Multi-Beam Geodesic Lens Antenna with Enhanced Aggregate Gain in the $\mathrm{K_a}$-band

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***Abstract*—New mobile generations, i.e. 5G and 6G, will operate in the millimeter-wave band to support higher data rates. Novel antenna technologies must be investigated to mitigate the higher losses in this frequency band. One promising technology for this specific application is geodesic lens antennas. Here, we propose an analytical model that calculates the far-field distribution of a geodesic lens. This model was used to design a multibeam 9-port geodesic lens with a widened radiation pattern. A coverage sector of 134° in the H-plane is achieved with a gain roll-off better than 3 dB at 28 GHz.**

***Keywords*—Geodesic lens, quasi-optical antenna, 5G, 6G, multi-beam antenna, aggregate gain.**

I. INTRODUCTION

To enable enhanced mobile broadband, massive machine type communications and ultra-reliable low latency communications, the new mobile cellular network generations, including 5G and 6G, need high data rates that can be obtained in the millimeter-wave [1, 2]. Among other contenders, lens antennas are considered a promising candidate to mitigate the effect of the high free space losses, while maintaining a simple and cost effective feeding structure [3]. More specifically, geodesic lens antennas have been investigated for this specific application. A geodesic lens can be implemented in a fully-metallic configuration, reducing the losses in the overall antenna [4]. In this context, geodesic lenses typically mimic the operation of a Luneburg lens [5, 6]. However, with a discrete number of ports, a Luneburg lens has a significant gain variation across its field of view [7]. To overcome this limitation, the beams can be widened by de-focusing the lens [8, 9]. Therefore, a better overlap between beams can be achieved in the far-field, resulting in enhanced aggregate gain over the service area. Here, we propose a geodesic lens antenna with 9 ports and enhanced aggregate gain.

II. GEODESIC LENS MODEL

In [10], Rinehart introduced a coordinate system to represent any point of a rotationally symmetric geodesic lens. This is composed by a radial coordinate ρ, an angular coordinate ϕ and the value of the function $s(\rho)$, where $s(\rho)$ is determined as in [11]:

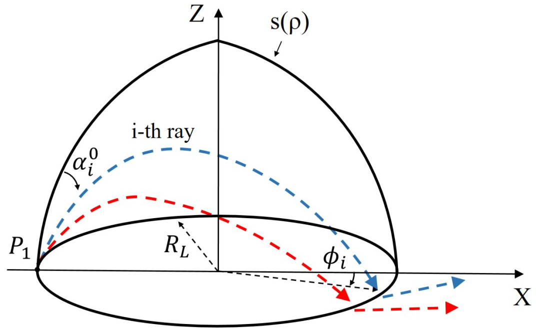

Fig. 1. Illustration of rays propagating along a geodesic lens.

$$s(\rho) = A(\rho)\rho + B \cdot R_L \arcsin(\rho/R_L) + C(\rho) \quad (1)$$

where $A(\rho)$, B and $C(\rho)$ are explicit in Eq. 9 in [11].

The trajectory of an arbitrary ray inside a geodesic lens is represented in Fig. 1. The i-th ray starts at $P_1[\rho_0 = R_L, \phi = \pi]$ forming an angle α_i^0 with the meridian and travels across the lens remaining its angular momentum constant. The differential equation that describes the path of the ray inside the lens is:

$$d\phi_i = \pm \frac{L_i \dot{s}(\rho) d\rho}{\rho\sqrt{\rho^2 - L^2}} \quad (2)$$

Therefore, the distance travelled by the i-th ray inside the lens is:

$$\psi_i = 2 \cdot \int_{L_i}^{R_L} \sqrt{\dot{s}(\rho)^2 \cdot \left(1 + \frac{L_i^2}{\rho^2 - L_i^2}\right)} d\rho \quad (3)$$

The ray exits the lens at a point $P[\rho_0 = R_L, \phi_i]$, forming an angle $\pi - \alpha_i^0$ with the meridian.

