Compact Half-Luneburg Lens Antenna Based on a Glide-Symmetric Dielectric Structure

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Abstract—In this letter, we present a planar half-Luneburg lens antenna based on a glide-symmetric dielectric structure. The proposed half-Luneburg lens antenna provides a compact alternative to planar beamformers such as conventional Luneburg and Rotman lenses, as well as pillbox antennas. Importantly, we demonstrate that the peak gain of the half-Luneburg lens antenna is less than 1 dB lower than the peak gain of a conventional Luneburg lens antenna, despite being almost half the size. The proposed antenna can steer its beam in a 50° range with scan losses lower than 2 dB and side lobe levels below −10 dB. The proposed design is validated experimentally with a robust and cost-effective implementation using additive manufacturing.

Index Terms—Additive manufacturing, dielectric lens antennas, glide symmetry, half-Luneburg lens.

I. INTRODUCTION

The new non-terrestrial and terrestrial communication systems are intended to partially operate at higher frequency than their predecessors [1]. Specifically, the available spectrum at K- and Ka bands is considered for the emerging low Earth orbit satellite constellations and fifth-generation (5G) communications [2], [3]. Quasi-optical planar beamforming antennas are cost-effective alternatives to phased arrays for beam steering applications at these frequencies [4], [5], and parallel plate waveguide (PPW) antenna solutions based on lenses (e.g., the Luneburg [6] and Rotman [7] lenses) and reflectors (e.g. pillbox antennas [8]) have been proposed. Furthermore, quasi-optical beamformers are typically ultra-wideband and readily meet the bandwidth requirements for the emerging communication links [9]–[12].

The wide scan range in Luneburg lens antennas is a direct consequence of the rotational symmetry of the lens [13]. However, also due to this rotational symmetry, conventional Luneburg lenses have a length (F) equal to the aperture width (D). As a result, the size of the Luneburg lens is substantial if a high directivity is needed. Nonrotational symmetric beamformers typically provide scan angles ranging between ±30° and ±50°, but are similarly limited by the large F/D ratio, varying between 0.7 and 1 for most reported designs [14]–[19].

The half-Luneburg lens provides a compact alternative to the conventional Luneburg lens, at the cost of a reduced scan range (typically ±30°) [20]–[22]. A half-Luneburg lens is obtained by placing half of a Luneburg lens over a reflecting surface, and as a result, the size of the beamformer is halved (i.e., F/D = 0.5). It is noteworthy that the focusing properties of the Luneburg lens are maintained, but over a reduced scanning range.

The literature on planar half-Luneburg lens antennas is limited [23]–[25]. In [23], a planar half-Luneburg lens antenna based on a fully metallic pin-type metasurface is presented. However, the demonstrated scan range of the antenna is only ±15° and the antenna must be produced using milling, which results in costly manufacturing at millimetre-wave frequencies [26], [27]. In [24], [25], scanning ranges up to ±30° are presented; however, these designs feature large heights (above one wavelength) and can be unnecessarily bulky for some applications.

In this letter, we present a planar dielectric half-Luneburg lens antenna. The lens is based on the design in [28], and is implemented with a dielectric glide-symmetric metasurface. The use of dielectrics enables a thin lens, which facilitates vertical stacking of several lenses into an array, thus allowing two-dimensional beam scanning. The design is robust to manufacturing tolerances and can be cost-effective using additive manufacturing. We also provide a comparison of the proposed half-Luneburg lens design to alternative planar beamforming techniques.

II. HALF-LUNEBURG LENS

The Luneburg lens transforms a spherical/cylindrical wave from a point source at the contour of the lens to a plane wave at the opposite side of the lens [6]. The lens is defined by the refractive index distribution

\[ n(\rho) = n_0 \sqrt{2 - \left( \frac{\rho}{R} \right)^2} \]

(1)

where ρ is the radial position in the lens, R is the radius of the lens, and \( n_0 \) is the refractive index of the surrounding medium (i.e., for \( \rho > R \)). Fig. 1 illustrates the refractive index distribution and operation of the Luneburg lens.
The operation of the half-Luneburg lens is illustrated in Fig. 2(a). The half-Luneburg lens also transforms a spherical/cylindrical wave from a focal point into a plane wave. The plane wave is at a specular angle to the feed position and is identical to the plane wave from a conventional Luneburg lens excited at the virtual feeding point obtained by mirroring the feeding point in the reflecting surface. For planar implementations of the half-Luneburg lens, the reflecting surface is replaced with a reflecting wall closing the PPW section containing the lens.

In practical realizations, the focusing property of the half-Luneburg lens is impaired by the finite size of the reflecting surface, which results in spillover losses, as illustrated in Fig. 2(b). The spillover leads to reduced directivity and an additional lobe in the radiation pattern. The additional lobe is at a symmetric angular direction to the main beam. For feeds at an angle close to $\theta_f = 90^\circ$, the spillover can be substantial. Therefore, the scanning range of the antenna is typically limited to feed positions at $\theta_f \lesssim 75^\circ$. Furthermore, feeds close to $\theta_f = 0^\circ$ experience large reflections from the reflecting surface/wall and the aperture is partly blocked by the feed. Therefore, the scanning range is typically limited to feed positions at $\theta_f \gtrsim 15^\circ$.

