Collective fabrication of LMST thermally-stable surface-mount ceramic devices for millimeter-wave bands

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***Abstract* — A CMOS-like collective fabrication is implemented in laser-machined ceramic substrate technology (LMST) to enhance the manufacturing process of passive components based on ceramic materials. Several Chebyshev filters were developed with this approach for communication applications operating at 26 and 42 GHz. Thermal characterization tests were performed on regular Alumina and thermally-stable LMST filters to determine the feasibility of their use in communication systems under harsh environments. A transition design strategy compatible with the process is introduced for both device testing and surface-mount implementations.**

***Keywords* — LMST, micro-machining, surface-mount, ceramic filters, thermal stability, millimeter-wave, 5G.**

I. Introduction

Unlike SIW technology, the structures conceived with LMST are directly carved into the substrate creating trenches and supports [1]. This approach provides high flexibility for the conception of micro-machined discrete surface-mount components or monolithic subsystems developed on ceramic substrates. Ceramic materials present good performances in terms of loss tangent and require less area thanks to their permittivity. Besides, their ability to withstand fluctuations in temperature, dissipate heat and remain functional at high operating power levels and temperatures make ceramic materials an interesting choice for reliable devices under harsh conditions. Nowadays spacecraft systems, satellite communications links and military applications demand high performance devices working in a wide temperature range (–55°C to 125°C). Even more, temperature issues were reported in the first generation of 5G mobile phones as a consequence of the high data rate [2].

There is a constant necessity for electronic devices to provide better features in terms of area, performances, reliability and cost for these applications. In the case of ceramic technologies, they are usually more expensive than SIW devices manufactured in organic PCB substrates and rather costly for large-scale production. Hence, affordable fabrication strategies are required to reduce the manufacturing costs. In CMOS processes, scaling and collective fabrication have been widely used in the semiconductor industry to increment the density of integrated circuits and maximize the profits [3]. The high permittivity inherent to ceramic materials could contribute to enhance the scale of integration. Besides, the implementation of collective fabrication in LMST technology could lead to the automation of the manufacturing process, reduction of the fabrication time and costs, and better control of the metal coating process.

In this work, the collective fabrication of passive filters was applied on two ceramic substrates with different electromagnetic (EM) and temperature properties. As in CMOS processes, a verification step was performed to test and identify failed components before the final device extraction. The design of coplanar access for probe station measurements also provides a flip-chip SMD transition once the device is separated from the substrate. Furthermore, a thermal reliability study was conducted on Alumina devices. Problems caused by temperature drift were addressed to extend the operating range for power and communication applications under hostile environments. The technology improvements were implemented in a thermally-stable substrate for 5G millimeter-wave (mm-Wave) filter development.

II. LMST process enhancement

A. Collective fabrication

Collective fabrication was utilized in a LMST fabrication run for 5G mm-Wave band applications at 42 GHz [1]. A set of 15 passive devices were etched in a 20 mm x 20 mm x 0.66 mm Alumina substrate ($\epsilon_r = 9.8$ and $tan\ \delta = 5.10^{-4}$ at 42 GHz) and covered in silver with

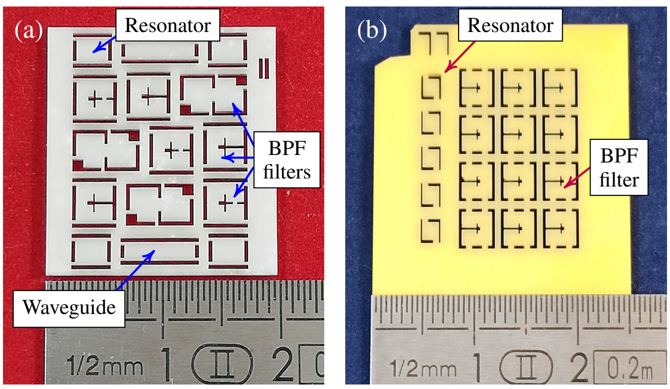

Fig. 1. Laser micro-machined collective fabrication on ceramic substrates: (a) Alumina ($\epsilon_r = 9.8$) and (b) thermally-stable material ($\epsilon_r = 24.1$).

