GREATER DESIGN FLEXIBILITY WITH SELECTIVELY METALLIZED 3D PRINTED RF CERAMICS

WHITEPAPER

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I.

INTRODUCTION

Ceramics are widely used as “hard” substrates for high power and high performance RF applications from high power sub-1 GHz applications, space-grade assemblies, thin-/thick-film passives, to experimental research at extreme temperatures and frequencies. Given the relatively high thermal conductivity and high/low operating temperatures of RF ceramics, this class of materials is generally used in applications where high temperatures and forces are involved in the manufacturing process, such as wirebonding. There are also planar circuit processes that use ceramics as a circuit substrate, such as low-temperature co-fired ceramics (LTCC) and high-temperature co-fired ceramics (HTCC). Ceramics are also widely used for constructing RF components and dielectric portions of components, such as filter resonators.

Lapped/polished sheets and machined ceramic stock have historically been the only viable methods of manufacturing technical ceramics to necessary tolerances and shapes useful for RF applications. Recent developments in 3D printable technical ceramics have opened the doors to RF ceramic fabrication with greater degrees of freedom than previous manufacturing methods. Moreover, advancements in selective metallization paired with these 3D printed RF ceramic parts enable the complete manufacturing of 3D RF passives and even more complex structures, such as passive integrated RF assembly housings.

This whitepaper aims to educate readers on how ceramics are used in RF applications, a primer on 3D printed technical ceramic fabrication processes, selective metallization and how it pertains to 3D printed ceramics. Furthermore, this whitepaper includes application examples of how 3D printed technical ceramics can benefit RF manufacturing.

II.

TYPICAL RF CERAMICS MATERIALS, MANUFACTURING, AND USES

Technical, or engineering, ceramics are used throughout the RF industry as dielectric substrates and structures. Technical ceramics, namely high purity alumina (HPA), Magnesium Calcium Titanate (MCT), Aluminum Nitride (AlN), and Beryllium Oxide (BeO), are generally produced as sheets, tapes, or as stock material that is later machined to a desired shape using conventional machining technologies, such as computer numerical control (CNC) milling/lathing. Given the wide tolerances of as-fired ceramic sheets, these sheets are commonly lapped and/or polished to a desired specification for the end application. Sheet ceramics are very common substrates for thin-film and thick-film discrete electronic components, including resistors, capacitors, inductors, resonators, and even complete surface mount technology (SMT) filters.

Another use of ceramics for RF applications is Co-fired ceramic components and circuits, either low-temperature co-fired ceramic (LTCC) or high-temperature co-fired ceramics (HTCC). These processes involve using green tapes made of ceramic particles and polymer binders. These tapes can readily be machined while green via traditional machining methods, and metals can be filled in the voids or screen printed to fabricate circuit features. Layers of laminated co-fired ceramics can then be sintered with embedded components and even active components, realizing hybrid integrated circuits in a single process. In general, co-fired ceramic technology is used to fabricate rugged RF circuits with a substrate that is relatively low dielectric loss and decent thermal conductivity, with the potential to have mixed substrates of varying dielectric constant (Dk), with high levels of integration and dense interconnect potential.

In terms of dielectric performance, technical ceramics used for RF applications tend to have a wide range of relative dielectric permittivity from roughly 4 to 30, though an individual ceramic type has a fixed dielectric constant. Having an available range of dielectric constant is useful in many applications depending on the frequencies and type of components fabricated with the ceramic dielectrics. For instance, the Q factor of a filter resonator is dependent on the dielectric constant of the material, and a higher Q factor can be obtained in the same geometry using a higher Dk material. Moreover, a higher Dk material may also allow for smaller physical dimensions of RF circuits and transmission lines than lower Dk materials at the same frequency. Conversely, lower Dk materials can allow for higher frequency RF circuits and transmission lines to be designed to dimensions and tolerances that result in reasonable yields.

Mechanically, RF ceramics are brittle, but have relatively high compressive strength. A main advantage of technical ceramics is a high operating temperature and relatively good thermal conductivity compared to other RF substrates, including semiconductors. This is why applications that use high RF power or are in extreme environments, such as military/defense, aerospace, and space, often employ RF ceramics as substrates. This includes high power amplifier pallets, ceramic waveguide filters, and for high performance thin-film/thick-film components.

