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An Improved Two-Stage Process for Laser Prototyping of Microwave Circuits in LTCC Technology

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***Abstract*—An improved technique for laser prototyping of microwave circuits in LTCC technology is presented. This builds on previous work which demonstrated that laser machining of conductor layers on unfired LTCC tape could be used to fabricate multilayer microwave circuits without any patterned screens, stencils or masks. The improved process employs post-fire patterning of the top and bottom layer. In this way, sensitive microwave structures like couplers and filters can be fabricated on the outer layers because shrinkage uncertainty is no longer a problem. Track widths and gaps of 30 µm are demonstrated with edge definition of ±2 µm. A stripline coupler is successfully fabricated using this technique. The improved process can produce high precision microwave and millimeter-wave components on the outer layers and provides rapid system-in-package prototyping for research and development.**

***Index Terms*— ceramics, laser applications, microwave circuits, multichip modules, thick film circuits.**

I. Introduction

THICK film screen printing is key to electronics manufacture and improvement in the pattern resolution has attracted the attention of many researchers. The moderate capital investment and low running costs make thick film a very popular technology for hybrid circuit fabrication [1-3]. The evolution in multichip module technology has led to the development of co-firing technologies - first High Temperature Co-fired Ceramic (HTCC) [4-6] and later Low Temperature Co-fired Ceramic (LTCC) fabrication have dominated the development of thick film technology [7-9]. These co-firing technologies have certain advantages which benefit the fabrication of multilayer multichip modules. Most importantly, the various layers can be processed in parallel and laminated together at the end before being co-fired. LTCC has the additional benefit compared to HTCC that it allows the use of high conductivity metals like gold, silver and copper, which are essential for low loss microwave and millimeter-wave passive elements. The applications of LTCC technology are not limited to electronic packaging but also include MEMS packaging, microfluidics [10-12], sensors, actuators [13-15], etc. Thus, technological advancement in LTCC technology benefits multiple fields and the integration of high frequency components is key for realizing a wide range of wireless sensing systems – particularly in harsh environments where ceramic materials have a significant advantage over organic-based substrate materials.

The traditional process of screen or stencil printing is commonly used in industry for making LTCC modules. Engineers have pushed the limits of the feature size for LTCC conductors to tens of microns [16-18]. The current industrial standard for conductor track width and coupling gap is typically 75 µm to 100 µm, although 50 µm design features have also been demonstrated using screen printing [19]. Various deposition and etching techniques have been proposed to achieve better design resolution. One of these techniques is photolithography which can result in design features of 25 µm to 50 µm [20-22]. Track widths of 10 µm have been demonstrated using photosensitive conductive paste [23]. The fundamental drawbacks of using photosensitive pastes are the need for a chemical developer, the use of high resolution masks for each layer and, usually, the requirement for a fabrication facility with a temperature and humidity controlled environment. This increases the fabrication costs and production time and the need for masks is a significant nuisance when prototyping small quantities of a multilayer design for R&D purposes. At the other extreme, processes like focused ion beam and nanolithography can produce submicron features but they require very high capital investment and tremendous expertise in usage. Various laser-based etching and deposition techniques also exist, such as pulsed laser deposition, laser assisted chemical etching, laser induced forward lift, laser chemical vapor deposition, matrix assisted laser forward lift, laser activated surface deposition [24-26]. Each technique has certain advantages and disadvantages ranging from fabrication cost to circuit fabrication time, which set limits to the application of each technique. These processes can, however, produce design features of a few microns [27].

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Laser machining has also been used for making micro-heaters by direct etching of conductors on LTCC green tapes to produce conductor track widths of 50 µm and gaps of 80 µm [28]. Recently, a novel technique of laser machining of unfired LTCC conductor was proposed [29, 30]. It was demonstrated for the first time that rapid prototyping of LTCC microwave circuits with several layers was possible – with circuits being fabricated in a few hours time without any chemicals or masks. In this technique, a uniform layer of metal paste is printed on the unfired LTCC tape, dried, and then the desired conductor pattern is directly machined using a laser, obviating the need for patterned screens, stencils or masks. As well as reducing the cost and turnaround time for one-off prototypes, this makes layout changes on any particular layer straightforward for design iteration. In this previous work, track widths of 50 µm and gaps of 50 µm were demonstrated with an edge definition of ±5 µm.

