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Investigation of Cavity Fabrication Methods for Integrated Horn Antenna Structures in Low Temperature Cofired Ceramic (LTCC) Substrates

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***Abstract*—This article investigates various fabrication methods for integrated horn antenna structures in a ceramic multilayer substrate and presents a fundamental investigation for a following silicon-ceramic-based space sensing sensor. Precise alignment of the individual tape layers, via placement and implementation of the cavity design is crucial for this application. Due to process-related circumstances, cavity deformations and other undesirable defects affect the ceramic horn antenna structure. Different realization methods for cavities are investigated, e.g., fabrication in the green state of the ceramic and after the sintering process. The cavities are evaluated using x-ray examination, cross section, and scanning electron microscopy. By inserting carbon inlays into the cavities before the sintering process, the quality of the desired geometry is significantly increased. Furthermore, parameters for cavity fabrication after sintering using cold laser ablation were investigated and the feasibility of inclined sidewalls was demonstrated.**

***Keywords*—cavity, fabrication method, horn antenna, inlay, laser ablation, LTCC**

Introduction

Multilayered printed circuit boards are often used for integrated antennas because of lower permittivity, which leads to enhancement of the antenna performance in general [1]. The usage of Low Temperature Cofired Ceramic (LTCC) for antenna applications due to low cost, high packaging density, and dielectric properties of the material system, has already been demonstrated in various publications. Advantages of using ceramic for antenna applications compared with other materials are, for example, thermal stability, mechanical strength, and dielectric properties. The LTCC multilayer technology facilitates a convenient fabrication approach for the integration of miniaturized horn antennas with a precise geometrical control and three-dimensional (3D) capabilities. In comparison with classic printed circuit board materials, ceramic has a higher dielectric constant, which limited the antenna design. To overcome this problem, excess ceramic material can be partially removed before firing. Owing to the generated cavity as well as usage of the application in vacuum or air, the effective dielectric constant influences the fields of the antenna. This opens up completely new possibilities, which are used within this publication to create high performance horn antenna structures. Various methods for cavity realization in LTCC material can be used, such as punching or laser cutting. Typical antenna structures have bone shaped [2] or rectangular [3] openings in the LTCC. Silver or gold pastes are usually used for conductor metallization. Silver has better conductivity, resulting in lower losses in high-frequency applications and is more cost-effective, whereas gold is more chemically stable and does not corrode, leading to higher reliability.

An innovation is the implementation of a scanning function for horn antennas using silicon-ceramic (SiCer) technology. Ceramic material with a thermal expansion coefficient adapted to silicon is required to allow the sintering of silicon and ceramic into a composite substrate. The SiCer technology combines advantages of LTCC technology and Micro-Electro-Mechanical Systems (MEMS) and opens various possibilities in terms of manufacturing and integration for sensor applications, such as fluidic sensors and pressure sensors. An actuated MEMS structure is fabricated in silicon, allowing the final antenna to be moved in different directions to enable scanning. The horn antenna structure is implemented in the ceramic. Fig. 1 shows the application concept of the SiCer-based radar antenna with a scanning function.

Previous experiments showed that the ceramic distorted at the cavity corners due to sharp corners and cracks occurred. This contribution presents a fundamental investigation of different cavity designs and fabrication methods for integrated horn antennas in LTCC for radar application. The focus of this study is the characterization of the optimal cavity design. A gold metallization system is used, as there are currently no specific silver paste systems available for the customized ceramic tape. The integrated horn antenna structures in LTCC with different cavity designs and fabrication methods are evaluated using x-ray examination, cross section, and scanning electron microscopy (SEM).

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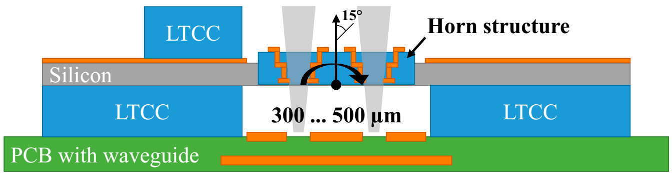

Fig. 1. Application concept of an adjustable horn antenna for radar purposes using SiCer technology.

