinuities. An advantage of using the static solver for this function is that it processes very quickly, since it does not have a time-marching component. This feature enables its capability for a solution over a very dense grid, to provide a high-resolution picture of field variation in complex and highly discontinuous structures.

In the areas of very high field variation, the static solver is employed to calculate correction factors which improve the accuracy of the dynamic solution over the coarse grid [4]. These correction factors are calculated from the static field solver by dividing the static field solution for either a surface or line integral by the integral approximation of the coarse grid, as illustrated by Equations (1) and (2), where CF_x is the line integral correction factor and CF_A is the surface integral correction factor.

$$CF_x = \frac{\int \vec{F} \cdot d\vec{l}}{\overline{F} \cdot dl} \tag{1}$$

$$CF_A = \frac{\iint \vec{F} \cdot d\vec{x} \cdot d\vec{y}}{\overline{F} \cdot dx \cdot dy} \tag{2}$$

($\overline{F}$ is the discretized field value over the integration interval.) These correction factors can be applied afterwards to the time-domain field solutions generated by the FDTD code in a way similar to [5] and can significantly accelerate the simulation time of skin-depth related effects.

5. Conclusion

Prony's method and two linear predictor-based techniques (covariance and forward-backward) have been evaluated through comparing their performances for high resonant structure such as RF-MEMS. From the comparison of voltage signatures, the numerical results show that linear predictors work better than the predictor using Prony's method. In addition, the covariance method generates more efficient results than the forward backward method, since it saves more CPU time for a smaller model order and a higher decimating factor. All three approaches demonstrate high levels of accuracy in the calculation of macroscopic S-parameters.

To further decrease the computational time while maintaining a satisfactory accuracy, the FDTD algorithm has been coupled with a quasistatic field solver, which can provide correction factors for coarse grid simulations. The computational cost of the static solver is almost negligible, especially when compared with the cost of incorrect excessive gridding based on a "guess" of areas of fine meshing.

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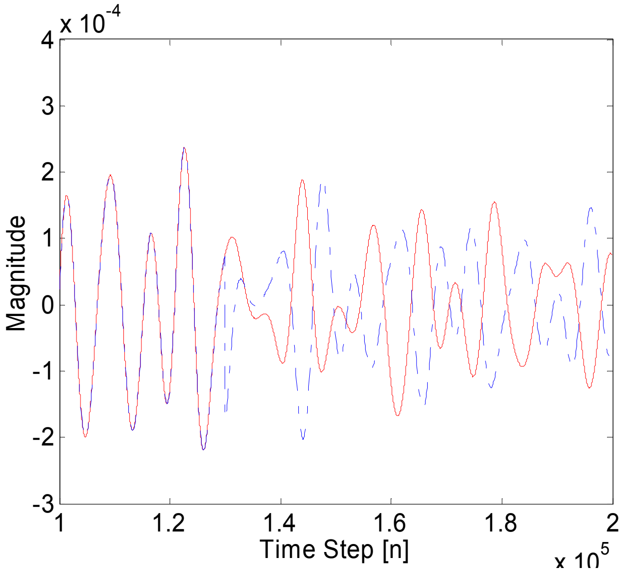

Figure 1: Comparison of direct FDTD data set with predicted field record using Prony's method

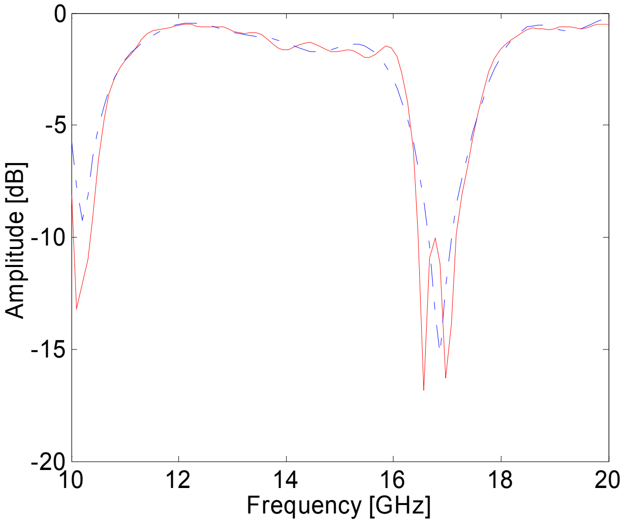

Figure 2: S21 of RF-MEMS Tuner (solid) FDTD, (dashed) FDTD plus Prony's method

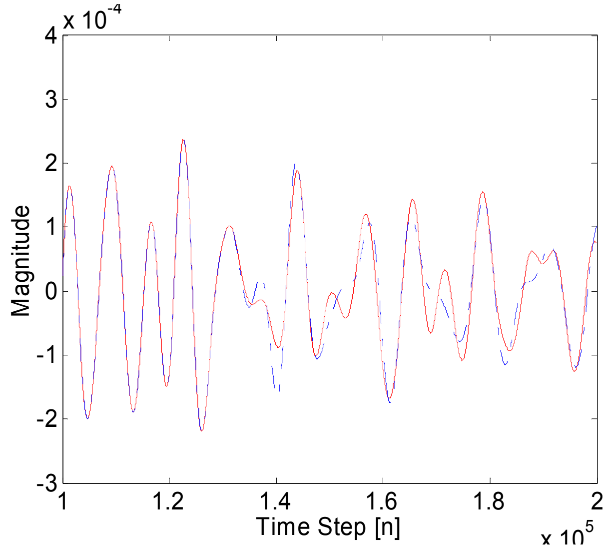

Figure 3: Comparison of FDTD data set with AR-predicted field record using the covariance method

