2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI) | 978-1-6654-4228-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/USNC-URSI52151.2023.10237912

Materials Design for Charge-Programmed Additive Manufacturing of Antennas

Zhen Wang(1,3), Zhenpeng Xu(1,3), Junbo Wang(2), Ryan Hensleigh(3), Yahya Rahmat-Samii(2), and Xiaoyu Rayne Zheng(1,3)

(1) Department of Materials Science & Engineering, University of California, Berkeley, CA 94720, USA (rayne23@berkeley.edu)

(2) Department of Electrical and Computer Engineering, University of California, Los Angeles, CA 90095, USA

(3) Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

***Abstract*—Antennas fabricated with traditional manufacturing methods typically carry redundant weight and are limited in 3D architecture complexity. Current additive manufacturing (AM) methods also lacks the capability to construct antennas with multiple materials. The charge-programmed multi-material AM process demonstrated in this work allows the design and manufacturing of antennas with previously unattainable mechanical properties. In this paper, we discuss the principles behind the multi-material printing and the versatility of the selective metal deposition process. We also introduce the material designs that enables the variation of material property, which makes it possible to print both stiff and flexible antennas.**

I. Introduction

Additive manufacturing (AM) is emerging as a powerful tool for fabricating antennas. Compared to traditional manufacturing approaches such as printed circuit board processes, molding, computer numerical control machining, etc., AM is advantageous in the capability of creating arbitrary complex geometries without incorporating excessive materials owing to its unique materials build-up mechanism. Taking such benefits, 3D printed antennas, including horns, waveguides, and dielectric antennas, have been reported with enhanced performances in different aspects [1]. These examples, however, are constructed mainly by single materials (either all-dielectric or all-metal). While multi-process AM can potentially perform conductive coating on 3D printed dielectric structure, the lack of selectivity and limited access to complex 3D geometries exclude a considerable amount of antennas from current AM approaches.

The charge-programmed multi-material 3D printing technique [2] integrates multiple materials and functionalities into 3D devices, which is achieved by programmed volumetric deposition of one (or multiple) materials into arbitrary 3D micro-architectures (Figure 1a). The printed structures had programmed surface charge regions, enabling the selective deposition of functional materials into complex 3D architectures based on localized electrostatic interactions. Selective volumetric depositions have not only been realized for single metals but also for diverse material combinations, such as ceramics, semiconductors, magnetics, and colloidal nanomaterials (Figure 1b-e). For antenna applications, charge-programmed AM can achieve sophisticated 3D architected lattice materials with interpenetrating dielectrics and metals, allowing free space for designing antennas being ultra-light and yet mechanically robust. In this paper, we present the materials design principles enabling charge-programmed multi-material printing of lightweight antennas with unique mechanical properties and competitive antenna performances.

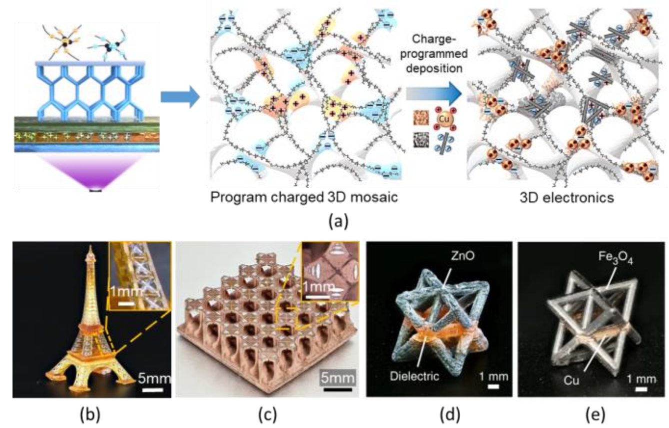

Figure 1. (a) Schematic illustration of the charge-programmed multi-materials printing. (b-e) Photographs of selectively plated samples [2]: (b) a miniature of the Eiffel Tower with a dielectric main body and internal struts plated with metallic-grey Ni–P; (c) a 3D antenna array with white dielectric and red copper areas; (d) composite octet truss combining dielectric and zinc oxide (ZnO); (e) composite octet truss combining Cu and ceramic magnetite (Fe_3O_4).

II. Charge-programmed Multi-material AM of High-performance Antenna System

A. Charge-programmed selective deposition

Charge-programmed selective deposition for the fabrication of antennas is based on a multi-material printing system (Figure 1a). Resins with positive, negative, or neutral charge polarity were alternately solidified and bound to the previously built layer of the printed parts. The process was repeated layer by layer, pin-pointing multiple materials with different polarities into their designated coordination in 3D space. The charged surfaces immobilize the oppositely charged catalyst species, which in-situ catalyze the subsequent deposition of functional materials. In this work, positively charged palladium ions, Pd(II), were absorbed by the negatively charged resins and further reduced into Pd to catalyze the reduction of Ni-P or Cu. Meanwhile, the neutral resin remained uncoated due to the lack of catalyst. In such a way, the printed objects obtained patterned structures that selectively integrated different functionalities in designated locations with a resolution as high as the 3D printer could achieve. As shown in Figure 2a and 2b, Ni-P alloy was selectively deposited on the negatively charged area of the octet while the yellow dielectric was bare without metal. The energy dispersive X-ray spectroscopy (EDX) detected the appearance of element Ni after the deposition.

B. Meterials design for antenna application

Charge-programmed selective deposition allows a wide range of space for materials design. Particularly for antenna applications, a varioty of combinations of conductivity and dielectric constant, the most crucial parameters, can be achieved as shown in Figure 2d, suggesting the versitality of the charge-programmed selective deposition for custom tailored antenna applications.

