Wide-Angle Ceramic Retroreflective Luneburg Lens based on Quasi-Conformal Transformation Optics for mm-Wave Indoor Localization

P. Kadera¹, (Graduate Student Member, IEEE), J. Sánchez-Pastor², (Graduate Student Member, IEEE), H. Eskandari³, T. Tyc⁴, M. Sakaki⁵, M. Schüßler², R. Jakoby², (Member, IEEE), N. Benson⁶, (Member, IEEE), A. Jiménez-Sáez², (Member, IEEE) and J. Lacik¹, (Member, IEEE)

¹Brno University of Technology, Department of Radio Electronics, Brno, 616 00, Czech Republic
²Technische Universität Darmstadt, Institute of Microwave Engineering and Photonics, Darmstadt, 64283, Germany
³ Ferdowsi University of Mashhad, Department of Electrical Engineering, Mashhad, 9177948944, Iran
⁴ Masaryk University, Institute of Theoretical Physics and Astrophysics, Faculty of Science, Brno, 611 37, Czech Republic
⁵ Universität Duisburg-Essen, Institute of Technology for Nanostructures and Technology, Duisburg, 47057, Germany

Corresponding authors: Petr Kadera (e-mail: kadera@vutbr.cz) and Jesús Sánchez-Pastor (e-mail: jesus.sanchez@tu-darmstadt.de).

This work was funded by the Quality internal grants of BUT, project no. CZ.02.2.69/0.0/0.0/19_073/0016948 and the German Research Foundation (“Deutsche Forschungsgemeinschaft”) (DFG) under Project-ID 287022738 TRR 196 for Project C09. We acknowledge support by the German Research Foundation and the Open Access Publication Fund of Technische Universität Darmstadt.

ABSTRACT

This paper presents a quasi-conformal transformation optics (QCTO) based three-dimensional (3D) retroreflective flattened Luneburg lens for wide-angle millimeter-wave radio-frequency indoor localization. The maximum detection angle and radar cross-section (RCS) are investigated, including an impedance matching layer (IML) between the lens antenna and the free-space environment. The 3D QCTO Luneburg lenses are fabricated in alumina by lithography-based ceramic manufacturing, a 3D printing process. The manufactured structures have a diameter of 29.9 mm (4 \(\lambda_\text{g}\)), showing a maximum realized gain of 16.51 dBi and beam steering angle of ±70° at 40 GHz. The proposed QCTO Luneburg lens with a metallic reflective layer achieves a maximum RCS of -20.05 dBsmq at 40 GHz with a wide-angle response over ±37°, while the structure with an IML between the lens and air improves these values to a maximum RCS of -15.78 dBsmq and operating angular response between ±50°.

INDEX TERMS Transformation optics, Luneburg lens, impedance matching, lens antenna, retroreflector, ceramic 3D printing, indoor localization, mm-wave, artificial dielectrics, chipless RFID.

I. INTRODUCTION

The area of passive retroreflective devices for mm-wave (30-300 GHz) and THz wave (0.3-10 THz) communication, objects tracking and indoor localization and identification has recently received increased attention [1]-[14]. Retroreflectors are devices that reflect an incoming electromagnetic (EM) wave into the direction of its arrival and serve for radar cross-section (RCS) enhancement, thus increasing detectability of the specified objects, e. g. drones, satellites, or airplanes. Retroreflectors based on different technological realizations in available literature are presented. For example, Van Atta arrays are formed by planar patches [1] or substrate integrated waveguides [2]. Moreover, frequency-coded corner reflectors are achieved by employing frequency selective surfaces [3]-[4] or dielectric resonator arrays [5]-[7]. A large amount of retroreflective structures are based on lenses by incorporating a reflective layer, such as frequency-coded fused silica spherical lenses [8]-[9], or lenses backed by a photonic crystal (PhC)-based structures [10], such as a polyethylene lens with a Bragg grating [11], and planar [12] or spherical [13] gradient-index Luneburg lens backed by planar PhCs. Finally, the Luneburg lens can also be employed to achieve an
omnidirectional retroreflector when it is surrounded by slant polarizers [14]. Most of the aforementioned references comprise frequency coding, enabling their employment in different areas. For instance, in chipless indoor self-localization systems [3], the ability to distinguish between retroreflectors inside the building allows for a precise position calculation, which is achieved by incorporating different and distinguishable frequency-coded signatures to the reflected wave of each retroreflector [3]-[13]. The advances in those researches bring unconventional retroreflectors based on metasurfaces [15]-[18], or on transformation-optics (TO) principles [19]-[23]. A summary of different retroreflectors and their operational angular range is presented in Table 1. However, the metasurfaces and TO-based retroreflectors have been proposed and realized only up to centimeter frequency bands (0.3-30 GHz) or in optics, outside the mm-wave region.

