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RF SYSTEM-ON-PACKAGE (SOP) DEVELOPMENT FOR COMPACT LOW COST WIRELESS FRONT-END SYSTEMS

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ABSTRACT

This paper presents the development of RF System-on-Package (SOP) architectures for compact and low cost wireless radio front-end systems. A novel 3D integration approach for SOP-based solutions for wireless communication applications is proposed and utilized for the implementation of a C band Wireless LAN (WLAN) RF front-end module by means of stacking LTCC substrates using μBGA technology. LTCC designs of high-performance multilayer embedded bandpass filters and novel stacked cavity-backed patch antennas are also reported. In addition, the fabrication of very high Q-factor inductors and embedded filter in organic substrates demonstrate the satisfactory performance of multilayer organic packages. The well known full-wave numerical techniques of FDTD and MRTD are used for the modeling of adjacent lines crosstalk, of the Q-factor of embedded passives and for the accurate simulation of MEMS structures.

INTRODUCTION

The current drawbacks of most commercially available microwave, millimeter wave, and high-speed optoelectronics transceiver front-ends include the relatively large size and heavy weight primarily caused by discrete components and separately located modules. Multilayer ceramic and organic-based SOP implementation is capable of overcoming this limitation by integrating components that would have otherwise been acquired in discrete form, and MMICs in a single package, hence the term System-on-Package (SOP) [1,2]. On-package components not only miniaturize the module, but also eliminate or minimize the need for discrete components, thereby reducing the assembly time and cost as well. In addition, less discrete components improves reliability because of the reduced solder joint failures. In this paper, we present highly miniaturized LTCC and fully-organic-based radio front-end packaging components and architectures utilizing Dupont's standard 951 tapes and Georgia Tech's PRC process for compact low cost wireless front end systems.

In particular, we present a very compact 3D-integration concept suitable for C-band RF front-end module by means of LTCC substrate stacking method using μBGA ball process. Results from the characterization of RF vertical board-to-board transitions and from the accurate modeling of the μBGA ball are reported for the first time for RF applications. A C-band high performance second-order narrowband bandpass filter design with two cascaded coupled line sections, and a via-fed stacked cavity-backed patch antenna designed to fully cover the required band (5.725-5.825 GHz), both embedded in multiplayer LTCC substrate, verify the advantages of 3D integration.

Finally, organic-based multilayer very high Q-factor inductors (up to 180) and embedded filters demonstrate the very satisfactory performances of multilayer organic packages.

3D INTEGRATED WIRELESS MODULE DEVELOPMENT

Figure 1 illustrates the proposed novel concept of module integration. Two stacked LTCC substrates are used and board-to-board vertical transition is ensured by μBGA balls [3]. Multi-stepped cavities into the LTCC boards provide spacing for embedded RF active devices and thus lead to significant volume reduction by minimizing the gap between the boards. Cavities provide also integration capabilities for MEMS devices such as MEMS switches. Active devices can be flip-chipped as well as wire-bonded. Passive components, off-chip matching networks, embedded filter and antenna are implemented directly into the LTCC boards by using multi-layer technology [4]. Standard BGA balls ensure interconnection of this high density module with a mother board such as FR4 board. The top and the bottom substrates are dedicated respectively to the receiver and transmitter building blocks of the RF front-end module. Special care is required for the optimization of the board-to-board transition in order to maintain ground and 50-Ohms matching continuity, as well as to address coupling and resonance issues.

Tests structures have been designed for the characterization of μBGA 4 mils diameter balls. Both TRL calibration and TLL de-embedding techniques have been used to extract S-parameters and a hybrid equivalent circuit that includes an RLC ∏-network and a transmission line model. A single μBGA RF transition shows insertion loss less than 0.1 dB (Fig. 2) and return loss about - 17dB up to 10 GHz.

To improve the insertion loss, a high performance second order narrow-band band-pass filter with two cascaded coupled line sections has been developed in stripline configuration using a 10-layer LTCC process. A schematic view is presented in Fig. 3. Filter performance has been measured and exhibits a –2.9dB insertion loss, – 20.8dB return loss, about 200 MHz bandwidth and image rejection greater than –20 dB as shown in Fig. 4.