As technical ceramics are brittle, care while machining is required, and some methods that create high impulse stresses, such as laser cutting, require additional methods to prevent cracking or shattering of ceramic parts during machining. If the process allows, ceramics can often be more easily machined while green, though effects, such as shrinkage during sintering, must be taken into account to ensure final dimensions and tolerances.

III.

ADDITIVE MANUFACTURING (AM) CERAMICS

Given the ability for ceramics to be sintered in post-processing, there are a variety of AM methods that use binders to fabricate 2D and 3D structures. The general ceramic AM process is to use ceramic particles, usually in the form of powders, mixed with a binder that will later be baked-off during sintering. The binder allows for the green ceramic part to be handled and possibly machined prior to sintering. Due to the removal of the binder during sintering, all AM ceramic methods result in some level of shrinking depending on the volume of the binder in the green part compared to ceramic. In general, a greater amount of shrinkage during sintering is not desirable as tolerances are wider and there are other manufacturing considerations to ensure that the sinter part is as designed.

The main methods of AM manufacturing of 3D ceramic parts are fused deposition modeling (FDM) and photopolymerization methods, such as stereolithography (SLA)/digital light projection (DLP), material jetting, and some forms of binder jetting [1]–[4]. Of the above, SLA/DLP methods of AM can likely result in the highest resolution and best-as-printed green ceramic parts with the lowest shrinkage rates. DLP processes with technical ceramic photoresins in particular can be both relatively rapid, high resolution, highly repeatable, and with very low shrinkage rates. The advantages of DLP printing of technical ceramics enables the fabrication of relatively large parts with thick cross-sections while still retaining tight tolerances [5], [6]. With this approach less post-processing is needed prior to sintering, and in many cases, no additional post-processing is needed after firing.

FIGURE 1. *Sintered alumina parts fabricated using Fortify's DCM technology.*

Top to bottom: impeller, high Dk GRIN lens, Isogrid REinforced Rocket Nozzle, Steam cooling heat transfer device, high temperature heat sink.

III.

AM technologies enable very complex and high resolution 3D ceramic structures in latices, with internal voids, more refined curves, better green surface finish, and often greater repeatability than traditional manufacturing methods. Moreover, AM DLP 3D-printing with photo resin slurries eliminates the dust and debris of subtractive manufacturing, which for some ceramics is hazardous to human health. Moreover, given the complexity and resolutions made possible by DLP 3D-printing ceramics, quantities of intricate and small feature size parts can be manufactured in batches that ensure uniformity of the parts. AM ceramics may allow for the elimination of processing steps and allow for batch manufacturing which may reduce the manufacturing cycle time. AM technologies and material suppliers that can produce the materials and systems for RF ceramics are also available within the United States, which makes outsourcing these materials and systems unnecessary. This regional availability also significantly reduces manufacturing logistics and fulfillment cycles.

IV.

CERAMIC METALLIZATION INCLUDING SELECTIVE METALLIZATION OF RF CERAMICS

RF Ceramics are robust and high performing dielectric materials, which is why ceramic dielectrics are a main dielectric component of many critical and high power RF systems. Many RF components are dielectric structures combined with metallic structures to realize complete RF passive components. This includes traditional RF passives, such as inductors, capacitors, resonators, couplers, transmission lines, waveguides, dividers/combiners, and even newer technologies like metamaterial structures.

To be able to fabricate these structures, precision metallization is needed with tight tolerances and high repeatability.

This could mean tight control of the overall metal thickness and surface finish for fully metallized parts, but also selective metallization, which can result in structures that would be impractical to manufacture traditionally. With selective metallization and AM RF ceramics, full 3D RF circuits with integrated RF passives can be fabricated, including the assembly housing. Such an approach presents a scalable and reproducible single-process for manufacturing volumes of high resolution RF ceramics, passives, and housing/shielding with previously impractical degrees of freedom for RF designs. It may also be possible to replace traditionally machined RF metallic structures, in some cases, depending on the cost and complexity of the structures, as a metallized ceramic structure may be lower weight and may also potentially be fabricated with greater degrees of freedom.

