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 mBGA technology. Results from the characterization and the modeling of RF vertical board-to-board transitions using mBGA process are presented for the first time. 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.**

I. 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. Multi-layer 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). On-package components not only miniaturize the module, but also eliminate or minimize the need for discrete components and thereby reduce 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 development 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 Gband RF front-end module by means of LTCC substrate stacking method using µBGA ball process. Characterization of the RF vertical board-to-board transition and an accurate µBGA ball modeling are reported for the first time for RF applications. A high performance second order narrow-band band-pass filter design, with two cascaded coupled line sections, for C-band, and a via-fed stacked cavity-backed patch antenna designed to fully cover the required band (5.725-5.825 GHz), embedded in multiplayer LTCC substrate are presented.

Finally, the multi-layer organic packaging development is reported such as very high Q-factor inductors (up to 180) and embedded filter, and shows the high performances of multi-layer organic package.

II. 3D INTEGRATED WIRELESS MODULE DEVELOPMENT

Figure 1 illustrates the new module integration concept we proposed. Two stacked LTCC substrates are used and board-to-board vertical transition is insured by µBGA balls. 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 provides also integration opportunity for MEMSs devices such as MEMS Switch. Active devices can be flip-chiped 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 [1]. Standard BGA balls insure 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 in the board-to-board transition to maintain ground, 50-Ohms matching continuity and address coupling and resonance issues.

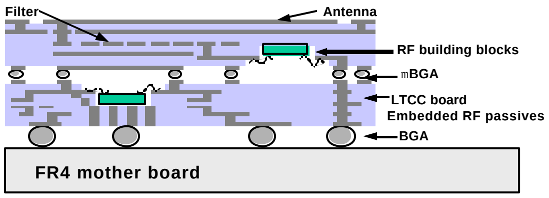

Figure 1: 3D integrated module concept view.

II.1 Characterization and modelling of the board to board transition.

It has been shown that CPW line is the best configuration to avoid vertical coupling between transmission line on the board and on the IC in BGA and flip-chip technology [8]. However the significant reduction of the gap between the two stacked boards, caused by using µBGA ball process, arouses the need of modified CPW design. An accurate model for the µBGA balls is also required to optimize the RF vertical transition design. Tests structures have been designed for the characterization of µBGA 4 mils diameter balls. Both TRL calibration and TLL de-embedding techniques proposed in [2] have been used to extract S-parameters and a hybrid equivalent circuit including RLC ? -network and transmission line model has been developed to model the µBGA RF transition as shown in Figure 2.

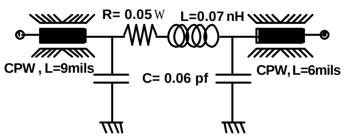

Figure. 2. Extracted mBGA hybrid model.

A single µBGA RF transition shows insertion loss less than 0.1 dB and return loss about - 17dB up to 10 GHz. Figure 3 shows the extracted performances of a single ball transition. Post full wave simulations have also been performed to validate the developed models.

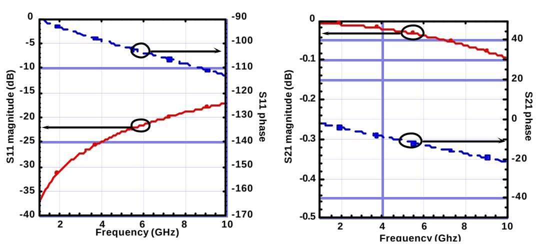

Figure. 3. Extracted mBGA S-parameters.

II.2 LTCC filter development.

We have developed a high performance second order narrow-band band-pass filter with two cascaded coupled line sections embedded in strip-line configuration to improve insertion loss. This design is based on a 10 layers LTCC process. A schematic view is presented in Figure 4. Coupled lines have been bent to fit into the module shape and via walls are used to connect ground planes and reduce parallel plate modes. Filter performances have been measured and exhibit a –2.9dB insertion loss, – 20.8dB return loss, about 200 MHz bandwidth and image rejection greater than –20 dB as shown in figure 5.

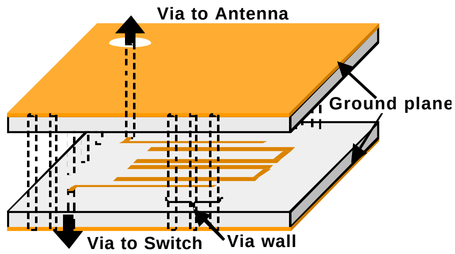

Figure. 4. Design schematic of a band-pass filter.

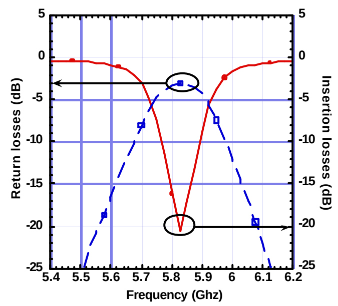

Figure. 5. Performances of the band-pass filter.

II.3 LTCC Antenna development.

A via-fed stacked cavity-backed patch antenna has been designed (based on a 10 layers LTCC process) for IEEE 802.11a 5.8 GHz band as shown in Figure 6 [3]. The heights of the lower and upper patches (400 mils × 400 mils) are respectively 8 mils (2 LTCC GL550 layers) and 32 mils. The input impedance characteristic of the stacked-patch antenna is shown in Figure 7.

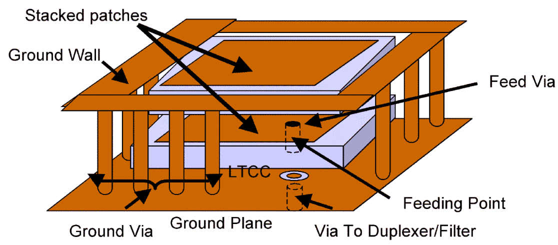

Figure. 6. Stacked patch antenna.

