Broad Frequency LTCC Vertical Interconnect Transition for MultiChip Modules and System On Package Applications

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***Abstract*—Various stripline structures and flip chip interconnect designs for high-speed digital communication systems implemented in low temperature co-fired ceramic (LTCC) substrates are studied in this paper. Specifically, two different transition designs from edge launch 2.4mm connectors to stripline transmission lines embedded in LTCC are discussed. After characterizing the DuPont™ 9K7 green tape, different designs are proposed to improve signal integrity for high-speed digital data. The full-wave simulations and experimental data validate the presented designs over a broad frequency band from DC to 50 GHz and beyond.**

Keywords—Full-tape-thickness feature; LTCC 9K7 interconnect; multi-chip-module (MCM); quasi-coaxial vertical transition; signal integrity; system on package (SOP)

I. INTRODUCTION

Electronic systems require high routing density, low losses, and a cost effective interconnect and packaging solution. Low-temperature co-fired ceramic (LTCC) multilayer substrate technology combines these characteristics, making it a well-suited candidate for miniaturized system on package (SOP) and densely integrated multi-chips modules (MCM) [1]. The design of high performance, high frequency components requires low losses such as those seen in LTCC. Initially, we characterized the LTCC 9K7 green tape and confirmed the low loss material properties by comparing with the datasheet provided by the manufacturer. The extracted dielectric constant and loss tangent was then implemented in a full-wave simulation using *Ansoft* HFSS. The vertical transition is modeled and optimized to realize a connection between a microstrip and an embedded stripline in LTCC through a via. As mentioned in previous work, large capacitive effects occur at the via transition [2] and consequently reduce the frequency bandwidth of the components. To compensate for the capacitance between the ground and the signal via trace, Schmückle *et al.* proposed to lower the ground of the microstrip section compared to the grounded stripline [2]. Another option is to introduce air cavities underneath the signal trace as demonstrated in [3], placing them between a coplanar waveguide (CPW) and stripline via vertical connection for SOP applications at 60 GHz. Furthermore, Baras and Jacob proposed an advanced broadband interconnect for multi-chip-modules (MCM) [4]. The idea consists of screen printing the inter layers and connecting them together through vias to form a ground structure surrounding a central signal via. Although this technique has been successfully implemented, it adds complexity to the design of the screens for the layers involved. In this work, we present two vertical via interconnect structures with good performance over a large frequency band from DC to 50 GHz. Our design approach fully exploits the electrical and mechanical properties of the DuPont™ LTCC 9K7 green tape. The first proposed topology is based on the insertion of air cavities underneath the via transition to lower capacitive effects. The second approach consists of a coaxial structure embedded in LTCC to reduce impedance mismatch and increase the frequency bandwidth performance compared to existing techniques.

II. CHARACTERIZATION OF DUPONT™ 9K7 LTCC GREEN TAPE™

Knowledge of the electrical properties (i.e. complex permittivity) of the substrate is the key to the design of radio frequency/microwave circuits. The ring resonator technique [5] was used to fully characterize at radio frequency (RF) the Dupont™ 9K7 low temperature co-fired ceramic (LTCC). The LTCC properties include the extracted dielectric constant or real part of the effective permittivity and losses as a function of frequency from 1 GHz to 20 GHz. By identifying the different resonant frequencies and their respective Q-factor, it is possible to extract the material properties of the substrate. A standard RF benchmark, courtesy of IMST GmbH [5], is used in this process as shown in the inset of Fig. 1. Measurement of the transmission coefficient as presented in Fig.1 shows the resonant frequencies occurring in the frequency band of interest. The measurement and Short-Open-Load-Thru (SOLT) calibration of the network analyzer is realized

