Analysis of MEMS and Embedded Components in Multilayer Packages using FDTD/MRTD for System-on-Package Applications

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Abstract **The FDTD and MRTD full-wave numerical techniques are applied to the modeling and analysis of embedded components, such as MEMS and integrated antennas, in multilayer packages. Preliminary design rules are derived for minimized-crosstalk transmission lines, for a wideband compact transition and for an ultra-thin MEMS switch that can be used in practical tuning applications. In addition, the effect of the packaging in the antenna radiation performance is evaluated and "hot spots" of high field concentration are identified and treated for the improvement of the overall system efficiency. Lastly, the quality factor and the bandwidth of an embedded inductor is calculated and possible ways of minimizing the loss factors are further investigated.**

1. Introduction

The explosive growth in wireless communications (3G Cellular Systems, 802.11 WLAN's) has spawned a great deal of research in electronic packaging for high performance devices. Multilayer embedded components, ultracompact efficient antenna technology and micromachining technology are critical to meet the cost and performance requirements for a higher level of multifunction integration in the development of wireless transceivers, since they can considerably reduce the MMIC real estate and the amount of needed discrete elements. For the modeling of all of the above wireless elements, time-domain full-wave techniques demonstrate numerous advantages since they are robust and easy-to-program, they can use wideband excitations that allow for one simulation to cover the entire frequency band of interest and can be easily parallelized on relatively inexpensive hardware, making it possible to simulate large structures. In this paper, the popular Finite-Difference Time-Domain (FDTD) and its adaptive expansion, MultiResolution Time-Domain (MRTD), are applied to the analysis of MEMS and embedded passives (inductors, antennas, wideband transitions and transmission lines) for multilayer system-on-package (single-packaging RF module) [1] transceivers.

2. FDTD/MRTD Techniques

The FDTD [2] method is one of the most mature and versatile time-domain numerical techniques and has been used on a wide variety of structures. The use of variable gridding along with effective parallelization approaches allows fine details of large structures to be modeled. Curves and diagonal elements can be modeled using stair stepping. In addition, a wide variety of FDTD enhancements make possible the modeling of small gaps, multidielectric/membrane configurations and resonating passives. Macroscopic results, such as S-parameters and impedances, can be determined by probing and comparing voltages and currents at different points in the structure. The MultiResolution Time-Domain Technique (MRTD) [3] is an adaptive generalization of the FDTD technique that is based on the principles of Multiresolution analysis and makes use of wavelets to alleviate the computational burdens of FDTD for complex or large structures, such as multilayer packages or MEMS, where the position of the boundaries is time-changing and the membrane thickness is much smaller than any other detail in the transverse direction. The MRTD technique allows the cell resolution to vary with both time and position. The wavelets can be used to represent higher levels of detail along with higher frequency content. As fields propagate through the structure the resolution can be varied to allow for the rapidly changing fields. In this paper, simulated results for a CPW-microstrip transition, a minimum-crosstalk geometry of finite-ground microstrip lines, a multi-layer inductor built in organic package, a MEMS switch and a packaging-adaptive antenna will be summarized.

3. Modeling of Embedded Components and MEMS

A. CPW-Microstrip Transition

The CPW-microstrip transition simulated is shown in Fig.1. The loss of this transition can be optimized over a wide frequency range with the use of FDTD and design curves for various packaging specifications can be derived. The plot in Fig.2(a) shows S_{21} of this transition for a variety of lengths of the central straight section from 10 to 20 GHz. This data was obtained using time-domain voltage probes at the input (V_1) and output (V_2) of the transition, converting them to frequency domain through the use of a Discrete Fourier Transform and identifying the reflected voltage through the use of a reference input voltage (V_{ref}) derived by the simulation of a through CPW line [2]. In addition, the use of the full-wave FDTD, that provides the values of all electromagnetic components throughout the geometry, offers a more intuitive visualization of the circuit. For example, in the transition the electric fields have to change smoothly from a coplanar waveguide mode to a microstrip mode, in order to minimize the local reflections. Thus, in the design process it is desirable to identify where this transition takes place and optimize the tapering. Fig. 2(b) is a plot of total electric field for a transverse cross-section of the transition. It can be seen that at the position of this cross-section, the field is mostly in a CPW mode, though a microstrip mode has started to develop below and at the edges of the signal line. The relative amplitudes of the E-field provide an intuitive design rule for the spacing between the CPW ground and signal line, so as to not suppress the microstrip mode.

