Novel Uniquely 3D Printed Intricate Voronoi and Fractal 3D Antennas

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***Abstract*—While 3D printing has enabled the rapid prototyping of numerous 3D structures, only very few designs have exploited this technology to create structures that are difficult or impossible to manufacture in any other way. In this paper, a novel surface modification technique is combined with high-resolution Stereolithography 3D printing to enable arbitrary 3D antenna designs that have never been demonstrated before including a Voronoi tessellation for light weight, low volume, and aerodynamic properties and 3D fractal geometries featuring similar physical advantages. Both antenna topologies utilize a novel metallization technique, electroless copper plating, to overcome the highly lossy properties of common 3D printed dielectric materials.**

***Index Terms*—3D printing, Stereolithography, SLA, electroless plating, Voronoi, fractal, antenna**

I. INTRODUCTION

3D printing additive manufacturing techniques allow the rapid design and fabrication of free-form three dimensional objects with ease, requiring minimal material to achieve designs impossible with traditional subtractive machining.

In terms of RF, 3D printing offers the unique ability to realize on-demand a wide range of substrate thicknesses and variable dielectric constant values for gradient index substrates based on the material or infill, which has already seen utilization for dielectric lenses [1]. Most 3D printed designs consist of traditional 2D planar designs that are fabricated utilizing 3D-compatible materials, but often lack a true 3D factor enabling the realization of designs that could not be realized otherwise. One of the most advantageous features of 3D printed structures is the ability to print around the absence of materials leading to the easy realization of small or large cavities of complex shapes eliminating the need for complex machining and for interconnecting separately fabricated parts. A downside to stereolithography printing techniques is that the photopolymer resins demonstrate a trend of high dielectric losses, a challenge that must be overcome to enable a wider utilization for the realization of RF designs, especially in higher frequencies [2].

To demonstrate the novel designs that 3D printing enables, this paper presents the first Sierpinski triangle 3D fractal antennas and the first Voronoi tessellated antennas. Both mathematically inspired antennas use mathematical formulations to derive new antenna designs which cannot be manufactured in any other manner, while utilizing electroless plating to overcome the highly lossy nature of commonly used 3D printed dielectric materials.

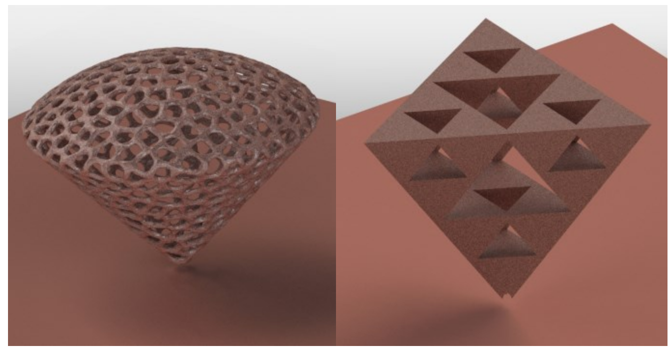

Fig. 1. (a) Voronoi inverted feed discone antenna model. (b) Fractal Sierpinski triangle antenna.

II. ANTENNA DESIGN

A. Voronoi Tessellated Inverted Feed Discone Antenna

Voronoi diagrams are widely used in a variety of scientific fields, from demonstrating wireless network capacity, to machine learning, and robotic navigation. The Voronoi tessellation occurs by subdividing a plane into polygons where the size and numbers of borders of each polygon is determined by finding the half way distance between user-generated seed points and finding the midpoint between its neighbors.

When any 3D model is saved into a STeroLithography (STL) file, a format commonly used for 3D printing, the model is discretized into a series of triangle polygons to rebuild the 3D object. Curved surfaces are approximated by the smallest segment size, similar to many electromagnetic simulators.

The Voronoi tessellated antenna consists of an inverted feed discone antenna as the base shape [3], similar to a bowtie in the radiator dimensions with a length 25.21mm and a flare angle of 87° for matching. The seed points are generated in order to create holes of approximately 2 mm radii.