There are several potential processes for metallizing ceramic structures from completely plating structures to using methods to selectively plate. Electroless plating can be used to plate virtually any structure with certain processes that can plate selectively using laser activation of seed material or other selective methods of depositing seed layers (i.e. sputtering, chemical vapor deposition, etc.) [7]–[9]. Electroless plating is a preferred method for high performance RF applications, as electroless methods enable plating on non metallic surfaces and tend to provide a more uniform base layer that can then be electrolytic plated to reach desired plated metal thicknesses.

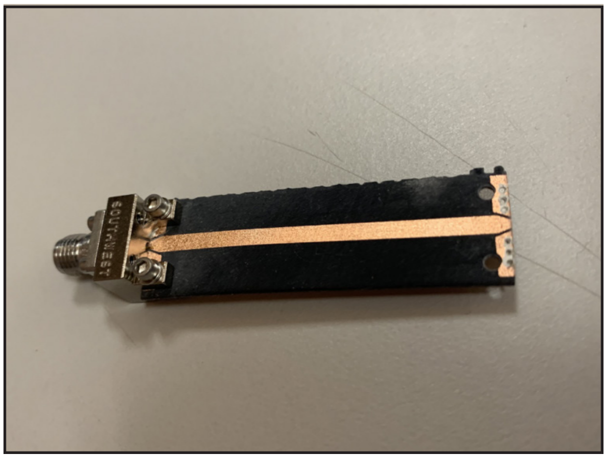

FIGURE 2.
Example of a Metallized 2" Microstrip

V.

3D PRINTED RF CERAMIC APPLICATION DISCUSSIONS

Though AM of technical ceramics has been possible for some time, much of the focus of research and development of these technologies and systems has been focused on non-RF applications. Recent capabilities in AM of RF technical ceramics has opened the door to a wide range of potential use cases for this technology that may bring many advantages and possibly even enable new use cases previously unviable with traditional ceramics manufacturing. The following sections of this whitepaper highlights several example applications where some research/development or exploration has been done, with discussions of how the latest methods of AM RF ceramics may bring advantages to these use cases and similar applications.

CERAMIC RF WINDOWS

RF windows, often used as pressure barriers or gas barriers, are critical components of klystrons, gyrotrons, and more recently, particle accelerators. RF windows are also often integrated into waveguide interconnects (waveguide pressure windows) to prevent certain gas mixtures from escaping the waveguide internal cavity or otherwise being contaminated by the outside environment. In general, RF windows are used in high power applications, where the heating from high power RF and potentially high differential pressure across the window are possible. RF ceramics have often been used for this application due to their general ruggedness, relatively low dielectric loss (loss tangent), and ability to be bonded to surrounding metal frame/supports [10].

Typical RF windows are monolithic flat structures fabricated from ceramic sheets bonded to metallic flange material. Care must be taken in the design of the flange and how the flange is bonded to the ceramic window material. It is possible, however, with an AM of ceramic material, that some of these design constraints could be reduced or greater RF transparency could be achieved using small scale but still rugged lattice structures instead of a monolithic window. It is also possible that an AM ceramic RF window could be designed that moves the ceramic/metal bonding region further outside of the window area, which could potentially result in higher pressure capability or otherwise ease the design/fabrication of RF windows. Furthermore, such a process should allow for the integration of a RF lens with an RF window, which can lead to more desirable beam characteristics or to negate the effects of an RF window.

An AM RF ceramic process could be used to completely fabricate a ceramic window without the need for a metal flange, though this would introduce additional considerations given the difference in brittleness between common RF window flange materials and AM technical ceramics.

CERAMIC RF LENSES

There have been substantial R&D efforts and even fielded products that take advantage of AM RF lenses for a wide range of applications [11]–[14]. The majority of these discussions have been about photopolymer lenses, including recent advancements in low-Dk and low-loss materials that require sophisticated mixing technologies. Though these processes can achieve very high resolution lenses that operate well to w-band frequencies, they are made of photopolymer resins that have operating temperatures in the hundreds of celsius and relatively low thermal conductivity. Hence, RF lenses fabricated with photopolymer are suitable for a wide range of applications, with the exception of high power RF use cases where the lenses may exceed typical operating temperatures and cannot be adequately cooled.