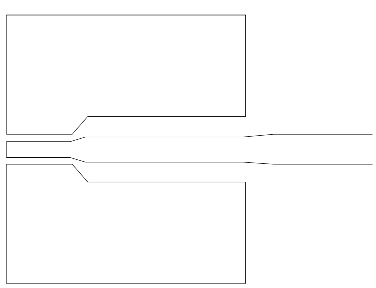
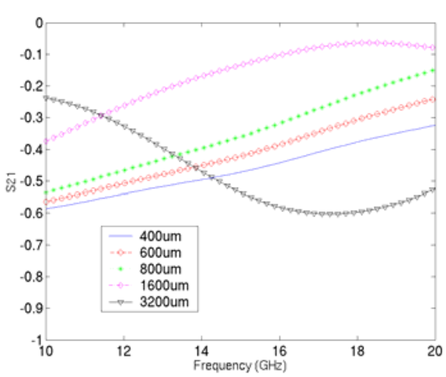


Fig. 1. CPW to microstrip transition



(a)

Fig. 2(a). S21 for various central line widths

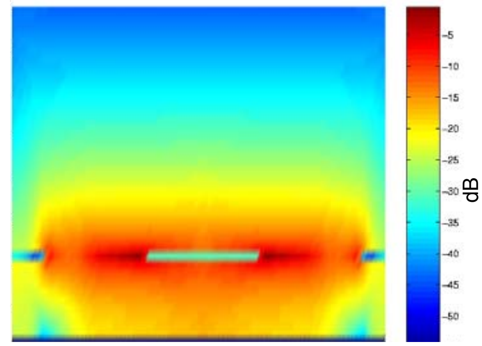


Fig. 2(b). E-field distribution

B. Microstrip-Line Coupling

Embedded transmission lines are commonly used in multilayer packages, where the use of non-continuous grounds can lead to increased crosstalk effects. The FDTD technique has been used for the estimation of the coupling of the finite-ground microstrip lines of Fig. 3 [4]. The results for a particular line spacing are presented in Fig. 4. They were obtained by combining two simulations, an even and an odd mode excitation. In addition, to help illustrate the causes of the unwanted crosstalk, the electric and the magnetic field distributions have been calculated and plotted along a transverse cross-section. It is apparent from the simulations that most of the coupling is through the magnetic field lines, leading to the design conclusion that attempts to reduce the coupling should focus on magnetic shielding.

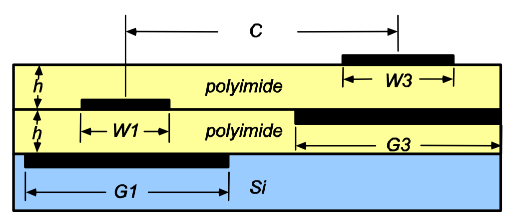


Fig. 3. Embedded finite-ground microstrip lines.