### III. Planar Glide-Symmetric Dielectric Half-Luneburg Lens Antenna

#### A. Implementation

The half-Luneburg lens antenna designed in this work is based on the design in [28]. A brief description of the lens is included in this letter. For a more detailed analysis, we refer the reader to [28].
close-up view of the half-Luneburg lens is illustrated in Fig. 4(b). Fig. 4(c) shows the setup for the radiation pattern measurements.

B. Results of the Half-Luneburg Lens Antenna

The simulated and measured reflection coefficients for the seven ports of the half-Luneburg lens antenna are presented in Fig. 5, and the port numbers are indicated in the inset. For ports 1–6, the reflections are below $-10$ dB from 22 to 32 GHz. Port 7 experiences increased reflections due to its position above the reflecting wall. The simulated and measured reflection coefficients agree well.

Fig. 6 presents the simulated electric field distribution at 28 GHz for all ports. For ports 2–7, a plane wave can be observed at the output of the antenna. For port 1, a substantial amount of the fields does not intersect the reflecting wall, and as a result, port 1 experiences considerable spillover losses.

The simulated and measured H-plane radiation patterns at 22, 27, and 31 GHz are presented in Fig. 7. At each frequency, the simulated and measured patterns are normalized to the peak simulated and measured realized gain, respectively. The spillover for port 1 manifests as an additional lobe at negative $\phi$ angles. For ports 2–7, clean patterns are observed throughout the frequency range. For these ports and frequencies, the scan losses are above $-2$ dB and sidelobe levels are below $-10$ dB, in both simulations and measurements. Again, the simulations and measurements agree well, confirming the robust implementation to manufacturing errors.

Fig. 8 presents the simulated and measured peak realized gain for all ports. The peak gain of the center port of the conventional Luneburg lens antenna in [28] is included in Fig. 8(a) for reference. We note that the proposed half-Luneburg lens
Fig. 8. (a) Simulated and (b) measured peak realized gain of the antenna. The simulated gain for the center port of the conventional Luneburg lens antenna in [28] is included as a reference in (a). The peak gain in the half-Luneburg lens is roughly 1 dB lower than the one in the conventional Luneburg lens.

Fig. 9. Size and weight comparison between the proposed half-Luneburg lens antenna and the conventional Luneburg lens antenna in [28].

antenna provides a peak gain that is less than 1 dB lower than the gain of the conventional antenna, despite being almost half the size and weight, as illustrated in Fig. 9. The reduced size of the half-Luneburg lens antenna comes at the cost of increased scan losses and reduced scan range when compared to the conventional Luneburg lens antenna.

Table I presents a comparison of the proposed half-Luneburg lens antenna to alternative planar quasi-optical beamformers. The comparison is done in terms of $F/D$, scan range, and scan loss. The conventional Luneburg lens provides a wide scan range and low scan losses, but has a large $F/D$ ratio. Nonrotationally symmetric beamformers, e.g., Rotman and geodesic PPW lenses and pillbox antennas, are typically slightly more compact than the Luneburg lens antenna, but with reduced scan range and increased scan losses. The half-Luneburg lens provides a compact alternative with a slightly reduced scan range. Note that the scan range and scan loss reported for the antenna designed in this work corresponds to ports 2–7. In other words, port 1 is excluded from the values in Table I due to the reduced performance. Compared to the half-Luneburg lenses in [24], [25], the design proposed in this letter has a thin profile and is compatible with a stacked-lens design for two-dimensional beam scanning.

IV. CONCLUSION

In this letter, we design and experimentally validate a half-Luneburg lens antenna. The half-Luneburg lens is implemented using a glide-symmetric dielectric structure and is based on the conventional Luneburg lens designed in [28]. The lens is placed in a PPW and is fed by seven waveguides, each producing an independent beam. The beam steering in the antenna is intended to be done by electronic switching between the waveguide feeds. The antenna provides a peak gain of 17.3–18.7 dBi in the frequency range 22–32 GHz. The antenna has scan losses lower than 2 dB and sidelobes below $-10$ dB in a $50^\circ$ range. It is noteworthy that the presented half-Luneburg lens antenna has a peak gain that is less than 1 dB lower than the conventional Luneburg lens antenna in [28], despite being almost half the size. A comparison of the proposed antenna to alternative planar quasi-optical beamformers demonstrates the merits of the proposed half-Luneburg lens antenna in applications that require a compact beamformer with scan range requirements up to $50^\circ$. The scan range can be extended by allowing for larger in-plane dimensions or reduced performance in terms of scan losses and sidelobe levels. Alternatively, the feeding element can be designed to reduce the spillover. The proposed beamformer produced with additive manufacturing techniques proves to be a robust and cost-effective solution at millimeter-wave frequencies.

ACKNOWLEDGMENT

The authors would like to thank the Premix group for supplying the filaments used for the manufacturing of the lens. They would also like to acknowledge Pilar Castillo-Tapia for the valuable technical discussions.
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