A 3D Printed Terahertz Metamaterial Lens for Beam-Steering Applications

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Abstract—This paper introduces an additively manufactured terahertz (THz) metamaterial lens (metalens) with 3D phase-shift unit cells. The metalens was fabricated using a conductive and dielectric multimaterial 3D printing technique. The fabricated metalens comprises 22 × 22 phase-shift unit cells with seven metal layers printed in a single substrate. Fed by a steerable 6-dBi WR-06 waveguide, the proposed metalens demonstrates a beam-steering performance over the frequency band of 110 ~ 130 GHz. The achieved focal-to-diameter ratio (F/D) is 1.02, and the beam-steering range is ±30° with a peak gain of 18 ~ 21.1 dBi at 120 GHz. The results prove the feasibility of the proposed metalens in THz beam-steering applications.

Keywords—3D printing, phase-shift, terahertz, beam-steering, metalens, D-band.

I. INTRODUCTION

Terahertz (THz) techniques in the frequency band above 100 GHz have recently attracted a surge of interest for potential applications in the 6G communication systems. To achieve dynamic and reliable communication, the beam-steering technique [1] is highly expected to be deployed in 6G network. Over the last decade, beam-steering techniques have been comprehensively reported, for example, leaky-wave antennas [2], phased array systems [3] and hemispherical silicon lens [4] and Luneburg lens [5]. The demonstrated designs can realize high gain performance, which improves the Effective Isotropic Radiated Power (EIRP) at the THz bands. However, leaky-wave antenna systems are based on frequency scanning, which may reduce spectrum efficiency. The phased array systems are expensive and require complicated frontend configuration, which might cause more power consumption. The classic optical lens concepts inspire the hemispherical and Luneburg lenses. However, the fabricated prototypes are often bulky in profile and may introduce sizeable dielectric loss if the low-loss dielectric material is not applied.

Metamaterial lenses (metalens) are believed to be an exciting technology for beam-shaping and possibly steering using elaborately designed phase-shift unit cells. Studies on metamaterial have demonstrated its strong plasticity. They can be designed with the functions of transmittance enhancement [6], orbital angular momentum (OAM) [7], 1D beam-steering [8], and near-field focusing (NFF) [9]. However, these complex unit cells are difficult to achieve in THz bands due to fabrication challenges.

In this paper, a multilayer metalens is proposed for beam-steering applications. The metalens comprises 22 × 22 phase-shift unit cells, which are composed of seven metal layers in a single substrate. The proposed 3D metalens was fabricated through a piezoelectric printing system [10], which can print both conductive and dielectric structures simultaneously. The achieved metalens unit cells can realize a full cycle of phase-shift by stacking circular patches, with flexible arrangement of the spaces among the metal layers. The proposed metalens was excited by a standard WR-06 waveguide probe. The proposed metalens can realize a beam-steering performance by rotating the waveguide along a predefined trajectory of ±30°.
and the distance between each patch is 300 μm, the number of patches increases with the increase of transmission phase delay and the diameter of the patch can be adjusted to fit the phase step of the transmission phase. The parameter H1 is fixed as 2 mm, the upper limit of height of the dielectric material (H2). By adjusting the height of the substrate, the transmission phase-shift of the unit cell increases. The dielectric constant and loss tangent of the material are 2.5 and 0.02, respectively. The schematic of the beam-steering metalens is shown in Fig. 1 (c), where α represents the rotation angle (incident angle) of the feed point and θ is the main beam angle, the rotation centre of the feed point is behind the metalens, and the distance between them is dz = 2.5 mm.

Fig. 2 shows the transmission phase-shift of the proposed eight metalens unit cells. The thickness of the unit cells can be divided into four stages, 2.0 mm, 1.5 mm, 1.0 mm and 0.5 mm. The unit cell can be considered a combination of an air box and a dielectric box. For the unit cells with the same thickness, one can adjust the diameter of the circular patches to increase the phase delay. According to the design rule, the minimum microstrip patch width should be more than 110 μm [11]. The proposed circular patches are more robust and less sensitive to fabrication errors when printing. The minimum layer thickness is 0.3 μm for the conducive layer and 2.5 μm for the dielectric layer. The maximum substrate thickness to be fabricated is 3 mm, with a fabrication tolerance of ±5%. The fabrication tolerance might worsen when the printed substrate approaches the limit of the allowed thickness.