Compared to advanced RF photopolymer resins, RF ceramics have higher Dk, lower loss tangent, significantly higher operating temperature, higher thermal conductivity, and superior abrasion/chemical corrosion resistance. Therefore, for high power, high temperature, or otherwise extreme environmental applications, an AM RF ceramic lens can be used in place of an AM photopolymer lens with many of the same benefits. Given the higher Dk of RF ceramics, RF lenses made with these materials would also be somewhat smaller for the same frequencies and performance or exhibit enhanced focusing performance in the same footprint. This also limits the high frequency extreme of this material, as at higher frequencies the internal structures of AM lenses become smaller and eventually approach the resolution limits of the manufacturing process.

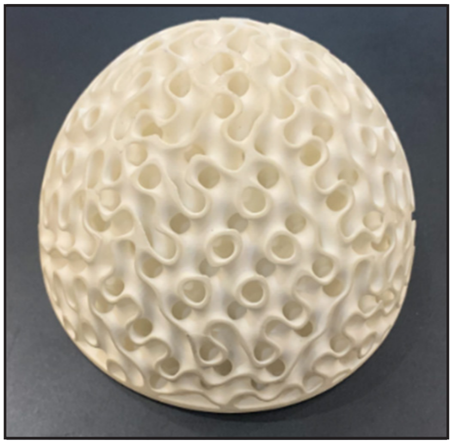

FIGURE 3.
A hemisphere GRIN/luneburg style RF lens fabricated using high purity alumina resin and Fortify's DLP 3D printing technology.

FULL-3D PRINTED RF PASSIVES COMPONENTS AND CIRCUITS USING 3D PRINTED CERAMIC WITH SELECTIVE/ NON-SELECTIVE METALLIZATION

As previously discussed, a Full-AM RF ceramic with metallization process can enable the fabrication of RF passives, circuits, and housing/shielding with greater degrees of freedom than was previously practical with traditional approaches to machining ceramics[15]–[23]. Limitations of traditional machining methods have often resulted in the forms that certain RF components take. RF assemblies and circuits have historically been restricted to layered 2D approaches, such as with LTCC and HTCC technology. With greater degrees of freedom, RF components and circuits could be designed fully in three dimensions instead of layered 2D. With this technology it is possible to 3D print and metalize a complex RF structure, such as a hollow or voided spiral, that would be impractical or impossible to machine traditionally.

Full-AM RF ceramic structures with selective metallization could even be used to fabricate RF circuits with integrated passives and potentially realize entirely different form factors, such as folding or alternative methods of coupling or shielding. An example of these concepts is a 3D folded branch line coupler featured in [17]. This new process may enable more compact or more geometrically optimized RF structures that fit more efficiently in space constrained structures. An additional example is a full-3D RF assembly/circuit nestled efficiently between structural members of a small unmanned-aerial vehicle (UAV), which have extensive cost, weight, and space constraints.

A simple example of an RF component that is typically planar and may have a more desirable footprint if fabricated as a fully 3D part, is the folded hybrid coupler design from [17] (see Figure 4). Hybrid couplers are conventionally fabricated using planar laminates with etched surface metallization, often using high frequency PCB manufacturing methods (see Figure 5). Another example is leveraging 3D-printed ceramics to enable compact and high performance folded branchline couplers with helical microstrip transmission line segments that result in a component footprint that is a small fraction of a planar counterpart.

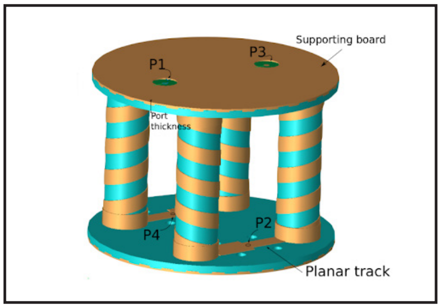

FIGURE 4:
Model of the HYBF folded hybrid branch-line coupler with helical-microstrip lines. [17]

