ADVANCED HIGH FREQUENCY LTCC MATERIALS FOR APPLICATIONS BEYOND 60 GHZ

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***Abstract* — In this paper we will present an application of advanced Low Temperature Cofired Ceramic (LTCC) technology beyond 60 GHz. Therefore a RF frontend for 76-81 GHz radar frequency was built. LTCC is a well established technology for applications for consumer handheld units <5 GHz but will provide solutions for applications for high frequencies in the range of 60 GHz and beyond. Radar sensors operating in the 76-81 GHz range are considered key for Advanced Driver Assistance Systems (ADAS) like Adaptive Cruise Control (ACC), Collision Mitigation and Avoidance Systems (CMS) or Lane Change Assist (LCA). These applications are the next wave in automotive safety systems and have thus generated increased interest in lower-cost solutions especially for the mm-wave frontend section.**

I. INTRODUCTION

LTCC is a promising technology as fine pitch interconnect and functional substrate for high frequency applications and System-in-Packages (SiPs). Applying photolithography on LTCC, punching of vias smaller than 80µm and fine line stencil printing increase the 3D integration density of LTCC SiPs. LTCC with thermal vias and heat spreaders is a capable technology for thermal management of heat sensitive applications to handle and control the junction temperature. LTCC is a standard technology for passive integration in RF – applications up to 10 GHz. Typical relative permittivity in the range of 6 to 9 allow small and efficient circuit designs for filters, multiplexers, couplers, antennas etc. from about 1 to 10 GHz. The main cause for losses in that frequency range is the conductor loss of the metal structures.

The main advantages of the LTCC technology for RF – applications (< 5 GHz) are small electrical structures due to high dielectric constant (DC), high functionality in small volumes due to multilayer designs and low component price due to high 3D integration rate. In HF applications > 50 GHz, however, ceramic is not a preferred material because a high dielectric constant (DC) is not necessary for small electrical structures and the performance suffers from higher losses of high DC materials. But the development of an enhanced LTCC ceramic combined with high resolution LTCC technology makes it possible to fulfill all requirements for these applications.

Usually soft substrates with a dielectric constant in the range of 2 to 3 are used for realization of millimeter wave circuits. From TDK side the goal of this development was to overcome the disadvantages of LTCC for millimeter wave applications and to show the possibilities of that technology in the case of a 79 GHz radar module.

One possibility and clear advantage in LTCC is to produce rather complicated 3 dimensional electrical structures without increasing production costs. Therefore, a Laminated Waveguide (LWG) [1] in LTCC was chosen as antenna feed line instead of a standard microstrip line or coplanar waveguide which are typically used on soft substrates. Similar to traditional rectangular waveguide with fully shielded cross section, LWG avoids the occurrence of surface waves, and the radiation losses are low, both being unwanted parasitic effects in the case of other transmission lines when used in that frequency range.

II. ADVANCED LTCC TECHNOLOGY

A. *Electrical properties*

As mentioned in the introduction for applications up to 110 GHz material loss is the main property which has to be investigated. In Figure 1 the losses in dB/cm of a LWG at 79 GHz for the LTCC systems, *"BM"*, *TDK "standard" LTCC* and *TDK "optimized" LTCC*, which were available for the first prototype samples are shown. The losses were measured using a transition to standard WR-12 waveguide presented in **[1]**.

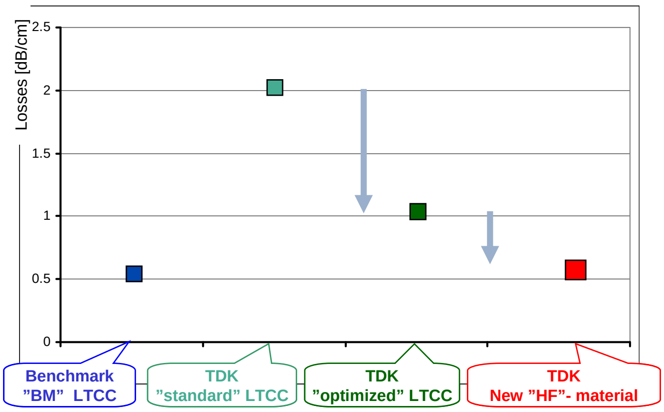

Figure 1: Transmission Loss of a LWG in LTCC at 79 GHz for three different LTCC materials and finally the new developed *HF*-material of TDK, which is capable for non-shrink as well as for plate able fine line.