The use of retroreflectors at mm-wave frequencies allows for wider absolute bandwidths, i.e., a better ranging accuracy and smaller devices, as well as higher antenna gains [6]. More details can be found in our previous work [13], where a combination of a spherical 3D Luneburg lens with 2D PhC coding particles is introduced at 80 GHz. Further, in [24], we addressed the current limitations of a lens-based system due to limited angular response and overall reduced compactness of the coding particles, i.e., having to adapt the employed planar coding particles (2D PhC, resonating element arrays) to the spherical surface of a lens introduces undesired effects. For example, in [4] the curvature of the employed cross-dipole frequency surface decreases frequency selectivity. In addition, in 2D PhC-based coding [12], the curvature of the lens introduces structural distortions that results in a large angular separation needed between coding particles. To answer these challenges, we proposed a theoretical concept of a 3D flattened quasi-conformal transformation optics (QCTO) Luneburg lens backed by a 3D PhC coding structure [24], which showed a large potential for developing integrated wide-angle passive frequency-coded retroreflective devices since the flat bottom of the QCTO lens allows for easier integration of different coding particles. However, the required high permittivity of the lens ($\varepsilon_r = 17.5$) does not allow the usage of the same material as for the PhC coding part ($\varepsilon_r = 9.5$). Therefore, including the manufacturing and integration options enabled by ceramic 3D printing [25]-[26], a new design addressing this problem is required.

This paper presents the design and manufacturing of a ceramic wide-angle 3D QCTO Luneburg lens working in the Ka-band, as the first step towards frequency-coded monolithic ceramic-based tags for indoor localization applications. The design incorporates an impedance matching layer (IML) to the air as well. The high permittivity of alumina allows wide coverage angles while ensuring very stable operation in harsh environments (high-temperature, ionizing, chemically polluted) [3]. To the knowledge of the authors, this is the first time that an alumina-based QCTO Luneburg lens antenna with wide 3D operating angular range is presented, and its performance as a retroreflector is evaluated. The paper is organized as follows: Section II presents a study on QCTO Luneburg lenses; their maximum required permittivity and angular range. Section III deals with the manufacturing restrictions, their effects on the lens performance and fabrication process realized by ceramic 3D printing, and the measurement results. In Section IV, the achieved results and future improvements are discussed.

### II. QUASI-CONFORMAL TRANSFORMATION OPTICS ENABLED LUNEBURG LENS

| Ref. | Retroreflector type | Operational angle [°] | Freq. coding | Freq. [GHz] |
|------|---------------------|-----------------------|--------------|-------------|
| [1]  | Van Atta array      | $\pm 52^\circ$        | no           | 200         |
| [2]  | Van Atta array      | $\pm 42^\circ$        | no           | 78.6        |
| [3]  | Cross-dipole FSS + trihedral corner | $\pm 22^\circ$ | yes | 77         |
| [4]  | Gridded square-ring FSS + trihedral corner | $\pm 24^\circ$ | yes | 105        |
| [7]  | Spherical DR + dihedral corner | $\pm 20^\circ$ | yes | 84 100  |
| [8]  | Cross-dipole FSS + spherical lens | $\pm 38^\circ$ | yes | 160        |
| [9]  | Cross-dipole FSS + spherical lens | $\pm 60^\circ$ | yes | 82         |
| [10] | Cylindrical PhC DR + 2D planar Luneburg lens | $\pm 65$ | yes | 237.7      |
| [13] | Cylindrical PhC DR + 3D spherical Luneburg lens | $\pm 72^\circ$ | yes | 76.5       |
| [14] | Omnidirectional 3D spherical Luneburg lens | $\pm 180^\circ$ | no   | 30         |
| [15] | Planar metasurface with metal mirror | $\pm 32^\circ$ | no   | 10         |
| [17] | Planar metasurface with helicity-switching | -70 to -40 ** | yes | 10         |
| [18] | Spin-locked metasurface | 10 to 20 | no | 15         |
| [19] | Optics surface transformation (microchannel planar surface) | $\pm 80^\circ$ | poten- tially | -         |
| [20] | Omnidirectional transformation optics | $\pm 180$ | poten- tially | 8.9        |
| [22] | Flattened trihedral corner with transformation optics | $\pm 45^\circ$ | no | 8          |
| [23] | Parabolic with Schwarz-Christoffel transformation optics | $\pm 57^\circ$ | no | 5          |
| [24] | 3D PhC DR + 3D QCTO Luneburg lens | $\pm 75^\circ$ | yes | 79         |
| This work | Alumina 3D QCTO Luneburg lens | $\pm 50$ | yes | 40         |