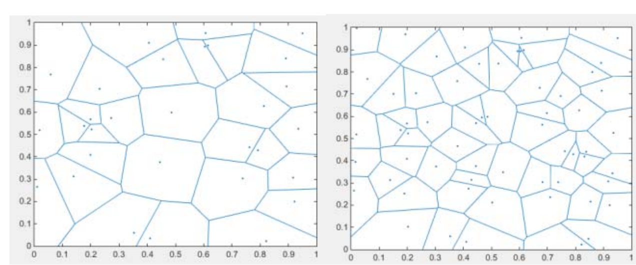

Fig. 2. Voronoi Diagrams with (a) 30 and (b) 60 randomly generated seed points, respectively.

B. Sierpinski Triangle Fractal Monopole Antenna

The 3D Sierpinski Triangle fractal antenna is designed utilizing a self-similar design consisting of an equilateral triangular pyramid as the base shape. Assuming that n defines the amount of iterations, the amount of triangle pyramids is 4^n. The proof-of-concept structure presented in this paper is derived for $n = 2$ with an exterior largest edge of length 32.45 mm. For each consecutive iteration, the fractal designs occupy 50% less volume, which leads to reduced material usage and fabrication time for most 3D printing techniques. In order to simulate and fabricate, the triangles feature a 10% overlap at the connecting vertices in order to strengthen the design for printing and mounting.

III. Two Step Fabrication Process

Two processes for fabrication were utilized in this design. First, the dielectric parts were printed with a Form 2 stereolithography printer. For metallization, a new method was attempted to obtain complex conductive coating of intricate 3D antennas regardless of the design complexity.

A. 3D Stereolithography Printing

While inkjet printing techniques can be characterized with the dots per inch (DPI) in which each dot can be represented as a 2D pixel, 3D printing characterizes the smallest point of resolution as a voxel. A voxel tends to be non-uniform in resolution on its X, Y, and Z axes. A more advanced method of 3D printing, called stereolithography (SLA) was developed in the 1970's which exposes photosensitive liquid resins to UV (or even visible) light to crosslink the photopolymer. As the material crosslinks with the previous layer, the final prints are more isotropic in strength than other 3D fabrication techniques.

The original SLA systems were based around "top down", laser-based exposure where the build plate lowers into a vat of the photopolymer resin, with each layer being traced with a UV laser from the top. The limitations of a system of this nature included the requirement for a vat full of resin equal to the size of the print. Recent advances have now use a "bottom up" approach, where the build plate is pressed against a transparent window and the UV exposure occurs from below. This allows much larger designs, as only a small amount of photopolymer is necessary to cover the transparent window. When the photopolymer crosslinks from exposure, the material adheres to both the build plate and the transparent window, creating stress forces that may split the print from the build plate. In order to reduce these adhesion forces, hard transparent windows are often coated with a Polydimethylsiloxane (PDMS) coating (or other non-bonding, flexible material). Photopolymers tend to be more lossy than thermoplastic polymers and are of similar dielectric constant values [2]. While multimaterial systems have been demonstrated for proof-of-concept purposes, there are none commercially available and this technique features the capability of only single dielectric printing as of now, and post processing is needed to clean off excess resin from the print [4].

The designs herein were fabricated utilizing a low cost Form 2 laser-based SLA printer utilizing the Clear resin photopolymer (Form Labs) with 25 µm layers using a 140 µm spot size, 250 mW, 405 nm laser, leading to a voxel resolution of approximately 140x140x25 µm^3. The accuracy of a print has a tolerance up to approximately 127 µm. Removable support structures were utilized in order to minimalize potential failures which may occur due to stress forces between the transitions at the tips of the Sierpinski triangles and the large surface area of the next printed layer.

B. Metallization

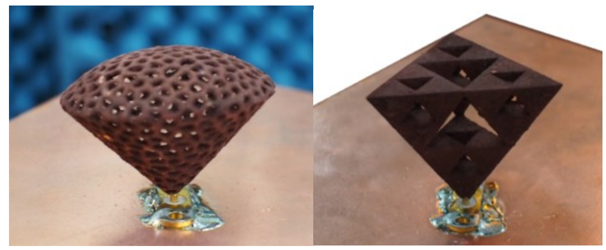

Fig. 3. 3D Printed and electroless copper coated (a) Voronoi and (b) fractal Sierpinski triangle antenna.