With *"BM"* a benchmark material is indicated which is very established at TDK for a radar module in the 24 GHz range. This material was the only commercial available mass production material at market at that time. The *BM* is excellent in terms of low loss but has some limitations: Since the material can only be free-sintered the shrinkage control is essential and therefore very critical and complex. The shrinkage process causes additional displacements of the 3D metal geometry which is mandatory for the antenna structures or bond matching structures and therefore for the entire resolution. Furthermore the *BM* is not stable in any plating process which limits the outer metallization and especially the outer metallization finishing and therefore assembly technology.

In Figure 1 the material with the highest losses (*TDK "standard" LTCC*) is the TDK *standard* material used for lower frequency applications. The *TDK "standard" LTCC* is a constrained system which is plating stable but with definitely too high losses for good millimeter wave application.

With some adjustments this system could be improved in terms of losses (see Figure 1: *TDK "optimized" LTCC*). Even the transmission losses of 1 dB/cm are finally reached, however, we did not achieve the values of the *BM* system. The typical losses of transmission lines on competitive non-LTCC millimeter wave substrates are as well in the range of 1 dB/cm, thus TDK's optimized *"standard" LTCC* with LWGs already shows similar transmission losses.

With the latest development (see Figure 1: *TDK New "HF"-material*) which leads to the *New HF*-material we are competitive to the electrical properties of the *BM* system. Additional to the electrical properties this system can be sintered in a non shrinkage process and is stable in any chemical treatment which is essential for the photo imaging and finishing process.

In Figure 2 the measured losses of a 50 Ohm microstrip line is shown. The measured values show the poor losses of the *standard* LTCC compared to the *BM*-material, as already explained. But this graph should highlight that the transmission line model used for the simulation is excellent suitable to describe the situation in our technology.

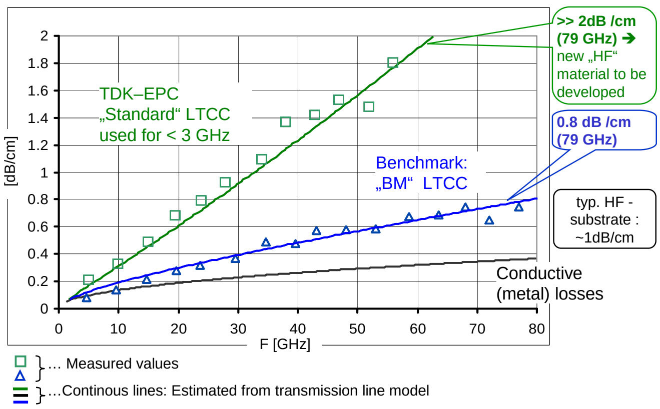

Figure 2: Measured losses of a 50 Ohm microstrip line.

Additionally Figure 2 makes it obvious that in the standard frequency range for LTCC around 2 GHz the dielectric losses of the material do not play any essential role for the overall losses of a microstrip line but only the conductor losses.

B. Chemical and mechanical properties of the New "HF"-material

The *New HF* LTCC is a co-fire low sinter glass ceramic comparable to the standard commercialized material in terms of sinter conditions. The improvements which lead to the low losses are based on the glass composition. Additional to the High-Q properties this *New HF* LTCC material system can be processed in a constrained technology. This technology is excellent according x-y-accuracy and area utilization. This system is capable to be processed in 8-inch which is essential since this process is very well established as standard process in TDK's production line. Hence, the entire production line, with the process steps comprising punching, via filling, inner metallization printing, stacking, firing and all backend processes can be used in the standard setup.

C. Fine-Line Technology

1) Outer Metallization

Beyond the LTCC frontend production a fine line outer metallization is necessary to achieve all requirements for the RF structures on the top of the LTCC. The standard LTCC – top layer Ag metallization can be applied co-sintered (together with sintering of the entire stack) or post-fired (applied after sintering) which is performed with a screen printing process followed by additional Ni-, Pd-, and Au-platings to achieve a Au-, Cu- or Al-wire bondable surface with high reliability. In this case a minimum line widths as well as a minimum spacing between metal structures are ≥ 100 µm typical.

