3D PRINTING MULTI-FUNCTIONALITY:
Embedded RF Antennas and Components

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***Abstract* — Significant research and press has recently focused on the fabrication freedom of Additive Manufacturing (AM) to create both conceptual models and final end-use products. This flexibility allows design modifications to be immediately reflected in 3D printed structures, creating new paradigms within the manufacturing process. 3D printed products will inevitably be fabricated locally, with unit-level customization, optimized to unique mission requirements. However, for the technology to be universally adopted, the processes must be enhanced to incorporate additional technologies; such as electronics, actuation, and electromagnetics. Recently, a novel 3D printing platform, Multi^{3D} manufacturing, was funded by the presidential initiative for revitalizing manufacturing in the USA using 3D printing (America Makes – also known as the National Additive Manufacturing Innovation Intuitive). The Multi^{3D} system specifically targets 3D printed electronics in arbitrary form; and building upon the potential of this system, this paper describes RF antennas and components fabricated through the integration of material extrusion 3D printing with embedded wire, mesh, and RF elements.**

***Index Terms*—antenna, micro-strip 3D printing.**

I. INTRODUCTION

In recent years, 3D printing has produced many exciting advances for high value highly customizable products. This ability, to create on-demand prototyping, has garnered interest from medical applications to the defense and aerospace industries. However, until recently, the structures produced using 3D printing have been purely mechanical in nature [1-13]. In order to overcome this limitation, the W. M. Keck Center for 3D Innovation, located at the University of Texas at El Paso, has been investigating the process of incorporating electrical components and sensors directly into the material extrusion 3D printing (ME3DP) process, commercially known as fused deposition modeling (FDM) [1-3].

In order to provide the complete spatial control and device functionality required to produce next generation electronic 3D printed structures, the W. M. Keck center is in the process of constructing a novel Multi^{3D} manufacturing system. This exciting technology is funded by the *America Makes* presidential initiative, created in order to revitalize manufacturing in the United States. The Multi^{3D} system (Fig. 1) is aimed to provide: extrusion of multiple thermoplastic materials, micromachining, and the ability to embed multiple types of wires and fine pitch meshes. The penultimate goal of the exciting system is the production of 3D printed structures integrating complex polymer materials (Radiation shielding or high permittivity), electrical components (microcontrollers, interconnects and sensors), thermal management systems (heat piping or radiators), and antenna communication systems.

The America Makes system operates by taking advantage of the layer-by-layer nature of ME3DP. For example, this system will be able to print a layer of thermoplastic, embed electrical interconnects, place a microcontroller, and then continue printing additional layers of thermoplastic. After a few additional printed layers, the system is able to embed a copper mesh ground plane, print dielectric spacers of a secondary material, and then embed an antenna. The result would be a monolithic structure with antenna/ground plane functionality as well as a microcontroller or balun control system connected to an SMA connector. Full system integration, as described, would allow full three-dimensional design freedom including: component placement, material placement/properties, and electrical routing. The link between the various manufacturing stations is a six-axis robot that will function as a "work piece handler." The work piece will be transported on a portable build

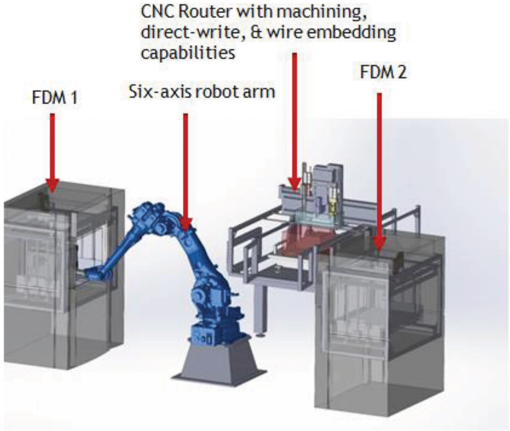

Fig. 1. CAD rendering of multi3D system showing multiple build bays, a CNS router, and two FDM machines. The blue automated arm moves the build platform between bays.

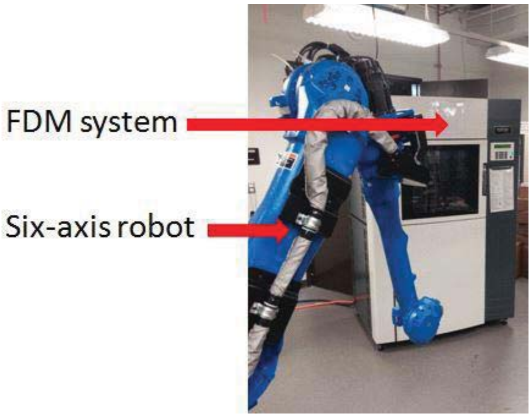

Fig. 2. Multi^{3D} system in present arrangement, shown is one FDM 400mc and automated arm used to move the build platform from between build bays.

platform and encompassed by a heated travel envelope that will mitigate drastic thermal changes known to cause warping. The system is shown in Fig. 2.

