Laser-machined ceramic band-pass filters development for mm-Wave applications

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***Abstract*—An overview of the laser-machined substrate technology (LMST) development, together with the difficulties and strategies adopted to achieve good electromagnetic (EM) performances in ceramic-based millimeter-wave (mm-Wave) devices are discussed. Several generations of band-pass filters were implemented at 40 GHz during the technology enhancement showing good characteristics without tuning corrections. The manufactured samples of each topology were characterized to assess the process repeatability, a necessary information for industrial massive millimeter-wave (mm-Wave) components fabrication.**

***Index Terms*—LMST, millimeter-wave, ceramic, filters, 5G, communications.**

I. Introduction

The rapid expansion of mobile data transfer applications and IoT evolution during the last decade have demanded the development of low latency high-speed data rate communication systems. For the first time, millimeter-wave bands have been implemented in the new generations of mobile communications (5G and upcoming 6G) to increase the bandwidth and leverage the underutilized frequency spectrum. The application of beamforming and massive multiple-input multiple-output (MIMO) technologies to boost mobile communications requires a large amount of antenna arrays and electronic devices associated [1]. Numerous terrestrial and satellite link networks are actually being deployed implementing these technologies to provide continuous service from space to every part of the planet. Therefore, low-cost reliable hardware components with good performances are required to work under harsh conditions [2].

Substrate integrated waveguide (SIW) filters have been widely utilized in communication applications, specially on radio-frequency front-ends due to their low-loss, low-cost, compact, flexible, and mass-producible features [3]. Furthermore, their implementation in ceramic materials could provide compact devices with good EM properties and power handling capability. In this work, the development of a generic three-step manufacturing process and the continuous improvement of the technology is discussed. The process has been focused on laser-carved Alumina substrates for mm-Wave passive filters and enhanced to obtain the best possible performances through several filter fabrication runs. Many SIW-like filter topologies were implemented in this technology as proofs of concept for millimeter-wave communication applications. The technological limitations addressed and the different strategies adopted are exposed.

II. LMST technology development

LMST technology is a simple three-step generic manufacturing process [4][5] that consists of etching the device layout on the substrate (step 1), plating the component with a metallic coating (step 2) and engraving final details such as ports or transmission lines on the surface (step 3). In order to achieve an interesting balance between size reduction, low manufacturing cost and EM performances, the process was specifically enhanced for mm-Wave devices developed on ceramic substrates. A 25 μm spot YAG laser with a manufacturing accuracy of 10 μm was chosen to meet the specifications of Q-band applications without further tuning steps. The first manufacturing tests were carried on with this setup in [4]. A 4-pole dual-mode Chebyshev and a 6-pole quasi-elliptic filters were implemented on a commercial 0.25 mm thick Alumina substrate with $\epsilon_r = 9.75$ and $tan\ \delta = 0.0033$. A 3 μm copper layer was deposited with electroless copper plating and covered in gold as an antioxidant protective layer. Additionally, TE_{201}/TE_{102} dual-mode ceramic resonators were fabricated to characterize the overall losses of the technology. A maximum quality factor of 150 and a conductivity of 10 $S/\mu m$ were measured at 40 GHz. Manufacturing inaccuracies showed an average tolerance of ± 10 μm with a maximum deviation of 27 μm in the device pattern and ± 3 μm and ± 15 μm on the top face engraving, respectively. The measured filters response (fig. 1) manifests a central frequency shift of 300 MHz and a total insertion loss of 3.5 dB due to the low quality factor obtained.

The purpose of the first generation (G1) was to test the methodology and highlight the main fabrication constraints. Two factors were clearly identified as limitations: the losses inherent to the Alumina substrate and the low quality of the metallic coating deposited with electroless copper plating. Figure 2 depicts the theoretical influence of the metal layer conductivity, substrate loss and thickness on the unloaded quality factor (Qo) in a TE_{102} rectangular cavity resonator. As it can be seen, an increment of the conductivity up to 20 $S/\mu m$ together with a higher quality ceramic substrate ($tan\ \delta = 5.10^{-4}$) could enhance the quality factor up to 320 at 39 GHz. Moreover, the substrate thickness in TE_{m0n}