Technology	Frequency [GHz]	Unloaded Q	Filter order	Size (mm^3)	Area (mm^2)	Reference
LTCC	41.8	333	4	5.5 x 2.3 x 0.6	12.65	[4]
DRIE SOI	38	343	3	7.41 x 15.32 x 1.5	113.52	[5]
Laser micro-machining	36.2	550	4	5.9 x 24.4 x 0.76	143.96	[6]
LMST	**26**	**360**	**4**	**3.08 x 3.48 x 0.65**	**10.72**	**This work**
	42	**700**	**4**	**3.38 x 3.11 x 0.66**	**10.51**	
u-coax	35.9	829	1	3.33 x 3.33 x 0.70	11.09	[7]
PCB (air-filled SIW)	38	1065	4	7.11 x 24.42 x 4.57	173.67	[8]
Micro-machining	28	1500	8	3.4 x 33.7 x 1.5	114.58	[9]
	60	1230-1470	4	5.75 x 13.6 x 1.8	78.2	[10]

Table 1. Millimeter-wave manufacturing technologies.

aerosol deposition. In order to test the manufacturing process, the devices were developed using the same specifications and topologies implemented in [1]. No special considerations were taken during the engraving of the metal layer since no structural or adherence problems were observed. Figure 1 depicts the collective manufacturing implementation of several passive components. Every component is confined in frames and linked to the substrate by mechanical supports. The devices were placed along the substrate in a zig-zag pattern to make the best possible use of the available surface. The supports were design to have no influence on the device and avoid EM field leakage in the surrounding area during the preliminary measurements. Several samples were fabricated and compared to test the process dispersion. Measurements show a good repeatability for the same fabrication run within the dispersion reported in [1]. Return losses between 15 and 18 dB were obtained for single-mode Chebyshev topologies (fig. 2) while insertion losses do not exceed 0.95 dB in any case. A maximum frequency shift of 300 MHz as a consequence of the permittivity dispersion and a bandwidth reduction between 100 and 400 MHz were observed. Post-manufacturing laser corrections could be performed to overcome this problem and achieve the final specifications.

A comparison of the main features with other technologies used for the manufacturing of mm-Wave devices is necessary to highlight the advantages and disadvantages of LMST. Table 1 lists the main characteristics for several manufacturing technologies in K-, Ka- and Q-band, ordered by the quality factor. Micro-machined bulk quartz blocks have the best Qo among the rest of the technologies. Nevertheless, 4-pole filters at 60 GHz occupies 7.44 times more area than LMST filters at 42 GHz. High quality factors can also be achieved with air-filled SIW technology. However, these devices are thicker due to the PCB stacking. A compact 3-pole band-pass filter was reported in [8] with $Q = 1065$ and a size of 7.11 mm x 24.42 mm x 4.57 mm, larger than the devices presented in this work. Micro-coaxial technology can reach good performances, but the manufacturing process is more complex and requires a clean room to perform the fabrication. DRIE SOI and other laser micro-machining technologies have lower quality factor and in the case of laser micro-machining [6], the size of the components is larger due to the lower permittivity of the substrate (fused silica). Finally, LTCC technology can be as compact as LMST or even more but the quality factor is one of the lowest.

B. *Temperature drift*

Temperature stability and power handling capability are major aspects in electronic systems reliability under harsh environments. Heating due to power dissipation or environmental temperature fluctuations could produce malfunctions or shifting of the frequency band. Under these conditions, bulk components as waveguide technologies provide better power handling capabilities than planar technologies. In order to characterize the temperature constraints of LMST Alumina filters, a non-destructive thermal analysis was performed in a test bench compound by a Peltier cell controlled by a temperature source. The devices under test (DUTs) were separated from the frame and measured with a ZVA 87 VNA connected to a 125 um pitch GSG probe tip. The DUTs were gradually heated with the Peltier cell in steps of 10 °C between 30 and 125 °C while device temperature was monitored with a sensor. A frequency shift around 200 MHz (0.48% of the central frequency) and a degradation of Qo from 700 to 667 was measured in Alumina resonators. In the case of passive filters the pass band shifts to lower frequencies while the bandwidth remains stable due to the

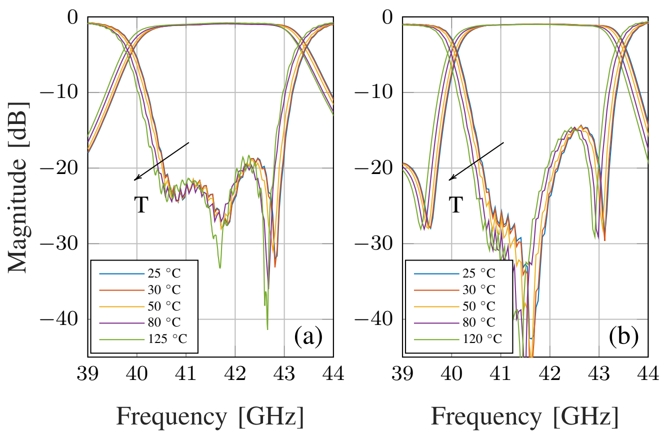

Fig. 2. Alumina band-pass filters exposed to several temperatures: (a) single-mode filter and (b) single-mode filter with transmission zeros.

homogeneous temperature distribution in the device (fig. 2). This is an undesired effect that strongly depends on the system specifications. For instance, the thermal stability of tunable filters or filter banks utilized in RF transceiver front-ends is of the utmost importance since the filter shift could cause an overlap between adjacent channels.

