# Development of a Planar LTCC GRIN Lens for 60 GHz Open-Ended Waveguide Antenna

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***Abstract* — This study deals with the design, realization and evaluation of a gradient index lens (GRIN) made of low-temperature cofired ceramic (LTCC) for millimeter-wave communication systems at a frequency of 60 GHz. The LTCC GRIN lens presented here utilizes a radial refractive index profile achieved by varying the dielectric properties within the LTCC structure by punching 100 µm holes in the green LTCC sheets. We present the optimization of the refractive index gradient using zones within the LTCC structure, the simulated radiation patterns, the steps of the LTCC fabrication process and the experimental verification of the lens performance. The fabricated WR15 waveguides with lenses are characterized in an anechoic chamber and show an antenna gain of 16.6 dBi at 60 GHz. The experimental results confirm the theoretical predictions very well and show a significant improvement in beamforming and gain.**

***Keywords* — ceramics, LTCC, GRIN lens, multilayer, Van Atta arrays, retrodirective arrays**

## I. Introduction

In high-frequency technology, lenses are crucial for manipulating and guiding electromagnetic waves. They enable precise control of the direction of propagation of signals in the microwave and millimeter wave ranges and are therefore indispensable for the development of efficient antenna and transmission systems. [1]. Gradient index lenses (GRIN) are a planar type of radio frequency lenses. These lenses use a graded refractive index profile to influence the direction of wave propagation, which is important for waveguide designs of microwave and millimeter wave components. GRIN lenses help to miniaturize antenna systems and improve their performance by modifying the wavefronts to optimize beam shaping and steering [2]. In recent years, there has been increasing interest in planar lenses and their development in the field of wireless communication and radio frequency identification systems. Common manufacturing processes for these lenses are classic PCB technology [3] or additive 3D processes [4].

Compared to these technologies, Low-Temperature Cofired Ceramic (LTCC) technology offers various advantages for high-frequency technology and for the development of planar lenses. First, the middle dielectric constant of LTCC materials in the range of 5-8 enables the miniaturization of high-frequency components, which is essential for space-constrained applications [5]. Additionally, LTCC materials such as Ferro A6M and DuPont 9k7 exhibit low dielectric losses at high frequencies starting at 30 GHz, resulting in more efficient, higher performance components [6]. Another significant advantage is the excellent thermal stability and thermal conductivity of LTCC materials [7], which enable the heat generated by high frequency components like radar chips to be effectively dissipated. This ensures improved reliability and longevity of the components. The ability to create multilayer ceramic structures also opens up the possibility of manufacturing complex three-dimensional circuits and integrated planar lenses, leading to further miniaturization and functional integration [8]. LTCC's compatibility with numerous passive and active components simplifies system integration and enables the development of complex modules like metamaterial lenses [9]. The robustness of LTCC components qualifies this technology for use in harsh environments like hot or wet ambiences, such as those found in communications and space technology [10]. The precision and reproducibility of the LTCC manufacturing process results in highly accurate and quality-consistent components.

In this paper we present an implementation of GRIN lenses in LTCC technology at millimeter-wave frequencies. We show the encountered challenges during the design and manufacturing processes and provide preliminary experimental results that demonstrate the feasibility and potential advantages of this approach.

## II. GRIN Lens Design

To test the feasibility of the LTCC technology, a GRIN lens for gain enhancement of an open-ended WR15 waveguide was designed. The design is based on [5].

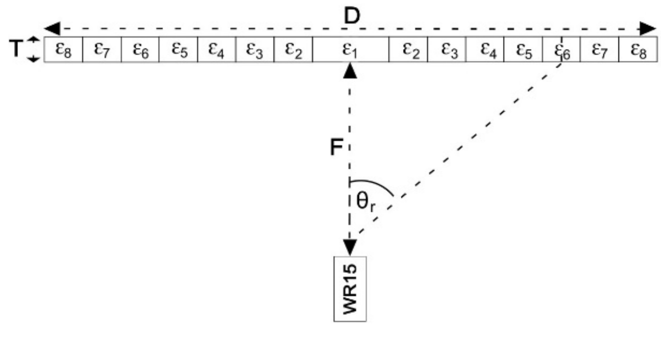


Figure 1. Cross section of the antenna. The GRIN lens with eight subzones is placed at a distance F from the open-ended WR15 waveguide.