* 6 dB drop from its maximum RCS value.
** Frequency-dependent angle of retroreflection.
* Simulated only
The transformation optics theory has gained popularity in the last two decades for providing a systematic approach to the design of invisible cloaks [27]-[31], conformal antenna arrays [32]-[33], directivity enhancers [34]-[35], waveguide bends and couplers [36]-[38]. TO has also been employed to modify the geometry of various dielectric lenses [39]-[53].

The transformation optics establishes a relation between the fields and the material between two spaces: the virtual space where the wave propagation properties are known, and the physical space. A spatial deformation is applied to the virtual space to attain a desired behavior for the electromagnetic waves. Using the transformation optics recipe, one can calculate a transformation medium for the physical space that mimics the desired space transformation. The transformation medium is quite complex if the underlying transformations are general. However, employing conformal and quasi-conformal transformations simplifies the derived material and leads to an all-dielectric, isotropic solution [42], [43], [51].

The QCTO has been used to modify the geometry of the Luneburg lens [54], by flattening a portion of the lens contour [40], [44], [50]-[53]. This creates a planar surface suitable for placing a 3D PhC medium with an array of embedded high-Q resonators for frequency coding as proposed in [24]. However, by applying QCTO to the Luneburg lens, the required maximum relative permittivity values increases drastically compared to the conventional Luneburg lens [40], [44], [50]-[53]. This drawback results in a more significant impedance mismatch at the boundaries between the modified lens and the surrounding medium (usually free space). Furthermore, this mismatch is amplified if a larger portion of the lens contour is flattened. The solution for this defect was proposed by Biswas et al. in [52] where an anti-reflective (AR) layer was added to the flattened area of the QCTO lens resulting in an improved antenna impedance matching and an enhancement of the antenna gain in an angular range of ± 55° with a maximum required relative permittivity of 2.9. The work [52] also reported that by increasing the AR layer thickness, one could improve the impedance matching at the expense of decreasing the maximum antenna gain for very broad scan angles. Therefore, it is necessary to pay more attention to the AR layer design to attain broad scan angles over ± 70°, as shown in [24], [40], [53]. This scenario is further investigated in section C.

The design process of the flattened QCTO Luneburg lens can be divided into 5 steps:

1) Quasi-conformal mapping of the original Luneburg lens permittivity profile in the given virtual space (Eq. 1) onto the permittivity profile in the physical space (Eqs. 2-3).
2) Limiting the resulting permittivity profile to the maximum and minimum values achievable by a ceramic 3D printing process using the alumina ceramics for the selected building unit cell (cross).
3) Creating the discretized 3D model (solid cubes in Fig. 3b) by using customized MATLAB code for the full-wave simulations in CST Studio Suite.
4) Assigning the targeted 3D permittivity distribution of the QCTO lens to the closest available permittivity values for the selected unit cell (Fig. 11).
5) Replacing the solid cubes by the crosses with corresponding dimensions for creation of the suitable 3D printing fabrication model (Fig. 13).

A. QUASI-CONFORMAL MAPPING OF THE LUNEBURG LENS

We assume that the Cartesian coordinates that define the virtual and physical spaces are \((u,v)\) and \((x,y)\), respectively. The virtual space is a rectangle with a height of 60 mm and a width of 120 mm that is attached to the Luneburg lens with a diameter of 60 mm. The bottom-left corner of the rectangle is at \((-60\,\text{mm}, -9.33\,\text{mm})\). The relative permittivity of the virtual space follows the below equation (1):

\[
epsilon_v = \begin{cases} 
2 \frac{u^2 + v^2}{R^2} & \text{for } |u^2 + v^2| \leq R^2, \\
1 & \text{elsewhere}
\end{cases}
\]

where \(R\) is the radius of the lens (30 mm) that is centered at the coordinate’s origin. The virtual space and the vertical \(u\)-constant and horizontal \(v\)-constant lines are depicted in Fig. 1 as well as the relative permittivity of the virtual space. The \(\theta \approx 144^\circ\) angle defines the lens steering angle.