Following the Huygens-Fresnel principle, a ray can be modelled as a secondary point source when it approaches the aperture of the lens. This has been effectively tested in the case of parallel plate waveguide lenses [5, 12]. Therefore, the far-field can be approximated as the sum of the contribution of these sources:

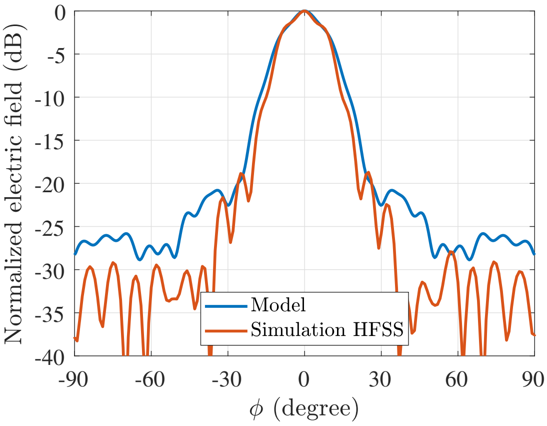

Fig. 2. Comparison of the radiation pattern obtained with the proposed method and a full wave simulation in ANSYS HFSS.

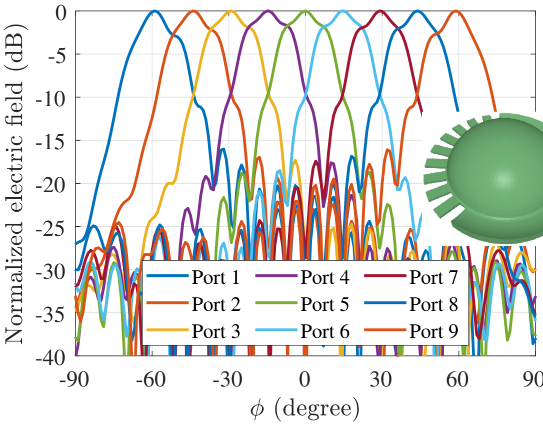

Fig. 3. Radiation pattern of the geodesic lens antenna with 9 ports at 28 GHz.

$$E_z(x,y,0) \propto \sum_{i=1}^{n} P'(\alpha_0^i) \cdot \frac{e^{-jk_0(\psi_i+R_i)} \cdot \cos(\phi-\alpha_i^0)}{R_i} \qquad (4)$$

$$R_i = \sqrt{(x-R_L\cos\phi_i)^2+(y-R_L\sin\phi_i)^2)} \qquad (5)$$

where k_0 is the phase constant in the air and $P'(\alpha_0^i)$ is the power of each ray given by:

$$P'(\alpha_i^0) \propto \frac{P'(\alpha_i^0)}{\sqrt{(x_{i+1}-x_{i-1})^2+(y_{i+1}-y_{i-1})^2}} = \frac{P'(\alpha_i^0)}{2R_L\sqrt{1-\cos(\phi_{i+1}-\phi_{i-1})}} \qquad (6)$$

Here, we have assume a $cos^q(\alpha)$ field distribution with $q = 2.3$.

III. GEODESIC LENS ANTENNA DESIGN

In previous works [4, 5], the geodesic lens antennas, mimicking a Luneburg lens, had a crossover between adjacent beams around 6 dB below the beam peak. Here, our goal is to achieve a beamwidth of 20 degrees and a side lobe level of -15 dB in order to have a stable aggregate gain in the far field. To accomplish this, the aforementioned model was used, resulting in a lens with $\rho_2 = 3.4\lambda$ and $M = 1.004$.

In Fig. 2, the comparison between the radiation pattern calculated by the analytical model and a full wave simulation with ANSYS HFSS is shown. The analytical model and the full-wave simulation are in good agreement.

A 9-port geodesic lens was designed following the previous design parameters. The results of the radiation pattern achieved with a full wave simulation are represented in Fig. 3.

IV. CONCLUSION

We proposed an accurate model to compute the radiation pattern of a geodesic lens, which is faster than a full-wave simulation. An analytical model was used to derive the rays in a geodesic lens, which was used to design a lens antenna with a 20° beamwidth in the H-plane.

The gain of the antenna is the 14.6 dBi and has a coverage range of 134° with a crossover between adjacent lobes higher than -3 dB at 28 GHz.

This solution provides enhanced aggregate gain across the coverage, which is desired in millimeter-wave communications.

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