In this proposed enhancement to the laser machining prototyping technique, the laser patterning is conducted in two stages; the inner layers are machined as before in the unfired state, whilst the outer layers are patterned post-firing. The minimum strip width and gap on the top layer have been reduced to 30 µm by using this modified technique. The edge definition has also been improved to ±2 µm, meaning that designs with high impedance lines on thin LTCC sheets can be realized, reducing the need for dummy layers. A major limitation in the performance of LTCC microwave circuits comes from the shrinkage characteristics. The shrinkage of LTCC tape is predictable within a certain margin of error but still leads to unpredictable results, especially for tight coupling structures and filters. By using this two-stage technique, the most critical structures can be made on the outer layers, avoiding the problems of shrinkage and the resulting fabrication tolerance issues. For microwave and millimeter-wave circuits this is an important improvement because the outer layers can then be used for the more critical components.

II. Process Overview

The process is similar to traditional LTCC circuit fabrication but the screen or stencil printing stage is replaced by laser machining. This alternative technique of patterning conductors on unfired LTCC tapes has proved to be very efficient, fast and cost effective [29]. The laser ablates the selected portion of the metal layer leaving behind the required conductor layout on the substrate. Careful optimization of the laser parameters is required to remove metal effectively without damaging the substrate underneath. The optimization procedure for the laser parameters has been discussed previously [29] and once these have been established the technique produces commendable results.

In the improved process, each sheet of LTCC substrate was preconditioned in a laboratory oven at 120°C for 30 min to undergo the initial shrinkage. The sheets were then separately placed in the laser machine to make the via holes and fiducials for alignment. The laser machine used in the experiment was the LPKF ProtoLaser 200™. The specifications of this laser are given in Table I. The vias were then filled with a screen printer, with the protective covering on each sheet used as a via filling mask. The bleeding of vias does not matter at this stage as the sheets are screen printed again with a uniform coating of conductive metal layer. The via filling mask was then removed and a thin layer of conducting paste (DuPont HF612) was printed uniformly. A standard 280 mesh screen with emulsion thickness of 10 µm was used. The sheets were then dried in an oven at 80°C for 10 minutes. The print resulted in a nominal dried metal layer thickness of 20 µm. After cooling, the sheets were loaded in the laser machine and the desired conductor pattern was machined on each layer, one by one, except for the top layer. The patterned layers were then aligned and stacked and they were then placed in an isostatic laminator (Keko ILS-4) and laminated together at 300 bar for 10 min in warm water at 70°C. After lamination, a standard firing profile was used to sinter the ceramic and conductor paste by burning out carbon at low temperatures of 600°C followed by ceramic sintering at around 850°C. The stack was left to cool down naturally prior to laser machining the top conductor layer. The fired stack was loaded in the laser machine and top layer was patterned - with proper alignment to the layers underneath using vias, as discussed in Section III. The whole two-stage fabrication process is shown in Fig. 1. The final circuit can be re-fired to remove carbon residuals form the top surface if needed.