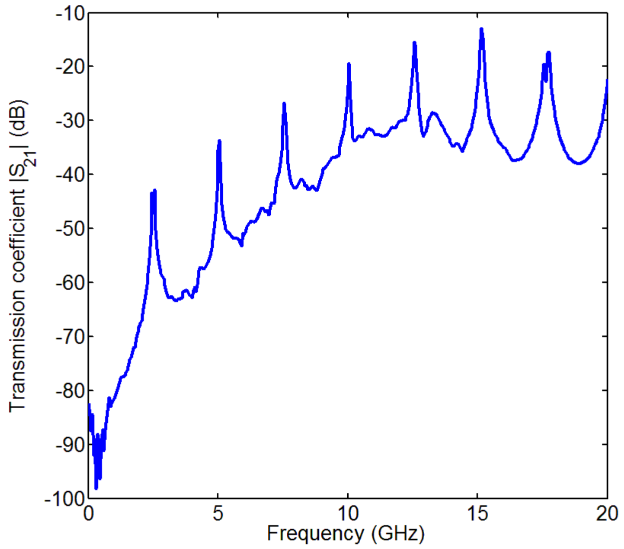

Fig. 1. Measured transmission coefficient (S_{21}) of the stripline ring resonator using the IMST RF benchmark as shown in the inset to extract the electrical properties of Dupont™ 9K7.

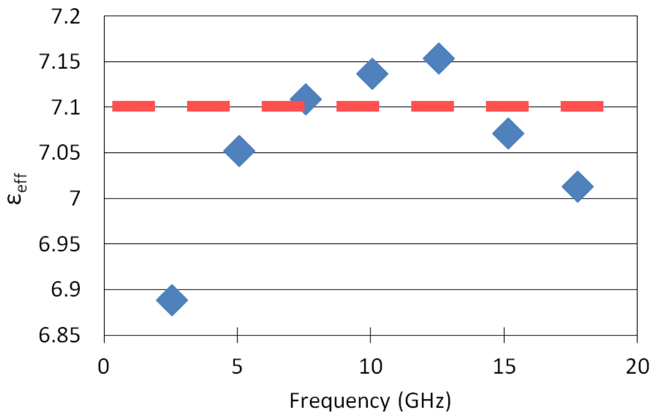

Fig. 2. Extracted relative permittivity of DuPont™ 9K7 LTCC as a function of frequency using the ring resonator technique. The red dashed line corresponds to the data furnished by the manufacturer (ε_{eff}=7.1±0.2).

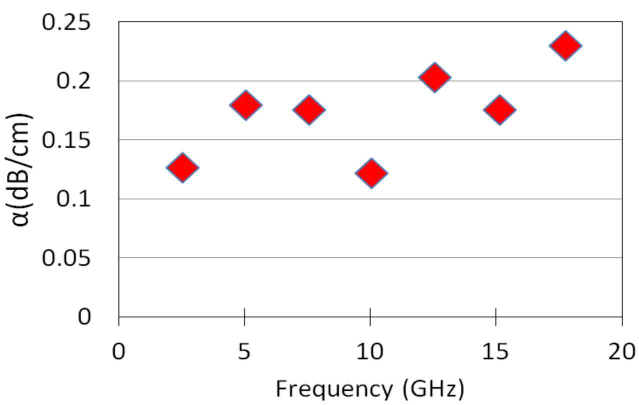

Fig. 3. Extracted losses of DuPont™ 9K7 LTCC as a function of frequency using the measurement shown in Fig.1.

directly on the LTCC substrate using a probe station to minimize errors. The extracted relative effective permittivity and losses of DuPont™ 9K7 from the measured transmission coefficient (S_{21}) shown in Fig. 1 is presented in Figs. 2 and 3 respectively. Although, the presented results agree with the data from the manufacturer, the losses are a higher than expected (α_{10GHz}=0.003 dB/cm). DuPont™ characterizes LTCC green tape without metallization using a split cavity measurement method. In our case, the metallic and surface roughness losses are added [6] which explains the difference between our experimental results and data provided by the manufacturer. It should be noted that silver paste is used in the fabrication process for the metallization of the signal traces and ground planes of the stripline and microstrip transmission lines.