Metallization remains a major challenge depending on the exact printing process or design. Recently, a new copper electroless plating method was developed that is compatible with the acrylate nature of the resin [5]. While electroless deposition has been demonstrated on SLA prints in the past utilizing gold [6], most reported efforts rely on a surface roughness etching [7].

On the contrary, the electroless deposition of copper on the SLA printed designs presented in this paper was performed following the procedures reported in [5] that relies on surface modification that is compatible with the acrylate resin. with modification. Briefly, the samples were immersed in an ethanol-based saturated palladium chloride (Sigma-Aldrich, St. Louis, MO, USA) solution for 5 min. The samples were taken out from the palladium chloride solution, let sit on paper towel for 5 seconds (to remove the extra palladium chloride solution not absorbed to the samples), and then incubated with a homemade copper electroless deposition bath for 1 hour in an incubation shaker (25 °C, 100 rpm). The aqueous-based copper electroless deposition bath was made by dissolving appropriate amounts of cupric sulfate (anhydrous, Mallinckrodt Baker, Phillipsburg, NJ, USA) and sodium potassium tartrate tetrahydrate (Alfa Aesar, Ward Hill, MA, USA) to realize a concentration of 0.19 M and 0.67 M, respectively, adjusting the pH of the resulting solution to 12.5 using an aqueous NaOH solution, and finally adding appropriate amount of formaldehyde (37% in water, Alfa Aesar) to make a concentration of 220 mM. The copper-coated samples were then carefully rinsed with DI water and dried in air.

After the electroless deposition of the complex structures was completed, multiple points were measured to verify

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connectivity, all displaying 0.000 Ω via an ohmmeter. Connectivity was verified between both opposite ends of the device on multiple axis, as well as a random assortment of 5 mm separated measured points.

IV. Results

All simulations were done with CST's Time Domain Solver, while all measurements of the 3D-printed metallized Voronoi (Fig. 3(a)) and fractal Sierpinski (Fig. 3(b)) prototypes were performed with an Anritsu 37369A VNA. The results demonstrate that both antennas are well matched over a broad frequency range (Fig. 4) and feature an omnidirectional radiation in the azimuth plane (Fig. 5). Frequency shifts were originally visible due to variations in the fabricated feeding structures, and with additional modeling to take into account the length of the SMA connector and its effect on the structure. This frequency shift is visible in the Voronoi S11 results. The variation in magnitude for the fractal antenna indicates additional losses in the system, possibly at the interconnect of the SMA and antenna.

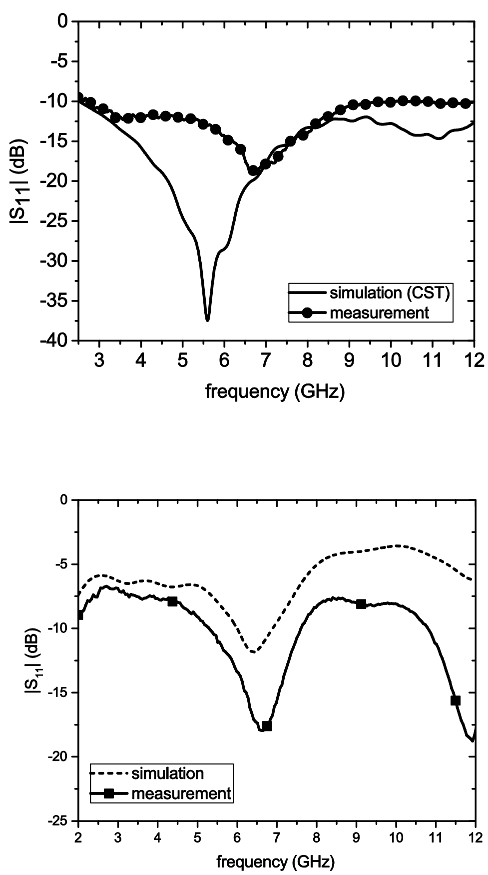

Fig. 4. Simulation vs Measurement S11 results for 3D printed (a) Voronoi and (b) fractal Sierpinski triangle antennas.