LTCC Horn Antenna and Fabrication

A. Antenna Design

The initial design of the horn antenna structure, ceramic thickness, and cavity geometry are based on preliminary simulations and technological boundaries. The simulated horn antenna structure in LTCC is depicted in Fig. 2 and boundary parameters for the antenna based on the simulation are listed in Table I.

The number of ceramic layers and their shrinking behavior determines the horn antenna height. Stepped cavities form the sidewalls of the waveguide and are surrounded by a via fence and conductor layers. The via array in each layer consists of 12 vias with a diameter of d = 250 µm and a pitch equal to or greater than 350 µm. This via pitch is chosen to reduce leakage that could cause undesired field or radiation effects and may lead to directivity loss [3]. Conductor metallization between each LTCC tape layer is used to connect the via fence [2] and serves as a wide ground connection to reduce parasitic inductances.

B. LTCC Process

To achieve the preferred substrate thickness of approximately 350–400 µm after sintering according to the simulation, five LTCC layers with a layer thickness of ∼133 µm are used for this investigation. The manufacturing process is similar to the standard ceramic process [4, pp. 686–700]. The vias are punched into the individual LTCC tapes with a punching machine (PTC APS 8718) to create the via fence. The vias are filled with gold paste using a via filler (VF-1000, Pacific TriNetics Corporation) with a ∼75 µm thick fill mask. Screen-printed conductor metallization on each layer connects the vias through the ceramic (EKRA M2, ASYS Automatisierungssysteme GmbH; stainless-steel screen, 400 µm mesh, 18 µm wire diameter, 25 thick emulsion). To guarantee a bonding between the LTCC layers the conductor metallization is meshed with a line-space of 95 µm. The cavities are cut out separately for each layer with a 355 nm UV picosecond laser ablation system (microSTRUCT C v2.0, 3D-Micromac AG). After the cavity fabrication, all processed LTCC layers are stacked and isostatic laminated (82°C, 21 MPa, 4 min). The substrate is sintered in a sintering furnace (PEO603, ATV Technologie GmbH). The temperature increases evenly until the maximum sintering temperature of 900°C is reached and held for 25 min. Finally, the sintered ceramic is mechanically cleaned with an abrasive sponge to remove particles and cut into the desired substrate dimension. Fig. 3 shows a schematic illustration of the integrated horn antenna structure in LTCC.

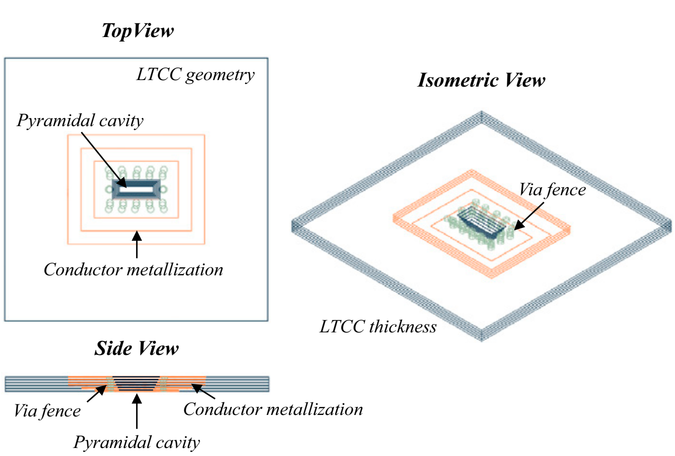

Fig. 2. Simulation model of the integrated horn antenna in LTCC.