III. Broadband Vertical Interconnect

A. *Vertical transitions*

The vertical transition structure consists of a microstrip-to-stripline vertical transition through a 152 µm via. The vertical transition induces a capacitive effect which can be reduced using two different techniques. As the physical expression of a capacitance is given by $C=\varepsilon\varepsilon_0\,A/d$, it is possible to minimize it by increasing the number of LTCC layers between the trace and the ground plane (increase d) [2] or by decreasing ε (i.e. using air cavities) [3]. The stripline configuration already utilizes eight LTCC layers, so the second option is preferred. To decrease the capacitance effect, a small air cavity is implemented underneath the vertical transition to replace the LTCC (having a relative permittivity of LTCC ~ 7.1) as shown in Fig. 4. The ground plane of the microstrip is also the top ground plane of the stripline, so 10 layers of LTCC are required (eight for the stripline and two for the microstrip).

The simulated and measured scattering parameters are presented in Fig. 5 from DC to 50 GHz. To achieve accurate measurements over the frequency band, the SOLT (short, open, load, thru) calibration of our PNA (an Agilent E8361A) was carried out from 1 GHz to 50 GHz. The intermediate frequency was set to 70 Hz to minimize noise and 201 frequency points were considered.

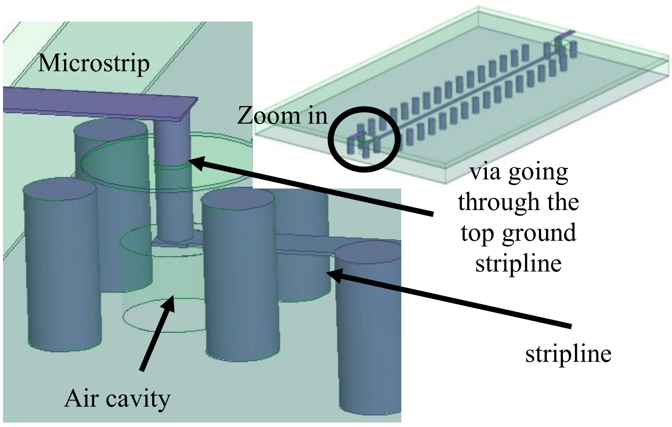

Fig. 4. Microstrip to stripline vertical transition configuration. The top ground of the stripline is used as the microstrip ground,

The reference planes of the two port networks are at the input of the Southwest Microwave connectors. The effects of the connectors were taken into consideration in the simulations and measurements and are not de-embedded in the results presented in Fig. 5. The dimensions of the structure are summarized in Table 1.

TABLE I
DIMENSIONS OF THE STRUCTURE IN MICRON

Symbol	Length
Thickness per Green Tape™ layer	110
Thickness of metal print	15
Width of microstrip	280
Diameter of via	152
Pitch of signal ground vias	400
Pitch of stripline ground via	762
Diameter of stripline ground antipad	762
Width of stripline	200

Discrepancies occur between the measurements and simulations. For instance, a resonant frequency occurs at 15 GHz, which is not predicted in the full-wave simulation obtained from *Ansoft HFSS* [8]. The investigation of the fabricated structure through cross sectioning highlighted fabrication issues. The cross section of the devices presented in Fig. 6 demonstrates that during the firing process a significant amount of silver paste migrates into the air cavity. LTCC Green Tape™ tends to shrink during the firing process, and the manufacturer estimates that the shrinkage of the LTCC 9K7 green tape is 9.1±0.3 %. Consequently, the silver paste used to fill the vias is squeezed outside of the desired region as shown in Fig. 6.

