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A 2D Transmitarray-Augmented Luneburg Lens Antenna for Millimeter-Wave Applications

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***Abstract*—This paper demonstrates a circular transmitarray-augmented Luneburg lens antenna for beam-forming at a millimeter-wave (mmWave) regime. The proposed structure is comprised of an augmentation of 80 dielectric cubes phase correction layer and two semi-circular 10-layer Luneburg lenses. The circular transmitarray-augmented Luneburg lens antenna is fed by a 9 dBi horn antenna at normal incidence and an oblique incidence of −15°. The beam is successfully transmitted with an angle up to +45°. When the feed is oriented in normal incidence, a pencil beam is transmitted at 166° and 151° with a realized gain of 20.3 dBi, and sidelobe level (SSL) below −10.0 dB, at 28 GHz.**

I. Introduction

Enhancements in antenna systems are crucial in the millimeter-wave (mmWave) spectrum. Escalating demands for fifth-generation (5G) networks are addressing critical needs involving high transmission data rates [1]. Phased array antennas [2] are pivotal in wireless and satellite communications. However, they present challenges including high costs and power consumption. Transmitarray antennas [3] are regarded as a viable solution for cost-effective beam-forming and as a concept found its way into novel technologies of holographic beamforming and reconfigurable intelligent edges [4]. Besides, the Luneburg lens [5] is widely used in embedded systems for beam-steering [6], [7] and beam-scanning [8] at mmWave frequencies, owing to its advantageous features including directive beams, focusing abilities, and multi-beam generation.

This paper introduces an innovative two-dimensional (2D) transmitarray-augmented Luneburg lens antenna designed for mmWave applications. Featuring a compact, all-dielectric structure, this lens is readily manufacturable using 3D-printing technology, offering a cost-effective solution.

II. Design Aspects of the Circular Transmitarray-Augmented Luneburg Lens Antenna

A. The Luneburg Lens

The Luneburg lens is an optical instrument characterized by its capacity to transform a point source located at its periphery into a planar wave, which is then emitted in the opposite direction from the lens. The refractive index (n) distribution of the Luneburg lens is characterized as follows.

$$n^2 = \epsilon_r = 2 - \left(\frac{r}{a}\right)^2 \quad (1)$$

Where r is the radial distance from the center, a is the radius of the lens, and ϵ_r is the relative dielectric permittivity. The proposed Luneburg lens consists of ten dielectric layers with a diameter of 200 mm and a thickness of 10 mm. The effective permittivity of these layers gradually increases from 1.19 in the outermost layer to 1.99 in the innermost layers.

Full-wave electromagnetic simulation was employed to examine the phase profile along two specific cross-sections: one aligned with the direction of incident energy and the other with the direction of the transmitted beam. The required phase Δ_ϕ is determined by (2). In this relationship, ϕ_t denotes the phase of the transmitted beam while ϕ_i denotes the phase of incident energy. This phase analysis was pivotal for the development of the subsequent phase correction layer.

$$\Delta_\phi = \phi_t - \phi_i \quad (2)$$

B. The Phase Correction Layer

A plane wavefront traversing a dielectric structure whose relative dielectric permittivity ϵ_r experiences a phase delay ψ which can be determined by (3) [9]. In this formula, S is the structure thickness, c is the speed of light in vacuum, and ω is the angular frequency.

$$\psi = (\sqrt{\epsilon_r} - 1) S \frac{\omega}{c} \quad (3)$$

For the realization of 360° transmission phase delay at 28 GHz with a material's permittivity of 4.5, a material's thickness of 10 mm is required. The fundamental unit is a cubical form with dimensions 5 × 5 × 10 mm^3. Consequently, the phase correction layer is designed using two sets of 1 × 40 dielectric cubes. These are vertically positioned between two semi-circular Luneburg lenses as depicted in Fig. 1.

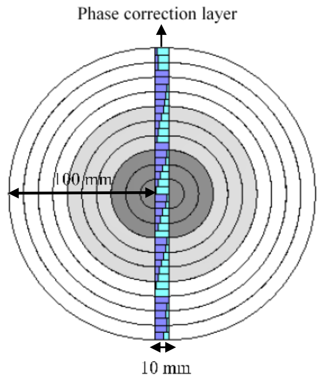
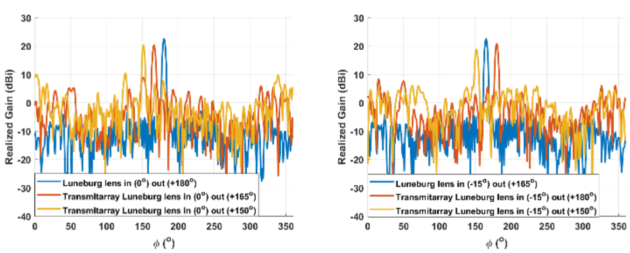


Fig. 1. Sketch of the proposed 2D transmitarray-augmented Luneburg lens. The phase correction layer is made of a filament with relative dielectric permittivity of 4.5 represented in purple and air represented in blue.

III. Simulation Results and Discussion

The proposed 2D transmitarray-augmented Luneburg lens was simulated utilizing CST Microwave Studio [10], employing a horn antenna with a gain of 9 dBi and an aperture size measuring 14.5 mm x 11 mm.

First, the Luneburg lens was simulated using the horn antenna at a normal incidence. Then, two distinct phase correction layers were added to transmit the beam at angles of +165° and +150°. The symmetrical nature of the Luneburg lens allowed for achieving a focused beam opposite to the incident wave at +180° with a realized gain of 22.6 dBi and sidelobe levels (SLL) below -24.6 dB at 28 GHz. Conversely, our transmitarray-augmented Luneburg lens demonstrated effective transmission across the frequency band of 24 – 30 GHz. At 28 GHz, it transmitted beams towards angles of +166° with a realized gain of 20.3 dBi and SLL below -11.4 dB, and towards angles of +151° with a realized gain of 20.3 dBi and SLL below -10.0 dB. Simulated far-field radiation patterns of these three different Luneburg lens variants are depicted in Fig. 2a.



(a) (b)

Figure 2. Simulated far-field radiation patterns for the Luneburg lens and transmitarray Luneburg lens excited at 28 GHz by a 9 dBi horn: (a) at 0° and (b) at −15°.

Additionally, the horn was rotated −15° to illuminate the Luneburg lenses. Similarly, it achieved the focused beam at +165° due to the lens symmetry. When the phase correction layers were employed, the beam was transmitted at +180° with a realized gain of 20.8 dBi and SLL below −12.4 dB, and at +151° with a realized gain of 18.8 dBi and SLL below −12.5 dB. Simulated far-field radiation patterns for the three distinct variants of the Luneburg lens are given in Fig. 2b.

IV. Conclusion

This paper presents an analysis and design aspects of a two-dimensional (2D) circular transmitarray-augmented Luneburg lens antenna suitable for millimeter-wave (mmWave) applications. Constructed from ten dielectric layers with a 200 mm diameter and a 10 mm thickness, the Luneburg lens was examined through full-wave simulations to evaluate phase fields and develop an effective phase correction layer. This layer, made up of dual 1 × 40 dielectric cubes, each 5 × 5 × 10 mm^3 in size, was strategically placed between two semi-circular Luneburg lenses. Feeding the antenna with a 9 dBi horn antenna, both at normal and −15° oblique incidences, yielded a successfully transmitted beam with angles reaching up to +45°. These results underscore the potential of this antenna configuration for advanced beam-forming applications in the mmWave frequency spectrum, including reconfigurable intelligent edges.

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