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RF COMPONENTS BASED ON ADVANCED ADDITIVE TECHNOLOGIES

N. DELHOTE, O. TANTOT, S. VERDEYME, S. BILA, D. BAILLARGEAT
*XLIM UMR 7252, University of Limoges/CNRS,
123 Avenue Albert Thomas, F-87060 Limoges, FRANCE*

F. ROSSIGNOL, T. CHARTIER
*SPCTS UMR 7315 CNRS, Université de Limoges/CNRS,
12 Rue Atlantis, 87060 Limoges Cedex, France*

ABSTRACT: Recent advances on rapid prototyping technology allow the fabrication of RF electronic devices on flexible substrate materials but also on ceramic and other bulk materials using electrically functional inks. In this paper on the fabrication of RF components using metallo-dielectric based inkjet technology and Ceramic based stereolithography. Several applications are considered. Fabrication and experimental works are described.

I. INTRODUCTION

For supporting future needs in high frequency electronics, it is necessary to develop new technological approaches. In terms of integration, main requirements are to be able to manufacture complex 2D and 3D miniature structures and to mix dielectric materials and metals. LTCC (Low temperature co-fired ceramic) [1] is a possible approach. It allows the use of low temperature fired ceramic material and high conductivity metals (gold, silver). But this technology presents some limitations: component manufactured by LTCC are made by the stacking of single tape therefore limiting the achievable geometries (2.5-D configurations instead of true 3-D). Blind holes, tranches or metallic walls could not be easily made (even if close solutions are proposed like via fences instead of metallic walls). Moreover, it is extremely difficult to mix dielectric materials. The stereolithography technology (SL) fulfills this goal under specific constraints. This latter consists in manufacturing of complex components in 3D [2-4]. Up to now, this technology is based on one dielectric manufacturing and the combination of metallic and dielectric materials in single one fabrication step is not available yet. Recent advances in inkjet printing technology allow the realization of complex metallo-dielectric structures in a one-step fabrication [5-7]. Using such approach we aim to manufacture innovative high frequency components to gain compactness, performance and flexibility in design. One of the challenges we have to face up, is to optimize a dielectric ink which can be cured at low temperature ($\sim 900^{\circ}\text{C}$) and thus being compatible with high conductivity metallic ink like silver nanoparticles ink. In this context, two ceramic based additive technologies are described in this paper: (1) An ink-jet printing approach, with a first printing test of multimaterial and multilayer components based on silver nano particles and low temperature fired ceramic material inks. (2) A ceramic based SL technology dedicated to RF component fabrication. As shown, both ink-jet printing and SL technologies are candidate to be alternative technologies for future RF components.

II. INKJET TECHNOLOGY

A. Inkjet Printing Principle

This technique is based on the superposition of thin layers of diverse materials in order to build 2D or 3D component, using multi nozzle piezoelectric printheads delivering precise volume of ink droplets (few pL) on a substrate (Fig. 1).

Fig 1. inkjet printing technology principle.

Fig 2. CERAPRINTER Xseries

This technique allows the use of functional ink which can contain dielectric or metallic particles (conductive ink). It is versatile and shows a good precision of realization thanks to the fully automatization of the whole printing process.

B. The Printing Equipment

The printing system is a high accuracy and versatile Drop-On-Demand 3D multimaterial printer: CERAPRINTER X-Series, designed and manufactured by CERADROP for digital manufacturing of components (printed electronics and new energy sources). The equipment is based on a patented technology that can print on up to 4 materials with any discrete resolution thanks to automated printhead switching and orientation. The system is built around industrial printhead technology, thus allowing high process repeatability, high jetting accuracy and a wide range of material compatibility. The system includes all the necessary features for high-level R&D, pre-production work and small batch manufacturing thanks to the development of two different softwares: (1) an automated jetting analysis software which generates a full report on jetting quality, (2) a CAD/CAM software for component design and printing job definition that takes into account all the process parameters. Thanks to its bottom-up approach, printing parameters can be defined according to material and component design characteristics (splat diameter, layer thickness, filling strategy, droplet pattern, etc.). In addition, the software features a simulator that allows the user to view the print script and quickly identify potential issues. An IR drying system helps evaporating solvent into the printed layer between two or several successive deposition steps.

The ink thickness of typical printed silver layer on a substrate is $3\mu\text{m}$. We can increase this thickness by printing more layers. A curing step is then needed to burn the chemicals composing the ink (mostly water, dispersant and viscosity adjusting chemicals) to get a $2.4\mu\text{m}$ thick layer for the case of silver ink.

