Ultra-Lightweight Transmitarray Antenna Enabled by Charge-Programmed Three-Dimensional Multi-Material Printing

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***Abstract*—We for the first time introduce charge-programmed three-dimensional (3D) multi-material printing to large-aperture antenna fabrication, and present the development of a circularly-polarized, ultra-lightweight transmitarray antenna at 19 GHz. This transmitarray contains three layers of metallic patterns spaced by dielectric supporting structures. This entire antenna is manufactured in a single-step process, in contrast to the traditional methods using printed circuit board process which requires alignment and bonding of multiple layers. Significant weight reduction in the antenna is achieved by selectively printing the supporting dielectric material. The 12-cm-diameter transmitarray weighs only 5 g, which can be an order of magnitude reduction compared to one based on common laminate.**

I. INTRODUCTION

Transmitarray antennas are known for their advantages of high-gain, low-profile, and free of feed blockage. A transmitarray typically consists of multiple layers of metallic patterns, which are essential for the transmitarray unit cells to achieve the desired transmission magnitude and phase. The manufacturing of a transmitarray traditionally employs the printed circuit board (PCB) process (Fig. 1 left): the metallic patterns are made by removing the excessive copper from a complete piece of copper-plated laminates; multiple pieces of such boards with copper patterns are then bonded or air-spaced to build the transmitarray. The dielectric laminate, though being important to the electromagnetic property of the antenna, in many cases is not necessary but rather for supporting purposes. The excessive dielectric accounts for the majority portion of antenna weight and dielectric loss, and this is inevitable with the traditional manufacturing process. Therefore, to further reduce the mass of such a multi-layer antenna, innovative manufacturing techniques are necessitated.

The charge-programmed three-dimensional (3D) multi-material printing recently reported in [1] offers a new possibility in the manufacturing of multi-layer antennas such as a transmitarray (Fig. 1 right). Compared with other additive manufacturing methods, it allows one to volumetrically develop electronic devices within complex 3D layouts in a single step. This offers a new degree of freedom to engineer the structure of the antenna, leading to several potential advantages such as significant weight reduction. Such antenna weight reduction can bring huge merit for many applications such as satellite and CubeSat planetary missions, where the mass of the antenna system is critical [2].

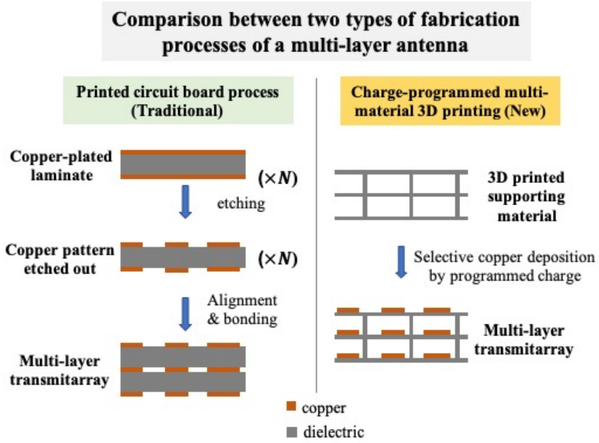

Fig. 1. Comparison of traditional PCB process (left) and the novel charge-programmed 3D printing (right) in manufacturing of multi-layer antenna.

In this work, we employ the charge-programmed 3D printing technique and present the design, fabrication and measurement of a circularly-polarized (CP), ultra-lightweight transmitarray at 19 GHz.

II. DESIGN AND FABRICATION OF THE TRANSMITARRAY

The unit cell designed at 19 GHz consists of three copper layers with identical ”S-ring” shaped pattern (yellow part in Fig. 2a). Minimum dielectric structures (green part in Fig. 2, $\epsilon_r \approx 3.6$) are included merely for supporting the metallic pattern and maintaining the necessary spacing between layers and between adjacent unit cells. The unit cell exploits the rotation-phase property, and it provides different CP phase

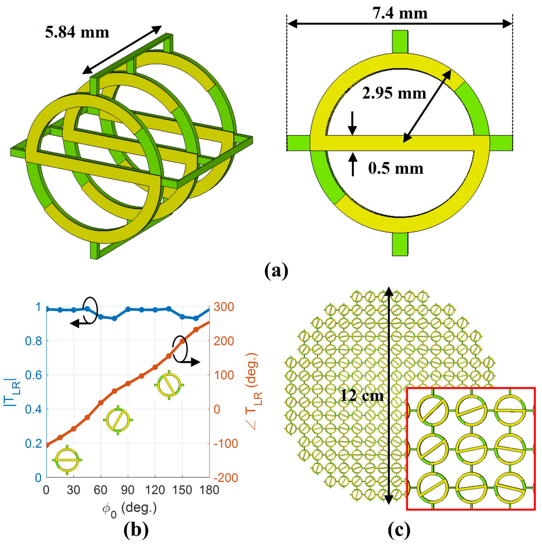

Fig. 2. (a) The S-ring unit cell design and the key dimensions. (b) The simulated transmission coefficient (T_{LR}) versus different element rotation angle phi_0 at 19 GHz. (c) The transmitarray design based on S-ring unit cell.