A via-fed stacked cavity-backed patch antenna [5] has been designed, using the same process, for IEEE 802.11a 5.8 GHz band as shown in Fig. 5. The input impedance characteristic of the stacked-patch antenna is shown in Fig. 6. The 10-dB return-loss bandwidth of the antenna is about 4%, fully covering the required band (5.725-5.825 GHz). At 5.8 GHz this antenna has a desirable gain (near 6 dBi) and very low cross-polarization (less than –35 dBi).

MULTI-LAYER ORGANIC BASED PACKAGE

A multilayer packaging process using an organic material developed by Georgia Institute of Technology's Packaging Research Center offers the potential to be the next generation technology of choice for SOP-based RF-wireless, high speed digital and RF-optical applications. The proposed SOP configuration incorporates low cost materials and processes consisting of a core substrate (FR-4 for example) laminated with two thin organic layers. The thickness of the core substrate is 40 mils while the thickness of the laminate layers are 2.46 mils each. Fabricated prototypes of CPW-microstrip transitions can be used up to 20 GHz. CPW inductors and HGP inductors using multilayer organic technology exhibit Q=182, SRF=20GHz and L_{eff} =1.97 nH and the C-band bandpass filter of Fig. 7 that consists of a square patch resonator with inset feed lines has a bandwidth of 1.5 GHz and a minimum insertion loss of 3 dB at the center frequency of 5.8 GHz. Also, a lifted slot antenna has been successfully implemented in the package.

FULL-WAVE DESIGN TECHNIQUES: FDTD/MRTD

The FDTD [6] method is one of the most mature and versatile time-domain numerical techniques and it has been used for 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) [7] 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 (Fig.8) 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 addition, the optimization of solid-state and nonlinear devices requires the effective modeling of complex structures that involve mechanical motion and wave propagation. Due to computational constraints, most commercial simulators utilize various approximations in order to provide fast and relatively accurate results. The drawback of these approaches is that transient phenomena and nonlinearities are not modeled effectively, leading to the degradation of system-level performance. Alternatively, full-wave techniques provide higher accuracy but suffer from excessive execution time requirements, thus making their efficient numerical implementation very critical. The MRTD technique has provided a mathematically correct way to significantly decrease execution-time and memory requirements while avoiding any approximations.

MODELING OF CROSSTALK, Q_FACTOR AND ELECTROMECHANICAL EFFECTS

Embedded transmission lines are commonly used in as feeding networks of MMIC's in multilayer packages, where the use of non-continuous grounds could lead to increased crosstalk effects. In this paper, the FDTD technique is used for the estimation of the coupling of the finite-ground microstrip lines of Fig. 9 [8]. The results for different line spacing and for a ground connecting via (optimized design) presented in Fig. 10 have been obtained by combining two simulations, an even and an odd mode excitation.

One of the critical passive components in RF application 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 2-turn planar inductor in organic material has been analyzed by FDTD that employs both variable grid and parallelization to increase efficiency and the results are compared with the measured ones [9]. The Q-value difference in Fig. 11 is expected due to the fact that the simulation does not include the loss and roughness of the metal.

One example of a MEMS structure that benefits from simulation in MRTD is the MEMS capacitive switch shown in Fig. 12. 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.

CONCLUSION

We have presented a very compact 3D-integration concept, based on two stacked LTCC substrates connected by means of μBGA balls. Results from the characterization of such board-to-board transitions and from the accurate modeling of the μBGA ball are reported for the first time in RF applications. A high performances second order narrow-band band-pass filter with two cascaded coupled line sections has been presented. A via-fed stacked cavity-backed patch antenna has been designed to fully cover the required band (5.725-5.825 GHz) and implemented in multiplayer LTCC substrate. Multi-layer organic packaging developed for SOP is also discussed. Very high Q-factor inductors (up to 180) and embedded filter are presented as an example of the high performance of multilayer organic packages. The full-wave time-domain techniques of FDTD and MRTD have been used for the modeling of adjacent lines crosstalk, of the Q-factor of embedded passives and for the accurate simulation of MEMS structures.