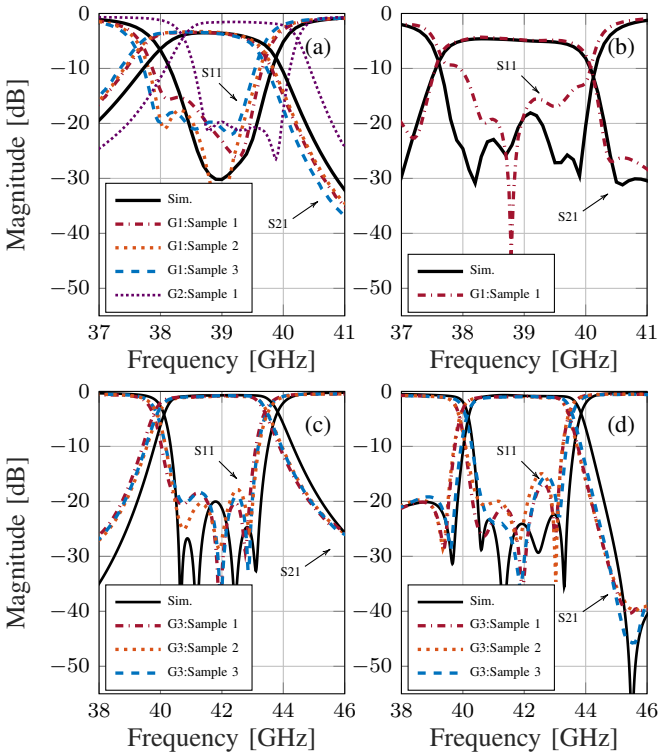

Fig. 1: LMST filters: (a) 4-pole dual-mode Chebyshev (G1 and G2), (b) 6-pole quasi-elliptic (G1), 4-pole single-mode Chebyshev G3 without (c) and with transmission zeros (d).

modes may help to increase the performances. For instance, a Qo around 700 could be achieved with a thickness of 0.6 mm. These considerations were implemented in the second generation (G2) of the 4-pole Chebyshev filter using a low-loss Alumina under development [6] ($\epsilon_r = 9.94$ and $tan\ \delta = 2.5.10^{-4}$). The electroless copper plating was replaced by an aerosol air-brushing silver coating with higher quality and better deposition control. A typical conductivity of 30 $S/\mu m$ at 39 GHz was expected for a 3 μm silver layer deposited with this process. As a result, the 5.98 mm x 2.76 mm x 0.6 mm dual-mode filters manufactured in this generation showed a significant Qo improvement of 250% (Qo $\approx$ 400) and an insertion loss reduction of 2 dB in comparison with previous devices (fig. 1.a). Nevertheless, the compact size and the individual fabrication hindered the devices manipulation during the silver aerosol deposition. As a consequence, the control of the process and the quality of the metal layer were compromised, achieving a poor conductivity and limiting the final quality factor.

Special considerations were implemented in the third generation (G3) to improve the aerosol silver deposition. Moreover, structural fragilities generated during the laser micromachining process on thin ceramic regions in the first quasi-elliptic filters generation were taken into account [4]. The technology was fully characterized and pushed to the limits to provide the designers with useful design rules [5]. The maximum substrate thickness feasible to be trimmed without

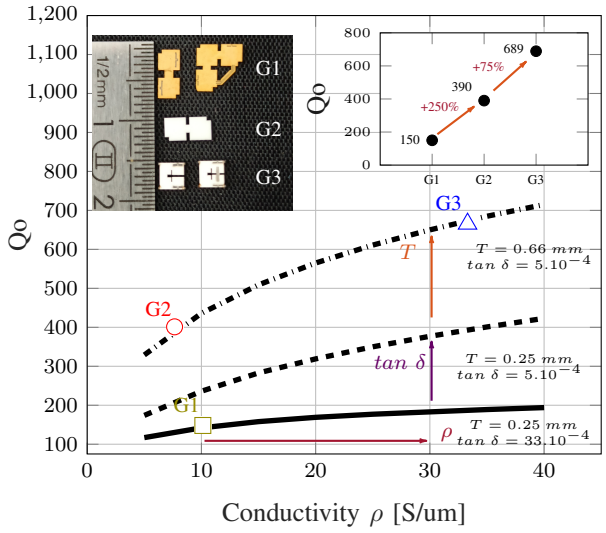

Fig. 2: Quality factor dependency with the substrate loss ($tan\ \delta$), electrical conductivity (ρ) and thickness (T) for a TE_{102} rectangular resonator.

loss of accuracy was 0.7 mm. Several band-pass filters were designed using the suggested design rules in a 0.66 mm thick Alumina substrate. The devices were contained in frames and attached to the substrate until the end of the process by mechanical supports with negligible electromagnetic impact on the filters. Trenches and supports were carved in the substrate during the first step to create those links. Considering that the laser inaccuracy increases with the etching depth, the lateral walls profile was characterized for the maximum substrate thickness. Measurements with a stylus profilometer reveal a slight slope on the lateral walls with an average deviation of 4 to 5 μm. The combined effect of the laser inaccuracy with the lateral walls imperfections results in a fabrication tolerance of 15 μm and a maximum deviation of 30 μm. Four rectangular cavity resonators were developed in a similar low-loss Alumina substrate ($\epsilon_r = 9.8 \pm 0.4$ and $tan\ \delta = 5.10^{-4}$ at 42 GHz) to corroborate the process enhancement and performances. The devices were more easily manipulated thanks to the surrounding substrate frames. Besides, the use of trenches helped to improve the aerosol silver particle deposition during the metallization process. Quality factors between 673 and 689 were measured in the manufactured resonators, demonstrating a significant improvement and maturity of the technology. The additional losses observed could be related to the higher lateral walls roughness due to the substrate cutting process. Roughness characterization on a trimmed support cross section exhibits an Alumina surface roughness of $r_{subs.} = 716\ nm$ as a consequence of the grooves led by the laser during the fabrication.