Additionally, the 3D printing dielectric inks (formed by acrylates) are relatively lossy in the THz band. Reducing the thickness of unit cells can help to reduce the dielectric loss and improve the metalens transmission coefficient. Then, the designed unit cells can be allocated in the centre of the lens aperture by optimizing the phase distribution of the metalens, which can help to enhance the gain. The phase distribution of the proposed metalens can be given by Fermat’s principle:

\[
\phi(x, y) = \frac{2\pi}{\lambda_0} \cdot \sqrt{x^2 + y^2 + F^2 - F} + \phi_0
\]

where the original focal length F is 21 mm, \(\lambda_0\) is the wavelength at 120 GHz and \(\phi_0\) represent the initial phase. According to equation (1), the feed source at the feed point in Fig. 1(c) is regarded as an ideal point source and radiates a spherical wave from the phase centre of the feed source. However, the ideal phase centre is non-existent. Therefore, the optimization of the focal length is needed, which is carried out by the full electromagnetic (EM) simulation tool - HFSS.

B. Optimization

In Fig. 3(a), by increasing the focal length F from 21 mm to 27 mm, the gain of the metalens increases obviously from 16.7 dBi to 21.6 dBi at 120 GHz. The optimized gain over the frequency band is from 19.1 dBi to 21.6 dBi. Compared with the gain of the waveguide, 12.5 ~ 15.7 dB Gain enhancement is achieved. When the rotation angle of the feed source (WR-06 waveguide) is 30°, the radiation patterns at 120 GHz with different dz are shown in Fig. 3(b). It can be seen that the main beam direction of the metalens increases with the increase of dz, and it becomes 30° when dz = 2.5 mm. Therefore, beam-steering performance is achieved by the proposed metalens while the incident angle α and beam angle θ are kept the same.

III. FABRICATION AND EXPERIMENTAL RESULTS
A. Conductive and Dielectric Multimaterial 3D Printing

The 3D printing is based on a piezoelectric system with two nozzles with deposition of liquid acrylate dielectric ink.
(DI) and conductive silver nanoparticle ink (CI), simultaneously. There are two printing heads with 512 nozzles for DI and CI. After the ink drops, an ultraviolet (UV) lamp is used to dry the DI drops, and an infrared radiation (IR) lamp is used to sinter the CI drops. In this way, the prototype is printed layer by layer, as shown in Fig. 4, where the DI and CI print heads are not shown. In this design, the prototype was printed on a Kapton film and peeled off when printing was completed. The solder mask was not applied since no lumped components were required to be soldered. The step-shaped structure with a non-planar feature was realized by using the 3D printing technique.

![Fig. 4. Fabrication process of the applied multimaterial 3D printing.](image1)

**B. Experimental Results**

Figs. 5(a) and (b) show the 3D printed 120 GHz metalens prototype. A D-band (110 ~ 170 GHz) far-field scanning measurement setup is built to measure the radiation patterns of the metalens at 120 GHz, as shown in Fig. 5(c). The measured radiation patterns match well with the simulated ones. The simulated results with different $\alpha$ are 21.5 dBi at $0^\circ$, 21.3 dBi at $-10^\circ$, 20.6 dBi at $-20^\circ$ and 18.3 dBi at $-30^\circ$ in H-plane, while the measured ones are 20.6 dBi, 21.1 dBi, 20.0 dBi and 18.0 dBi. Because of the symmetry of the structure, only half of the scanning angle is measured.

**IV. CONCLUSION**

This paper presents a 3D printed THz metalens for beam-steering applications. The proposed metalens can obtain about 14.1 dB gain enhancement fed by a standard WR-06 waveguide. By rotating the waveguide, the metalens achieves an excellent beam-steering performance within ±30° scanning angles. The proposed metalens demonstrated its potential in beam-steering and multibeam applications. The multibeam performance can also be achieved when a waveguide array is applied to excite the metalens. The proposed metalens is a promising candidate for the future THz beam-steering communication systems.

![Fig. 5. (a) Top view of the metalens. (b) Metalens with a WR-06 weveguide on an 1D scanning setup. (c) Simulated and measured radiation patterns at 120 GHz.](image2)

**REFERENCES**