The lens in its basic form is of cylindrical shape and consists of *r* concentric zones with varying electric permittivity $\varepsilon_r$, where chosen parameters were thickness of the lens *T*, limited by maximum assumed thickness of LTCC structure, focal length $F$ and $\theta_r$, an angle of incidence at the specific zone of the lens. These dimensions are marked at the cross section of the antenna structure in Fig. 1. The dimensions $T$, $D$ and $F$ are equal to 2, 30 and 26 mm respectively. The lens is designed to be fabricated using GT951 ceramic substrate with previously measured electric permittivity $\varepsilon_{max} = 7.2$ (at 60 GHz).

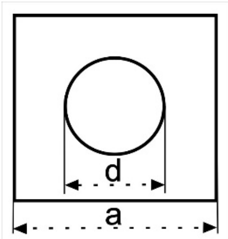


Figure 2: Top view of the unit cell.

Table I. Comparison of the parameters of the lens' subzones.

| Subzone No. (r) | $\varepsilon_{r'}$ (final) | Subzone T [mm] | No. of LTCC layers | Infill [%] | a [mm] |
|---|---|---|---|---|---|
| 1 | 7.2 | 2.02 | 10 | 100 | - |
| 2 | 6.85 | 2.02 | 10 | 86 | 0.479 |
| 3 | 6.26 | 2.02 | 10 | 62 | 0.287 |
| 4 | 5.44 | 2.02 | 10 | 23 | 0.403 |
| 5 | 7.2 | 1.19 | 6 | 100 | - |
| 6 | 5.55 | 1.19 | 6 | 28 | 0.21 |
| 7 | 7.2 | 0.733 | 4 | 100 | - |
| 8 | 7.2 | 0.092 | 1 | 100 | - |

In the first step, the lens with eight homogeneous dielectric subzones was designed (the permittivity gradient was determined in Table I). The subzones with the calculated values of relative permittivity can be realized by punching holes in the base dielectric material (thinning the substrate). A designed thinned dielectric consists of cuboid unit cells with a square base of dimensions $a$ x $a$ and cut out cylinder with a diameter $d$, as presented in Fig. 2. Diameter $d$ is equal to 0.1 mm in case of all designed dielectrics. The $a/d$ ratio determines the average permittivity of a subzone (see Table I).

The minimum achievable electric permittivity is limited by physical possibility of spacing the holes, as they cannot overlap. Since we wanted to obtain a wide range of permittivity, we had to replace impossible to realize low permittivity subzones with high permittivity layers compressed in Z axis. The same step had to be repeated twice more and this way four zones with different thicknesses were obtained, each zone consisting of subzones with different electric permittivity, as seen in Fig 3.

Also, a cylindrical cut-out was added in the center of the lens and the shape of the most outer subzone, which has the least impact on antenna radiation pattern, was changed to hexagonal, due to easier matching of layers during the fabrication process. Cross-section of the lens is presented in Fig. 3, while in Fig. 4 radiation patterns of source antenna, antenna with initial flat lens and antenna with lens with homogeneous dielectrics, after all transformations are shown.

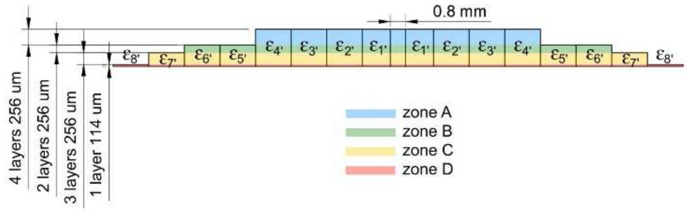


Figure 3. The cross-section detail of the designed GRIN lens.