Table I
Boundary Parameters for the LTCC Horn Antenna Structure Based on the Simulation Model

Parameter	Value
LTCC dimensions	10 mm × 10 mm
Ceramic thickness	0.35 mm – 0.4 mm
Conductor metallization	Gold (DuPont QR 150)
Via metallization	Gold (DuPont 5738R)
Via diameter	0.25 mm
Pitch via to via	equal to or greater than 350 µm
Cavity layer 1 [length × width]	1.3 mm × 0.25 mm
Cavity layer 5 [length × width]	1.7 mm × 0.65 mm

Design Consideration and Implementation

A. Cavity Fabrication Before the Sintering Process

The stepped cavities are realized in the green-state ceramic through a laser in each layer individually to create the desired design. Sharp corners of cavities can act as a stress concentrator and therefore initiate cracks during the sintering due to different shrinkage rates and thermal expansion mismatch. Rectangular cavities, rounded corners (100 µm diameter), and bone-shaped cavities (100 µm diameter) are investigated to determine the optimal geometry.

Considerations of the lamination and sinter set-up are crucial to maintain the cavity and guarantee high-quality results. To prevent the softened ceramic from flowing into the cavity during the melting phase, the substrate is placed with the widened opening facing upwards. A silicone mat is used for the isostatic lamination to ensure even pressure distribution and to protect the substrate surface. The pressure during lamination causes the silicone mat to be pressed into the first layers of the ceramic

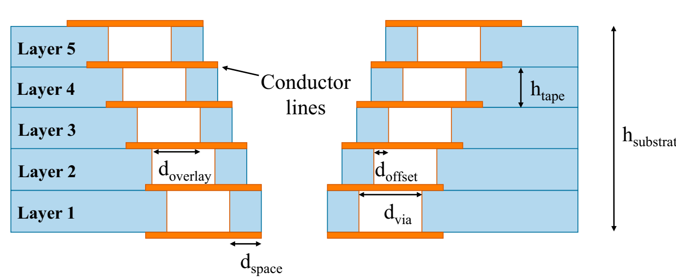

Fig. 3. Schematic illustration of the horn antenna in LTCC.

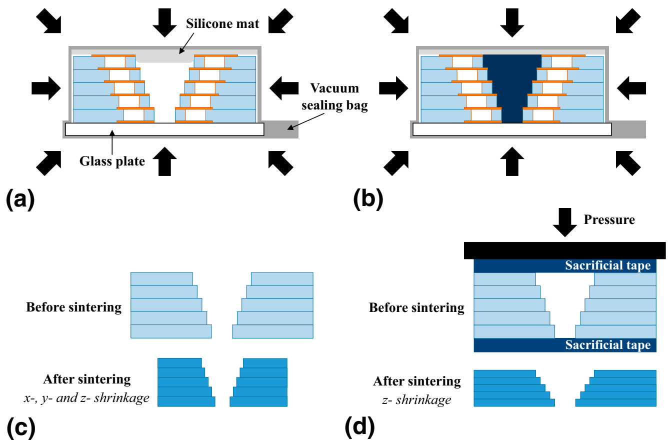

Fig. 4. Schematic illustrations of isostatic lamination without (a) and with carbon inlays (b), as well as free sintering (c) and constrained sintering with applied pressure (d) process [based on 4, pp. 695 and 707].

openings and deforms the edges of the cavities (Fig. 4a). The use of a cast silicone mat to stabilize the cavity during the lamination process was considered but rejected due to the small cavity openings. Throughout the fabrication process carbon tape inlays can be used to fill open space, this stabilizes the cavity walls and ensures the shape of the cavity (Fig. 4b). The inlays are inserted manually inside the ceramic cavities. Owing to the use of carbon inlays, the sinter profile had to be adapted and a 200 min holding phase at 580°C was added to burn out the inlays before the sintering phase.

Two types of sintering processes are available: free sintering (Fig. 4c) and constrained sintering (Fig. 4d). During the free sintering process, the ceramic is allowed to freely shrink without restrictions. This method requires a prior determination of the shrinkage percentage, which must be added to the initial design. Constrained sintering is achieved by laminating a sacrificial layer onto the LTCC and applying pressure during sintering, which restricts shrinkage in x- and y- direction and only allows shrinkage in the z-direction. A low pressure assisted sintering process with 4.6 kPa is typically used for SiCer substrates with fragile structures [5]. The constrained sintering method is used to maintain the shape and size of the LTCC substrate. Furthermore, an expansion of the design is not required.

