3D printed Ku band cylindrical Luneburg lens

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Abstract. The design of the cylindrical Luneburg lens manufactured by using 3D printing facilities was presented, fabricated and experimentally verified. The two different approaches to lens parameter discretization were applied to lens design and compared. The effective dielectric permittivity of Polylactic Acid (PLA) plastic samples with different infilling percentage were estimated by a resonant method.

1. Introduction

Luneburg lens is a well-known beamformer. It consists of a sphere with a gradient refractive index and a feed placed on its surface. The main advantages of the Luneburg lens in comparison with traditional phased array antennas are high gain, wide-angle scanning without a gain drop and low side lobe level. Such systems can be used for radar and telecommunication applications. The refractive index of the lens from center to outer radius changes from 2 to 1. The classical Luneburg lens ensures 2D beam steering. 1D beam steering can be provided by the cylindrical cut of a sphere.

For the practical implementation of the lens, the dependence of the refractive index has to be discretized. There are two different approaches to discretization: using the layers with the same thickness or using the layers with the same step of refractive index or dielectric permittivity. For the fabrication of such a layered structure, additive manufacturing technologies can be used. 3D printing methods allow reducing the cost of the production process. Gradient index (GRIN) lenses can be implemented by changing the volume percentages of plastic infill. Based on this approach, it is easy to change the dielectric constant along the lens. This method was proofed by design of a flat lens [1]. The dielectric permittivity of the layer can be adjusted by using a sub-wavelength unit cell instead of percentage of filling of the layer [2]. Additive manufacturing opens new possibilities for the manufacturing of GRIN lenses.

In this paper, a 5-layer cylindrical lens is considered. Two approaches for discretising the permittivity along the lens were used: with a uniform step of the thickness of the layer and a uniform step of the permittivity of the layer. The implementation of the lenses was carried out layer-by-layer changing the percentage of filling of the PLA plastic (Tiger3D PLA). For the lens design, the permittivity for PLA samples with a different volume percentage of infill was characterized by a resonant method. The samples of the cylindrical lens were fabricated and measured using a Ku band patch antenna as a feed. The measured results are in good agreement with simulated ones.

2. The cylindrical Luneburg lens: simulated and measured results

The Luneburg lens is a graded-index (GRIN) structure with spatially varying refractive index:
\[ n(r) = \sqrt{\varepsilon(r)} = \sqrt{2 - \left(\frac{r}{R}\right)^2} \]

where \( r \) is the distance from the centre of the lens and \( R \) is outer radius.

It is difficult technologically to implement a continuous changing of the refractive index, and therefore the dielectric constant of the material over the entire lens profile. It is possible to resort to the use of dissimilar materials and make a single lens out of them, but it is more attractive to use the same material. This approach can be implemented using 3D printing, which ensures the relative cheapness of production and the variability of designs due to the sequential deposition of the material.

The lens can be described as concentrically arranged cylinders with a certain set of permittivity values (figure 1). The lens stratification can be performed with a uniform step along the radial coordinate or with a uniform step of the dielectric constant. Both methods are characterized by a layered structure, with each layer corresponding to its value of the dielectric constant. It was decided to use a 5-layer structure because a further increase of the number of layers does not lead to an improvement of the lens characteristics [3].

![Figure 1. The permittivity discretization by a uniform layer thickness (a) and a uniform permittivity step (b).](image)

The distance from the center of the lens \( r \) was normalized to the outer radius defined as \( R \) (figure 1). The obtained values of the permittivity of the layers were used for full-wave EM simulation using CST Studio Suite. Two models with a radius of 5 cm (3\( \lambda \) at 18 GHz) and a height of 18 mm were designed. The patch antenna operating at 18 GHz was chosen as a feed. For the patch antenna was used a dielectric substrate (Taconic RF35) with a permittivity of 3.5, a height of 0.762 mm, and a dielectric loss tangent of 0.0018. The operational band of the antenna according to the level of -10 dB of the reflection coefficient is 4%. It is worth noting that the Luneburg lens is frequency independent and the operational band of it depends only on the operational band of the feed.

![Figure 2. Normalized gain for H-(a) and E-plane (b) for two types of Luneburg lenses at 18 GHz.](image)
permittivity, the realized gain is 17.7 dBi and the HPBW is about 11.5° with the side lobe level better than 15.4 dB.

