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Additive Manufacturing of Non-homogenous Dielectric Waveguide Structures and Filters

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***Abstract*—This paper investigates the use of 3D-printed alumina ceramics to achieve variable dielectric constants for novel microwave applications. An introduction to lithography-based ceramic manufacturing exhibits the novel process and material properties, while detailing printing techniques for achieving gradient and equivalent dielectric constants. Printed samples of non-homogeneous dielectrics are presented and briefly discussed. Potential end-use for microwave components are discussed with emphasis on future filter applications.**

***Index Terms*—Additive manufacturing, ceramics, dielectrics, dielectric materials, microwave filters, microwave propagation.**

I. Introduction

Additive manufacturing (AM) has become an enabling technology in microwave engineering [1]. Components with complex and varying design geometries can be prototyped and fabricated quickly at low cost. Metals and plastics (with subsequent metal coating) are the most commonly used materials for 3D printed microwave components. Reference [2] provides a general comparison of different approaches of manufacturing waveguides, including a discussion of metalization.

High performance ceramics are also widely used to achieve miniaturized, yet low-loss microwave components. They have been applied to e.g. dielectric resonators [3] which can be used to implement larger filter and antenna systems. Traditionally, the ceramics available come in fixed geometries and with predetermined dielectric constants which have to be chosen upfront to suit the application and frequency range of operation. These dielectrics are often used inside metal structures such as waveguides or cavities to implement a desired filtering function. Reference [4] provides a comprehensive look at the different AM methods that are used for ceramics, as well as comparisons of the material properties.

As AM enables the manipulation of the geometry at every point in a structure with little additional complexity, this paper aims to exploit this characteristic to influence the dielectric constant throughout structures for future applications in filters.

II. Theoretical Background and Design Considerations

The AM process made use of throughout this paper is Lithography-based Ceramic Manufacturing (LCM). A detailed Lithoz LCM process description is provided in [5]. However, it is important to specify some factors of the process and material as they pose limits on designs and realizable structures, and these formed part of the investigation areas in this paper. The Lithoz CeraFab 7500 was used for printing, some important parameters are: Material- Alumina, ε_r=9.9, Min wall thickness= 100 $\mu\mathrm{m}$, Max wall thickness = 5 mm, Mini layer height = 10 $\mu\mathrm{m}$, XY pixel size = 40 $\mu\mathrm{m}$.

A. Variable infill dielectric

The core concept being explored in this paper is to make use of the ability of AM to dynamically vary the ratio of dielectric medium to air using a lattice. This enables the printing of sections with varying dielectric constants throughout the structure. Changing the dielectric constant of a specific ceramic has also been shown to be possible by creating non-homogeneous regions by introducing porosity into the final material. Varying the constant from 12 to 90 of a given material was successfully realized in [6], [7] without losing the desirable low-loss characteristics. Through 3D printing, the same result can easily be achieved [8], [9]. A lattice-type structure can be designed to allow for the desired infill percentage, and through this, a specified dielectric constant can be obtained. Various models for predicting the dielectric

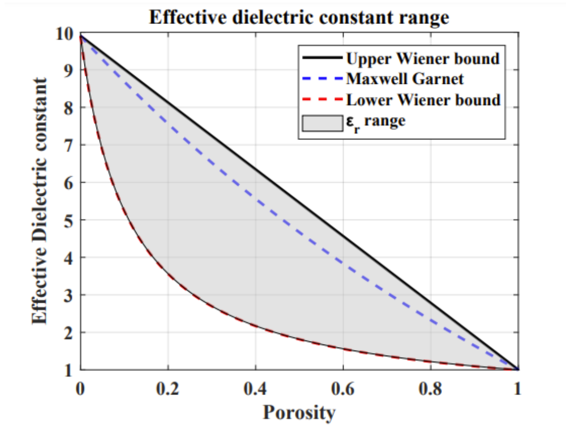

Fig. 1: Theoretical effective dielectric constant range vs. porosity.

constant of mixtures exist [10], with one of the most common being the Maxwell-Garnett given in (1).

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{h}} + 3f\varepsilon_{\text{h}}\frac{\varepsilon_{\text{s}} - \varepsilon_{\text{h}}}{\varepsilon_{\text{s}} + 2\varepsilon_{\text{h}} - f(\varepsilon_{\text{s}} - \varepsilon_{\text{h}})}, \tag{1}$$

where ε_{s} is the dielectric constant of the inclusion material used – in this case air , ε_{h} is the host material dielectric constant of alumina (ε_{r} = 9.9) introduced, and f is the fill ratio. The models are generally bounded by the upper and lower Wiener bounds which help provide a general expected range.

B. Dielectric Waveguide

Traditional waveguides are hollow structures where the propagation takes place with air as the dielectric. It is also possible to design these structures to use other mediums in place of air. The higher the dielectric constant, the smaller the waveguide becomes. The addition of the dielectric medium, however, introduces dielectric losses as the waves propagate through. Therefore, it is important to have low-loss dielectrics and take any additional losses introduced into account during the design process to meet a desired specification.

III. Filter Concept with Test Areas

A stepped impedance waveguide filter was chosen as a demonstrator, as it makes use of the variable dielectric concept as well as the ability to be printed without supporting structures. It consists of alternating sections of high- and low-impedance that correspond to equivalent circuit capacitances and inductances. Fig. 2 shows the conceptional filter designed and provides four areas that can be validated in smaller steps before being combined into a full filter. The four tested areas are discussed in further detail in this section.

1) **Porous structures for dielectric variability:** The ability to control the dielectric constant within the structure as well as from print-to-print needed to be verified. Porous cylinders, dielectric wedges with fixed lattices and fixed infill with varying lattice wedges were printed for characterization. These are shown in Fig. 3.