shift through rotation of the S-ring element. The transmission matrix representation of this property is as follows:

$$\begin{bmatrix} E^t_L \\ E^t_R \end{bmatrix} = \begin{bmatrix} T^{\phi_0=0}_{LL} & T^{\phi_0=0}_{LR} e^{j2\phi_0} \\ T^{\phi_0=0}_{RL} e^{-j2\phi_0} & T^{\phi_0=0}_{RR} \end{bmatrix} \begin{bmatrix} E^i_L \\ E^i_R \end{bmatrix} \tag{1}$$

where E^i_L, E^i_R and E^t_L, E^t_R are the left-hand CP (LHCP) and right-hand CP (RHCP) components in the incident and transmitted wave; ϕ_0 is the angle of rotation; $T^{\phi_0=0}_{**}$ are the corresponding CP transmission coefficients before the rotation of the element. To utilize the rotation-phase, the unit cell was optimized to achieve high transmission for the cross-handed polarization component. The simulated transmission coefficient T_{LR} versus ϕ_0 at 19 GHz is shown in Fig. 2b, high transmission (> 0.9) and 360° phase coverage with good linearity can be observed.

The transmitarray has a diameter of 12 cm with a focal length of 14.5 cm (Fig. 2c). The rotation angle of each element is properly determined such that the spherical phase from the feed is converted to a uniform phase at the exiting aperture. It is designed to work with a RHCP feed and generates a LHCP broadside beam. The transmitarray was fabricated with the charge-programmed 3D printing process as in [1]. The selective deposition scheme uses surface charge between 3D-printed substrate and deposition materials. We utilized two UV-curable resins (negatively charged and neutral resin), and a commercially available large-area stereolithography system (Anycubic). The dielectric sections are printed with neutral resin, while the ”S-ring” region was patterned with the negative resin. We paused and switched materials based on the part's digital design [3]. Once printed, the transmitarray was subsequently soaked in positive palladium catalyst solution (4mM), a dimethylamino borane reduction solution (10mM), and finally a copper electroless deposition solution, leaving behind metallic copper on the charged resin after several minutes. The fabricated transmitarray is shown in Fig. 3.

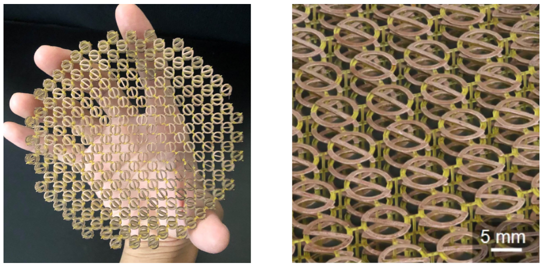

Fig. 3. Photo of the fabricated transmitarray: the dielectric structure appears as light yellow color, and copper trace appears as brown color. Note that dielectric structure also exists under the copper traces.

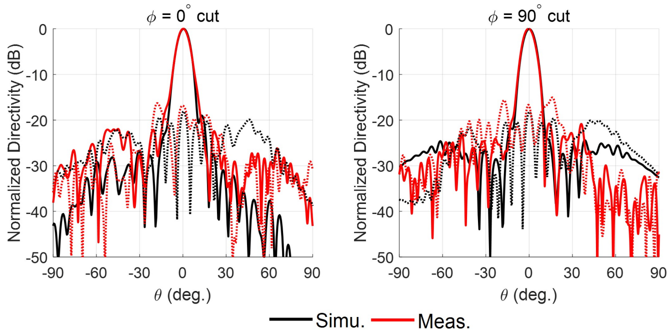

Fig. 4. The simulated and measured patterns of the transmitarray at 19 GHz. (Solid lines: LHCP patterns; dashed lines: RHCP patterns.)

III. MEASUREMENT OF THE TRANSMITARRAY

The fabricated transmitarray prototype was then measured in the spherical near-field range at UCLA. An RHCP patch array was used as feed. The measured patterns in representative far-field cuts are presented and compared with simulated results (Fig. 4). Good agreement with simulation was achieved, indicating that the transmitarray was accurately fabricated. The measured directivity at 19 GHz was 23.9 dBi (43.1% aperture efficiency), which is a desirable performance for this class of transmitarray. The fabricated transmitarray weighs only 5 g, whereas a transmitarray using similar element design but based on standard Rogers laminates (RO3003) can weigh about 70 g. In other words, a weight reduction more than 10 times can be realized. These encouraging results mark the successful demonstration of a CP, ultra-lightweight transmitarray antenna.

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