The physical space is a rectangle with side lengths equal to \(AB\) and \(AG\). The curved bottom boundary of the Luneburg lens CDE is flattened by the transformation. The quasi-conformal transformation between the virtual and physical spaces is calculated by solving the Laplace’s equation in the virtual space for the variables \(x\) and \(y\).

\[\text{FIGURE 1. The geometry of the virtual space containing the Luneburg lens with a diameter of 60 mm, centered at the origin. The relative permittivity profile of Eq. 1 is presented. The white lines are the vertical }\] u-constant and horizontal v-constant lines.\]
The following equations (2) represent the underlying differential equations and the Dirichlet and Neumann boundary conditions involved in the process.

\[
\begin{align*}
\nabla^2 x &= 0, \\
\frac{\partial x}{\partial N}_{AB} &= -60, \\
\frac{\partial x}{\partial N}_{FG} &= 60, \\
y_{AG} &= 60, \\
y_{BC,CD,DE,EF} &= 0, \\
\frac{\partial y}{\partial N}_{AG,BC,CD,DE,EF} &= 0, \\
\frac{\partial y}{\partial N}_{AB,FG} &= 0,
\end{align*}
\]

where \( N \) is the normal vector of the boundary. The above equations can be solved using MATLAB [55] or COMSOL [56] PDE solvers. After solving the Laplace’s equations, the \( x(u,v) \) and \( y(u,v) \) functions and their partial derivatives are derived. The permittivity distribution in the physical space is calculated by the following equation (3):

\[
\varepsilon'_i = \frac{\varepsilon_i}{x_u y_v - x_v y_u},
\]

where the sub-scripts denote partial derivatives.

The permittivity profile of the physical space and the corresponding mapped \( u \)-constant and \( v \)-constant lines are depicted in Fig. 2a. Note that the corresponding image points are labeled with a prime sign. The images of physical space’s \( x \)-constant and \( y \)-constant lines in the virtual space are depicted in Fig. 2b. The mapped physical space’s relative permittivity is included as well.

The original untransformed spherical Luneburg lens has a diameter of 60 mm, while the transformed flattened Luneburg lens has a bottom diameter of 34 mm and the center diameter of 52 mm while the minimum relative permittivity is limited to the value of 1. The height of the lens is then limited by the height of the physical space (60 mm) with the minimum relative permittivity of 1.11. The relative permittivity values below 1 are omitted because we focus on the implementation involving only dielectric materials. In addition, due to minimum achievable effective relative permittivity of the cross unit cell used for the alumina ceramic 3D printing fabrication process, which is about \( \varepsilon_{r,eff} = 1.27 \) (see Section V), the transformed QCTO Luneburg lens is further evaluated in a manufacturable region with a bottom diameter of 34 mm, a center diameter of 44 mm and a height of 32 mm. After
calculations of the lens relative permittivity distribution in COMSOL Multiphysics, the in-house MATLAB codes were created and exploited for generating a discretized lens for CST Studio Suite (Fig. 3).

The calculated maximum and minimum relative permittivity of the QCTO Luneburg lens is then 8.89 and 1.25, respectively. The relation between the maximum relative permittivity of the transformed lens and the half beam steering angle θ/2, is shown in Fig. 4. Our numerical calculation corresponds to the approach presented by Kundtz et al. in [40]. However, the calculation done by Biswas et al. in [52], [57] leads to the maximum relative permittivity of 4, that is caused by imposing a different Dirichlet boundary conditions. To verify the COMSOL calculations, we used a simplified lens model discretized into ringed cylinders with the CST time-domain solver in the Ka-band (40 GHz) and the WR-28 waveguide excitation placed at the lens edge. Note that in Fig. 4 we added available results from the literature. Generally, we can see good agreement with our results.