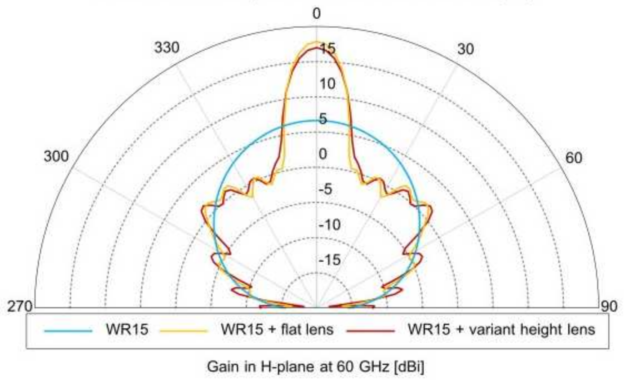


Figure 4. Simulated radiation patterns for open-ended WR15 waveguide with and without the designed GRIN lenses (gain in the H-plane at 60 GHz [dBi]).

To compare performance of a lens with homogeneous and punched dielectrics, due to too large mesh in simulation model, the original lens radius of 15 mm had to be reduced to 3.5 mm, and zone widths were reduced accordingly. Such lens was simulated and as presented in Fig. 5 good convergence of radiation patterns was obtained.

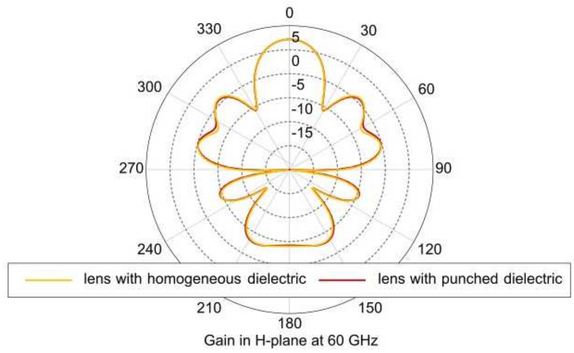


Figure 5. Simulated gain radiation patterns of lens model of reduced size (gain in the H-plane at 60 GHz [dBi]).

## III. LTCC Manufacturing

The DuPont material GT 951 with a data sheet permittivity of 7.8 was selected for the LTCC structure of the GRIN lenses. This material belongs to the glass-ceramic composites and, after sintering at typically 850 °C, consists of the solidified glass phase and the ceramic powder embedded in it.

### A. Punching and Lamination

The manufacturing of the GRIN lenses begins with the cutting and punching of the flexible LTCC tapes. Four lens structures were integrated on each 4 x 4 inch strip and produced in parallel. The structure was divided into 4 zones reflecting the cylindrical or pyramidal structure. While zone D only requires a tape of 114 µm green thickness, zones C, B and A consist of 3, 2 and 4 layers of 256 µm green thickness each, each made of (pre-) laminates (see Fig. 3).

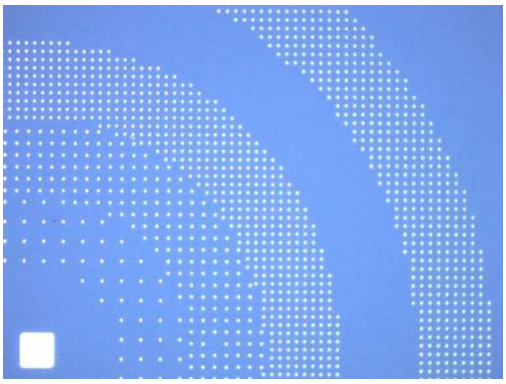

Figure 6. Punched 100 µm openings in LTCC green tape.