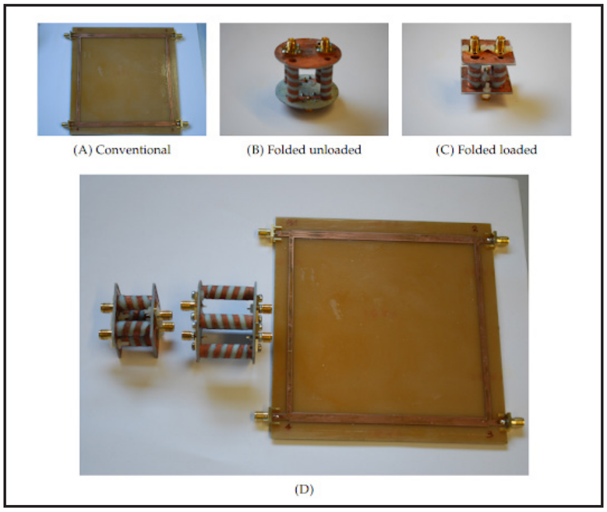

FIGURE 5:
Hybrid branch-line coupler prototypes. [17]

DIELECTRIC RESONATOR ANTENNAS AND INTEGRATED LENSES

Dielectric resonator antennas (DRAs), due to the nature of their dielectric structural design, are widely considered an enhanced alternative to patch antennas for microwave and millimeter-wave antenna arrays for the latest communications technology and sensing (radar) applications. DRAs can be designed to provide improved impedance bandwidth, efficiency, less sensitivity to manufacturing tolerances, a flexible feed arrangement, and potentially a more compact size than conventional patch antenna arrays[18], [24]–[29]. Moreover, the 3D structure of DRAs allows for greater degrees of freedom with the design to enhance overall antenna and array performance, including a wide range of possible DRA shapes (see Figure 6).

One of the most significant advantages of DRAs over other antenna types is that the size of a DRA is proportional to the wavelength at resonance divided by the square root of the relative permittivity of the dielectric material. Hence, a DRA operating at the same frequency as a microstrip antenna, and with the same dielectric, would be substantially smaller. There are also additional techniques available to further reduce the size of a given DRA. Another key aspect of DRAs is that if low-loss dielectrics are used with a high breakdown voltage and good thermal conductivity, DRAs can be designed to operate at high power levels. The conduction losses at millimeter-wave frequencies significantly limit the power handling capability of metallic antenna types and result in lower radiated efficiency compared to DRAs.

Therefore, a DRA made with a rugged material with desirable dielectric constant and low-loss tangent and a fabrication process capable of high resolution 3D structures could exhibit desirable characteristics for use in the latest high performance communication and sensing applications. With selective metallization and the ability to integrate RF lenses in the same structure, such a DRA array could be AM with a suitable ceramic and embedded feed/probe structure. This suggested method in essence enables a single-process DRA fabrication that, due to the nature of AM, could be rapidly iterated to allow for extensive experimentation and optimization with a reduced design cycle[28]–[38]. Ceramic materials are typically desirable for DRAs, as RF ceramics tend to present lower loss at higher relative permittivities than polymers. Given the challenge of conventional machining of ceramics, AM technologies can be used to realize more complex and potentially higher performing DRAs with greater degrees of freedom of critical features (See Figure 6 and 7).

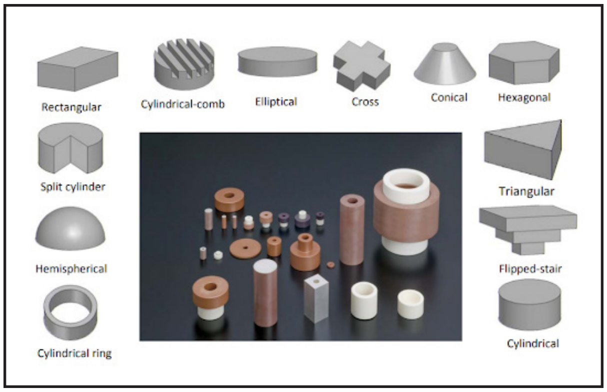

FIGURE 6:
Example DR geometries using conventional manufacturing techniques and stock ceramic materials. [24]