B. QCTO LUNEBURG LENS PERFORMANCE

To evaluate the designed QCTO Luneburg lens it is assumed that the excitation with the WR-28 waveguide is placed on the lens bottom surface. The numerical simulations in CST Studio Suite were performed in the Ka-band (26.5 GHz to 40 GHz) while the waveguide was shifted from the lens center to the lens edge in 2 mm steps to obtain the radiation patterns in the H-plane (azimuth) (Fig. 5) and the reflection coefficient responses (Fig. 6). The lens antenna realized gain achieves 16.12 dBi at the lens center and 17.31 dBi at the lens edge, steering the beam in the range of ±75°. The maximum reflection coefficient varies between -3.57 dB and -9.06 dB while shifting the feed position. In the next section, we analyze several impedance transformer profiles to improve the antenna impedance matching.

C. IMPEDANCE MATCHING LAYER

The effect of adding IML as an antireflective layer on the lens bottom surface was investigated in [52] with the conclusion that the Klopfenstein impedance matching profile with 0.5 λ0 layer thickness at the center frequency provides the largest beam steering angle while maintaining a sufficient level of impedance matching. Further, in [57], the exponential and Gaussian impedance matching profiles were evaluated with slightly worse beam steering capabilities. However, these evaluations were carried out on the low maximum relative permittivity (εr = 2.89) QCTO Luneburg lens. Since our designed lens has a much higher maximum relative permittivity (εr = 8.89), we investigate the combination of the lens and IML on the overall antenna performance for a broadband Klopfenstein, exponential, and Gaussian profiles described by the following equations (7)-(11), respectively [57]-[58].

$$\varepsilon_{\text{AB, Klopf}} = \left( \varepsilon \varepsilon_i(x, y) \exp \left[ \Gamma_z A \phi \left( \frac{y}{L} - 1, A \right) \right] \right)^2,$$  

$$\Gamma_n = \frac{1}{\cosh A}; \Gamma_s = \frac{1}{2} \ln \left( \frac{\varepsilon_i}{\varepsilon_i} \right).$$
where $\varepsilon_0$ represents the relative permittivity of free space, $\varepsilon_r$ is the relative permittivity of the transformed lens gradient-index profile, $L$ represents the antireflective layer thickness, $I_m$ is the maximum passband ripple (0.001 in our case), the function $\phi(x, y)$ describes expanded power series of the first kind Bessel function of the order one, $\lambda_0$ is the free-space wavelength at the center frequency.

The discretized impedance matching profiles were implemented by MATLAB codes and are shown in Fig. 7. In our case, the thickness of the broadband IML is chosen to be 0.5 $\lambda_0$ (3.5 mm at 40 GHz) to accommodate 5 cells in the longitudinal direction to achieve better manufacturing mechanical stability and the requirement of the integer count of cells (assumed building unit cells size is 0.7 mm x 0.7 mm x 0.7 mm). The influence of the broadband IML on the antenna radiation patterns and the reflection coefficient are depicted in Figs. 8 and 9.

From the comparison of the broadband IML, the exponential profile provides the largest improvement of the antenna gain while maintaining the maximum beam steering angle of $\pm 75^\circ$ and the reflection coefficient better than -11.7 dB in the whole Ka-band. Further, the Klopfenstein profile provides slightly better impedance matching with reflection coefficient better than -15.4 dB. However, the antenna gain is 0.48 dB less than for the exponential profile at the lens center. In addition, compared to the exponential

\[
\phi(x, A) = \frac{1}{2} \sum_{m = -\infty}^{\infty} \frac{A^m}{m!(m+1)!} (1 - y^2)^m, \tag{9}
\]

\[
\varepsilon_{\text{exp}} = \left( \sqrt{\varepsilon_r} \exp \left[ \frac{y}{L} \ln \left( \frac{\sqrt{\varepsilon_r(x, y)}}{\sqrt{\varepsilon_0}} \right) \right] \right) \varepsilon_0, \tag{10}
\]

\[
\varepsilon_{\text{exp}} = \left( \sqrt{\varepsilon_r} \exp \left[ \frac{2}{L} \ln \left( \frac{\varepsilon_r(x, y)}{\varepsilon_0} \right) \right] \right) \varepsilon_0, \tag{11}
\]
profile, the Gaussian profile gives 0.95 dB lower antenna gain, and for lens without the IML, the gain improvement of 2.7 dB is achieved at the lens center. The comparison of selected IML and corresponding lens antenna parameters at a frequency of 40 GHz is summarized in Table 2. The higher antenna gain at the lens positions (8 mm; 15 mm) for the case without the

TABLE 2. QCTO Luneburg lens antenna parameters with different IML at various position of the lens excitation at a frequency of 40 GHz.

