Ceramic additive manufacturing as an alternative for the development of miniaturized microwave filters

C. Carceller, F. Gentili, W. Bösch
Technische Universitaet Graz
Inffeldgasse 12, Graz 8010, Austria
Email: carlos.carcellercandau@tugraz.at

D. Reichartzeder, M. Schwentenwein
Lithoz GmbH
Mollardgasse 85A, 1060 Vienna, Austria

***Abstract*—Continuous developments in additive manufacturing (AM) processes have created new tools to respond to some of the challenges facing microwave filters. In this work, we propose the use of the AM process known as lithography-based ceramic manufacturing (LCM) as a way to miniaturize microwave filters. With this technique, very complex shapes can be reproduce with high fidelity out of ceramic materials. Given the outstanding miniaturization properties of ceramics, it is possible to adapt classical filter configurations into ceramic structures, thus drastically reducing their size. Two application examples manufactured with LCM will be presented and discussed in this paper, showcasing the possibilities of this technology.**

***Index Terms*—Additive manufacturing, ceramics, miniaturization, microwave filters.**

I. Introduction

Ceramic materials have been frequently used to miniaturize microwave components [1]. Whether they are found in planar substrates, dielectric-filled waveguides or dielectric resonator blocks, the shape of ceramic structures tends to be simple: rods, pucks, sheets, cubes, etc. [2]–[4]. This is, in some part, due to the difficulty of shaping ceramics, given the brittle nature of these materials. In order to increase their ductility, ceramic powders are typically combined with ductile polymer binders that are later thermally removed, once the desired shape is obtained.

This approach is common for most ceramic manufacturing techniques. What separates the new additive manufacturing approaches from traditional ones is that no mold is necessary to form the ceramic material into the desired shape. On the one hand, shapes that molds can create are limited. For instance, cavities, lattices, etc. are difficult to create with traditional techniques, but much simpler with additive manufacturing. On the other hand, the bulk of the cost in traditional techniques is associated with the creation of the mold and machining of the green body [5], whereas in additive manufacturing techniques the main cost is the so-called printer machine. For that reason, simple shapes are created at a lower costs with traditional techniques whereas, with additive manufacturing, the complexity of the shape is not a factor when assessing the cost of a part. Consequently, additive manufacturing techniques expand the possibilities and scope of application of ceramic materials within microwave components.

In this paper, the use of Lithography-based Ceramic Manufacturing (LCM) is proposed as an ideal procedure to develop complete filtering structures partially or completely filled with ceramics. A brief introduction to this manufacturing process will be provided in the next section, followed by the presentation of two prototypes developed with this technology.

II. Lithography-based Ceramic Manufacturing

Additive manufacturing (AM) techniques embrace the notion that a given shape can be created by piling up a number of layers of a certain material with very specific cross sections. AM approaches can be classified according to the techniques employed to shape and attach the different layers, for instance, selective laser sintering (SLS), electron beam melting (EBM), fused filament fabrication (FFF), stereolithography (SLA), etc. Depending on the building material and application, some AM approaches are more suitable than others.

The goal of this work is to develop miniaturized microwave filters using ceramics as building material. Given the success of the AM technology known as Lithography-based Ceramic Manufacturing in accurately reproducing small complex ceramic structures for industrial applications [6], this work proposes its use in the development of miniaturized filters.

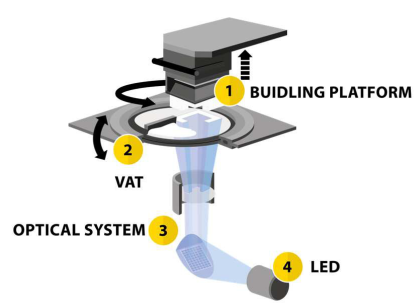

Fig. 1. LCM system employed to manufacture the green body.

The manufacturing process involving this technique can be explained in four steps:

1) Preparation of the CAD model.
2) LCM of green body.
3) Sample cleaning.
4) Thermal post-processing.

The process starts with a CAD drawing representing the 3D structure to be manufactured. Before this model can be fed into the LCM machine, an adequate layer-by-layer deposition strategy has to be defined. The best possible growth direction has to be determined, which frequently requires tilting the structure with respect to the building platform. In that case, a series of supporting elements have to be included in the CAD drawing, in order to minimize the presence of overhangs and guarantee the structural robustness of the manufactured part.