The composition of the negative resin directly influences the antenna performances which relies on the quality of the plated Cu layer as well as antenna's mechanical robustness. Based on the molecular configurations of the polymerized photo-monomers, the negative resins were formulated to deliver either stiffness or flexibility for the printed antennas, as shown in Figure 3a. By tuning the ratio of trimethylpropane triacrylate (TMPTA) and bis(2-(methacryloyloxy)ethyl))phosphate (PDD), we achieved a balance between the cross-link density and charge density. This enabled a uniform catalyst distribution on the stiff and

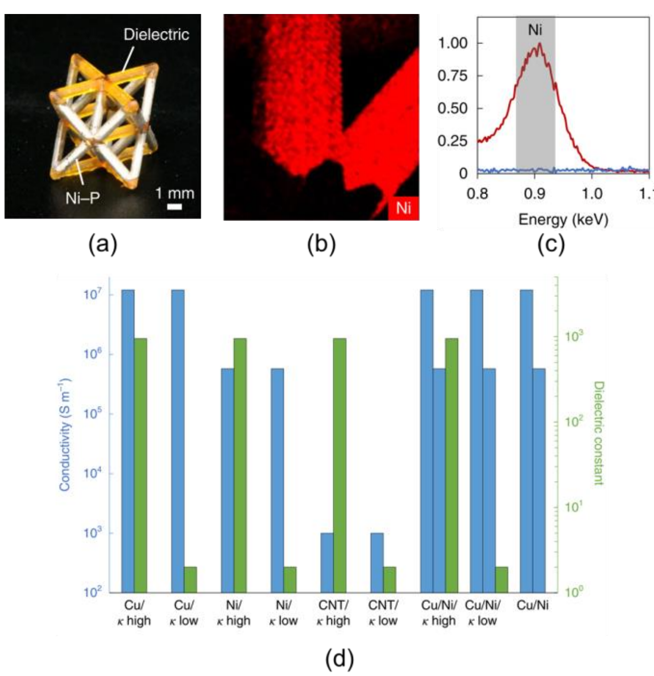

Figure 2. (a) Photograph of a selective nickel octet. (b) Element mapping showing the selective distribution of Ni over the octet. (c) EDX spectrum of Ni before (blue) and after (red) deposition. (d) The wide range of combinations of conductivity/dielectric achieved by the charge-programmed selective deposition [2].

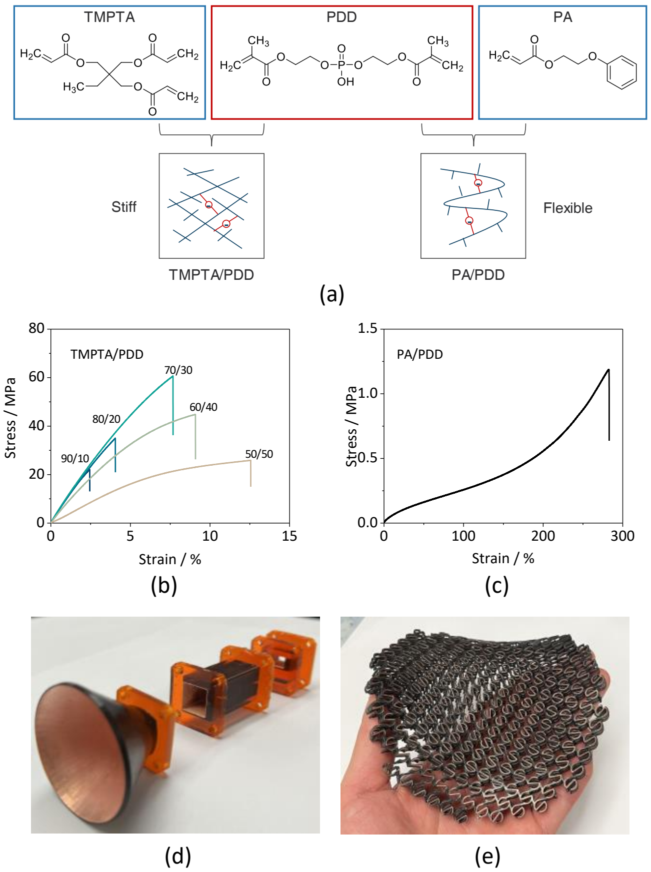

Figure 3. (a) Chemical compositions of the photo monomers and the schematic molecular configurations of the stiff negative resin and the flexible negative resin. (b) Stress-strain curves of TMPTA/PDD resins. (c) Stress-strain curves of a PA/PDD resin. (d) Photograph of a 3D printed stiff K-band horn antenna with a dielectric body and Cu coating on the internal surface comprised of a flaring conical horn, a septum polarizer, and a meandered waveguide. (e) Photograph of a flexible 3-layer transmitarray with selectively plated S-shape Cu conductive pattern.

tough negative resins and consequently grew a crack-free conformal Cu coating on the surface, serving excellent electrical properties for a K-band horn antenna (Figure 3b, 3d). By replacing TMPTA with ethylene glycol phenyl ether acrylate (PA), we fabricated transmitarray with considerable flexibility, which promises potential for deployable antennas (Figure 3c, 3e).

REFERENCES

[1] D. Helena, A. Ramos, T. Varum and J. N. Matos, "Antenna Design Using Modern Additive Manufacturing Technology: A Review," in IEEE Access, vol. 8, pp. 177064-177083, 2020, doi: 10.1109/ACCESS.2020.3027383.

[2] R. Hensleigh, H. Cui, Z. Xu, J. Massman, D. Yao, J. Berrigan, and X. Zheng, "Charge-programmed three-dimensional printing for multimaterial electronic devices." *Nature Electronics*, 2020, 3(4), pp. 216–224.