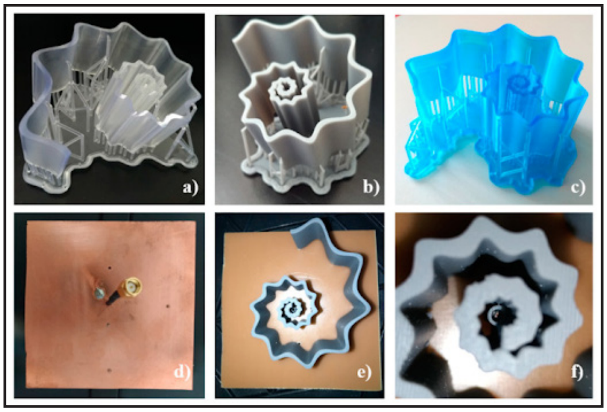

FIGURE 7:
SsDRA prototypes: (a) Clear V04 resin SsDRA (DRA1); (b) Grey V04 resin SsDRA (DRA2); (c) Tough blue V05 resin SsDRA (DRA3); (d) Coaxial cable, SMA connector, and pins on the ground plane; (e) Top view of the assembled SsDRA prototype; (f) Detailed view of the SsDRA's origin with feed guides. [38]

WAVEGUIDE ASSEMBLIES & COMPONENTS

AM waveguide components and assemblies have been of interest to military/defense, aerospace, and space organizations for several years [31], [39]–[45]. Many of these efforts have focused on processes that result in completely metallic components. Though the AM of metals does enhance the degrees of freedom when fabricating waveguide parts compared to conventional waveguide manufacturing methods where waveguide interconnect, components, and assemblies must be made in several machinable parts and later assembled and tuned, the available metal AM methods do have some drawbacks. One of the most significant is that these methods often result in metallic surface finish that results in degraded waveguide performance at higher frequencies compared to surface finish achievable with traditional machining. This tradeoff can sometimes be overcome with additional post processing steps, but the post-processing methods come with their own drawbacks and limitations.

Another option that is being explored is the AM fabrication of dielectric structures that are then either fully plated or selectively plated to realize waveguide parts. Plating/coating polymers or ceramics with metal can result in much lower weight and improved surface finish parts than full metal AM parts, as well as potentially offering lower production times and lower manufacturing costs. Metal plated/coated AM waveguide parts present some advantages for aerospace and space applications where weight and space constraints are significant. An example of this is a conformal array antenna manufactured using an SLA process with spray metalization (See Figure 8).

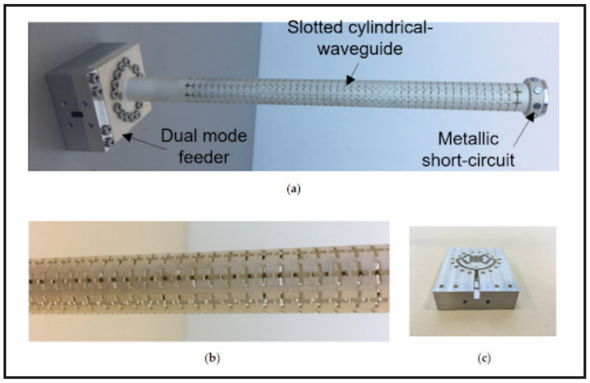

FIGURE 8:
Photographs of the conformal array antenna manufactured by SLA + spray metallization: (a) whole antenna prototype; (b) slotted cylindrical waveguide detail; and (c) dual-mode feeder. [45]

V.

For some higher power applications or for use in environments that have wider temperature extremes, it may be desirable to use plated/coated ceramics as the base material as opposed to polymers. AM technical ceramics are available with operating temperatures exceeding 1000 degrees Celsius, well beyond that achievable with polymers resins. It is also possible that the sintering process could be optimized for surface finish which may result in improved surface finish for AM ceramics compared to polymers. This could allow for plated/coated ceramic waveguide parts that operate to higher frequencies or with better performance than polymer counterparts. In the case where precious metals, such as platinum, or expensive manufacturing processes are involved, a metallized ceramic waveguide structure could be made more economically while avoiding CTE mismatches between parts in the assembly.

VI.

CONCLUSION

The recent availability of technical ceramics with good RF performance features and selective/ non-selective metal coating technologies has opened the door for a wide range of potential applications of AM ceramics. These use cases range from rapidly prototyping high performance RF parts to manufacturing assemblies with integrated RF passives in a single process. As this technology is just emerging, the near future may bring more ceramic options, metal coating/ plating systems, and demonstrations of these technologies to inspire research and product development efforts.

For more information on ceramics 3D printing capabilities **get in touch** with Fortify's additive ceramic experts.

VII.

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