The antennas analyzed in this paper are only a small fraction of the potential geometries. Fig. 3 shows a few additional embedded antennas which were fabricated, and can be directly embedded into the sidewall of spaced based platforms, such as the mock-up cubesat shown in Fig. 3b. Initial antenna and micro-strip fabrication has incorporated patch antennas, multi-layer micro-strips, and spiral dipole antennas [14]. These three examples contain monolithic geometries and multiple layers of components, which are designed to be incorporated with the Multi^{3D} system. Each represents an advance in potential a particular area of embedded communication systems, but all can be incorporated into 3D printing, and have undergone multiple prototyping versions, highlighting the flexibility of 3D printing. More information on the patch antenna can be found in [14].

II. ANTENNA FABRICATION AND RESULTS

A. Spiral Dipole Antenna

A spiral design was selected for its small size and circular polarization, and an Archimedean spiral was chosen over logarithmic to facilitate the fabrication using embedded wires. Although spirals are naturally bidirectional, a ground plane was added to improve the directionality. Traditionally, a unidirectional spiral may be backed by an absorbing cavity to eliminate the back lobes. However, this radiation can instead be reflected by spacing the ground plane $\lambda/4$ away from the spiral such that the reflections reinforce radiation at a desired frequency [15]. This also has the benefit of keeping the spiral low-profile by avoiding the bulky cavity of absorber. However, this approach comes at the expense of the normally wide-band nature of the spiral, creating resonances that are particularly sensitive to the physical spacing of the device.

The physical structure spiral dipole antenna, shown in Fig. 4a, was designed using SolidWorks®, and fabricated using a Stratasys FDM 400mc. The Sprial antenna was printed on Stratasys polycarbonate (printed using T16 print tips) calibrated with raster widths of 254µm. The FDM 400mc printed the polycarbonate base of the antenna with default temperatures, raster orientation, and raster spacing. This dipole antenna was fabricated using approx. 3 cubic inches of material, which corresponds to approx. 1/34 of a container of polycarbonate filament, or about 12 U.S. dollars.

The spiral pattern was designed for 1.0 - 10.0 GHz, with the ground plane spaced a quarter-wavelength away in polycarbonate ($\varepsilon r=2.9$) to reinforce frequencies at 2.0 GHz. The resonances created by this spacing were observed to be sensitive to the fabrication, although they were reproducible and could be optimized to a particular frequency. The spiral antenna itself was designed using CST Microwave Studio and saved as an Autocad® file. The spiral design was then converted to .gcode and exported to the gantry mounted wire embedding system. This wire embedding system utilizes a specially designed ultrasonic head which produces localized heating within the copper wire and then forces the wire below the thermoplastic surface. The ultrasonic head and embedding process can be seen creating a fractal antenna in Fig. 3a.

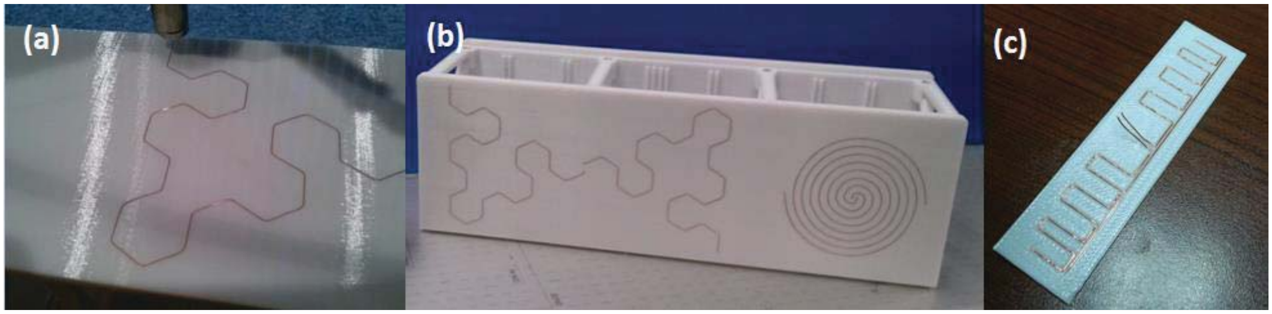

Fig. 3. A custom ultrasonic horn is shown embedding a 32 gauge wire into the sidewall of a polycarbonate cubesat design (a). The final cubesat with both a fractal antenna and a spiral antenna embedded on the side wall (b), this was done using ultrasonic embedding. (c) A dipole antenna was embedded on a 2mm thin polycarbonate sheet using a 26 gauge wire and a thermal embedding method.