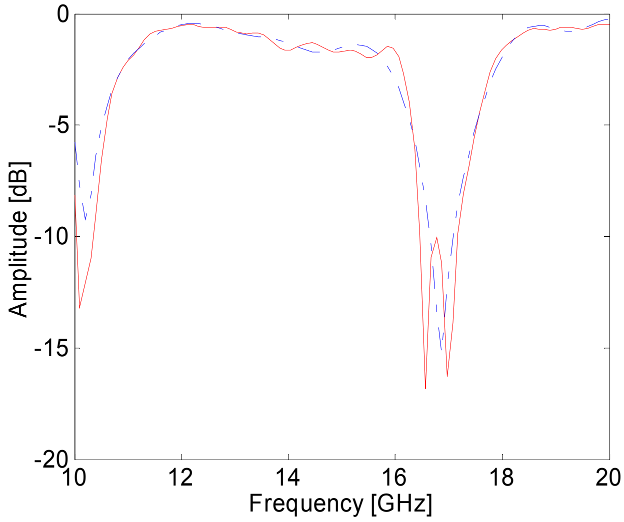

Figure 4: S21 of RF-MEMS Tuner (solid) FDTD alone, (dashed) FDTD plus the covariance method

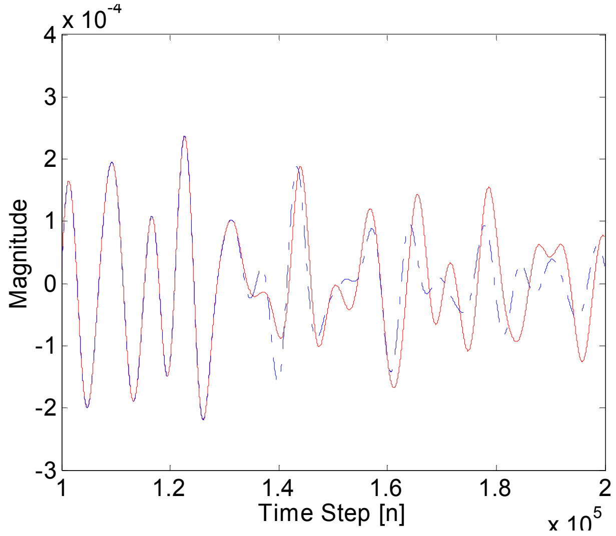

Figure 5: Comparison of FDTD data set with predicted field record using forward-backward method

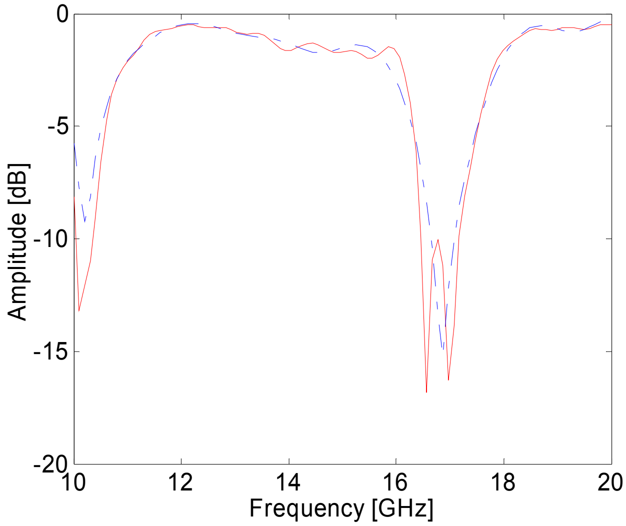

Figure 6: S21 of RF-MEMS Tuner (solid) FDTD alone, (dashed) FDTD plus the forward-backward method

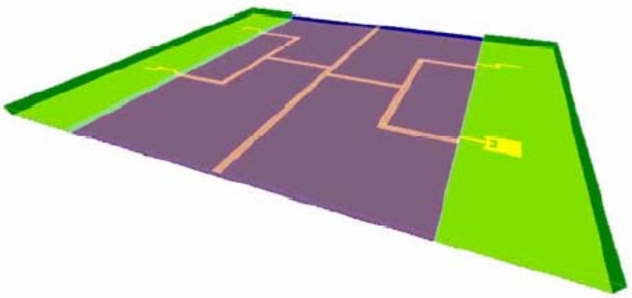

Figure 7: Diagram of simulated ‘2×2’ RF-MEMS Tuner