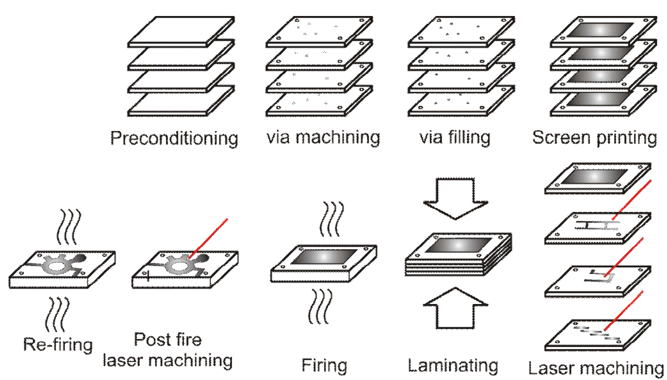

Fig. 1: Two-stage laser machining process steps

III. Alignment Technique

The main challenge with this new technique is the alignment of top layer features with the layout on the layers underneath. The buried layers are machined and fired before the top conductor layer is printed and patterned. The layout on the inner layers was compensated for the predicted shrinkage of the LTCC tape by over-sizing it by the nominal x-y shrinkage percentage. This means that the fiducial positions change after firing. In any case, alignment fiducials waste substrate space. A rather elegant solution is proposed in which vias are used as reference markers. Since the vias on the top layer are machined and filled before firing, so their position is compensated at the layout stage to take shrinkage into account. After firing, all vias and the design features on inner layers should, ideally, return to their desired locations. The vias on the top layer can, therefore, be used as alignment marks for the top layer conductor patterning. This results in a very accurate alignment of top layer features with respect to the layers beneath.

TABLE I
LASER PARAMETERS

Wavelength (nm)	Maximum power (W)	Maximum pulse repetition rate (kHz)	Maximum machining speed (mm/s)	Focal diameter (µm)	Beam profile
1064	13	100	1000	25	square

IV. Post-Fire Etching Analysis

The post-firing laser machining is not very different from the unfired laser machining but further optimization of the laser parameters was required since the material properties are quite different. This optimization was carried out in a similar way to the original process on unfired material [29]. It was found that, since the organic vehicles are removed from the conductor during firing, the laser energy was better confined in the conductor resulting in better design resolution. The laser pulse energy was varied and the sample was analyzed with a surface profiler (KLA Tecknor) to analyze the penetration depth and penetration width in the post-fired conductor. The laser fluence was varied from 2 J/cm^2 to 3.7 J/cm^2 and the penetration depth varied accordingly from 4 µm to 9 µm. The result is given in Fig. 2.

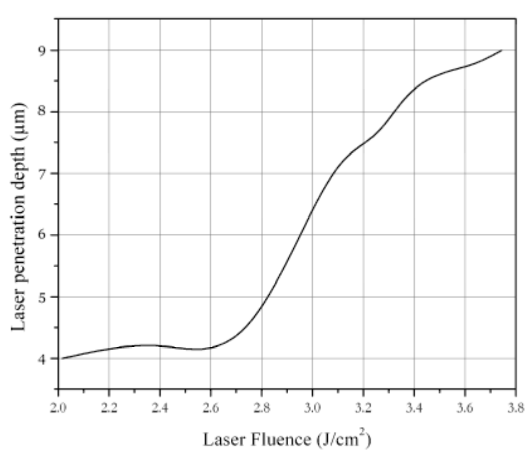

Fig.2: Laser penetration depth vs. laser fluence, for fired conductor

Since the post-fired conductor layer is 12 µm thick, complete removal of conductor from the base of ablated channel cannot be achieved even at the laser fluence of 3.7 J/cm^2. However, higher energy degrades the minimum achievable resolution by increasing the channel width. Hence, the laser energy was not increased any further but instead the processing cycle was repeated at low power in order to completely remove any residues of conductor from the bottom of the channel. Various conductor free channels were etched by sweeping the laser fluence from 2 to 3.7 J/cm^2. These channels were then analyzed for the laser penetration width by using a surface profiler. The profiler results showed that the channels were *V* shaped as illustrated in Fig.3. As the fluence was increased, the base of the channel started broadening and Fig. 3 shows how the cross-sectional shape of a channel changes from *V* to quasi-*U* for fluence of 2.0 J/cm^2, 2.8 J/cm^2, 3.2 J/cm^2 and 3.65 J/cm^2.

