Fully 3D-Printed Lightweight Combination of a Circularly Polarized Transmitarray and a Feed Horn

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***Abstract*—The growing demand for high gain and beam steerable antennas onboard small satellites has motivated research on lightweight antenna technologies. We present a lightweight transmitarray antenna system including a 19-GHz, circularly polarized (CP), three-layer transmitarray, and a K-band CP feed horn with a built-in septum polarizer. Both the transmitarray and the horn are fully 3D-printed using the novel charge-programmed multi-material 3D printing process. The total weight of the printed horn and the 12-cm diameter transmitarray is only 17 g, which is about an order of magnitude lower than a conventional transmitarray system of this size in K-band. The transmitarray uses the horn as feed and achieves a measured directivity of 24.1 dB at 19 GHz, corresponding to 45.1% aperture efficiency.**

I. Introduction

Weight reduction is an antenna research topic gaining special attention in the emerging applications of small satellites and CubeSats [1]. The increasing demand for high gain and beam steerable satellite antennas further amplifies the significance of lightweight antenna technologies because of the increased electrical and mechanical complexity associated with beam steering. Innovations in lightweight satellite antennas have been made in different aspects including novel antenna concepts, use of advanced materials, optimization on structures, etc [1]. The introduction of additive manufacturing (AM) to antenna development has enabled researchers to pursue innovative possibilities on these fronts. However, most AM technologies are only suitable for printing either dielectric or metallic material exclusively, and this limits the types of antenna that can be developed. The recently reported charge-programmed 3D printing [2] technique demonstrated an unmatched advantage of developing complex 3D structures with mixed metal and dielectric in a one-time process. It contains two major steps, i.e., the multi-material stereolithography (SLA) and the selective metal deposition process (Fig. 1). First, the multi-material SLA is applied to print the 3D dielectric body with designated charged areas; then, metal (e.g., copper) is selectively deposited on the charged areas to form the desired metallic pattern. This novel technique can potentially manufacture a broad category of antennas that are otherwise difficult or impossible to build using other AM methods.

In this work, we exploit this unique advantage of charge-programmed 3D printing, and for the first time demonstrate a fully 3D-printed lightweight transmitarray antenna system (Fig. 1). It includes a 19-GHz circular polarized (CP) transmitarray and a K-band CP feed horn with a built-in septum polarizer. The transmitarray consists of three layers of copper elements supported by a specially designed dielectric skeleton that minimizes weight. The horn has a dielectric body with a copper-coated interior surface, making it much lighter than traditional all-metal horns.

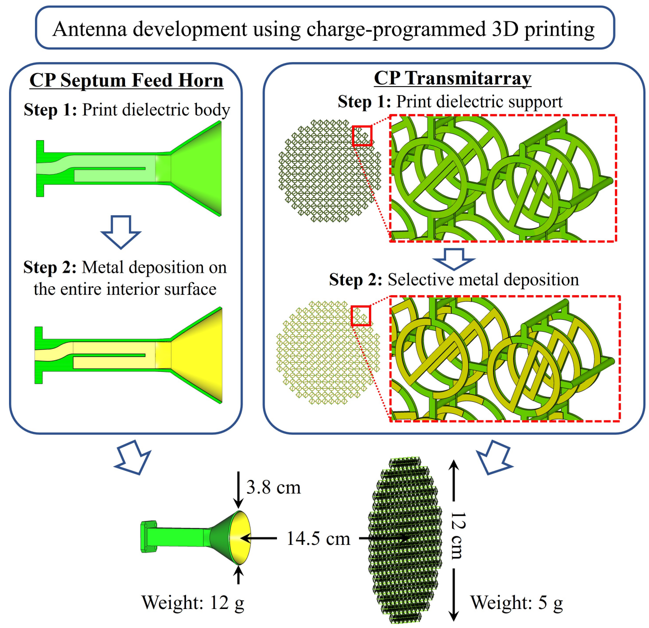

Fig. 1. Illustration of the manufacturing process of the lightweight transmitarray antenna system based on the charge-programmed multi-material 3D printing.

II. Circularly Polarized Transmitarray

The CP transmitarray unit cell (Fig. 2a) is evolved from the S-ring unit cell in [3] by adopting the 3-layer “S”-shaped element design but removing the bulky dielectric laminate. The three identical copper layers (yellow part) are separated by air gaps. The dielectric skeleton (green part) is included only to support the copper element and keep the inter-element and inter-layer spacing. Such a skeleton-supported design minimizes the use of dielectric material, which will significantly reduce the mass of the transmitarray. The working principle of the unit cell abides the geometrical phase property: the rotation of the S-ring element generates different CP transmission phases in the orthogonal polarization component. For example,