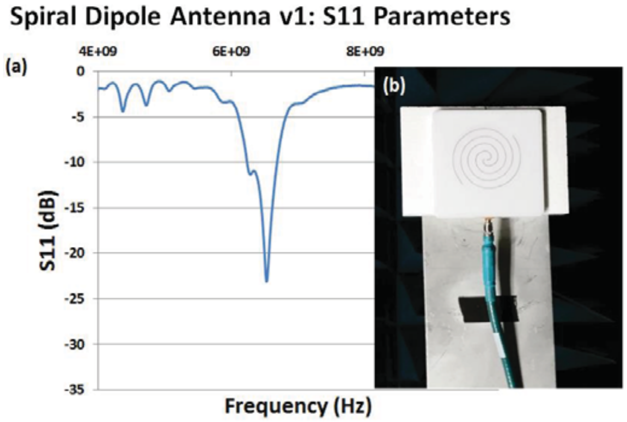

Fig. 4. Experimental S11 parameters of dipole spiral antenna (a). The spiral antenna in the process of being measured at NASA Glenn Research center (b), not shown is back reflecting plane added post process to increase signal.

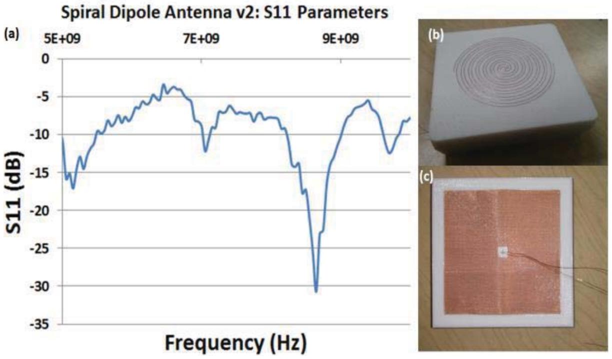

Fig. 6. Experimental S11 parameters of a dipole antenna with an embedded/encapsulated mesh back reflecting plane (a). The spiral antenna after embedding (b), and the back reflecting plane before embedding and encapsulation (c).

The resulting antenna was tested in an anechoic chamber at NASA Glenn Research Center, and can be seen in Fig. 4a, with the S11 parameters shown in Fig. 4b. The resulting radiation pattern and return loss are shown in Fig. 5a and Fig. 5b. In order to showcase the prototyping flexibility of our system, a second dipole was designed with an embedded mesh reflecting ground plane. The new prototype antenna was fabricated with the same procedure as the previous version. However, this version was fabricated using approx. 15 cubic inches of material, which corresponds to approx. 1/6 of a container of polycarbonate filament, or about 66 U.S. dollars. Following the ultrasonic spiral embedding, a fine pitch mesh ground plane was embedded with a thermal embedding process, and then encapsulated with additional layers of thermoplastic in the FDM 400mc. This antenna can be seen in Fig. 6b and Fig. 6c and the S11 parameters are shown in Fig. 6a. The experimental and simulated radiation pattern is shown in Fig. 7a and the return loss is shown in Fig. 7b.

B. Microstrip

The microstrip antenna used in this work was designed in ANSYS HFSS (Fig. 6a) and then exported to SolidWorks® for additional design processing. The build was separated into three build/embedding steps. The resulting micro-strip is a three layer monolithic design incorporating two vertical interconnects. This antenna was built using a table top MakerBot ME3DP which is representative of possible additions to empty bays within the Multi^{3D} system.