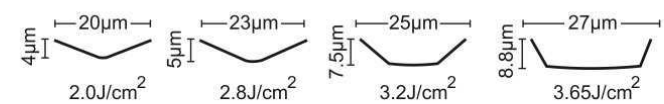

Fig 3: Illustration of the laser energy penetrating phenomenon

A comparison of channel width for different laser fluences, shown in Fig. 4, demonstrates the change in profile with laser power. It was observed from the surface profiler results that the mean width (MW) of the channel at the top (entry position) and channel bottom when compared to the physical width at half of the penetration depth (HPD) were not equal. The MW occurred above the width at HPD. This result is shown in Fig. 5.

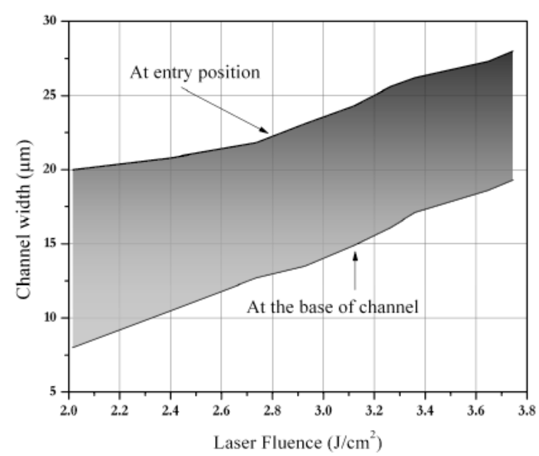

Fig. 4: The width at the entry and the base of the conductor channel vs. laser fluence

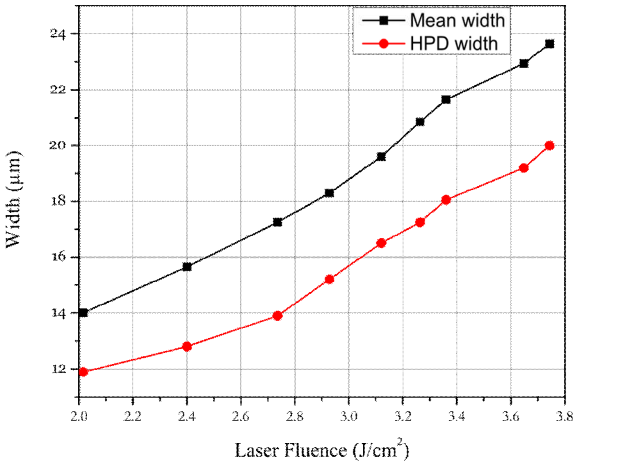

Fig. 5: Mean width comparison with the width at half of penetration depth

This observation showed that the walls of the channels were curved, as shown in Fig. 6 (a), not straight. The cross-sectional shape of the channel can be approximated by two straight lines, with the lower lines tilted at an angle θ_1 to the vertical and the upper ones at an angle θ_2, where $\theta_2 > \theta_1$ as shown in Fig. 6 (b). This is a valid approximation since the channel is machined in multiple laser machining cycles so the entry of the channel is exposed to laser energy more times than the portion at the bottom, giving a wider profile on entry. The minimum resolution with optimum edge definition is thus achieved by repeating the laser machining cycle more than once. Once the desired layout features were isolated completely at the bottom of the channels, the remaining unwanted bulk conductor area was removed by laser sublimation of conductor, leaving behind only the desired conductor pattern on the LTCC substrate.

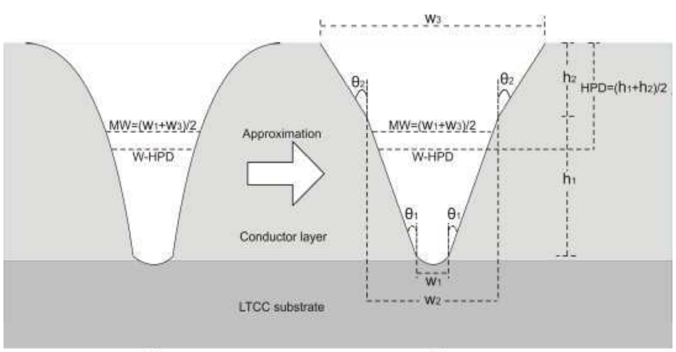

Fig. 6: Cross-sectional profile of a laser ablated conductor channel (gap)

