Hybrid Additive Manufacture of Conformal Antennas

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Abstract—This paper presents a new digitally driven manufacturing process chain for the production of high performance, three-dimensional RF devices. This is achieved by combining Fused Filament Fabrication of polyetherimide based polymer with selective light-based synthesis of silver nanoparticles and electrochemical deposition of copper. The resultant manufacturing method produces devices with excellent DC electrical resistivity (6.68 μΩcm) and dielectric properties (relative permittivity of 2.67 and loss tangent of 0.001). Chemically modifying and patterning the substrate to produce the metallization overcomes many of the limitations of direct write deposition methods resulting in improved performance, adhesion and resolution of the antenna pattern. The fabricated demonstrators cover a broadband range of 0.1 GHz – 10 GHz and the measured results show a direct agreement with the simulated design over a wide frequency band. Overall the materials used as a substrate have a low relative permittivity and lower dielectric loss than FR-4, thereby making them well suited for antenna applications.

Keywords—3D Printing; Conformal Antennas; Additive Manufacturing; Capsule Antennas; Polyetherimide

I. Introduction

New manufacturing processes are required to generate novel and advanced antennas for the next generation of aerospace, biomedical, and consumer electronic devices [1]. This is particularly beneficial to the design and fabrication of antennas for ingestible capsules used in medical diagnostics [2]. Conventional RF Antennas are typically mass-produced to achieve economic viability, however these template-based methods are geometrically restricted and do not allow mass customization. Additive manufacturing has the potential to create complex 3D objects but is limited to a single material class therefore requiring secondary processing such as direct write to deposit the conductor pattern on a conformal surface [3]. This paper presents a new digitally driven method for the fabrication of high performance antennas on planar and conformal surfaces that can be directly employed in microwave circuit manufacture. This is evidenced by the close agreement of the antennas with the simulation results over a wide frequency band, covering all communication standards below 6 GHz, as well as satellite communication frequency bands. Furthermore, the developed process compares favorably to commercially available printed circuit board (PCB) technology in terms of conductor surface roughness and the polymer substrate dielectric properties.

II. Fabrication Method and High-Frequency Properties

Polyetherimide-based polymer filament is 3D printed using a modified Fused Filament Fabrication process using an extrusion temperature of 350°C, and a bed temperature of 195°C. This 3D substrate is then chemically modified and patterned with a newly developed method of locally synthesizing Ag nanoparticles using selective light irradiation [4]. In order to create the required thickness of conductor layer a secondary electroless copper plating process is employed using electroless plating (Fig. 1).

In order to validate this new process chain for the agile and rapid manufacture of bespoke and geometrically complex RF and microwave circuits, a capsule antenna for applications in medical robotics was designed, fabricated and measured. The 3D antenna is constructed through the conformal selective metallization of silver nanoparticles onto the cylindrical polyetherimide surface. Unlike planar substrates, the surface normal is continuously varying on curvilinear surfaces, which presents added fabrication challenges. The antennas were designed using the commercially available 3D Finite Element Method simulation package Ansys Electronics Desktop and were subsequently measured in free space.

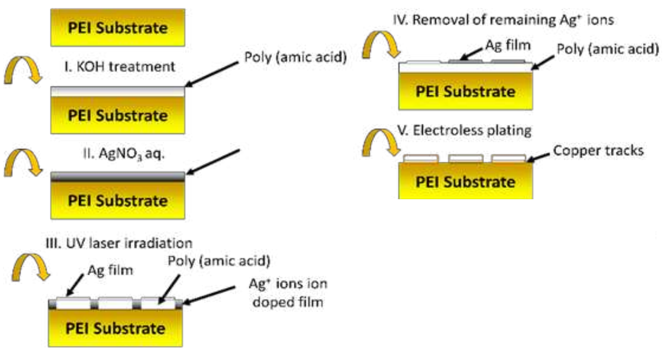
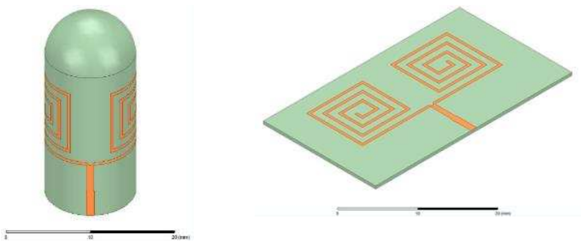


Figure 1: Schematic of the proposed process for directly forming silver patterns on a polyetherimide surface

III. RF DESIGN OF THE CAPSULE ANTENNA

One area where this new process is particularly suited to enable novel applications is the field of capsule robotics for medical diagnostics. Currently, conformal capsule antennas are implemented either on a separate substrate which is then wrapped around the capsule and fixed with adhesive, or via single-core copper wire fixed in difficult-to-fabricate grooves [2, 5, 6]. The ability to directly and selectively deposit copper with high peel strength on the cylindrical capsule surface will lead to increased reliability of these capsules, as well as opening up design freedoms to allow new and novel antenna configurations.

A typical capsule antenna is a printed planar monopole, extending $\lambda g/4$ above a ground plane. As the frequency ranges used to communicate with ingestible capsules are typically quite low, e.g. 434 MHz [7], these monopoles are often implemented as a meander or spiral line as a size-reduction measure [8]. In this case, we have used two spiral monopoles, connected in parallel, to ensure wide solid angle coverage. The designed antennas are illustrated in Fig. 2a and Fig. 2b for the conformal and planar versions, respectively. The conformal antennas were realized on 3D printed capsules using a Polyetherimide based material as dielectric. The thickness of the capsule wall is 500 µm, while the thickness of the planar substrate is 800 µm.