In the present work the transceiver chip has to be wire bonded typically with Au wires and special bond matching structures on the LTCC are necessary for a low loss wide band transition in the desired frequency range from 77 to 81 GHz. For such bonding structures as well as for the antenna structures a higher resolution and accuracy are necessary. With standard screen printing the demands in the present work could not be fulfilled with respect to fine pitch, flatness and roughness. For that reason a special *Fine Line Process* based on photo imaging technology has been developed for top layer metallization. Figure 3 shows one example of the top layer structure (here a through standard for TRL calibration on LTCC) with standard screen printing in comparison to the Fine Line Process.

The photo imaging and plating of a Cu outer metallization is very established in the PCB world but had to be developed for the LTCC technology. Since the assembly of the transceiver chip has to be Au wire thermosonic bonding the finishing has to be in accordance to this technology and requirements.

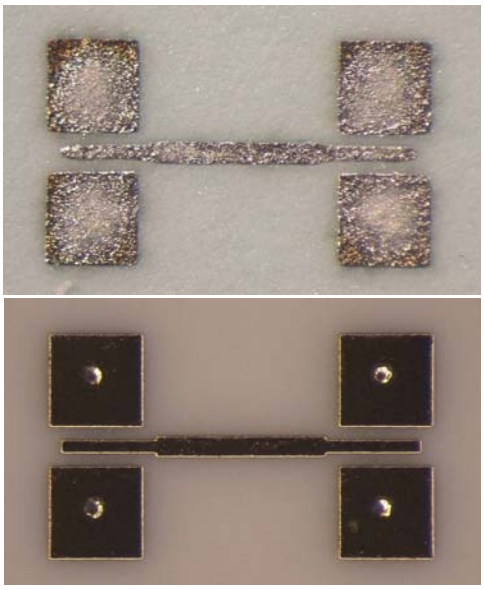

Figure 3: Screen printed *BM* material (no plating process possible!) (top) vs. TDK photo imaged fine line process plated with electroless, NiPdAu (bottom).

Not only for the photo imaging with Cu fine line but also with the standard finishing of the co-fired or post-fired outer metallization which is Ag or an Ag alloy with Pd or Pt the ceramic has to withstand the chemical plating conditions. Since for LTCC quite a lot of circuit trees are floating the finishing has to be electro less. Therefore electroless Ni electroless Pd flash Au (ENEPIG) is becoming more and more standard for finishing. Since the electroless plating is harsher in terms of chemical attacks compared to electro plating the LTCC has to withstand severe chemical alkaline and acid attacks. For the photo imaging and finishing plating stable LTCC is necessary which is fulfilled with the *New HF* LTCC system.

2) Inner Metallization

For the inner metallization the standard screen printing is still the main stream application with line clearance of 100 µm and line width of 75 µm in mass production with 140 prints without screen wiping and print accuracy within the tolerances. For more challenging demands the so called pressure assisted screen printing with electroforming dual layer stencils was developed at TDK. In Figure 4 such a stencil with a customized grid and functional layer according the patterning (vias and lines) can be seen. The main advantage is the fact that the via fill and the fine line patterning of the inner metallization can be performed in one step. With the stencils with customized openings a resolution of 50 µm can be achieved for mass production with high reliability.

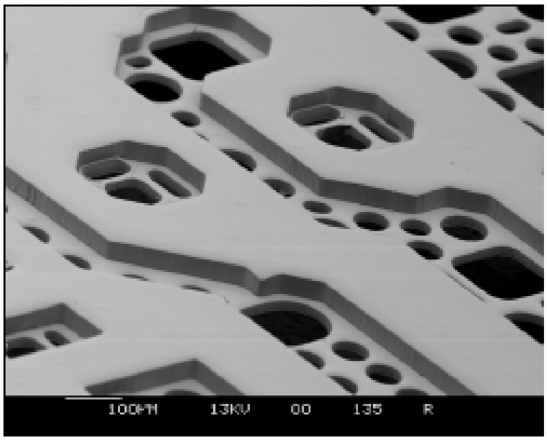

Figure 4: Electroforming Dual Layer Stencil. Via filling and innermetallization can be performed in one step.

3) Via Punching

To connect the fine line photo imaged outer metallization with the fine line inner metallization the diameter and the pitch of the vias have to shrink. 100 µm vias with 200 µm pitch were the design rules yet. With the new demands for high density designs a 80 µm via diameter is becoming more and more the standard. Since TDK is using multi punching tools up to 260 needles which punch simultaneously with 14 Hz in outstanding shape and x-y accuracy no reasonable argument is given for laser punching. But for future demands and flexibility laser punching has to be taken under investigation again.