V. MINIMUM RESOLUTION

After a few optimization steps, conductor tracks with widths of 30 µm and gaps (channels) of 30 µm were achieved with an edge definition of ±2 µm. The channels were machined in two cycles: In the first cycle, a laser fluence of 3.4 J/cm^2 with machining speed of 200 mm/sec was used; for the second cycle, a laser fluence of 3.2 J/cm^2 with machining speed of 220 mm/sec was used. A photograph of the resulting conductor tracks and gaps are shown in Fig. 7. The edge of a track produced with the optimized process is presented in Fig. 8. The gap and conducting tracks are shown in Figs. 9 and 10 with higher magnification.

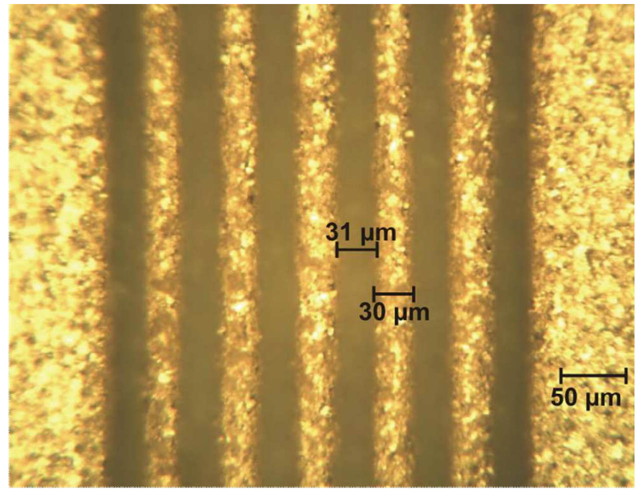

Fig. 7: Conducting tracks of 30µm and gaps of 30µm observed under 200 X magnification

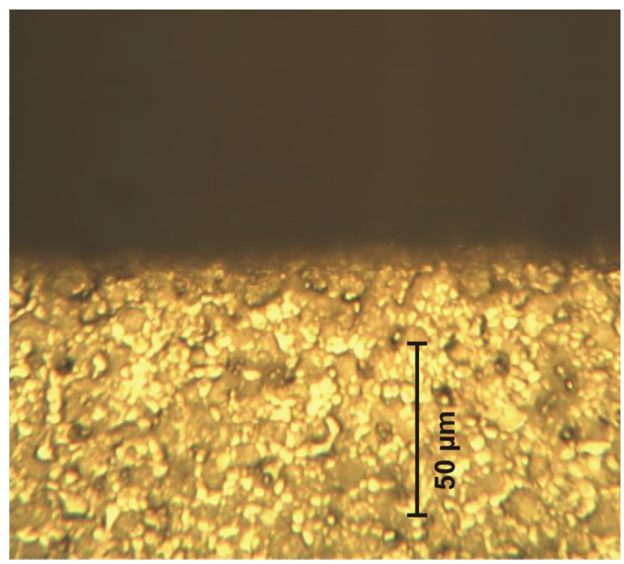

Fig. 8: Edge of a conductor observed under 400 X magnification

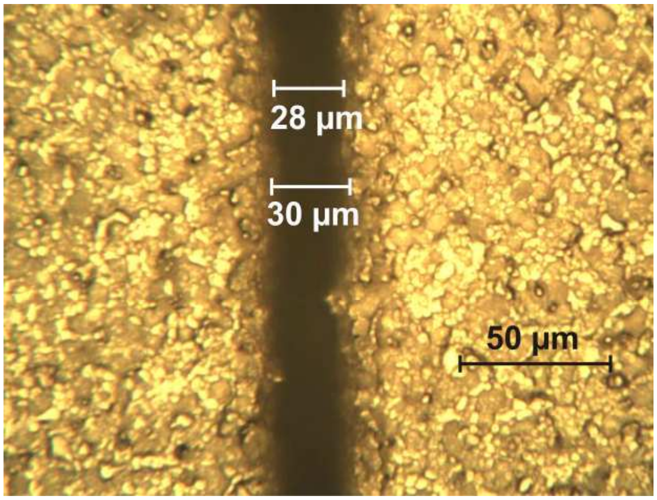

Fig. 9: Coupling gap of 30 μm observed under 400 X magnification.