| Excitation position | Impedance matching layer (Antenna gain [dBi] / Reflection coefficient [dB]) |
|---------------------|--------------------------------------------------------------------------------|
| 0 mm                | Exponential / Klopfenstein / Gaussian / None                                  |
| 4 mm                | 18.63/-11.7 / 18.87/-15.4 / 17.88/-5.6 / 16.12/-3.6                         |
| 8 mm                | 19.10/-12.9 / 18.90/-16.0 / 17.93/-7.7 / 19.46/-4.5                        |
| 12 mm               | 18.01/-14.0 / 17.97/-16.3 / 17.27/-9.6 / 16.67/-6.1                        |
| 15 mm               | 16.68/-13.3 / 16.52/-14.5 / 16.27/-11.2 / 17.31/-9.1                      |

IML is caused by a properly located focal point of an excitation waveguide. While for the case of the IML, the focal point is slightly shifted, which could be partially mitigated by creating a multi-sectional IML of different thicknesses as proposed in [57]. Due to those facts, the exponential IML is chosen for manufacturing.

III. FABRICATION AND MEASUREMENTS

A. LENS MODELS INVOLVING FABRICATION LIMITS

The designed flattened QCTO Luneburg lens must be discretized into unit cells which can be fabricated by the ceramic 3D printing process applied for this study [25]-[26]. This unit cell types should be ideally isotropic and easily manufacturable, such as crosses [59] and cubes with rods [60]-[61] suitable for 3D objects, or square hole blocks [62] and cylindrical hole blocks [63] applicable for 2D objects. In our design, we first evaluated the effective relative permittivity of the following unit cell types: crosses, cubes with rods and square hole blocks depicted in Fig. 10 by the numerical simulation of dispersion diagrams [64]. The effective relative permittivity and corresponding eigenfrequencies for which the permittivity value is valid are shown in Fig. 11. A 90° phase shift with E-field oriented in the vertical direction across the unit cell is assumed and the inner structure’s dimensions are varied (squared hole size, cross’s rod thickness, cube size for 100 µm thick connecting rods). To ensure the success of the ceramic 3D printing process, we need to consider the effect of over polymerization (i.e., unwanted polymerization in vicinity of illuminated pixels, due to the light scattering during printing) and set the minimum inner dimensions to 100 µm (cross, cube with rods), or 50 µm (squared hole block) which results in a 100 µm wall thickness between adjacent cells. Furthermore, the minimum separation between each wall is 150 µm, and the overall unit cell dimensions must be a multiple of 25 µm due to the minimum 3D printer’s pixel size. To comply with the trade-off between those limits and the maximum operational frequency of the lens, the overall selected unit cell size is 0.7 mm x 0.7 mm x 0.7 mm.

The alumina relative permittivity used for our design is 9.5 [25], leading to the effective relative permittivity values between 1.27 and 8.81, 1.27 and 5.77, and 2.23 and 9.13 in the cases of cross, cube with rods and square hole unit cells, respectively. According to this comparison, it is clear that the cross unit cell provides the best ability to vary the effective relative permittivity, which follows a nearly linear slope, while for the cube with rods, the effective relative permittivity increases exponentially and is limited to the maximum cube size of 0.65 mm. The squared hole unit cell shows a logarithmic increase of the effective relative permittivity, and its minimum achievable value is limited by the minimum wall thickness. We choose the cross unit cells for the 3D lens fabrication models based on this analysis. The ideal lens permittivity profile will differ from the actual one due to the limited number of feasible effective relative permittivity values for each unit cell type. The absolute difference of the spatial effective relative permittivity distribution between the ideal and the fabricated QCTO Luneburg lens is plotted in Fig. 12.
The mean absolute relative permittivity difference is 0.1465, with the greatest absolute relative permittivity differences concentrated at the lens's outer surface areas. The 3D printer limits the size of the green body to 64 mm x 40 mm x 100 mm. Further, the expected shrinkages caused by sintering are 1.22 and 1.28 in the xy plane and z direction (i.e., height), respectively. As a result, the maximum dimensions after sintering are restricted to 52 mm x 32 mm x 78 mm. Therefore, the designed lens was recalcualted to comply with the green body requirements, reaching a middle diameter of 36.4 mm, a bottom diameter of 28 mm, and a height of 25.9 mm. The example of the fabricated model including the exponential IML is depicted in Fig. 13. The comparison of lens antenna radiation patterns and reflection coefficient involving non-ideal permittivity distribution and lens size after final fabrication (including all size reductions) are shown in Figs. 14 and 15. The focal points of the reduced size lens were shifted accordingly to match the beam steering direction of the original size of the lens.