In the first production step, around 5000 openings (zones D, B and C) are punched for each strip, each with 100 µm holes and the required alignment holes. Fig. 6 shows in detail the arrangement of the 100 µm openings in an LTCC tape. In the second step, the partial pyramid surfaces (zones) of the lenses are stacked and pre-laminated with high precision using a KEKO stacker based on the alignment marks.

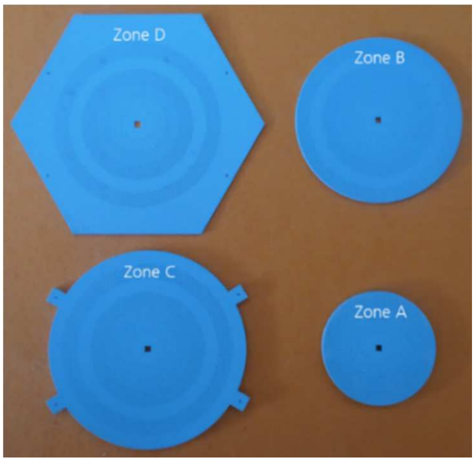


Figure 7. Pre-laminated LTCC sections of the GRIN lens.

In the third step, the lens zones are cut out of the pre-laminate using UV laser processing. The precise laser cut is made partly along the punched holes. Fig. 7 shows the pre-laminated and cut-out lens areas. In addition, a punched rectangular structure can be seen in the center of the laminate. With the help of this rectangular punching, the four lens areas are stacked on top of each other in the correct position with a prepared rectangular pin in the 4th assembly step and then finally laminated in the stacker at 150 bar uniaxially.

*B. Sintering*

To complete component production, sintering is carried out at a maximum of 850 °C in an LTCC sintering furnace from ATV. During the selected 10-hour sintering profile, the organic LTCC components are first burnt out at 400 °C, while in the second profile section the LTCC components are sintered at 850 °C for one hour. Fig. 8 shows the component after sintering. Apart from very fine cracks in the 100 µm zone D, no defects or distortions occurred after sintering, so that very good measurement results could be expected with the lenses. Two variants of the designed lens were fabricated, each variant with two copies. For the first variant (lenses L1 and L2) all four dielectric zones were manufactured. For the second variant (lenses L3 and L4), zone D was not laminated and sintered due to the slight defects mentioned above.

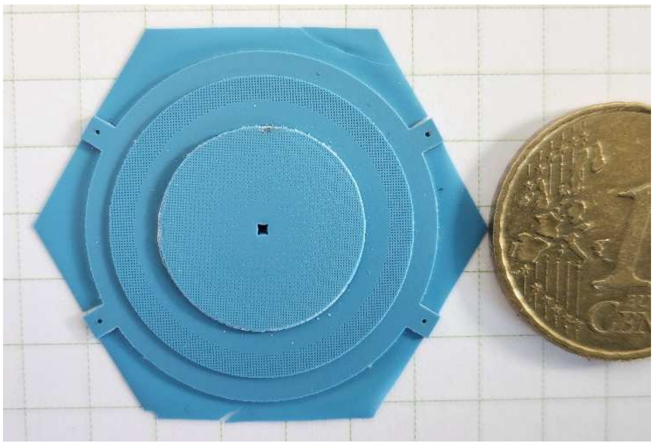

Figure 8. Sintered LTCC pyramided GRIN lens with all Zones.

## IV. MEASUREMENTS & DISCUSSION

All four manufactured dielectric lenses were assembled and prepared for characterization. To keep the lens at the proper distance, a spacer in the form of hexagonal tube with very thin walls, printed in SLA technology (with Grey Formlabs resin) was assembled with the antenna, as seen in Fig. 9.

Figure 9. The assembled antenna in a measurement setup, from the left: measurement fixture, WR15 waveguide, 3-D printed spacer and LTCC lens.