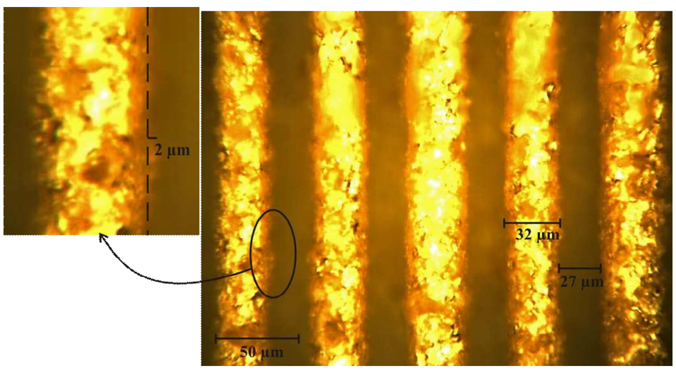

Fig. 10: 30 μm tracks and gaps under 400 X magnification

The surface profiler plot for the 30 μm tracks and gaps is presented in Figs. 11 and 12 to more accurately study the width and gap of the channel. It can be observed from Fig. 11 that the width of the channel is nominally 30 μm. The width of the track can be observed in Fig. 12 and is nominally 32 μm. The dotted line in Figs. 11 and 12 shows the boundary between the conductor layer and substrate underneath, and it can be observed from the two figures that the conductor was completely removed and the tracks were properly isolated.

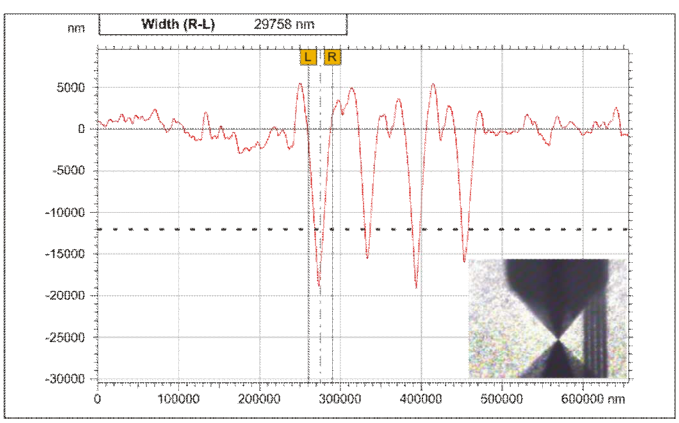

Fig. 11: Channel width as measured with a surface profiler

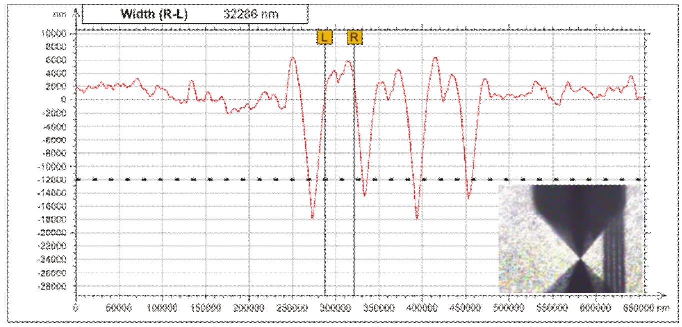

Fig. 12: Track width as measured with a surface profiler.