To implement a lens, it is necessary to define the effective permittivity of each layer as a percentage of the material filling of the layer. The dielectric permittivity can be recalculated to the percentage of filling of the PLA volume [1] by using (2):

$$\nu = \frac{\varepsilon_{\text{eff}} - 1}{\varepsilon_{r0} - 1},$$  \hspace{1cm} (2)

where $\varepsilon_{r0}$ is the relative permittivity of the filament for 3D printing, $\varepsilon_{\text{eff}}$ is the effective dielectric permittivity of the layer of the lens.

For calculations of $\nu$ it is important to know the permittivity of the PLA material with 100% infill. The resonant method of dielectric permittivity characterization was used. Five samples with a thickness of 3 mm were fabricated with different percentages of filling from 10% to 100%. The coplanar resonator was covered by the samples and the shift of the resonant frequency was used to determine the correspondence of the permittivity to the percentage of filling of the sample. The comparison between results obtained by (2) and the measured data is shown in figure 3. The permittivity of the 100% filled PLA sample was defined as 2.3.

![Figure 3](image)

**Figure 3.** Dependence of the dielectric constant on the volume of the PLA (a) and resonator, which was used for the characterization of material (b) and the samples made of PLA plastic with different filling percentage (c).

To describe the effective volume of plastic in the total volume taking into account the outer walls (usually a minimum wall thickness is equal to the diameter of the 3D printer nozzle) of each cylindrical layer, the following expression was used [1]:

$$d = \frac{\nu \pi (R^2 - r^2) - 2 \pi (R + r) \nu \pi (R^2 - r^2) - 2 \pi (R + r)}{\pi (R^2 - r^2) - 2 \pi (R + r)},$$  \hspace{1cm} (3)

where $t$ is the thickness of the outer wall determined by the diameter of the extruder nozzle, $R$ and $r$ are the outer and inner radii of the cylindrical ring respectively. The data for lens fabrication are presented in table 1.

| Table 1. Lens parameters for the fabrication |
|------------------|-------|-------|-------|-------|-------|
| Uniform thickness | $\varepsilon_{\text{eff}}$ | 1.99  | 1.91  | 1.75  | 1.51  | 1.19  |
|                    | $r/R$ | 0.20  | 0.40  | 0.60  | 0.80  | 1.00  |
|                    | $d, \%$ | 74    | 67    | 54    | 34    | 7     |
| Uniform step of dielectric const | $\varepsilon_{\text{eff}}$ | 1.90  | 1.70  | 1.50  | 1.30  | 1.10  |
|                     | $r/R$ | 0.45  | 0.63  | 0.77  | 0.89  | 1.00  |
|                     | $d, \%$ | 68    | 50    | 31    | 11    | 2     |
For the lens excitation, 4 samples of the patch antenna (16x22 mm) were fabricated and measured. The patch antenna was chosen due to the fact that it has a symmetrical radiation pattern in the E- and H-planes. The comparison between experimental results and measured ones is shown in Figure 4. According to the required percentage of PLA infill and radii of the layers, the two experimental samples of the lens were produced (figure 5). The radiation pattern of the lenses excited by patch antennas was measured in far field zone in the H plane. The measured and simulated results are in good agreement (figure 5).

![Figure 4. The reflection coefficient of patch antenna.](image)

3. Conclusion
In this paper, the 3D printed cylindrical Luneburg lens for Ku application was designed. For lens manufacturing, the samples with different infill percentage of PLA filament were fabricated and characterized by using a resonant method. Two lenses with different approaches to parameter discretization were simulated, manufactured and measured. The Ku band patch antenna was used as a feed source. The measured results correspond to the simulated ones.

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References
[1] Zhang, Shiyu, et al. "3D-printed planar graded index lenses." IET Microwaves, Antennas & Propagation 10.13 (2016): 1411-1419.
[2] Norooziarab, M., et al. "Millimeter-wave 3D Printed Luneburg Lens Antenna." 2019 IEEE Radio and Antenna Days of the Indian Ocean (RADIO). IEEE, 2019.
[3] Korotkov, A. N., S. N. Shabunin, and V. A. Chechetkin. "The cylindrical Luneburg lens discretization influence on its radiation parameters." 2017 International Multi-Conference on Engineering, Computer and Information Sciences (SIBIRCON). IEEE, 2017.