A second study was performed to determine the technology breakdown limits. In the first place, the devices were heated in an oven during two hours and stressed with three different temperature profiles. The maximum operating temperatures in each case were 80 °C, 125 °C and 200 °C. The frequency shift and Qo measured at these temperatures were in good agreement with previous test and subsequent measurements at room temperature exhibit no difference when compared to the fresh device. This behaviour suggest that no permanent damage was caused to the Alumina or the metal structure after being exposed to several temperature cycles. Bubbles and material detachment were observed in the silver coating after exposing the devices to temperatures greater than 200 °C (fig. 3). Further measurements exhibit malfunctions on the frequency response. The test was repeated on DUTs metallized with a fine copper layer (3 um) and protective gold coating. No structural damage or imperfections were observed this time on the metallic layer after stressing the devices with temperatures up to 300 °C.

C. Surface-mount transitions

Surface-mount technology (SMT) is being widely implemented in the industry of electronic devices as ICs or sensors for wireless communication and control systems. The use of this approach improves the manufacturing automation, thus decreasing the costs and area. These characteristics are interesting features to be integrated in LMST to provide low-cost reliable devices. Therefore, the technology should contemplate a manner to provide the designs with device testing and surface-mount transitions at the same time. Figure 4 shows the implementation of a common coplanar access for both on-substrate and SMD transition in a ceramic filter. The coplanar accesses are extended from the device to the frame using the supports (fig. 4.a). The transmission line was designed to match a 125 um pitch GSG probe to 50 Ω within

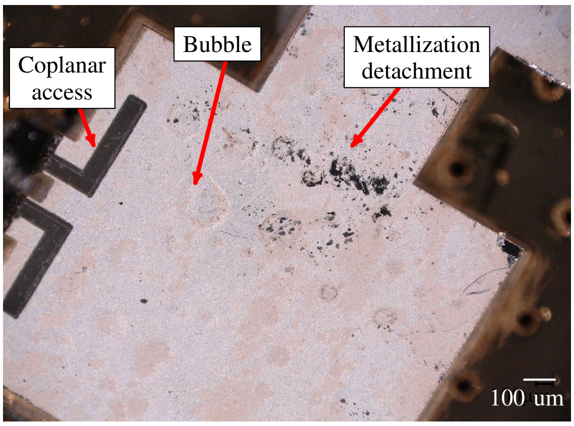

Fig. 3. Defects in aerosol-deposited silver layer after the exposure to temperatures greater than 200 °C.

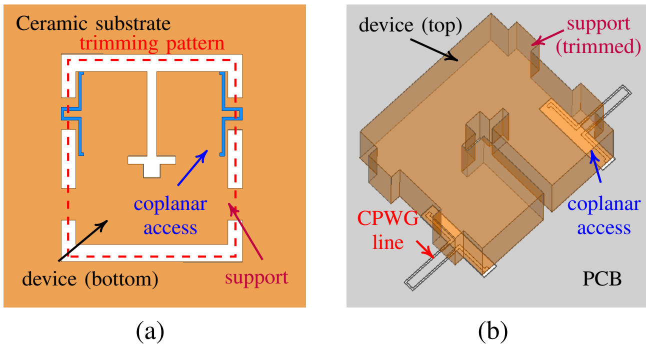

Fig. 4. Coplanar transitions on ceramic substrate (a) and PCB (b).

the operating band. Once the device is tested, the supports that link the component to the substrate are trimmed providing two functionalities: to separate the device from the substrate and to create the new transition. Finally, the device is flipped, surface-mounted on the PCB carrier, and connected to a 50 Ω CPWG line with a rectangular termination (fig. 4.b). A proper design should ensure a similar frequency response for both cases. Hence, the final SMD response could be predicted and tuning strategies applied during the testing stage. It must be taken into account that the permittivity on top of the transmission line is different for both cases. To overcome this problem the design is simultaneously optimized mixing 3D full-wave and circuit simulations [11].

III. Thermally-stable devices

The resonance frequency of regular Alumina devices typically decreases when the temperature increases. To minimize the frequency shift, thermally-stable materials are developed to compensate the drift with a positive temperature coefficient. In order to provide thermally-stable devices, the strategies shown in the previous section were implemented in a commercially available ceramic substrate with a coefficient of thermal expansion $CTE = 10\ ppm/°C$ and a thermal coefficient of frequency $\tau_f = 0 \pm 2\ ppm/°C$. The electrical permittivity and losses were characterized with a split cylinder resonator cavity method (SCR) [12] at 26 GHz. Measurements exhibit a $\epsilon_r = 24.1 \pm 0.7$ and $tan\ \delta = (8.5 \pm 5.2).10^{-5}$ at room temperature. The high Qo and electrical permittivity together with the temperature coefficient make the material ideal for compact filter applications like satellite multiplexing filter devices, radio-links for communication systems (LMDS), and military radars, among others.