V. Conclusion

3D printed stereolithography with copper electroless plating has been demonstrated as a viable method for the realization of highly complex 3D mathematically inspired antenna structures that have never been fabricated before and were impossible to manufacture with conventional methods. This novel reported metal-coated-plastic technique allows elaborate designs with full and uniform coverage with pure copper, while removing the typically high dielectric loss of commonly used photopolymer resins to enable low cost antennas of arbitrary 3D shapes. For the first time, 3D fractal Sierpinski triangle antennas and Voronoi tessellated antennas are demonstrated, enabled by these advances in 3D printing.

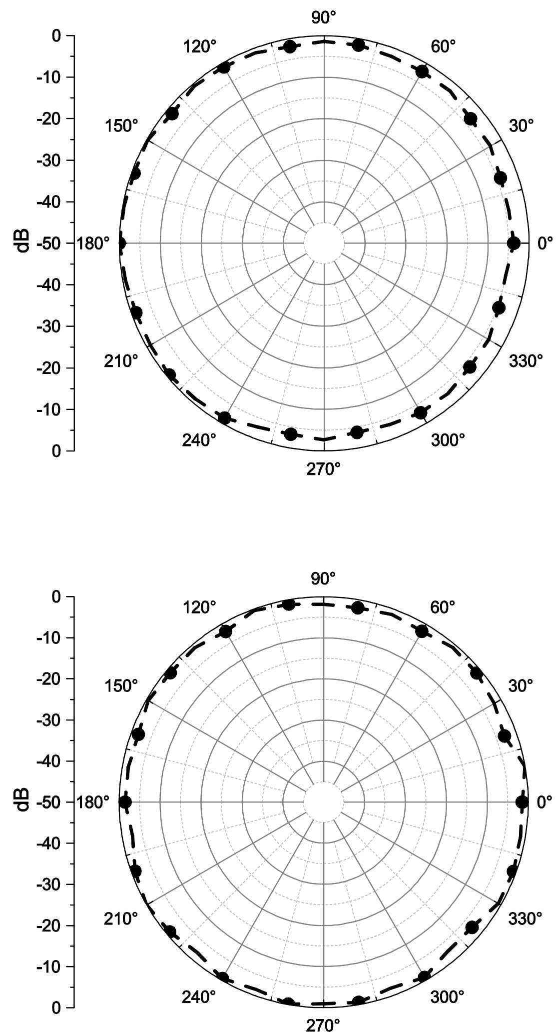

Fig. 5. Measured radiation patterns for the 3D printed (a) Voronoi and (b) fractal Sierpinski triangle antennas.

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REFERENCES

[1] H. Acikgoz, R. K. Arya and R. Mittra, "Statistical analysis of 3D-printed flat GRIN lenses," *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, Fajardo, 2016, pp. 473-474.

[2] P. I. Deffenbaugh, R. C. Rumpf and K. H. Church, "Broadband Microwave Frequency Characterization of 3-D Printed Materials," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 3, no. 12, pp. 2147-2155, Dec. 2013.

[3] Harris Corporation, "Inverted Feed Discone Antenna and Related Methods," U.S. Patent 7 286 095, 2016.

[4] Zhou, C., Chen, Y., Yang, Z.G. and Khoshnevis, B., 2011. Development of multi-material mask-image-projection-based stereolithography for the fabrication of digital materials. In *Annual solid freeform fabrication symposium*, Austin, TX.

[5] Yunnan Fang, John D. Berrigan, Ye Cai, Seth R. Marder and Kenneth H. Sandhage. "Syntheses of nanostructured Cu- and Ni-based micro-assemblies with selectable 3-D hierarchical biogenic morphologies," *Journal of Materials Chemistry*, 2012, 22, 1305–1312.

[6] Note: Three-dimensional stereolithography for millimeter wave and terahertz applications. Macor, A. and de Rijk, E. and Alberti, S. and Goodman, T. and Ansermet, J-Ph., *Review of Scientific Instruments*, 83, 046103 2012.

[7] Joseph, S, Quiñones, S, Medina, F & Wicker, R 2007, Effect of surface preparation methods on mechanical properties of 3D structures fabricated by stereolithography and 3D printing for electroless Ni plating. in *18th Solid Freeform Fabrication Symposium*, SFF 2007. University of Texas at Austin, pp. 377-391.