B. Cavity Fabrication After the Sintering Process

Another option is the post-fabrication of the cavity after the sintering process, such as laser ablation [6] or milling.

In this article, cold laser ablation was investigated with an unstructured ceramic. The sintered ceramic substrate is mechanically cleaned before the cavity is produced. A 1065 nm picosecond IR-laser (Schmoll PicoDrill HyperRapid50) with a ~40 μm spot size and a laser power of up to 36 W was used. Thin layers of the ceramic material are removed by tracing several times over the contours (shown with a rectangular cavity). Laser parameters, such as laser power, number of repetitions, and line distances, are crucial for the result. To achieve the pyramidal structure, the laser process must be carried out in several steps.

To utilize a post-fabrication process for ceramic cavities for antenna purposes, a method for metallizing the cavity walls must be investigated. A physical vapor deposition (PVD) was chosen for the subsequent metallization of the sidewalls of the cavity. To determine the adhesion of the sputtered gold layer (PVD Cluster CS400ES, VON ARDENNE GmbH), a ceramic with a prefabricated cavity was used. The ceramic has been cleaned before the sputtering process to remove particles. Inverse sputter etching was performed before applying a 20 nm Ti adhesion promoter layer and a 200 nm gold layer. Both sides of the ceramic were sputtered.

Fabrication Results and Discussion

The various implementation methods of the desired cavity geometry were visually inspected throughout the entire manufacturing process and documented using microscopy. Fig. 5 shows a comparison of rectangular cavities that were produced before sintering without (a) and with carbon inlays (b), as well as their sintering results without (c) and with inlays (d). As expected, the intended cavity is severely deformed without inlays and sometimes even closed due to the high pressure during the isostatic lamination process (Fig. 5a), resulting in a semiclosed cavity after the sintering process (Fig. 5c). The placement of ~130 μm thick carbon inlays (Fig. 5b) proved to be a challenge due to charging effects or breakage during handling, but the sintering result (Fig. 5d) shows the advantage of this method.

X-ray examinations are done to determine the shrinkage inside the ceramic and the influence on the via fence alignment. Fig. 6 depicts x-ray images of different produced horn antenna structures in LTCC. The cavities of the free sintered ceramics closed during the sintering process, representative for all free samples shown in Fig. 6a. This can be explained by using the original design for this test trial without taking shrinkage into account. The aim of this experiment was to determine whether free sintering could be used for the intended application. Since the x-ray picture of the free sintered sample looks promising, further tests are carried out after the shrinkage behavior has been determined.

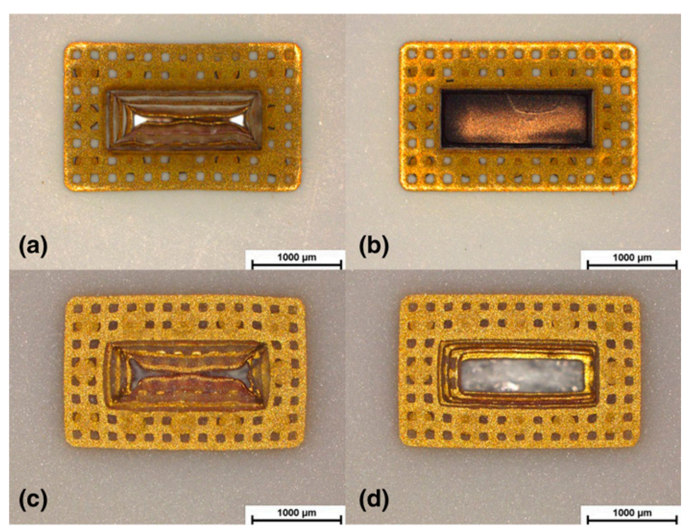

Fig. 5. Comparison of rectangular cavities produced in the ceramic green state without (a) and with carbon inlays (b) before the sintering and after the sintering process without (c) and with inlays (d).