D. Design prospective

Using the material with a permittivity constant around 7, the cross section of the LWG is in a range of 1×0.5 mm² (with a cutoff frequency around 60 GHz). Other substrates with lower permittivity would need larger cross sections to achieve the same cutoff frequency.

The usage of LWGs with the possibilities of their very low transmission loss is a clear advantage for higher permittivity LTCC materials. Furthermore, since LWGs can guide the waves within the ceramic bulk without using surface area, a very compact construction for the feeding network is possible. The antennas can be fed directly from below without disturbing the radiating structures on the top metal layer. With a LWG-based feeding network, the transceiver chip and antennas can be separated on the opposite sides of the module. The total size of the frontend is further reduced.

III. Application

Figure 5 shows the main components of the LTCC radar modules in a block diagram.

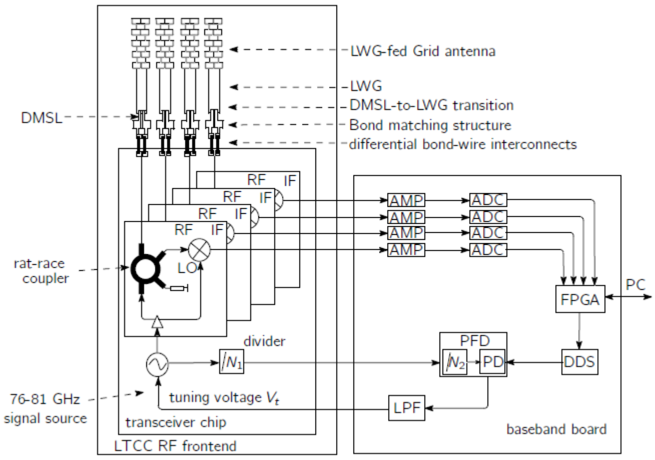

Figure 5: Block diagram of the LTCC radar sensor.

A detailed description of the frontend and its components using *BM* material can be found in [2] - [5]. The fundamental part of the frontend is a 4-channel fully differential SiGe transceiver chip [2]. Wire bond interconnects are used to guide the power from MMIC to differential microstrip line on top metal layer of LTCC.

At 77 GHz the bond interconnections are critical, since the loop length of wire bond (around 360 µm) is approximately tenth of the wave length. The length and the geometry of the wire need to be carefully controlled, otherwise they affect the entire performance of the system: high reflections on bond wire reduce the transmitted energy and the reflected energy lead to a large DC portion at the mixer output. By designing a bond matching network, the reflection on the bond wire can be keep at low level. To guarantee the appropriate bond ability the finishing of the outer metallization is essential. On the photo imaged Cu-fineline the finishing is the well established electroless NiPdAu.

LWG with lined-vias, side-, top-, and bottom metallic layers was designed as the transmission lines. After bond matching structure, the RF-power is transferred from the top metallic layer into the LWG with a DMSL-to-LWG transition which is described in [4]. The 3D model of the transition is shown in Figure 6.

As send and receive antennas, an LWG-fed grid array antenna including a vertical power divider was designed [5]. Finally, a 79 GHz short-range FMCW radar sensor was built with the designed LTCC RF-Frontend and a baseband board [6].

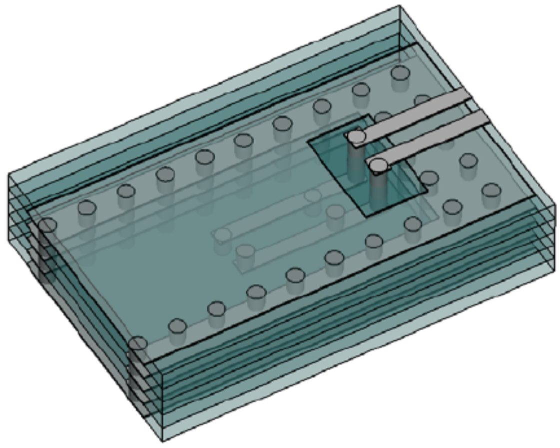

Figure 6: 3D-model of the LTCC DMSL-to-LWG transition.

IV. Results

The radar sensor with the LTCC RF-Frontend with *TDK "optimized" LTCC* and the baseband board is shown in Figure 7. The design goal to have the MMIC on opposite surface is demonstrated.