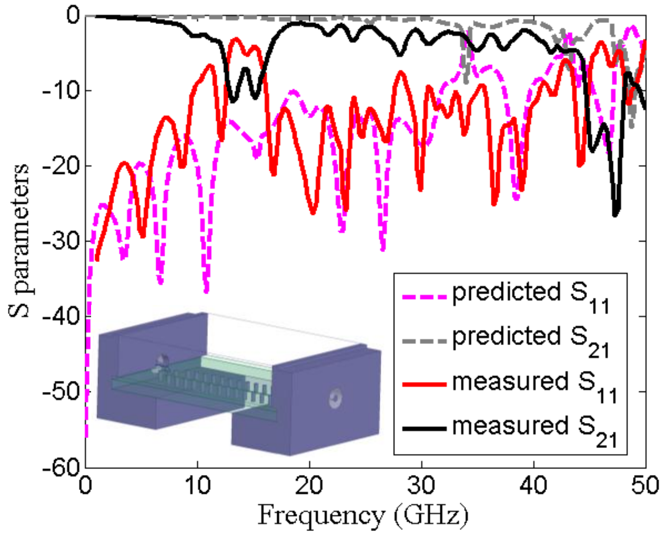

Fig. 5. Comparison of results using the simulated HFSS (predicted) and measured reflection (S_{11}) and transmission (S_{21}) coefficients of the stripline structure shown in the inset. The simulated and fabricated stripline is 3 cm long. The resonant frequency occurring at 15 GHz is due to fabrication tolerance.

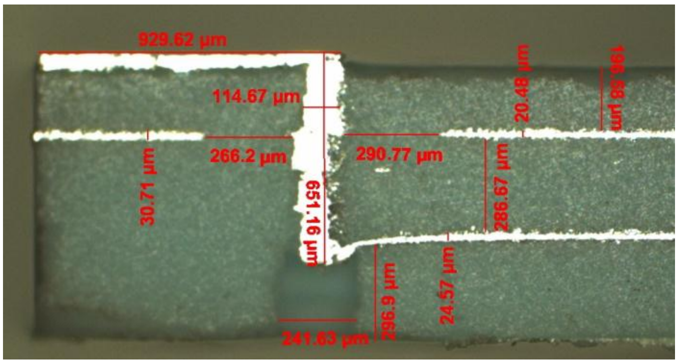

Fig. 6. Cross-section of the fabricated device highlighting the fabrication tolerance and fabrication issues. A significant amount of silver paste migrates into the air cavity due to the shrinkage of the LTCC green tape during the firing process.

B. *Quasi-coaxial transition*

A second transition structure was also evaluated to reduce the impedance mismatch occurring between the different interfaces. In this approach, the goal was to improve the transmission coefficient (S_{21}) and frequency bandwidth performance while at the same time being less subject to fabrication tolerances as compared to the traditional structures presented in Fig. 5.

The process uses full-tape thickness features, where a “nibbling” technique is used to create a trench in the LTCC tape, which is then filled with conducting paste [9]. The process of using consecutive punches in the Green Tape™ to realize trenches is also used to realize cavities in the LTCC. This process can be easily implemented, as the technology involved in the fabrication process does not require new machines and is based on the punching equipment already commonly used in the LTCC process. This technology can be integrated in LTCC DuPont™ 9K7 Green Tape™ because the shrinkage of the tape during the firing process is less significant, and more predictable, than that seen in other types of LTCC tape.

The approach taken for designing the quasi-coaxial transition was to use the punching technique to realize the external ground plane of the coaxial transmission line while the internal conductor was realized using the traditional via technique as shown in Fig. 7. The LTCC 9K7 was used as the dielectric medium (relative dielectric constant ε_r =7.1 as illustrated in Fig. 2) between the signal and the ground plane. The dimensions of the transmission lines were first calculated based on the desired characteristic impedance.

The diameter of the internal signal conductor trace is fixed by the size of the via punch (with a diameter of approximately 152 µm) and assuming a coaxial waveguide filled with LTCC (dielectric constant ε_r =7.1) the diameter of the external ground structure is retrieved using [9]. The dimensions are then optimized using the full-wave simulation software *Ansoft HFSS* and presented in the schematics in Figs. 8 and 9.

The predicted results of the reflection (S_{11}) and transmission (S_{21}) coefficients using *Ansoft HFSS* [8] are in

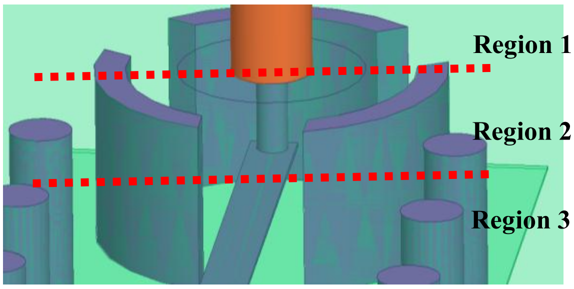

Fig. 7. As-simulated design of the high performance transition from the 2.4mm connector to stripline using a quasi-coaxial structure in LTCC.