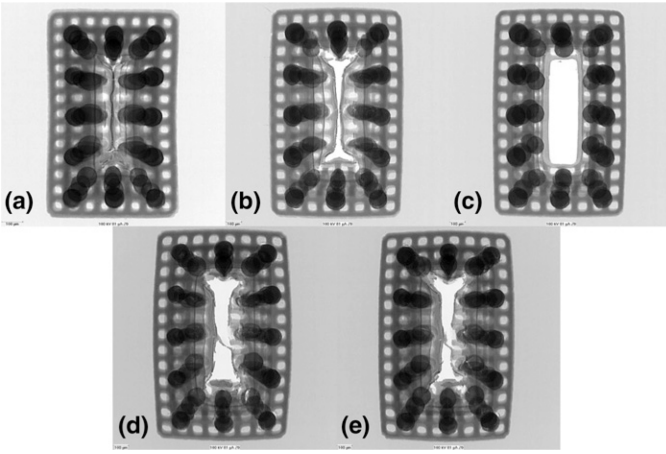

Fig. 6. X-ray examination of an integrated horn antenna structure in LTCC using different sintering methods (a: free sintered, b-e: constrained sintered) and cavity shapes (a-c: rectangular cavity, d: rounded corners, e: bone shaped cavity); processed without (a, b, d, and e) and with carbon inlays (c).

The images Figs. 6b and 6c are the same samples as shown in Fig. 5 and an increase in the via alignment due to the carbon inlays are visible. Both cavity designs with rounded corners (Figs. 6d and 6e) show connections between the opposing walls.

The x-ray results confirm the microscopic observations that carbon inlays significantly increase the quality of the cavity. All constrained sintered LTCC samples regarding the examined cavity design present distorted cavities without the use of carbon inlays and cannot be used for further investigations. A vast distortion of the via fence could not be noticed for any cavity design or fabrication method. However, the quality of the stepped horn cavity varies.

A cross section of a constrained sintered rectangular cavity with carbon inlays is illustrated in Fig. 7. The inclined via interconnects and the conductor lines between each ceramic layer as well as the stepped cavity are visible. Owing to the carbon inlays during the lamination and sintering process the cavity maintained its shape.

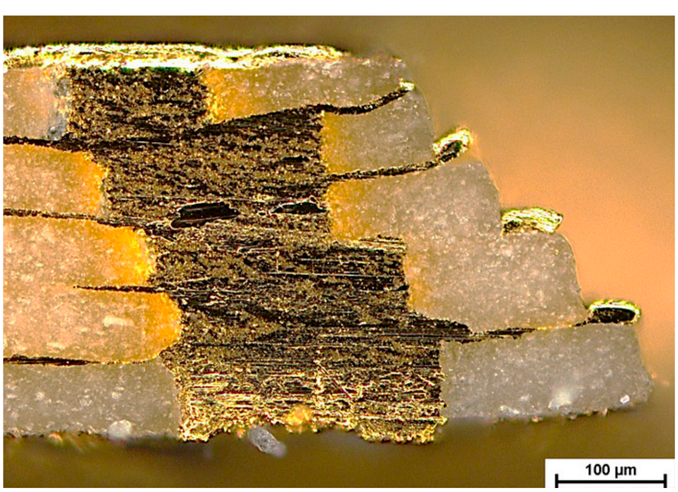

Fig. 7. Cross section of a constrained sintered rectangular cavity with carbon inlays during the lamination and sintering process.

The sputtered gold metallization on the ceramic visually appears to be a continuous layer. Electrical contact was verified using measuring tips on each side of the ceramic. The adhesive strength of the gold layer was tested with several tape pull-off tests. No peeling of the metallization layer could be noticed, indicating a reliable connection. The sample was inspected optically, a cross section was made and layer thickness was analyzed using SEM, see Fig. 8. The SEM examination showed that the conductor layer is closed, but the thickness varies between 72 and 325 nm depending on the position of the sample to the sputtering target.