To verify the functionality of the radar system, distance measurements were performed. The test setup is shown in Figure 8. The targets were detected leading to peaks in the signal spectra

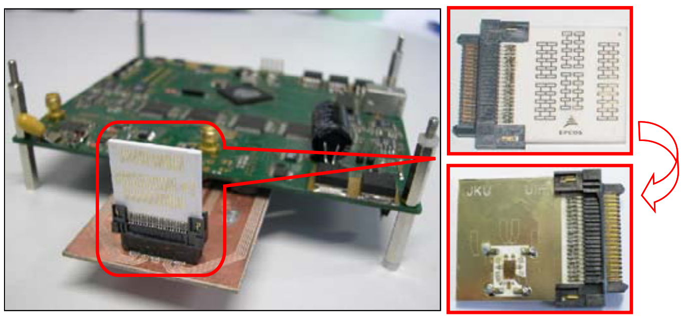

Figure 7: Radar sensor with LTCC RF-Frontend. MMIC bonded on opposite surface of LTCC module.

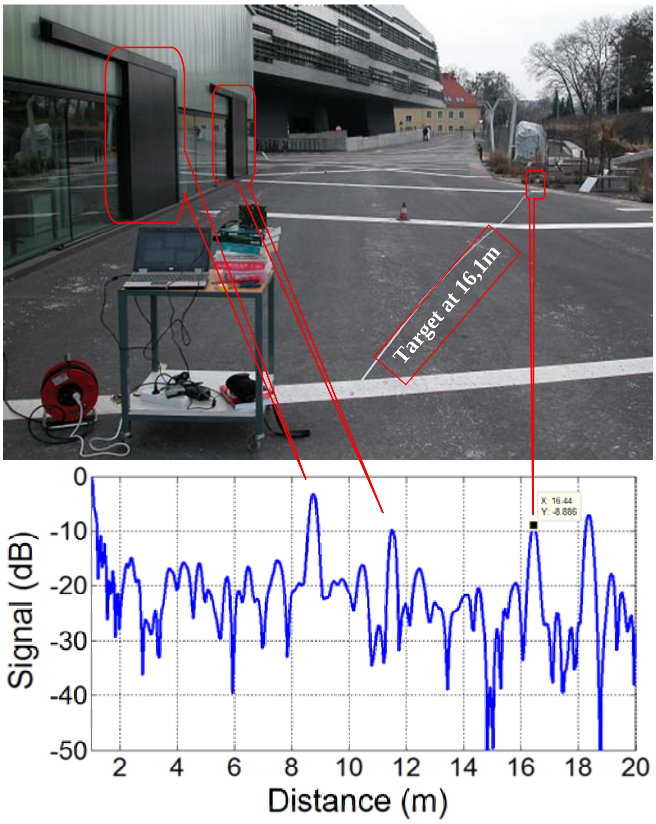

Figure 8: Distance measurement setup of the LTCC radar sensor and the measurement results.

V. Conclusions

In this paper the new advanced resolution LTCC technology and a new developed low loss HF material were tested with a highly integrated 79 GHz radar system based on an advanced 4-channel transceiver in SiGe technology. Due to the focus of the InRaS project on compact short and medium range sensors angle accuracy was of primary importance. Therefore, a novel mm-wave transceiver-architecture based on Tx-beam switching was designed. Furthermore, different substrate materials were investigated. The laminated waveguide as transmission line was studied. By choosing a suitable width of the LWG, the loss of the LWG with the bench mark material (*BM*) has achieved 0.6 dB/cm, which is half of the loss of MSL on traditional soft substrate. With the new developed *HF*-material of TDK we are in the range of the *BM* but with the advantage to have a non-shrink and plating stable LTCC.

Several transitions and bond matching structures were designed to guide the signal from the chip to the antenna. A grid array antenna offering high radiation efficiency and narrow beam width has been successfully designed on LTCC. A LWG vertical power divider was designed to feed the antenna. With this configuration, the chip and the antennas were placed on the different sides of the frontend and the dimensions of the LTCC frontend were reduced to only 23 mm × 23 mm.

A complete FMCW radar sensor was built based on this LTCC frontend and a baseband board. The thermal performance was measured and angle/distance measurements were taken. The measurement results prove the functionality of the LTCC frontend, and fulfill the design goals. It was shown, that it is possible to design a complete RF system in LTCC up to and beyond 80 GHz with lower transmission loss, smaller module sizes and a higher degree of integration compared to state-of-the-art frontends based on soft-substrates.

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