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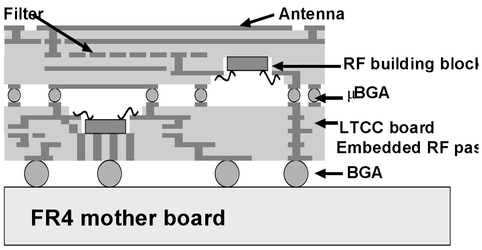

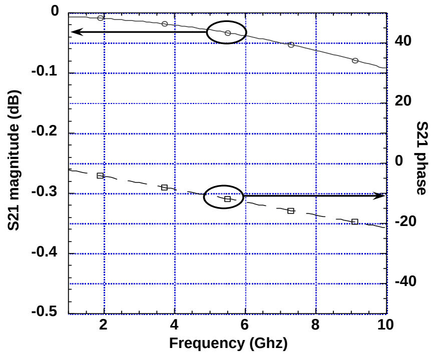

Fig. 1. 3D integrated module concept view.

Fig. 2. Extracted μBGA S21 parameter.

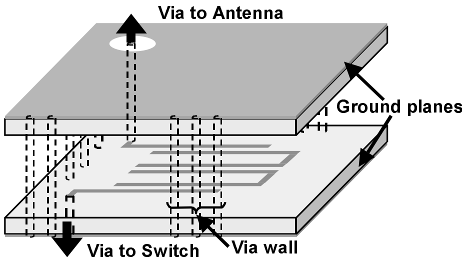

Fig. 3. Schematic of a bandpass filter.

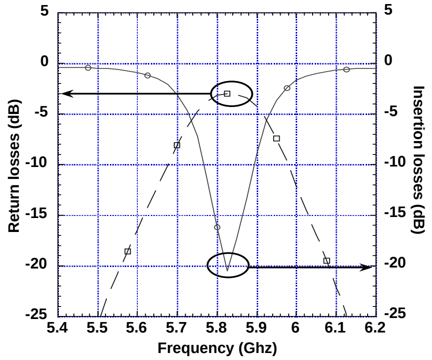

Fig. 4. Performance of the bandpass filter.

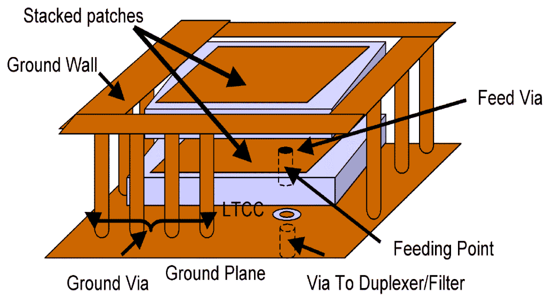

Fig. 5. Stacked Patch Antenna

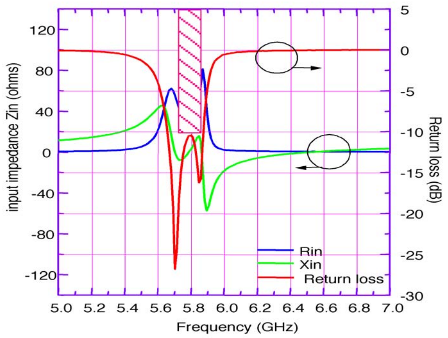

Fig. 6. Input impedance of the antenna.

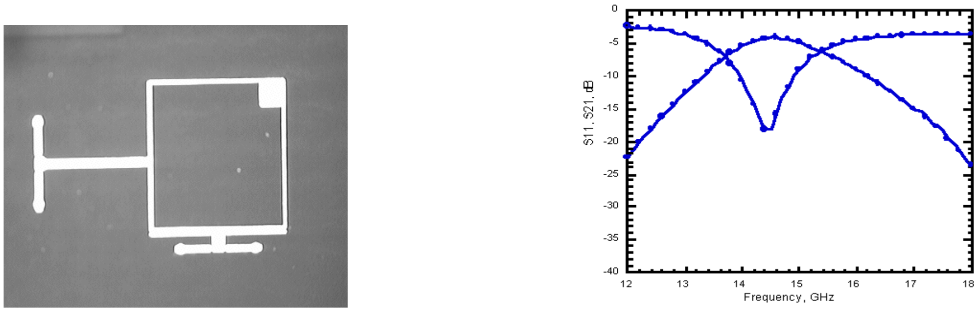

Fig. 7. Photo of organic-based bandpass filter and measurement results.