The non-ideal lens permittivity distribution leads to slightly reduced antenna gain at the lens center position (1.2 dB), but increased gain and decreased beam steering angle at the lens edge positions (up to 2.9 dB and 7 degrees). Due to the lens size reduction, the antenna gain and maximum beam steering capability are further reduced (up to 2.4 dB and 3 degrees), so the maximum beam steering angle of the designed lens is ±65°. By adding the IML, the antenna gain is further increased by 4.4 dB to the value of 16.23 dBi for the boresight direction. The 3D radiation patterns of the 3D QCTO Luneburg lens, including the full measurement setup (the lens with a holder and a metallic waveguide probe) are shown in Fig. 16. It can be observed that the designed lens holder has a minor effect on the lenses’ radiation patterns since it is designed as an open structure in the lenses’ radiation directions.

**FIGURE 12.** Absolute difference between the ideal and achievable effective relative permittivity of the QCTO Luneburg lens (fabricated version) in 3D version composed of the cross unit cells.

**FIGURE 13.** Fabrication model of the QCTO Luneburg lens composed of cross unit cells is shown in red color and the exponential IML is shown in blue color. The structure is cut in the middle.

**FIGURE 14.** Simulated radiation patterns of the QCTO Luneburg lens involving non-ideal spatial permittivity distribution [fab] and the final fabrication dimensions [after] at a frequency of 40 GHz.

**FIGURE 15.** Simulated reflection coefficients of the QCTO Luneburg lens involving non-ideal spatial permittivity distribution [fab] and the final fabrication dimensions [after].

**FIGURE 16.** 3D radiation patterns of the 3D QCTO Luneburg lens without exponential IML (realized gain) using solid fabrication models, (a) feed at the lens center; (b) feed at the lens edge.
ens’s narrow holes and channels, the cleaning consisted of 51 vol% of cured polymers, performed to convert the cleaned green samples to dense ceramics parts. First, samples were slowly dried in an electrical laboratory dryer. The maximum temperature and duration of the drying step were 140°C and 6 days, respectively. The dried samples were then sintered in another electric furnace and under ambient atmosphere. Since the dried parts still consisted of 51 vol% of cured polymers, heating rates were low up to temperatures of 430°C (i.e., the temperature by which polymer compounds will be fully decomposed into volatile components) to guarantee the fabrication of crack-free samples. In this study, the lens’s parts were sintered at 1600°C, and the sintering duration was 4 days. The fabricated lenses are illustrated in Fig. 18 where the lenses are illuminated with a light source to appreciate their solid core through the whole grid array structure.

B. QCTO LUNEBURG LENS FABRICATION

The lithography-based ceramic manufacturing (LCM) technology was employed for the realization of the discussed lens structures. With this 3D printing method, lens’s parts are created layer-by-layer via DLP-controlled polymerization of a photosensitive slurry [65], [66]. The utilized printer was a Lithoz CeraFab 7500 [67] with a printing resolution of 25 μm and a UV light source (wavelength: ~450 nm) for slurry polymerization.

Lens’s parts were printed using a newly formulated slurry (i.e., LithaLox 360 [67]) and with an illumination energy of 450 mJ/cm²/layer. LithaLox 360 was intentionally developed for the fabrication of delicate samples, such as the Luneburg lens structures and contains 49 vol% of high purity Al2O3 powder as well as 51 vol% of UV-curable polymers. Directly after printing, the parts were cleaned to wash out the residual unpolymerized slurry. This was done by dipping the samples in LithaSol 20 [67] cleaning fluid, letting them soak for 5 minutes, and then ultrasonication of the system for 2 minutes. To ensure the cleanness of the samples, especially inside the lens’s narrow holes and channels, the cleaning process was repeated 10 times for each sample.