Five TE_{101} resonators and twelve single-mode 4th order Chebyshev band-pass filters (BPF) were fabricated in a 25 mm x 25 mm x 0.65 mm substrate for 5G applications at 26 GHz mm-Wave band (fig. 1.b). Collective fabrication and surface-mount transitions were taken into account for the design. The devices measure 1.63 mm x 1.93 mm and 3.08 mm x 3.48 mm, respectively. The filters show a great area reduction thanks to the high substrate permittivity with dimensions similar to the Alumina filters fabricated at 42 GHz (see table 1). Electroless copper deposition was chosen to increase the operating temperature range, in spite of the

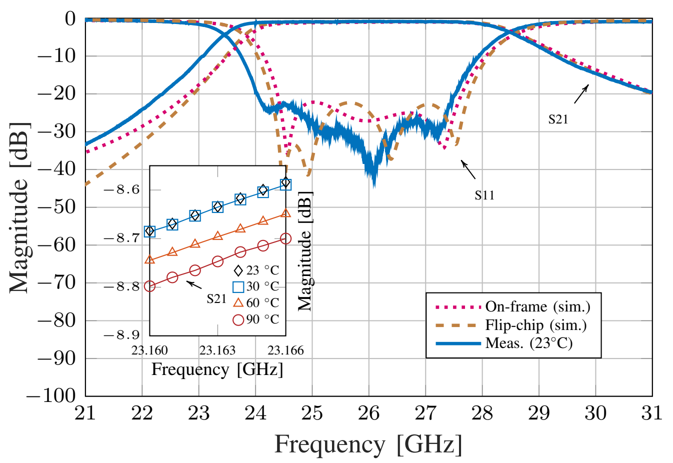

Fig. 5. 5G mm-Wave band thermally-stable filter: on-substrate/SMD simulations and measurements (23 °C, 30 °C, 60 °C and 90 °C).

performance degradation as a consequence of the combined contribution of the lower conductivity and the higher substrate losses. Resonator measurements show a maximum $Q_o = 360$ for copper coated resonators. The quality factor could be enhanced up to 600 by implementing TE_{102} modes filters and silver plating [1]. The coplanar access transitions were optimized to be assembled in a 0.4 mm thick RO4003C board. The board was chosen due to its proximity to the ceramic substrate CTE for a temperature range between -55 to 288 °C (11 $ppm/°C$ and 14 $ppm/°C$ in x- and y-direction). Figure 5 depicts the filter simulations for the optimized on-substrate/SMD transitions and the fabricated filter measured at room temperature. Measurements are in good agreement with simulations and the expected performances of the technology (insertion losses lower than 1 dB and 3.41 GHz bandwidth). No post-fabrication tuning process was implemented in these filters. A thermal analysis was performed as in Alumina devices from 30 °C to 90 °C (inset in fig. 5). A maximum frequency shift of 6.5 MHz from the center frequency (0.02% fo) and a bandwidth widening of 1.5 MHz were measured, representing a significant improvement compared to the regular Alumina devices.

Conclusions

LMST is a flexible technology with a good trade-off between size, quality factor and manufacturing complexity. To the best of the authors knowledge, LMST passive ceramic filters are one of the most compact devices when compared to other technologies. Nevertheless, ceramic technologies are usually expensive for its implementation in the industry. In this work, a CMOS-like collective fabrication was presented for LMST in order to automatize the process, reduce the fabrication costs and simplify the substrate manipulation during the metallization. Moreover, the fabrication process enhancement introduces the possibility of device testing and failed components detection in early stages. The application of SMT provides a higher flexibility process and encourages the creation of transitions useful for both testing and SMD connections. An hybrid circuit/EM simulation design strategy was utilized to optimize these transitions. Furthermore, the thermal behaviour of Alumina devices was analysed to evaluate their application for military and satellite communication systems. Experiments realized at $f_o = 42\ GHz$ show a maximum frequency shift of 0.48% f_o for operating temperatures up to 125 °C. Bubbles and cracks were identified on the aerosol-deposited silver coating over 200 °C. Thermal stability was enhanced by implementing collective-fabricated passive filters in a commercial low-cost high-Q thermally compensated substrate. The devices were copper plated to increase the maximum supported temperature. Surface-mount filters were designed as a case of study for 5G mm-Wave band applications at 26 GHz. As a result, highly-integrated and large operating temperature range devices were obtained with a significant thermal stability improvement.

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