After pre-processing the CAD drawing, the 3D model (including supports) is fed into the LCM machine. A schematic view of this machine can be found in Fig. 1. The building material employed by the LCM machine is composed of inorganic ceramic particles and a photoreactive organic binder. The binder hardens by photopolymerisation when exposed to blue light.

The green body is constructed attached to the building platform (see Fig. 1). When a new layer is to be added to the green body, the LCM machine lowers the building platform into the vat, thus submerging the green body in the building material composite. Making use of an optical system (involving a LED light and a digital micromirror device DMD array), the shape of the new layer is projected into the composite. In those areas exposed to the light, the photsensitive material hardens, and the new layer gets attached to the green body. Once this process is done, the platform is raised, and a blade used to wipe the excess of material and homogeneously refill the vat with the ceramic suspension.

Once all layers are attached, effectively forming the green body, a mechanical processing is required in order to prepare the part for the thermal cycle. In this second phase, the green body is manually detached from the support structure, and any remaining traces of uncured material are removed from it. In order to do so, an airbrush and a solvent are initially used, before an ultrasonic cleaning procedure is applied.

A final thermal processing is performed to give the material the adequate consistency and physical properties of ceramics. First, the green body is placed in a furnace in order to remove the polymer binder that keeps the ceramic material together. This process, known as thermal debinding, is the most time-consuming part of the overall manufacturing process. Then, the part is placed in another furnace at higher temperatures until the ceramic is finally sintered. The result is a ceramic object with the geometrical shape of the original 3D model.

III. Application Examples

A. Ceramic-filled dual-mode filter

The first application example illustrates how LCM makes possible to take a classical waveguide implementation and manufacture it as a single block out of ceramic material. In this case the structure is a TM dual-mode filter [7] and the ceramic material is alumina (99.4% TD, $\epsilon_r = 9.8$). Given the well-known miniaturization properties of ceramic materials, the resulting ceramic filter is significantly smaller than the classical air-filled implementation. Figure 2 depicts, for comparison purposes, the size of a filter implemented in alumina (left) and its air-filled equivalent (right).

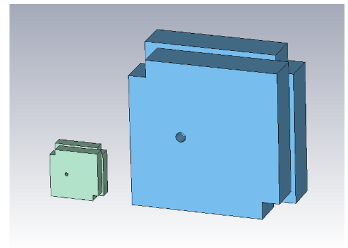

Fig. 2. Size of a TM dual-mode filter implemented with alumina (left) and its equivalent air-filled version (right).

The filter is composed of two square sections of alumina, where the TM_{210} and TM_{120} modes resonate. Two insets in opposite corners provide the required coupling between modes in the same cavity. In order to create inter-cavity couplings, two rectangular windows are placed in the middle of the filter. The motivation of this double window is twofold. On the one hand, it provides additional degrees of freedom to control the coupling between higher order modes, which can be used to prescribe the location of transmission zeros. On the other hand, the structure becomes more robust thanks to a distribution of the contact points between the two main sections. The overall structure has the S-parameter response shown in Fig. 3, including two transmission zeros on each side of the passband.

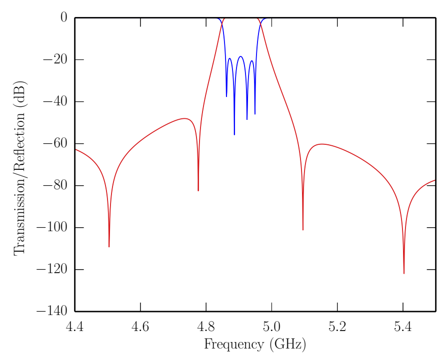

Fig. 3. Ideal S-parameter response of the dual-mode filter

The first step to manufacture this structure involves selecting the growth direction, in order to minimize the amount of supporting elements and overhangs. This direction was selected as shown in Fig. 4. As can be seen, the sections that require supports are the intra-cavity coupling insets and the inter-cavity coupling windows. These supports are integrated into the CAD model and manufactured with the same material as the rest of the structure. Once the LCM process has finished, they are manually removed from the body of the filter. The sample is then cleaned from excesses of uncured material and introduced in a furnace at 600°C to debind the structure by extracting the organic polymer binder. Finally, it is placed in a second furnace at 1600°C for the final sintering process. The result is the ceramic part shown in Fig. 5. To finalize the process and turn the structure into a filter, the ceramic part could be covered with a metal coating to shield the filter.