C. Characterization of the metallic ink (silver ink)

We first test the inkjet technology with the printing of different patterns and transmission lines. The printed objects are made with aqueous nanosilver ink using 256 printheads each having a diameter of $40\mu\text{m}$ on alumina substrates ($\epsilon_r = 9.1$ and $\tan \delta = 0.0001$ at 10 GHz) as seen in Figure 3.

Fig 3. Printing of 2D object with a silver based ink.

C.1 Inkjet printing accuracy

The observed fabrication accuracy of the inkjet technology is between 10 and $20\mu\text{m}$ depending on the geometry of the printed objects, the circular patterns being the most difficult to print. The minimal achievable gap is $38\mu\text{m}$ and the minimal line width is $32\mu\text{m}$.

C.2 Gaps between two metallic lines & Minimal width for a metallic line:

Fig 4. Gaps between two metallic lines

Fig 5. Minimal width for a metallic line

To test the minimal gap that can be achieved applying this technology, we print a pattern (Fig 4) with different gaps starting from a minimum of 10μm to a maximum of 2000μm. We obtain a minimal gap equal to 38μm with an average deviation between the measured value and the theoretical value is equal to 17 μm. Using the same process, we print a metal rectangular pattern having different widths (Fig 5) in order to determine the minimum width that can be printed, starting from a maximum of 2000μm till a minimum of 10μm. The minimum experimental width obtained is equal to 32μm with an average deviation between the measured value and the theoretical value is equal to 11 μm.

C.3 Circular gaps between two metallic parts and Minimal width for a circle model:

Fig 6. Circular gaps between two metallic parts

Fig 7. Minimal width for a circle model

We print many patterns with several forms like circles and negatives circles. Then, in order to find the minimum gap between two circles, we print several gaps with different width and the minimum obtained gap is equal to 40μm with an average deviation between the measured value and the theoretical value is close to 25 μm. For a circle geometry (Fig 7), the minimal printed value is 40μm with a mean deviation equal to 24μm. The circular shapes are thus typically harder to draw than rectangular ones. This is mostly due to the fact that 2D printing surfaces are composed of small circular droplets, making circular shapes more difficult to fill than rectangular ones.

C.4 Collision of the metallization

Fig 8. Homogeneous distribution of ink on a surface with roughness = 0.3μm

Fig 9. Heterogeneous distribution of ink on a surface with roughness = 0.9μm

To test the collision of the ink on the substrate, a particular attention on surface roughness is necessary. Figures 8 and 9 present the distribution of printed ink dots on two different surfaces with different roughness. In figure 8, we obtain a homogeneous distribution of ink, and the diameter of drops is the same on the entire surface presenting a roughness of 0.3 μm. We can conclude that we have a good precision and an excellent collision with a typical droplet diameter close to 35-40μm. However, in figure 9, the roughness is higher (0.9 μm), the distribution of ink is heterogeneous and some droplets are connected (not a desired behavior), so the collision test has a direct relation with the roughness. The fabrication tolerance of the inkjet technology is here again roughly equal to 20μm.

D. Printing of dielectric ink and RF components

D.1 Dielectric ink

We describe the fabrication of a multilayer structures using metallo-dielectric based inkjet technology. The first test is to print multilayer-capacitances. The structure itself is rather simple but is representative of many technological challenges. Firstly the metallic and dielectric inks should have the same firing temperature. Then, if we want to keep using the high conductivity silver ink, a low temperature firing ceramic material should be carefully used because the silver ink cannot

endure firing temperature more than 900°C. Finally, during the co-firing of the metallic and dielectric layers, the different materials should present the same shrinkage otherwise cracks can appear. Considering these different elements, the selected dielectric material has been the LTCC 51K65 from Heraeus (Germany) because of its low firing temperature of about 900°C and the size of its particles, mostly around 1µm. This material has been chosen because it shows interesting permittivity and loss tangent at microwave frequencies (at 1,824 GHz, $\epsilon_r = 68$, $\tan \delta = 1,20 \cdot 10^{-3}$; at 10,711 GHz, $\epsilon_r = 64$, $\tan \delta = 1,84 \cdot 10^{-3}$)

D.2 Printing of 3D Multilayer And Multimaterial Capacitance

We fabricate a MIM capacitance. This capacitance is presented in Figure 10. A short coplanar section is added for measuring the MIM capacitance Z_{11} parameter.

Fig 10. (a) 3D view and fabricated inkjet capacitance: (b) first metal layer, (c) dielectric layer, (d) final top metal layer.