The 10-dB return-loss bandwidth of the antenna is about 4%, fully covering the required band (5.725-5.825 GHz). The radiation pattern at 5.8 GHz is plotted in Figure 8. This antenna has a desirable gain (near 6 dBi, figure 8a) and very low cross-polarization (less than –35 dBi, figure 8b).

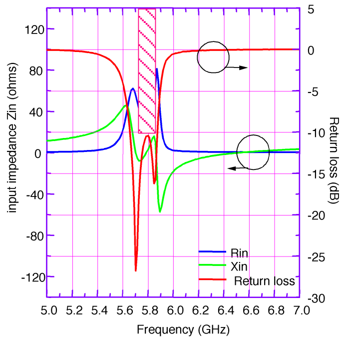

Figure. 7. Input impedance characteristic of the stacked patch antenna.

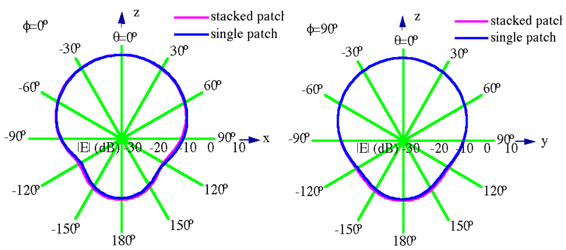

Figure. 8a. Radiation pattern of the stacked patch antenna, co-polarization.

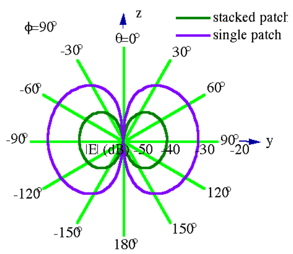

Figure. 8b. Radiation pattern of the stacked patch antenna, cross-polarization.

III. MULTI-LAYER ORGANIC BASED PACKAGE

A multi-layer packaging process using a organic material developed by Georgia Institute of Technology's Packaging Research Center offers the potential as the next generation technology of choice for SOP for RF-wireless, high speed digital and RF-optical applications [4]. Indeed, in most of the presently used microwave integrated circuit technologies, it is difficult to integrate the passives efficiently while maintaining the desired performance. Another critical obstacle in efforts to reduce the module size is the design of passive components, which occupy the highest percentage of integrated circuit and circuit board real estate. Design flexibility and optimized integration can be achieved with multilayer substrate technology in which free vertical real-estate is taken advantage of highly intergrable multilayer organic (MLO) technologie is thus being studied to achieve complete System on Package solutions (SOP). The current SOP configuration is shown in Figure 9.

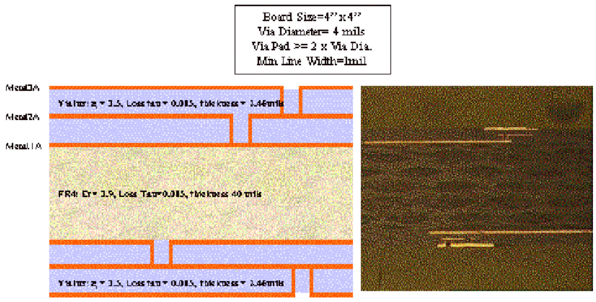

Figure. 9. Cross view of multiplayer organic based package.

It 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.
CPW-microstrip transition shows that it can be used up to 20 GHz.

III.1 Multilayer Inductors.

High Qs Inductors at the frequency range of interest can be obtained by designing Co-Planar Waves Guide (CPW) inductors and Hallow Ground Plane (HGP) [5] series and cascade inductors using multilayer organic technology. The CPW spiral inductor, avoids via losses, has reduced dielectric losses and increased SRF. The advantage of the HGP implementation includes shunt parasitic capacitance eddy current reduction resulting in higher Q. CPW inductors and HGP inductors using multilayer organic technology demonstrates a Q of 182, SRF 20GHz, Leff 1.97 nH.

III.2 Embedded filters.

Bandpass filter design for Ku band applications uses a broadside-coupled microstrip dual-mode square ring resonator [6]. This consists of a microstrip ring resonator that is perturbed by inserting a small metal polygon at one corner, Figure 10. The outputs are taken symmetrically with respect to this perturbation, which causes the resonator modes to split into two degenerate coupled modes, giving a second-order bandpass filter response. The advantages of this design are compactness (nominal edge length is $\lambda/4$) and controllability of the bandwidth by varying the size 'd' of the perturbation that causes mode splitting. Larger perturbations cause more mode splitting and result in a larger bandwidth. The strength of the capacitive coupling also controls the bandwidth. Strong coupling lowers the external Q factor of the resonator and increases the bandwidth. Figure. 11 shows a measured center frequency of 14.5GHz, bandwidth of 1 GHz and an insertion loss of 4 dB.

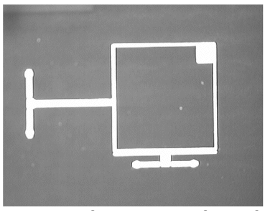

Figure. 10. Photo of band-pass filter for Ku band

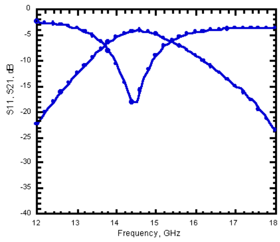

Figure. 11. Measurement of band-pass filter for Ku band .

VI. CONCLUSION

We have presented a very compact 3D-integration concept, based on two stacked LTCC substrates connected by means of µBGA balls. Characterization of the board-to-board transition and an accurate µBGA ball modeling 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 reported. Very high Q-factor inductors (up to 180) and embedded filter for ku band applications have been presented as an example of the high performances of multi-layer organic package.

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