This micro-strip was produced using acrylonitrile

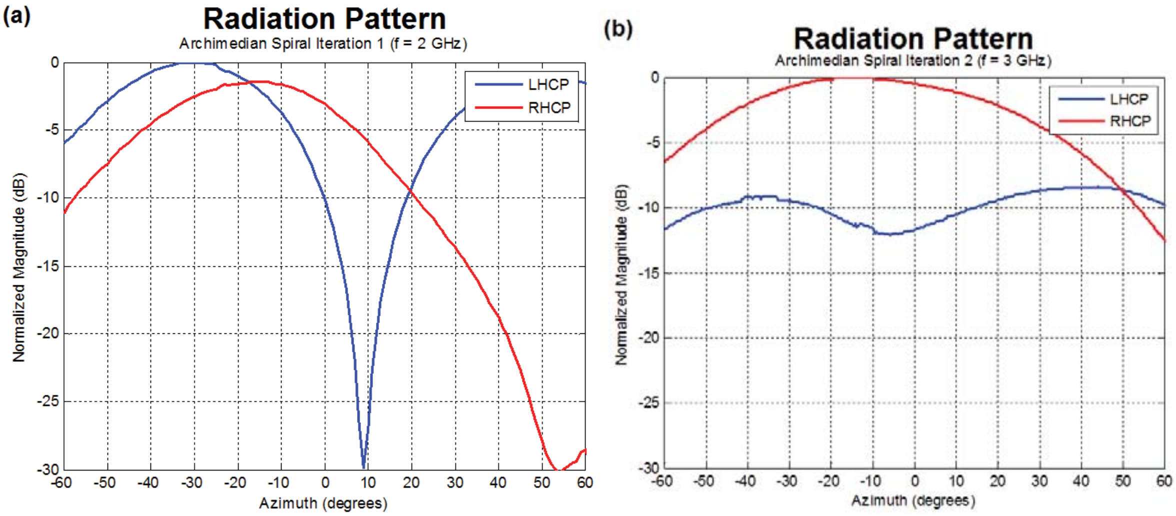

Fig. 5. Experimental and simulated (a) radiation pattern Archimedian spiral antenna v1at a frequency of 2.0 GHz. The (b) radiation pattern of the Archimedian spiral with an embedded back reflecting plane is shown at a freaquency of 3.0 GHz.

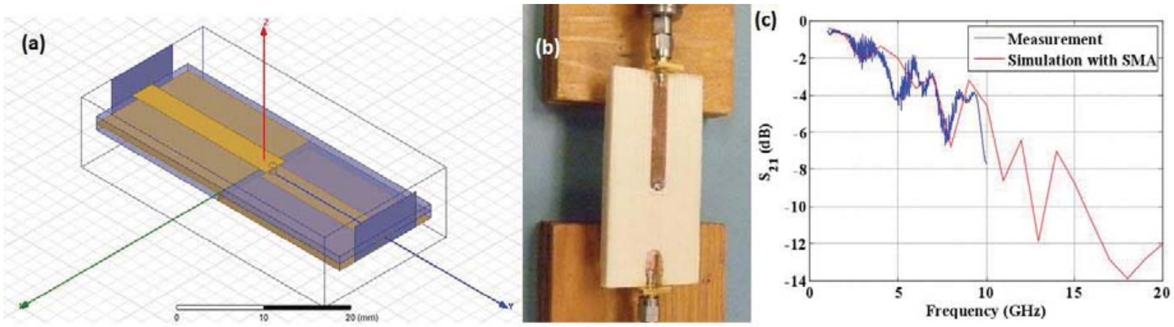

Fig. 8. A multilayer micro-strip designed in HFSS (a). The micro-strip being tested for S21 (b), this was after construction was completed and two SMA connectors were soldered to the mesh micro-strip. Measured and simulated S21 results are shown in (c), the micro-strip appears high loss due to impedance miss-match at the SMA connector.

butadiene styrene (ABS) and fine pitch copper mesh. The ABS was printed at 240 °C with a print bed temperature of 110 °C. SMA connectors were attached to both sides of the micro-strip design using solder, shown in Fig. 8b. All meshes were embedded using the same process explained in section IIa. The resulting antenna was tested using a network analyzer, the resulting transmission spectra (S21) is shown in Fig. 8c.

III. CONCLUSION

This work has examined the feasibility and flexibility of designing and fabricating complex antennas using a single 3D printing system. In particular, this work examined a multilayer micro-strip and a dipole antenna. The next version of the spiral antenna will incorporate an embedded mesh balun and compare the results to prefabricated duroid balun. Additionally, the next version of the micro-strip will implement unique mesh plane geometries to account for impedance matching constraints. However, using the Multi3D system, it will become possible to easily incorporate these, and other changes along with an even larger array of antenna designs, ranging from conformal designs to those embedded within the sidewalls of high cost items, such as cubesats.

Also, this work demonstrates that a 3D printing system capable of utilizing multiple build zones and embedding areas can increase the flexibility of an already extremely capable manufacturing platform. It is the hope that incorporating electronics, as well as these antenna systems into a 3D printed structure will farther advance the state of the art, and drive forward ME3DP technologies.

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