To produce this horn antenna structure, a number of different laser parameters were examined, such as laser power, repetitions, line numbers, and line spacing. The laser ablation results were determined with a laser scanning microscope (Olympus LEXT OLS 4000, Olympus Europa SE & Co. KG). Fig. 9 presents a 3D laser-scanned surface (top) with the corresponding (averaged over 300 μm width) profile cross section. The laser power was adapted during the process to achieve consistent quality. A laser depth in the ceramic of ∼130 μm was measured with the laser scanning microscope. Although the cavity was not completely exempted throughout the ceramic thickness, the sidewalls show promising results.

In contrast to rounded sidewalls, slanted walls with a ∼41° angle for a width of ∼80 μm could also be achieved, as shown in Fig. 10. However, it should be noted, that at a certain point, the steepness increases dramatically up to >80°. Even though the angled sidewall is promising for the application's requirements, the sudden increase in sidewall angle points toward cracking, which is most likely due to not optimized parameters.

Although laser ablation parameters are not currently fully adapted for the target horn antenna geometry, the feasibility of inclined cavity sidewalls has been demonstrated using picosecond

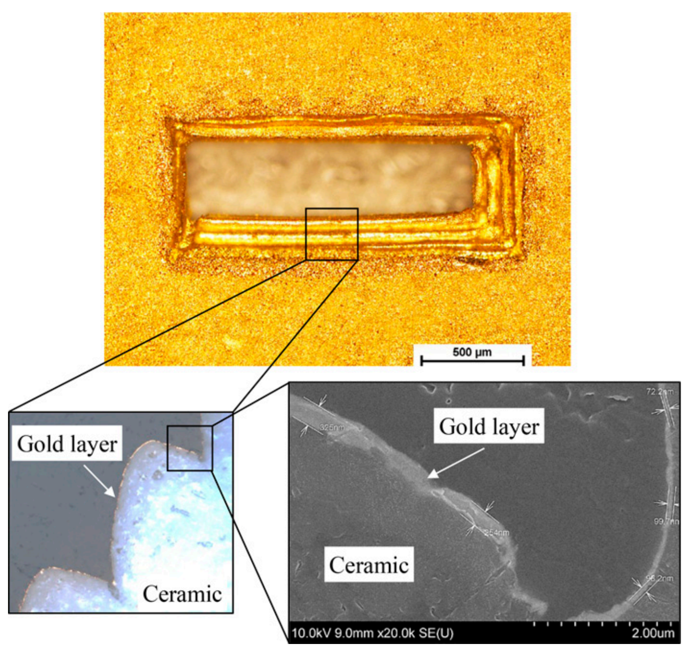

Fig. 8. Overview of a sputtered gold layer onto LTCC with a stepped horn cavity (top), cross section of the sample (left), and SEM examination with measured metallization layer thickness (right).

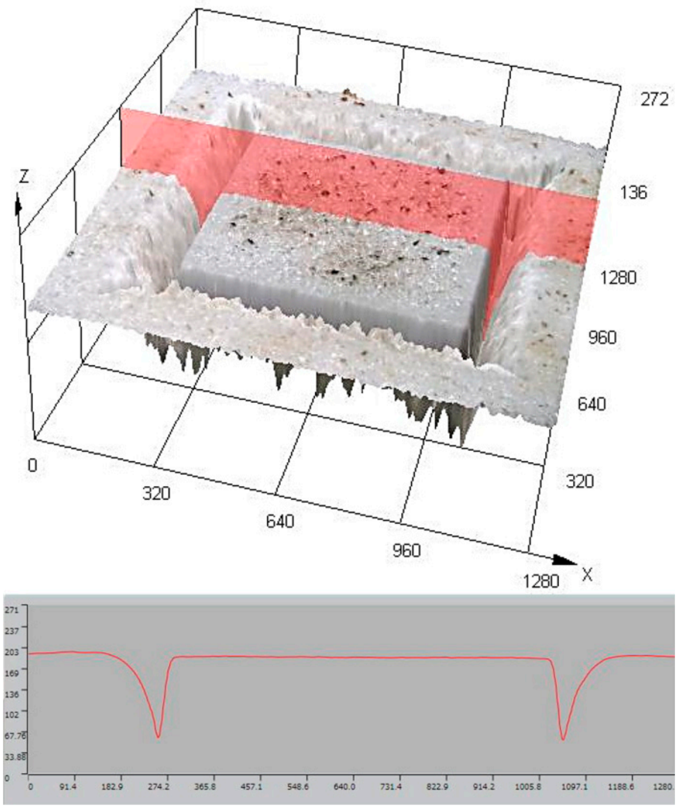

Fig. 9. Three-dimensional image of a laser-scanned surface after the generation of rounded cavity sidewalls with a ~130 μm deep laser cut into the ceramic.