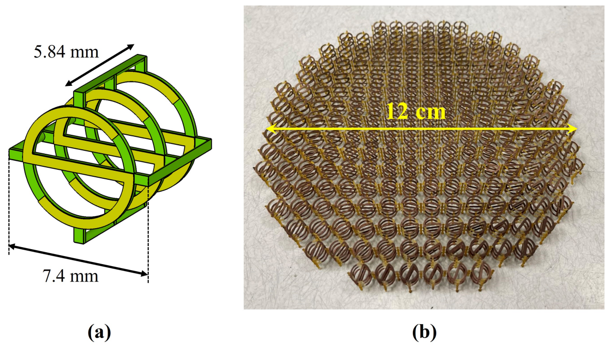

Fig. 2. (a) The CP transmitarray unit cell designed at 19 GHz. (b) The 12-cm diameter transmitarray manufactured using charge-programmed 3D printing.

under a right-hand CP (RHCP) wave excitation, the unit cell maximizes the magnitude of the transmitted left-hand CP (LHCP) component and introduces a rotation-dependent phase shift to the LHCP component. This allows the unit cell to provide any phase compensation in the $0° - 360°$ range without changing the geometry of the element.

A transmitarray with a 12-cm diameter aperture and a focal length of 14.5 cm was designed. It works with an RHCP feed and generates an LHCP broadside beam. The S-ring element in each unit cell was given a unique rotation angle based on the calculated phase shift required to compensate the incident spherical phase to a uniform phase at the exiting aperture. This transmitarray was fabricated using the charge-programmed 3D printing with a one-time effort (Fig 2b), without the need to align and bond different layers. The weight of this printed transmitarray is only 5 g, which is less than $1/10$ of a 12-cm three-layer transmitarray built with copper-plated laminate (estimated using Rogers RO3003 as in [3]).

III. Circularly Polarized Stepped-Septum Horn

The RHCP horn used for feeding the transmitarray is illustrated in Fig. 3a. It has a dielectric body with its interior surface completely covered by copper. The horn is designed with a standard WR-42 waveguide interface, which makes it easy to pair with a commercial coax to waveguide adapter (not shown) for excitation of the horn. A meandered waveguide transition is introduced to guide the excited wave to one port of the stepped septum polarizer. The other port of the polarizer is sealed with a conductor wall. Such a design allows the horn to be excited by a single port located on the center axis of the horn, keeping the horn compact and making it easier to align with the transmitarray. The other side of the polarizer is a square waveguide, which is connected with a square to circular transition that guides the wave to the circular horn for RHCP radiation. The horn was fabricated using charge-programmed 3D printing, followed by an extra step of electroplating to increase the thickness of the copper on the internal surface (Fig. 3b). The printed horn weighs only 12 g, which is less than $1/5$ of a standard gain horn in K-band. For measurements, a coax to WR-42 adapter from NARDA was used to excite the horn. The measured S_{11} of the horn is below -15 dB at 19 GHz, indicating a low return loss.

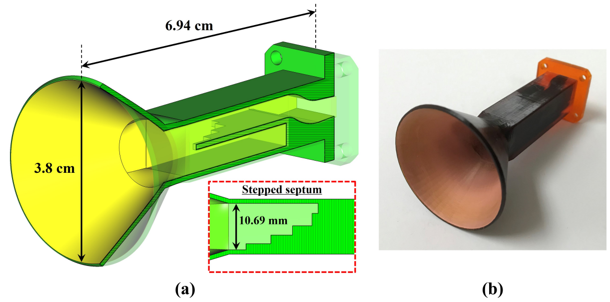

Fig. 3. The RHCP stepped-septum horn designed for K-band. (a) Overview of the horn and its internal structures. (b) Photo of the horn manufactured using charge-programmed 3D printing.

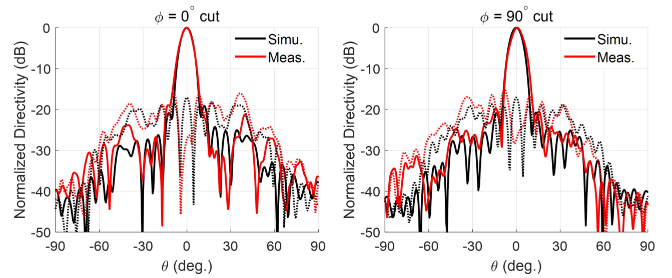

Fig. 4. Measured versus simulated 19-GHz radiation patterns of the transmitarray using the CP horn as a feed. (Solid lines: LHCP; dashed lines: RHCP.)

The horn was then used to illuminate the transmitarray, and the radiation pattern of the combined system was measured in the spherical near-field range at UCLA. Representative measured patterns at 19 GHz are compared with the simulated patterns in two orthogonal cuts (Fig. 4). Very good agreement between the simulated and measured results can be observed. The measured directivity is 24.1 dB, which corresponds to an aperture efficiency of 45.1% considering the 12-cm diameter circular aperture. Moreover, the combined weight of the horn and the transmitarray is only 17 g, which is promising for mass-critical application scenarios. These initial results indicate the successful development of both the feed horn and the transmitarray. This demonstration, involving two different types of antennas, implies the broad applicability of charge-programmed 3D printing in novel antenna fabrications. The presented AM technique and antenna design will facilitate the development of lightweight beam steerable antenna systems currently under investigation.

References

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