Antenna was measured in anechoic chamber in receiving mode using R&S ZVA50 network analyzer. H-plane gain radiation pattern of WR15 with lenses L1 – L4 were measured over 54 – 66 GHz bandwidth. Radiation pattern at 60 GHz and maximum gain over bandwidth are presented in Fig. 10 and Fig. 11 respectively. The measurement results of the WR15 waveguide combined with the LTCC lens show a realized gain 16.2-16.6 dBi at 60 GHz and a maximum of 18.8 dBi at 63 GHz.

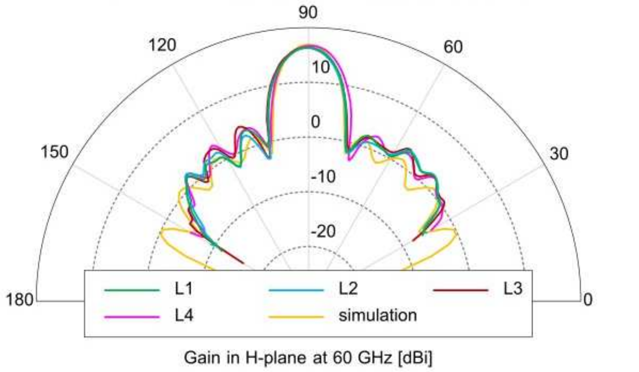


Figure 10. Measured (L1 to L4) and simulated gain radiation patterns [dBi].

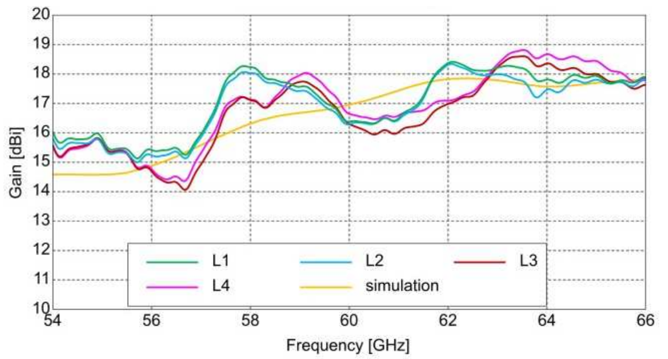


Figure 11: Measured (L1 to L4) and simulated gain vs. frequency.

Table 2 shows a comparison of the LTCC GRIN lens in terms of performance and size with 3D-printed polymer-based lenses as well as another LTCC lens solution.

Table 2 Comparison of lenses of different designs at a frequency of $f_0$ = 60 GHz

| **Ref.** | **Lens Type** | **Gain (dBi)** | **Size in λ at $f_0$** |
|---|---|---|---|
| [9] | LTCC Metamaterial | 15 | 3.8 x 3.8 x 0.384 |
| [11] | 3D printed | 15.3 | 6 x 6 x 6 |
| [12] | 3D printed | 20 | 8 x 8 x 4 |
| [13] | 3D printed | 25 | 30 x 30 x 1 |
| This work | LTCC GRIN | 16.6 | 6 x 6 x 0.36 |

## V. Conclusion

We have demonstrated that cylindrical shaped LTCC GRIN lens for a 60 GHz open-ended waveguide antenna could be realized in LTCC technology. For the gain radiation pattern and gain vs. frequency the measurements agree very well with the simulations, which speaks to the high manufacturing quality and reproducibility of the LTCC components. The LTCC process enables the further integration of beam steering components into the LTCC lens setup, such as Van Atta arrays components for mm-wave communication, which will be investigated in future work.

## Acknowledgment

This research was funded by the LDI MAGIC project (Reference No. project9280), which has received funding from the M-ERA.NET 3 Partnership for research and innovation on materials and battery technologies in support of the European Green Deal. The partnership receives support from the European Union's Horizon 2020 research and innovation program, as well as from national funding agencies from Germany (Sächsisches Staatsministerium für Wissenschaft, Kultur und Tourismus) and Poland (National Centre for Research and Development). The document reflects only the authors' views, and the commission is not responsible for any use that may be made of the information it contains.

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