pulsed laser ablation. To improve the achieved laser results, comprehensive optimizations are required.

By producing the cavity after the sintering process and applying the conductor layers the fabrication time of the green-state ceramic is reduced significantly and operator dependency decreases. In addition, the quality of the ceramic cavity increases since no influencing factors such as pressure during the lamination or sintering affect the cavity. To utilize the free sintering and post-fabrication method for the intended SiCer-implemented antenna application, additional sintering must be carried out to combine the ceramic with the manufactured MEMS structure in the silicon. By placing a green-state ceramic layer between the already processed materials both parts can be joined together through a sintering process. This method is called Substrate-on-Tape-on-Substrate and has been successfully demonstrated with SiCer-based differential pressure sensors [5].

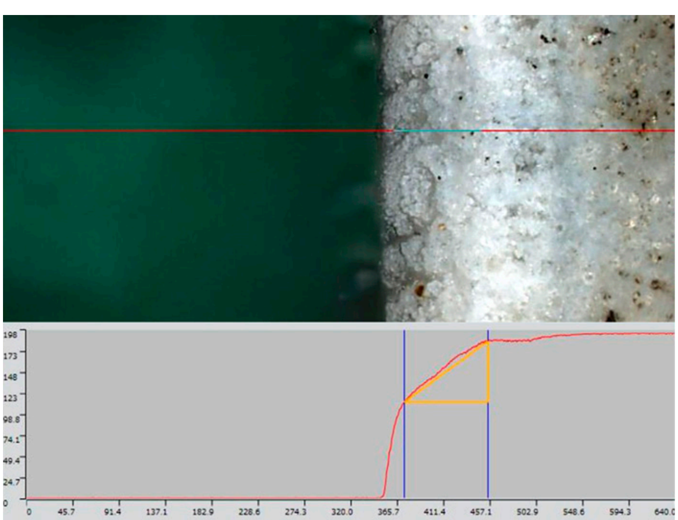

Fig. 10. Top view of the laser cavity (top) and the corresponding height profile (bottom) with determination of the sidewall angle.

Conclusion and Outlook

Fabrication methods for integrated horn antenna structures in LTCC with different cavity designs are presented. The fabricated horn antenna showed that the cavity consideration is essential to achieve a defect-free and ideal shape of the opening in the ceramic. Satisfactory results were achieved by constrained sintering with cavities fabricated in the green state of the ceramic and by using carbon inlays to maintain the cavity geometry during the fabrication process. Free sintering also showed promising results and after determining the shrinkage behavior and adjusting the design accordingly, a significant increase of the cavity quality can be expected. During the lamination process of the horn antenna structure before sintering, crooked and warped edges are inevitable due to manufacturing reasons. Further investigations and simulations are required to determine whether the deviation between the simulated model and the manufactured structures affects the antenna performance.

For prototyping and small batch numbers, carbon inlays proved to be a suitable solution to fabricate LTCC-integrated horn antennas. Cold laser ablation has proven to be a promising approach for producing such antenna structures on a larger scale. Furthermore, possible limitations in the antenna performance due to manufacturing-related deviations in the design could be avoided with this method. The obtained results will be integrated and examined in the future.

Based on the presented results further optimization of the antenna structure will be carried out in regard to weight reduction and increase of the antenna performance. The weight of the ceramic can be reduced by decreasing the ceramic dimensions and the conductor area. Changing the conductor metallization from gold to silver will increase the conductivity and lower the production costs of the integrated horn antenna structure in LTCC.

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