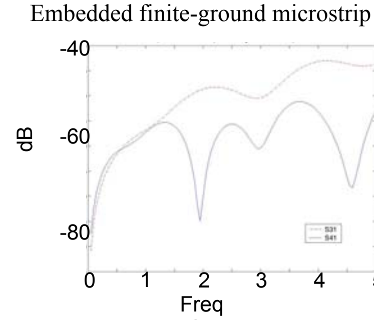


Fig. 4. Simulated S31 and S41 for a particular geometry

C. Multi-layer Inductor Built on Organic Package

One of the critical passive components in RF applications is the inductor. The Q-factor of the inductor significantly contributes to the phase noise of the voltage controlled oscillator and the gain of the power amplifier. A planar inductor built using an organic packaging method has been analyzed using FDTD and the results have been compared with measurement [5]. A 2-turn inductor (Fig.5-inset) is modeled to determine the quality factor, Q, using an FDTD code that employs both variable grid and parallelization to increase efficiency and reduce execution time. The FDTD update equations are derived directly from Maxwell's equations, and thus dielectric loss is taken into account in a straightforward manner. The value of the inductor can be determined from the S-parameters in the same manner as the measurements. The results of Q in both the simulation and measuremens (Fig.5) show good agreement. The value difference is expected due to the fact that the simulation does not include the loss and roughness of the metal.

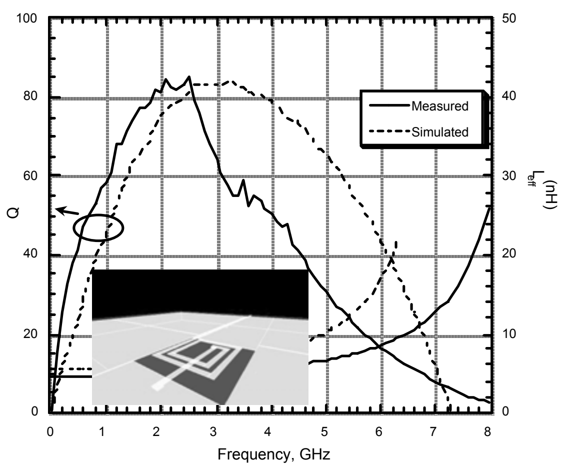


Fig. 5. Embedded finite-ground microstrip lines

D. MEMS Capacitive Switch

One example of a MEMS structure that benefits from simulation in MRTD [6] is the MEMS capacitive switch shown in Fig. 6. The gap between the plates in the switch is 1/175th of the substrate thickness. The simulation of this device in FDTD is tedious and slow because of the large number of cells that must be used in order to accurately represent the very small gap and substrate. In MRTD, the number of cells can be reduced by using the built-in adaptive gridding capability of the method. In addition, further efficiencies can be obtained in large simulations featuring this structure by allowing fewer cells to be used when the electric field variation near the cell is low.

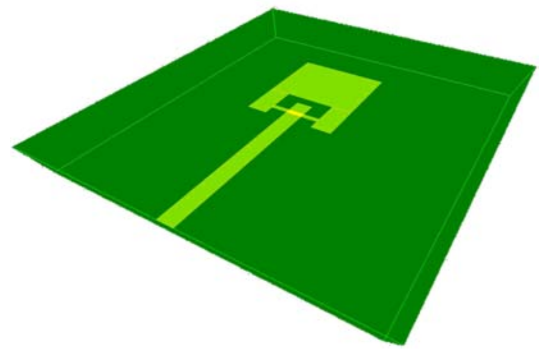


Fig. 6. MEMS switch feeding capacitive stub

E. Packaging Adaptive Antenna

The last simulated geometry is one packaging-adaptive multilayer antenna designed for IEEE 802.11a 5.8 GHz band (Fig. 7). Two square patches have the same dimensions and are stacked on a grounded LTCC GL550 (er=5.6) multi-layer substrate (layer thickness = 4 mils). The stacked patch is backed by a metal cavity while the lower patch is fed at its edge through a via from the filter. The return loss simulated is compared with the measured result in Fig. 8. Good agreement is noted. The 10-dB return-loss bandwidth of the antenna fully covers the required band (5.725-5.825 GHz). The radiation pattern at 5.8 GHz is plotted in Fig. 9. The co-polarized component for the stacked is very similar to that for a typical single patch, while the cross-polarized component is 10-dB lower due to a much shorter feed via for the stacked patch. Thus, time-domain tools predict correctly the bandwidth, as well as the packaging effect on the radiation pattern.