III. 5G MILLIMETER-WAVE FILTERS

Several ceramic passive filters were fabricated to meet the specifications of potential 5G front-ends. The devices were designed to operate in the European millimeter-wave band at

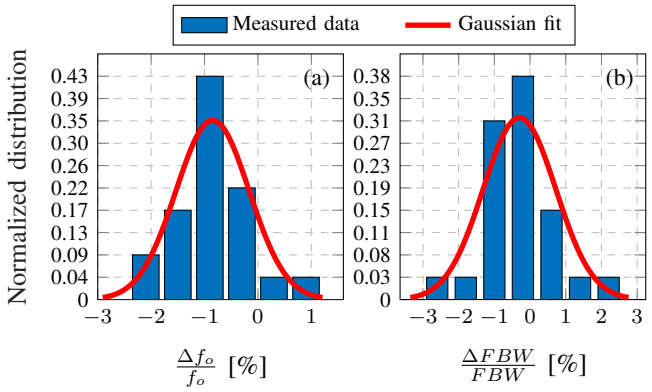

Fig. 3: LMST filters relative frequency shift (a) and fractional bandwidth mismatch (b) statistics and Gaussian distribution.

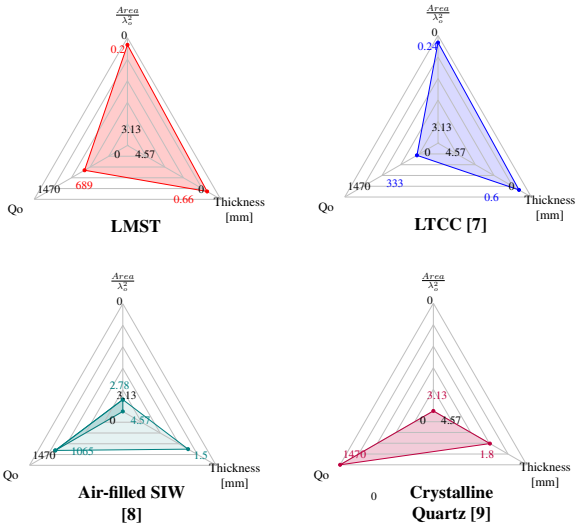

Fig. 4: Relative features comparison between LMST third generation filters and 40 GHz mm-Wave band fabrication technologies [6].

42 GHz (40.5 - 43.5 GHz) [2]. A 4-pole Chebyshev topology was implemented with the fundamental TE_{101} mode to obtain the most compact filter size as possible. The resonators were placed in a square fashion arrangement (G3 in fig. 2) for future surface-mount assembly compatibility with industrial pick and place machines. Figure 1 depicts the measured S parameters of several 3.13 mm x 3.24 mm x 0.66 mm filter samples manufactured during the third LMST generation. Return losses between $14.9\ dB \leq RL \leq 18.4\ dB$ and insertion losses $0.77\ dB \leq IL \leq 0.94\ dB$ were measured for filters with and without transmission zeros. Measurements show a good repeatability between samples and a clear improvement in comparison to previous generations.

The devices manufactured throughout the different generations provide valuable information about the process dispersion for industrial massive production of mm-Wave LMST ceramic devices. A statistical analysis of band-pass filter central frequencies and bandwidth mismatch was performed using the available data of 24 devices between the different topologies fabricated with this technology (fig. 3). The data fitted with a Gaussian distribution exhibits a mean frequency shift of $\mu(\frac{\Delta f_o}{f_o}) = -0.85\%$ with a standard deviation of $\sigma(\frac{\Delta f_o}{f_o}) = 0.69\%$ and a mean bandwidth mismatch of $\mu(\frac{\Delta FBW}{FBW}) = -0.29\%$ with a standard deviation of $\sigma(\frac{\Delta FBW}{FBW}) = 1.02\%$.

IV. Conclusion

The implementation of a simple generic manufacturing process for millimeter-wave passive filters development has been presented in this work. The fabrication flow was mainly focused on ceramic materials and enhanced to provide compact devices with good EM performances. The identification of the main technological constraints throughout the different generations was a critical aspect to overcome the process limitations and upgrade the features. Several rectangular cavity band-pass filters were designed showing a good agreement between specifications and measurements. The measurement of every filter sample provided valuable information to assess the typical frequency shift and bandwidth deviation to be expected from this technology. Furthermore, an extra tuning step could be implemented in case of more restrictive specifications. Even though the quality factor is lower than other mm-Wave manufacturing technologies around 40 GHz, 4-pole filter features comparison suggests that ceramic-based LMST filters are in a good balance between compactness (normalized to the free space wavelength λ_o), quality factor and maximum operating frequency (fig. 4). Manufacturing strategies for costs reduction will be taken into consideration in the following filter generations. Additionally, the use of temperature stable ceramic substrates and surface-mount assembly will be implemented to provide the technology with higher versatility for satellite communication systems.

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