An Overview of Novel Antennas Manufactured via Charge-Programmed Multi-Material 3D Printing

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***Abstract*—Charge-programmed multi-material (CPMM) 3D printing is a unique additive manufacturing technology that emerged recently and has shown promise in manufacturing innovative antennas. With CPMM printing, conductive materials such as copper can be selectively deposited on specified areas of the supporting structure, thus making it possible to develop antennas with intricate 3D structures and (or) interpenetrated metal and dielectric. In this invited paper, we provide an overview of the recent novel antenna developments at the University of California Los Angeles (UCLA) enabled by the CPMM printing method. This includes lightweight multi-layer transmitarrays for beam collimation and beam steering applications in K-band, as well as a monolithic K-band septum horn antenna.**

I. Introduction

The rapidly evolving additive manufacturing (AM) technologies have granted antenna engineers more freedom to design and prototype antennas that are otherwise very challenging to fabricate. The cost, size, and weight of the antennas can also be potentially reduced due to the removal of excessive material. While many types of antennas (e.g., all-dielectric antennas, waveguides, and horns) enjoy the benefit of AM, there are still antennas that existing matured AM methods can not manufacture. This is because most AM technologies are limited to printing only dielectric or metallic material. Although it is possible to create structures with mixed metal and dielectric by combining multiple processes, it often accompanies excessive operational complexity and limited access to intricate 3D patterns.

The charge-programmed multi-material (CPMM) 3D printing [1] technique offers a novel solution to fabricate innovative 3D antennas with interpenetrated metal and dielectric in a monolith process. The unique feature of CPMM printing contrasting other AM methods is the capability of selective metal deposition on specified surface areas of a 3D structure. This is enabled by two major steps as illustrated in Fig. 1: step 1, a multi-material micro-stereolithography process that directly prints the structure with charged resin on the selected area; and step 2, selective metal deposition on the charged area. Exploiting the CPMM method, the University of California Los Angeles (UCLA) has developed several unique antennas that achieved remarkable weight reductions and RF performances. In this invited paper, we provide a brief overview of these recent novel antenna developments at UCLA and summarize the key improvements compared with traditionally manufactured antennas.

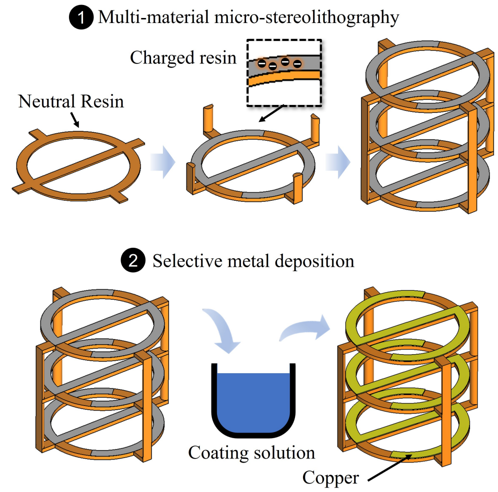


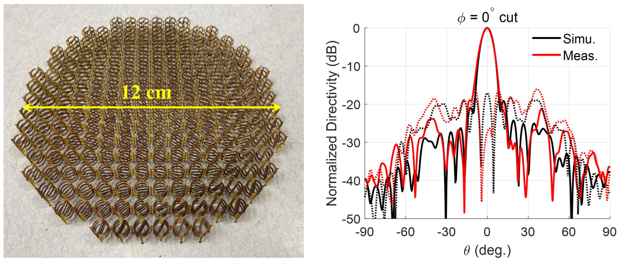
Fig. 1. An illustrative diagram showing the two major processes of the CPMM 3D printing technique. A single S-ring transmitarray unit cell is used as a representative 3D structure consisting of dielectric and multiple layers of selectively deposited conductor material.

II. UCLA's Recent Antenna Developments via Charge-Programmed Multi-Material 3D Printing

A. Ultra-Lightweight Transmitarray Antenna

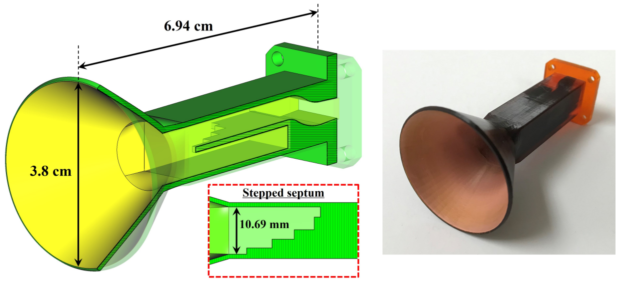
The first example of the application of the CPMM printing is an ultra-lightweight K-band circularly polarized (CP) transmitarray antenna designed at 19 GHz [2], [3] (Fig. 2). The transmitarray incorporates a three-layer S-ring unit cell, which provides $0 - 360°$ phase coverage based on element rotation. The unit cell uses the dielectric skeleton to support the copper element, thereby minimizing the use of dielectric and drastically reducing the weight of the transmitarray (as illustrated in Fig. 1). The 12-cm-diameter transmitarray was designed to correct the spherical phase from an RHCP feed source located at a focal distance of 14.5 cm, and to achieve a uniform phase at the exiting aperture. Each element in the transmitarray is rotated differently to provide the desired CP phase compensation.