Fig 11. Measured and simulated Z_{11} responses

The dimensions of this capacitance are 0.9 mm x 0.9mm with a total thickness of 30µm. In order to extract the dielectric constant and loss tangent of the dielectric layer as well as the capacitance of this component, the measured Z_{11} is compared to the simulated value (Fig 11). 22 capacitances have been measured, showing a very good reproducibility of the process. The extracted dielectric constant and loss tangent is 63.3 and $2.1 \cdot 10^{-3}$ respectively. The measured capacitance of 2 pF at 20 GHz is close to the simulated value which is 1.3 pF.

D.3 Interdigital and multilayer interdigital filters

We report here the printing of a band-pass filter and multilayer-interdigital filter mixing silver nanoparticles and low temperature fired ceramics based inks. The multilayer version being proposed to 80% of saves foot print for an equivalent behaviour at 800MHz. A first prototype printed and tested at 800 MHz is presented. The filter is printed by ink jet technology on alumina substrate as shown in figure 12 with a fabrication tolerance of the inkjet roughly equal to $\pm 20\mu\text{m}$.

Fig 12. Interdigital filter printed by ink jet technology.

Fig 13. Measured and simulated S_{11} and S_{21} responses

As shown is figure 13, the center frequency of the printed filters 722MHz and the bandwidth remains is equal 250 MHz. It exhibits an insertion loss of 3.2 dB and a return loss of 16 dB. Figure 13 also shows the simulated filter response taking into account the measured dimensions of the printed filter and on equivalent conductivity of about 15 S/μm for all the metal part of the filter. These simulations closely match like measurement response.

The last part describes the 3D ceramic stereolithography process and its ability to use several ceramic materials for the manufacturing of 3D complex parts.

III. CERAMIC BASED STEREO LITHOGRAPHY

Stereolithography is a fast prototyping technique which allows the fabrication of three dimensional structures with an average manufacturing accuracy close to 50 μm. This is an additive process, which requires no mask, no molding, or any special tooling [3]-[4]. The first step is to create a 3-D CAD file corresponding to the desired 3D object. Using this file which presents an accurate image of the structure, 15 to 200 μm thick are created and will be physically manufactured by spreading over a working surface a paste composed of ceramic particles in a monomer. The first layer paste is polymerized by a UV laser with a 30 μm spot size which draws the pattern corresponding to the first slice of the 3D object. The second layer of this paste is then deposited on the previous polymerized layer. This process is repeated until the 3D object is finished. Finally the 3D ceramic object is debinded and sintered through several baking cycles. Several 3D ceramic based structures dedicated to RF front end for space applications are studied. We present here fabricated components and the associated electrical behaviors.

A. BMT based six pole filter

Fig 14. Design of 6 pole filter

Fig 15. Fabricated resonator. Proof of concept.

This filter is based on a ring Dielectric Resonator. The design is optimized to obtain a high unloaded Q factor around 9000 at 11GHz. The filter is described in Figure 14 with 6 coupled resonators. Figure 15 presents the elementary fabricated ceramic based resonators as proof of concept. We use BMT $\epsilon_r=24.4$, $\tan \delta < 0.9510^{-4}@11\text{GHz}$, $\tau_f \sim 2.56 \text{ ppm/C}$ (+5MHz pour $dT=45^\circ\text{C}$) as ceramic material.

B. 3-D pyramidal and collective Ku band pass filters made in Alumina by ceramic stereolithography

A 3D pyramidal geometry for a low loss and compact (10.5 mm by 10.2 mm by 2 mm) filter is fabricated. Nine low footprint Alumina filters are manufactured in one single fabrication by a 3D ceramic stereolithography process. Thank to this technology, high unloaded quality factor resonators (above 1000) have been fabricated and associated to create a low footprint 4-pole Chebyshev filter. Its shielding are created with a Copper and Gold sputtering technique and its

input and output coplanar accesses are etched by a laser ablation technique. The association of these 3D technologies for the collective manufacturing of many filters in one ceramic part, lead to a low insertion loss filter working around 17.5 GHz. The manufactured filter is described in Figure 16. Figure 17 presents the electrical behavior and validates the poof of concept.

Fig 16. Ceramic based RF filter (elementary resonators / final filter)

Fig 17. Experimental electrical behavior

IV. CONCLUSION

This paper describes two specific manufacturing techniques dedicated to the fabrication of 2.5D and 3D RF components : multimaterial inkjet printing and ceramic stereolithography. These technologies are specifically developed in the University of Limoges with low loss ceramic materials, specifically chosen because of their interesting properties in the RF range: high permittivity, low loss, high mechanical strength and temperature stability. These materials are suitable for space but also for mass product applications. As described, we think that both multimaterial ink-jet printing and ceramic stereolithography are candidate to be alternative technologies for future RF components.

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