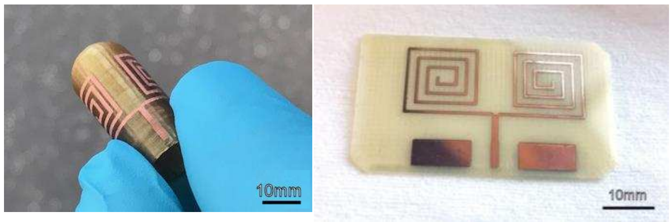
(a) (b)

Figure 2: 3D EM simulation model of (a) conformal capsule antenna design, and (b) planar antenna design

IV. FABRICATED SAMPLES AND MEASUREMENT RESULTS

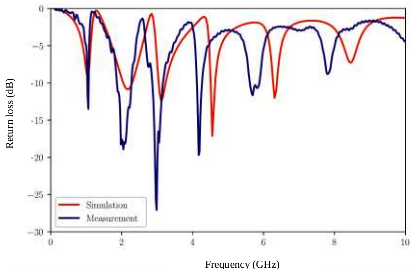
Some of the antennas that were fabricated using the newly developed hybrid additive manufacturing process are shown in Fig. 3. The return loss of these samples was then measured using a Keysight FieldFox N9917 Handheld Vector Network Analyzer (VNA), allowing the antennas to be measured both in a laboratory environment as well as in an anechoic chamber. The results presented here are for the antennas in a laboratory environment, however differences with anechoic chamber results were found to be minimal. The VNA was setup to measure 801 frequency points over the frequency range 0.1 GHz - 10 GHz. Single-port Short, Open, Load (SOL) calibration with mechanical standards were used to de-embed the effects of the connecting coaxial cable, however the contributions of the end-launch SMA connectors are still present in the measurements. The intermediate frequency (IF) bandwidth of the measurement receivers of the VNA was set to 10 kHz. Measurement results were then compared to simulation results obtained using the 3D electromagnetic FEM simulation software package ANSYS Electronic Desktop.

This comparison is presented in Fig. 4a, showing a close agreement between the simulation and measurement results for the conformal capsule antenna, however, there is a difference between the results above 4 GHz. This is most likely due to differences between modelled and actual relative permittivity of Polyetherimide based material at microwave frequencies, as well as the parasitic inductance and capacitance contributed by the SMA end-launch connector, which were not modelled in the simulation package. Another comparison, between the planar and conformal implementations, is shown in Fig. 4b. In both cases, there are multiple frequencies at which the return loss of the antenna is below -6 dB, which is the level normally used for antennas in more challenging environments, such as inside the human body [8]. As the antenna is a monopole, these resonant frequencies occur when the electrical length θ of the copper track is a multiple of $\lambda_g/4$ [9].

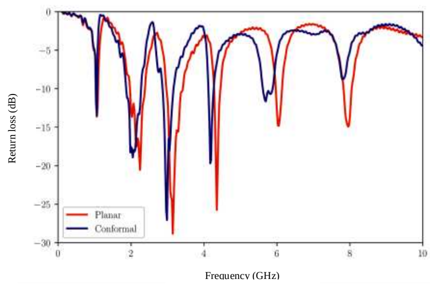


(a) (b)

Figure 3: Hybrid Additively Manufactured prototype of (a) conformal capsule antenna, and (b) planar antenna



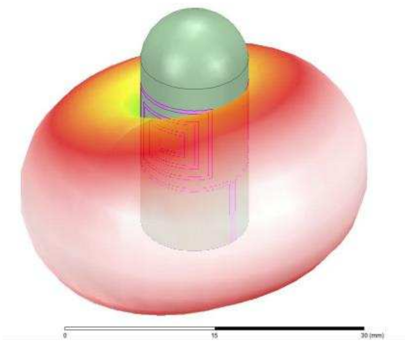
(a)



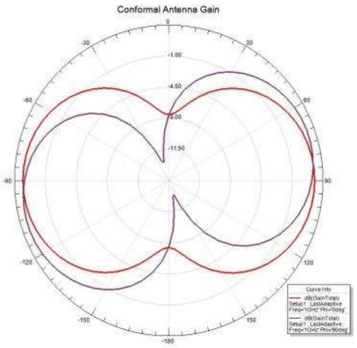
(b)

Figure 4: (a) Comparison between simulated and measured results for the capsule antenna design, (b) Comparison between measured results for capsule vs planar antenna design

The simulated radiation pattern of the conformal capsule antenna is shown in Fig. 5a for the first resonance frequency of 1 GHz. It can be seen that an omnidirectional coverage is achieved using the design proposed in this paper. Additionally, the E-plane and H-plane radiation pattern cuts are given in Fig. 5b. The maximum gain is negative, which is characteristic of ingestible and implantable antennas.



(a)



(b)

Figure 5: (a) Simulated radiation pattern of the conformal capsule antenna, (b) Conformal antenna gain: E-plane and H-plane radiation pattern

V. CONCLUSION & FUTURE WORK

In summary, a novel hybrid additive manufacturing platform has been developed opening up new design freedoms for the digital fabrication of RF antennas. The fabricated demonstrators covered a wideband frequency range of 0.1 – 10 GHz. The measured results show a direct quantitative and qualitative agreement with the simulated design over a wide frequency band. Future work will involve measuring the radiation pattern of the antenna in free space as well as inside a tissue phantom.

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