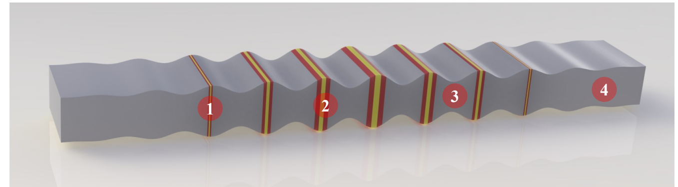

Fig. 2: Conceptual prototype filter with numbered verification areas.

Fig. 3: Printed dielectric wedge samples 80-40% porosity (left) and 30% geometry variations (right).

2) **Dielectric Gradients:** Additive manufacturing provides the unique ability to implement gradients of material without additional complexity. Cosine gradients from 80 to 25% infill shown in Fig. 4 were successfully printed and sintered. The samples were measured to achieve dielectric constant values of between 8 and 3.8. These can later be incorporated into more advanced designs.
3) **Bulky Lattice Combinations:** Final testing for this paper was to see how well combinations of bulk material and the lattice wedges could be printed and sintered. The difference in mass of the lattice structure and solid parts will cause them to sinter at differing rates; this can cause stresses or breakage and could require a redesign if unstable. These parts shown in Fig. 4 were successfully printed and sintered with only minor visible tearing.
4) **Bulky Parts:** As highlighted in design implications, a maximum wall thickness for the Hp360 should not be exceeded before sintering. This provides a challenge for dielectric waveguides or larger components as the designer will always be limited to being below that for one of the edges. Test prints as shown in Fig. 4 were conducted to assess potential solutions.

IV. Demonstrator Filter

For implementation, a fourth-order stepped impedance filter, centered around 8.8 GHz with a return loss of better than 20 dB, was designed. The filter was implemented using cascaded impedance inverter sections such as in [11]. The normalised coupling coefficients, normalised impedance inverter values, and related high and low impedance lengths(mm) are provided in the table in Fig. 6. The ε_{r1} value of the lattice section was chosen to be 3.8. This value is low enough to provide the required large change in impedance between the two sections, but not so low as to make lattice printing unnecessarily difficult. The prototype filter is shown in Fig. 5.

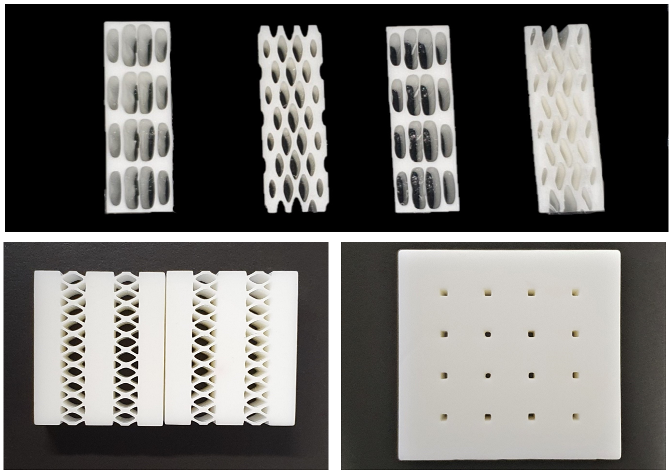

Fig. 4: Printed gradient (top), bulky lattice combination (left) and bulky part (right).

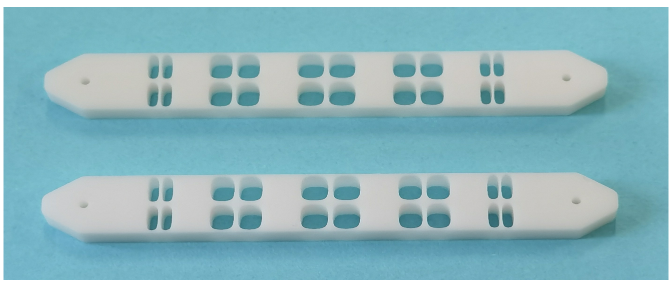

Fig. 5: Ceramic-based stepped impedance waveguide filter prototypes pre-metalization.

A probe feed was integrated into the structure on both sides to facilitate the RF measurements with SMA-connectors in the future. The simulated performance of the filter is shown in Fig. 6. Here a dielectric loss tangent of 8×10^{-5} was assumed, and even though some idealized assumptions were made such as no air gaps, no misalignment and perfect connections, the results underline the potential of the approach provided that the fabrication is flawless.

V. Conclusion

Based on theoretical limits, the paper presents practical considerations for the use of ceramic-based AM to achieve variable dielectric constants in monolithic printed structures. A conceptual filter design provided test areas that were investigated and presented. These then fed into the design for a stepped impedance filter prototype to verify the concept of which an initial idealized performance was given.

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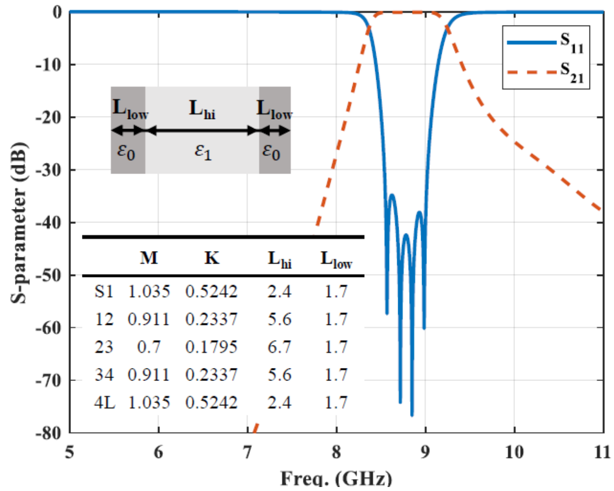

Fig. 6: Simulated filter idealised performance with design values.

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