The 12-cm-diameter transmitarray was monolithically manufactured with the CPMM printing and weighs only 5 g, which is nearly an order-of-magnitude weight reduction compared to a similar sized three-layer transmitarray based on traditional PCB laminates. The transmitarray was measured using an RHCP septum horn as feed (introduced in Section II-B). The measured patterns at 19 GHz suggest excellent agreement



(a) (b)

Fig. 2. The 12-cm-diameter ultra-lightweight transmitarray fabricated using CPMM printing [3]. A representative measured result of the 12-cm transmitarray using the CP septum horn as feed.



(a) (b)

Fig. 3. The monolithic CP septum horn antenna manufactured by CPMM printing [3]. (a) The internal structures of the horn showing the meandered waveguide and the stepped septum polarizer. (b) Photo of the printed horn.

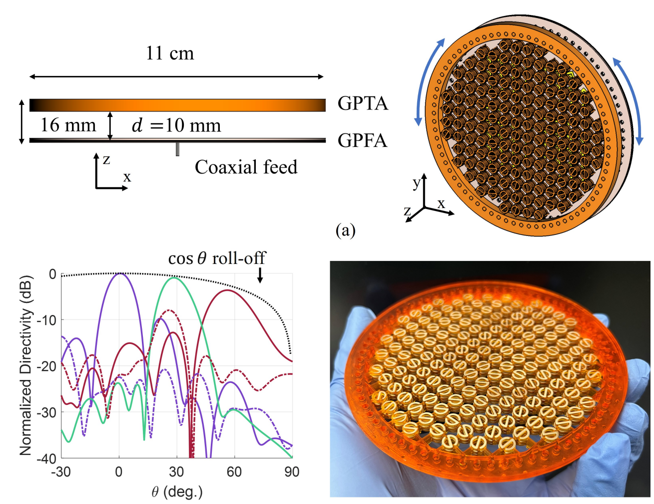
with simulations [Fig.2(b)], justifying the printing quality of this array. This ultra-lightweight multi-layer transmitarray is a good manifestation of the advantages of selective metal deposition offered exclusively by the CPMM method. This transmitarray unit cell structure would be impossible to realize with the traditional printed circuit board (PCB) process, and very difficult (if not unfeasible) using other AM methods.

B. Monolithic K-band Horn Antenna with Septum Polarizer

CPMM printing has the potential to manufacture a wide category of antennas without variation to the workflow. Another example of an antenna enabled by the CPMM method is a monolithic K-band CP horn antenna with a built-in stepped-septum polarizer and a meandered waveguide [3] (Fig. 2). The meandered waveguide feeds one port of the septum polarizer such that an RHCP wave can be generated. A square-to-circular transition section adapts the square waveguide of the polarizer to the circular horn. The horn is designed to be compatible with a commercially available WR42-to-coax adapter. When printing the polymer body of the horn, the interior surface is completely printed with charged resin. This allows the thorough coating in the inner faces to form the closed conductor channel of the horn. The horn weighs only 12 g because of the lightweight polymer body used, this corresponds to around 80% weight reduction compared to an all-metal version of the horn. The horn was used to feed the 12-cm transmitarray aforementioned.

C. Lightweight Transmitarray for Risley Prism Antenna

Mechanically beam steerable antennas rely on moving components to realize beam scan. Therefore, the increased system



(a) (b) (c)

Fig. 4. The CPMM-printed lightweight transmitarray used for a two-component beam steerable Risley prism antenna [4]. (a) The two-component Risley prism antenna. (b) Representative beam scan patterns of the antenna obtained from simulations. (c) Photo of the printed gradient-phase transmitarray.

complexity and the need to drive the moving parts necessitate novel lightweight antenna architectures to reduce system mass, mechanical wearing, and power consumption. We extend the concept of the skeleton-supported transmitarray unit cell and developed a lightweight transmitarray as part of a 19-GHz beam steerable Risley prism antenna [4]. The Risley prism antenna reported in [4] implements merely two components, i.e., a gradient-phase feed array (GPFA) and a gradient-phase transmitarray (GPTA) to realize 2D beam steering up to 56° in elevation (Fig. 4). The total height of the system is around one wavelength at 19 GHz, and beam steering is realized through the rotation of the two components. This antenna is a very low-profile mechanical beam steering system. The use of CPMM printing allowed us to fabricate the GPTA with a similar skeleton-supported structure proposed in [2], [3] to achieve further weight reduction. The transmitarray weighs only 28 g (including the frame for mounting). The characterization of the performance of the Risley prism antenna is part of the ongoing works.

References

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

[2] J. Wang, A. Papathanasopoulos, Y. Rahmat-Samii, R. Hensleigh, Z. Xu and X. Zheng, "Ultra-Lightweight Transmitarray Antenna Enabled by Charge-Programmed Three-Dimensional Multi-Material Printing," *2022 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM), Boulder, CO, USA,* 2022, pp. 293-294.

[3] J. Wang, R. Hensleigh, Z. Xu, Z. Wang, X. Zheng and Y. Rahmat-Samii, "Fully 3D-Printed Lightweight Combination of a Circularly Polarized Transmitarray and a Feed Horn," *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI), Denver, CO, USA,* 2022, pp. 645-646.

[4] J. Wang and Y. Rahmat-Samii, "A Novel Reduced-Complexity Low-Profile mm-Wave Beam Steerable Risley Prism Antenna," *2022 Antenna Measurement Techniques Association Symposium (AMTA), Denver, CO, USA,* 2022, pp. 1-6.