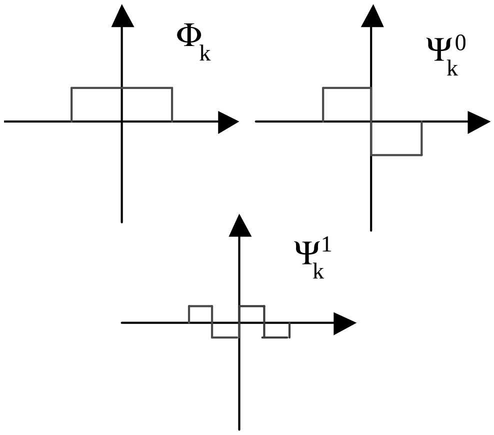

Fig.8 Haar Scaling (Φ) and Wavelet (Ψ) .

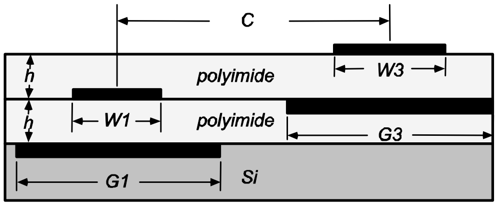

Fig.9 Embedded Finite-Ground Microstrips

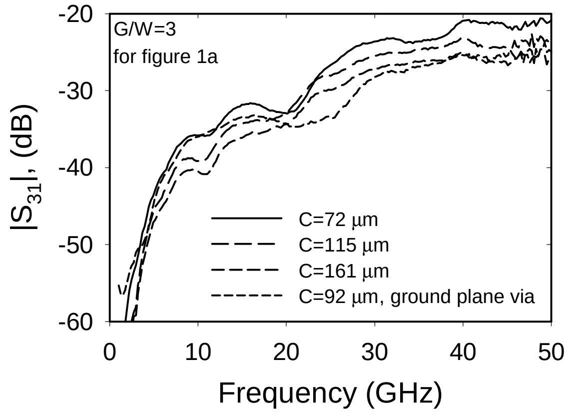

Fig.10 S_{31} for different line separations.

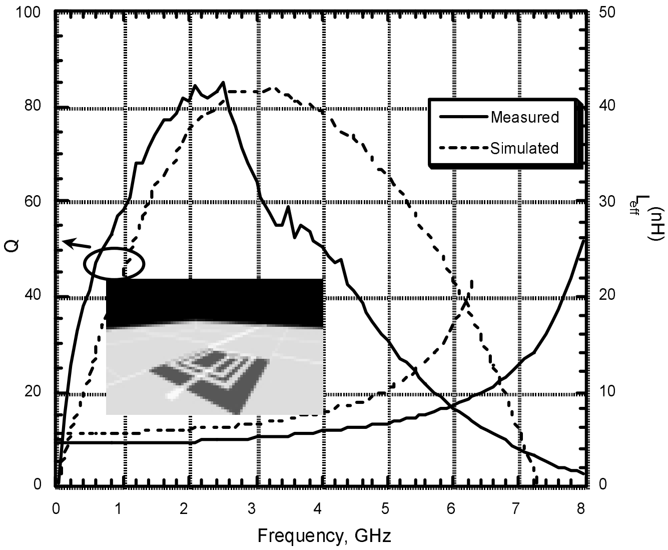

Fig.11 Organic-material Planar Inductor.

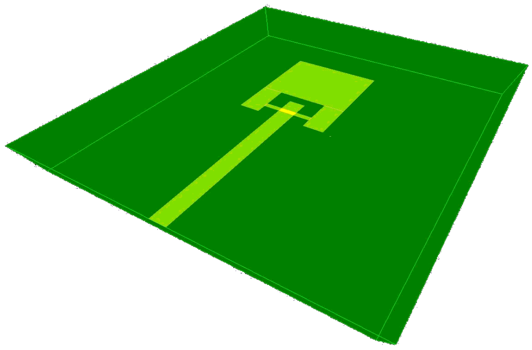

Fig.12 RF-MEMS Switch.