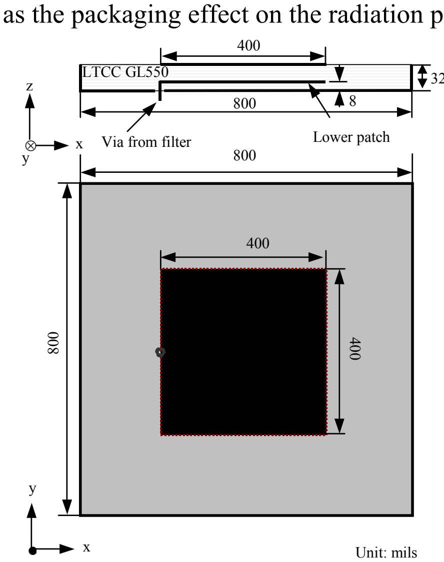


Fig. 7. Packaging adaptive stacked-patch antenna for IEEE 802.11a 5.8 GHz band

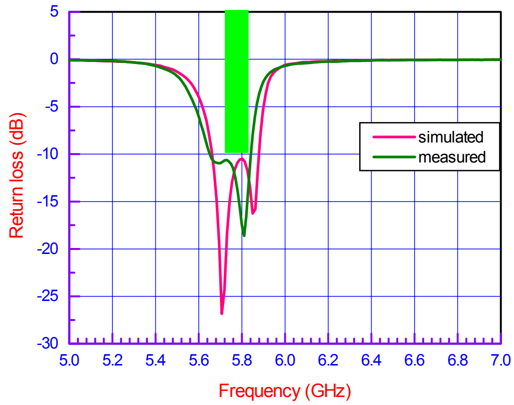


Fig. 8. Simulated and measured return loss of the stacked patch antenna for IEEE 802.11a 5.8 GHz band

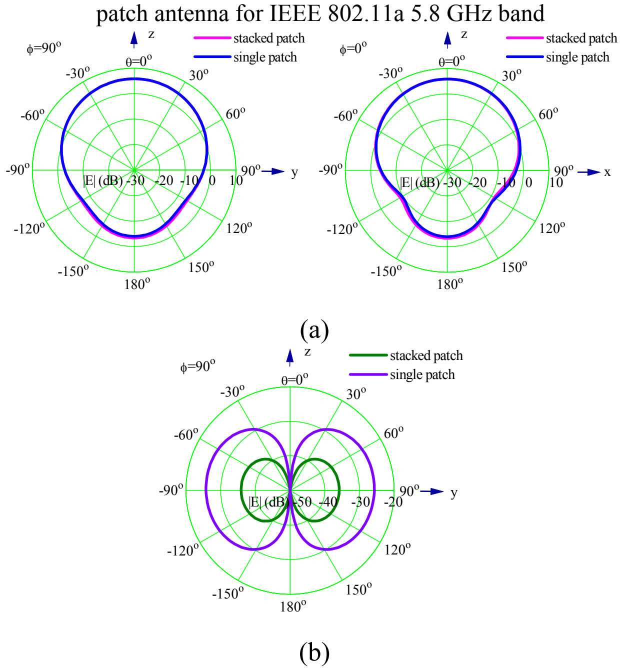


Fig. 9. Radiation pattern of the (a) copolarized and (b) cross-polarized component of the stacked patch antenna at 5.8 GHz.

4. Conclusion

Two full-wave time-domain methods, the finite-difference time-domain (FDTD) and the multiresolution time-domain (MRTD), have been applied to the modeling and analysis of embedded components, such as MEMS and integrated antennas, in multilayer packages. They have demonstrated a very high efficiency in the calculation of the scattering parameters and of the Q-factor, as well as in the estimation of the radiation pattern, of the packaging effects and of the parasitic crosstalk between neighboring geometries. In addition, their inherent capability of global electromagnetic field calculation allows for the identification of “hot spots” of high field concentration and for the derivation of physical-driven solutions for the improvement of the overall system-on-package efficiency.

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