VI. Stripline Branch-line Coupler Fabrication

In order to successfully demonstrate prototyping of a microwave circuit using the two-stage patterning technique, a stripline branch-line coupler was designed and fabricated. The purpose was to confirm that alignment of the top and bottom layers with the middle conductor layer in stripline could be achieved and that improved conductor definition could be achieved on the top layer. The two ground planes were connected by multiple grounding vias to ensure proper grounding. The four input/output ports of the structure were connected to microstrip lines on the top layer for measurement purposes. A diagram illustrating the stripline branch-line coupler is shown in Fig. 13.

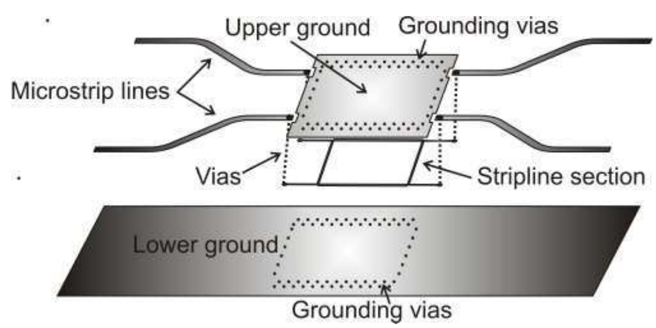

Fig. 13: Schematic illustration of stripline branch-line coupler

The middle layer, with the stripline signal conductor, was machined in the unfired state in the first machining stage. The structure was then aligned with the top layer using alignment fiducials on the corners so that the grounding vias connect both ground planes. The lamination is critical in the process since we have fully metalized layers on both top and bottom sides so if lamination is not carried out carefully there would be wavy or bendy edges of the substrate after firing because of the mismatch between the sintering temperature of the conductor and the LTCC tape. After lamination, the alignment holes were cut off the substrate to make it compact. The structure was then sintered in the furnace.

After firing, the circuit was cooled to room temperature and it was loaded back into the laser machine for the machining of the top layer. The vias used to connect the stripline coupler tracks to the top layer microstrip were used as alignment marks, although in principle any vias available in the design can be used for this purpose. The four encircled vias used for alignment between layers are indicated in Fig. 14.

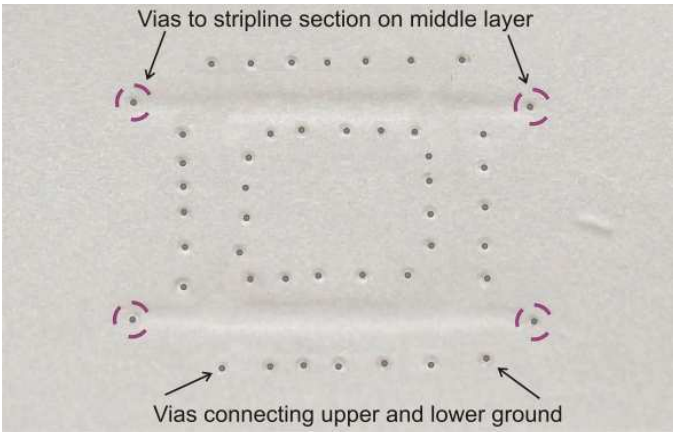

Fig. 14: Photograph of the fired coupler, viewed from the top

The top layer was then machined using the laser parameters given before. The dry laser ablation of the top layer resulted in sublimation and it left behind some micro-carbon particles. The device may be re-fired below 600ºC to remove this carbon, but re-sintering is not required. The final fabricated circuit with SMA connectors is shown in Fig. 15. The coupler was tested using an Agilent Technologies E8361A PNA. The magnitude result of the coupler is shown in Fig. 16 and the phase response is presented in Fig. 17.

