

Comparative Analysis of 3D Printable Multi-Layer Dielectric lenses for Space Applications

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Enhancing antenna directivity is essential for space communication like NASA's Artemis lunar mission, where maximizing electromagnetic energy efficiency is crucial for long-range space communication systems. Enhancing antenna directivity is crucial for modern long-range applications such as radar and space systems, where maximizing the efficient use of electromagnetic energy is critical. One way to increase directivity is by either increasing the antenna element or using an array of elements. Nevertheless, increasing the antenna size often leads to a significant increase in SWAP-C (size, weight, area, power and cost), due to increased hardware at RF front end (RF-FE) either in terms of RF chains or complex beamforming circuitry. A practical solution for these missions is integrating a lens with the antenna structure, which improves directivity without adding additional hardware to the RF-FE. Of course, in-situ 3D printing of RF components such as antennas, lenses, and other communication systems is critical for rapid adaptability to changing mission requirements, reducing dependency on Earth-based supplies. This imposes certain restrictions to the lens type and their design aspect.

Most common 3D printable RF lenses include Fresnel, Luneburg, GRIN, ellipsoidal and spherical lenses. Among these, our research focuses on Fresnel and Luneburg lens. The Fresnel and Luneburg lenses (a type of GRIN lens) were chosen due to their a) cost-effective realization using dielectrics which can be easily 3D printed, b) beam steering performance, and c) operation across wide bandwidths. On the other hand, GRIN and spherical lenses suffer from expensive fabrication due to the precise index gradient requirements, and is often bulky and suited for narrowband applications, respectively. Notably, Fresnel lenses are thin lenses made of dielectric material. In grooved Fresnel lenses, the lens consists of a single dielectric material, but each layer has a different thickness. In perforated Fresnel lenses each layer varies in thickness and is composed of a material with different relative permittivity. Fresnel lenses can focus light in a similar manner to standard optical lenses but are much thinner making them suitable for application where space is limited.

Luneburg lenses are spherical gradient index (GRIN) refractive lenses. The refractive index, n , of a Luneburg lens is 1 at the surface and increases toward the center reaching a value of $\sqrt{2}$. The refractive index can be easily evaluated as:

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

Where n is the refractive index, r is the radius at any given point (where $0 < r < R$), and R is the radius of the Luneburg lens. When an antenna is placed on the surface of a Luneburg lens, the EM wave exiting the lens becomes a plane wave. If the antenna is placed infinitely far from the lens, the EM wave will be focused to a point. Luneburg lenses are widely used in mmWave applications that require high directivity such as satellite communication and radars systems. Despite offering superior focus compared to Fresnel lenses and traditional lenses, Luneburg lenses require more space.

Simulations have been conducted on both Fresnel and Luneburg lenses individually to better understand their focusing capabilities working under these constraints. However, to our knowledge no research has yet compared the performance of both lenses together in terms of their focusing abilities, size, and performance with specific design constraints using certain dielectrics only. Consequently, by using full-wave simulations (e.g. ANSYS HFSS and ALTAIR FEKO) we simulate the focusing abilities of a two-layer, four-layer, and eight-layer Fresnel lens and a two-layer, four-layer, and eight-layer Luneburg lens. For each simulation, a 94 GHz resonant horn antenna serves as the feeding element and the lens is placed at the focal distance from the phase center of the antenna. The results and observations of our analyses will be discussed at the conference.