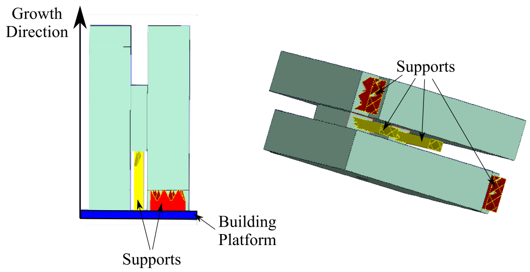

Fig. 4. Orientation of the dual-mode filter during the LCM process.

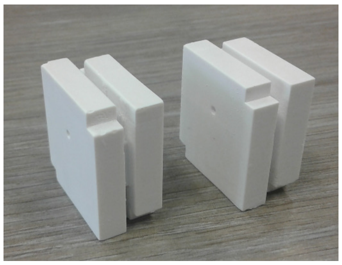

Fig. 5. Two samples of the TM dual-mode filter manufactured as a single part by LCM.

B. TM dielectric resonator filter

The second application example shows how LCM can be a solution to overcome some of the current challenges of microwave filters. In this case, the structure is a dielectric resonator (DR) filter in the TM configuration. This configuration is characterized by the inclusion of a thin dielectric rod within a metallic cavity. For ideal performance, the dielectric rod must have the same height as the cavity. With this configuration, pressure from the walls keeps the rod in place once the cavity is closed, thus minimizing the need for adhesive composites. Despite the convenience of this approach, it usually leads to cracks in the dielectric resonator, specially when employed in environments that are subject to significant changes in temperature, given the different temperature expansion coefficient of the metal and dielectric materials.

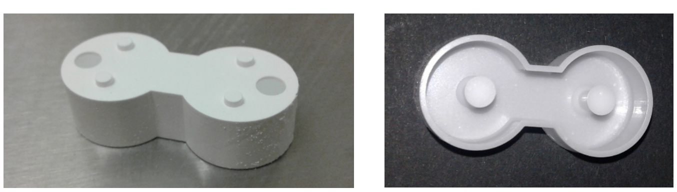

Fig. 6. Left: TM filter manufactured with LCM in alumina. Right: Sample manufactured without the top cover to display the inner part of the filter.

In this context, LCM is an attractive technology that can help overcome some of the limitations of this filter topology. With this technology, a complete cavity (including the dielectric rod and the cavity walls) can be manufactured in a single part out of a ceramic material, as shown in Fig. 6. This part is then externally metalized employing a metal coating. The two openings in the top wall indicate the location of the input/output connectors. In order to achieve an adequate alignment of these elements, small cylindrical posts have been manufactured in the top wall.

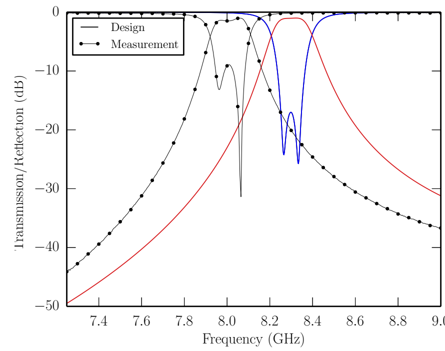

Fig. 7. Measured response of the TM DR filter, compared with design.

After metallizing the external walls of the cavity, the input/output connectors can be glued to these alignment posts to measure the response. Figure 7 shows the measured response compared with the design. The significant frequency shift that can be noted is mainly due to the effect of overpolymerization of the central posts in the LCM stage. This effect could be compensated in subsequent fabrications of the structure.

IV. Conclusions

The application of additive manufacturing techniques based on ceramic materials is proposed as an alternative to miniaturize microwave filters. With the lithography-based ceramic manufacturing approach employed in this paper, it is possible to develop monoblock structures with complex shapes built out of ceramic materials. Thanks to the miniaturization properties of these materials, classical waveguide structures can be replicated at a much smaller scale. Likewise, this technology enables designers to address some of the challenges of dielectric resonator filters. To exemplify the broad possibilities of this technology, two filter structures have been manufactured and discussed in this paper.

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