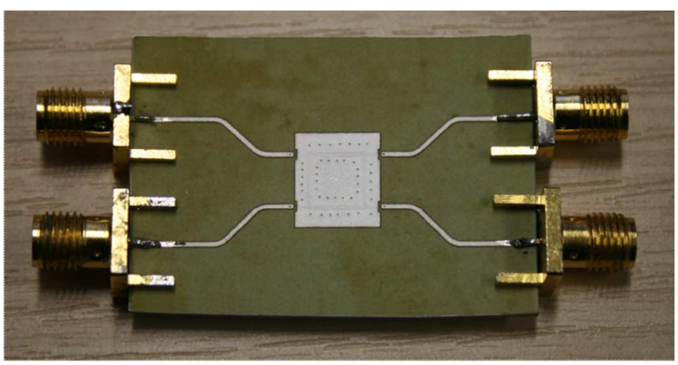

Fig. 15: Final structure after two laser machining stages

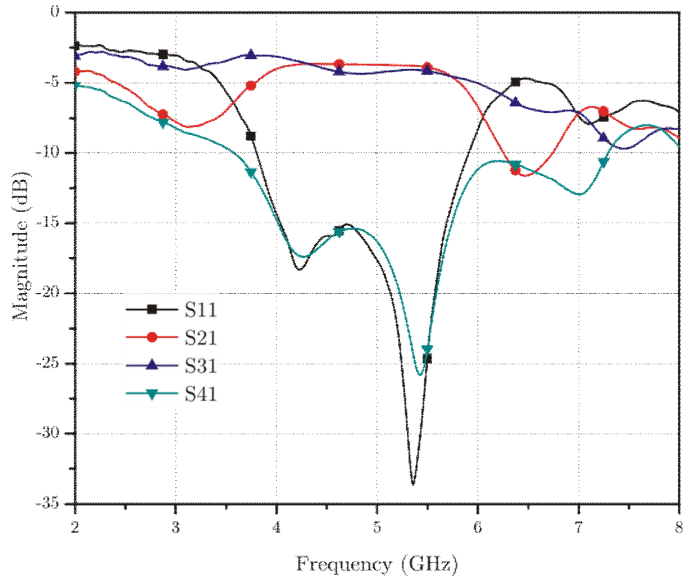

Fig. 16: Measured response of the coupler

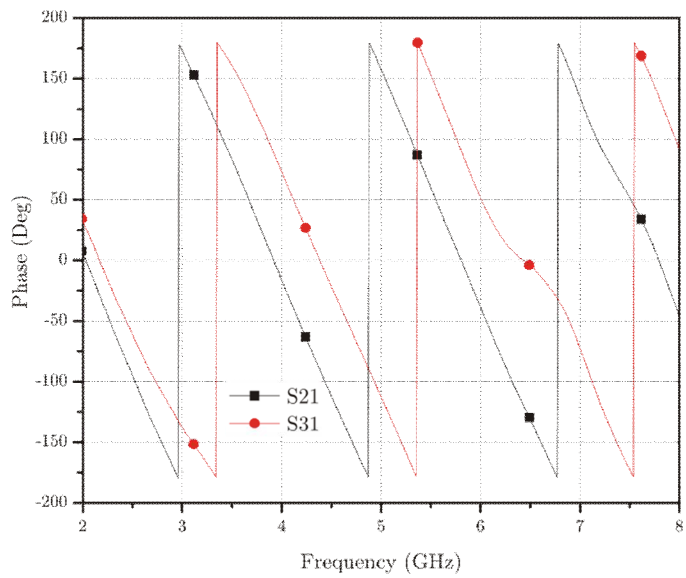

Fig. 17: Measured phase response of the coupler

VII. Conclusions

An improved rapid prototyping technique for LTCC microwave circuits has been demonstrated using a new two-stage machining process. By patterning the outer layers post-firing, improved conductor definition is achievable and critical components can be realized with less concern over shrinkage effects. The technique results in an improved minimum resolution of 30 μm for conductor tracks and gaps with the edge definition improved to ±2 μm. The technique was optimized using test patterns with various laser powers and writing speeds. A stripline coupler has been designed and successfully fabricated using the two-stage process. With high-precision structures now possible on the top and bottom side of the substrate, this technique is expected to be of great benefit for microwave and millimeter-wave system-in-package applications.

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