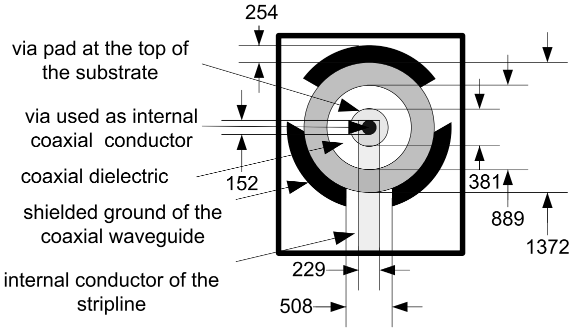

Fig. 8. Schematic of the mechanical design of the quasi-coaxial transition. Dimensions are in microns.

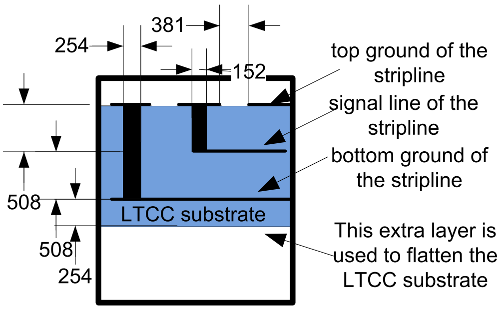

Fig. 9. Schematic of the cross section of the devices. The design consists of five 254 µm thick layers. An extra layer is added to flatten the LTCC substrate. All dimensions are in microns. The metallic conducting traces are nominally 15 µm thick.

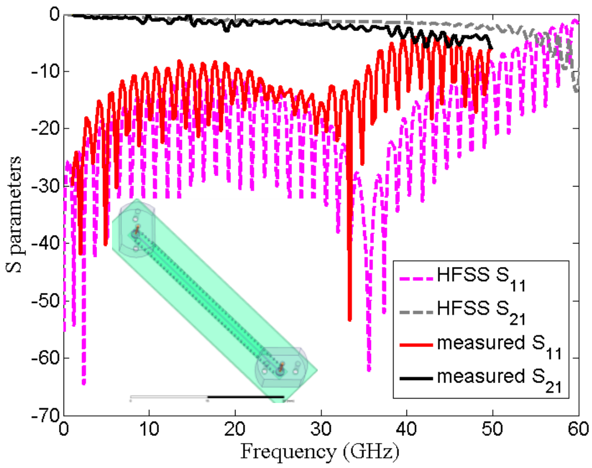

Fig. 10. Comparison of the simulated (using HFSS) and measured reflection (S_{11}) and transmission (S_{21}) coefficients of the stripline structure shown in the inset. The simulated and fabricated stripline is 5 cm long. The shift of the high-frequency resonance is due to connector misalignment.

agreement with the measured data, as shown in Fig. 10. The shift of the high frequency resonance around 35 GHz is due to our inability to perfectly align the connector signal pin to the signal via in the LTCC substrate.

IV. Conclusion

In this paper, two vertical interconnect transition structures are presented, as well the electrical characterization of DuPont^{TM} 9K7 LTCC. The characterization highlights the losses due to the finite conductivity of the silver paste and the surface roughness. One vertical interconnect transition was designed with air cavities fabricated and found to be strongly affected by fabrication tolerances. The difference between the predicted scattering parameters using the full-wave modeling and the measurement demonstrated that fabrication tolerances are a significant limitation to the use of this geometry due to the shrinkage of the LTCC tape during the firing process. The second transition consisting of a quasi-coaxial structure shows a significant improvement by reducing the insertion loss and improving the reflection coefficient at the connector/LTCC interface. In addition, it is more reliable and less subject to fabrication tolerances, which makes it suitable for system on package (SOP) applications at RF/microwave and millimeter-wave frequencies. The quasi-coaxial design is also suitable for surface mount interconnects such as Land-Grid-Array (LGA) or Ball-Grid-Array (BGA) technologies as applied to LTCC packaging.

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