Afterward, the following thermal processing steps were performed to convert the cleaned green samples to dense ceramics parts. First, samples were slowly dried in an electrical laboratory dryer. The maximum temperature and duration of the drying step were 140°C and 6 days, respectively. The dried samples were then sintered in another electric furnace and under ambient atmosphere. Since the dried parts still consisted of 51 vol% of cured polymers, heating rates were low up to temperatures of 430°C (i.e., the temperature by which polymer compounds will be fully decomposed into volatile components) to guarantee the fabrication of crack-free samples. In this study, the lens’s parts were sintered at 1600°C, and the sintering duration was 4 days. The fabricated lenses are illustrated in Fig. 18 where the lenses are illuminated with a light source to appreciate their solid core through the whole grid array structure.

C. LENS ANTENNA CHARACTERIZATION

The measurement of the radiation pattern was performed in an anechoic chamber with the antenna scanner NSI 700S-30 and a Vector Network Analyzer (VNA) R&S ZVA67 with a 23 dBi horn antenna used as a transmitting antenna. A standard WR-28 waveguide probe was used with the lens as a receiving antenna. The lens was sequentially placed into individual 3D printed holders with a gradually shifted excitation position by 3 mm to precisely control the excitation position. The arm with lens was then rotated in 1-degree steps by a computer controller. The lens with holder in the anechoic chamber is shown in Fig. 19. The measured gain of the QCTO Luneburg lens is shown in Fig. 20.
For the lens without the IML, the gain is 12.62 dBi at 40 GHz at the lens center. Due to the radiation pattern flatness, the measured gain at the lens edge achieves 8.75 dBi and 8.25 dBi with the maximum beam steering angle of 45° and 90°, respectively. The measured gain of the lens with the exponential IML at 40 GHz is 16.51 dBi at the lens center and 10.49 dBi at the lens edge with the maximum beam steering angle of 70°. It is obvious that IML improves the gain of the lens by nearly 4 dB. The input reflection coefficient responses of the lens for different positions with and without the IML is shown in Figs. 21 and 22. The improvement caused by the IML is significant mainly for the lens center position. The input reflection coefficient is lower than -10 dB in the whole Ka-band. Those values are in good agreement with the simulation results. The discrepancy of the measured gain for higher beam steering directions can be caused by the excessive alumina material trapped inside the lens which could not be removed during fabrication, and the interaction of the wave with the lens holder.

D. RETROREFLECTIVE LENS CHARACTERIZATION

The characterization of the lens with reflective layer was performed by employing the Vector Network Analyzer PNA-X N5247A from Agilent Technologies, with its bandwidth set between 30 GHz to 40 GHz and 10001 frequency points, as well as IF bandwidth of 5 kHz. The measurements were performed with an 18 dBi Ka-band horn antenna, connected to a right angle (90°) WR-28 waveguide to coaxial adapter, and then to the VNA via a K-V transition and a V(m)-V(f) cable. Moreover, the structures are located within the transmitting/receiving horn antenna’s far field, at a distance of 0.3 m. The corresponding measurement setup is displayed in Fig. 23. In this case, the reflective layer was implemented by a metallic 2 EUR coin, whereas an electronically controlled turntable was used to perform angular measurements with 1° resolution. For each angle, a reference measurement without the tag was taken and subtracted to the raw data, to remove the influence of reflections from the horn antenna, as well reflections from the surrounding environment. The measured reflection coefficients for the employed coin, as well as the two
A corner reflector (CR) with an edge of 8.3 cm is employed as a reference radar target, with an analytical RCS in boresight at 40 GHz of 5.48 dBsqm, according to (13) [69]:

$$\text{RCS}_{\text{CR(ref)}} = 10 \log \left( \frac{4\pi}{3} \cdot \frac{a^4}{\lambda_0^2} \right),$$  \hspace{1cm} (13)$$

where \(a\) denotes the corner reflector’s edge and \(\lambda_0\) is the free-space wavelength.

When the CR is placed at a distance of 0.3 m from the horn antenna, the latter is not located in the far field of the former, which starts at 3.67 m. Therefore, the RCS cannot be computed accurately with (12) and (13). Instead, the CR is measured when placed 4 m away from the horn antenna. Then, the magnitude of the received \(S_{11}\) in frequency-domain is predicted at a distance of 0.3 m by considering the received power \(P_r\) in a monostatic radar system (14):

$$P_r = \frac{G_i^2 \lambda_0^2 \text{RCS}_{\text{target}}}{(4\pi)^3} \cdot \frac{1}{d^4},$$  \hspace{1cm} (14)$$

where \(P_t\) is the transmitted power, \(G_i\) is the horn antenna gain, and \(d\) the distance between radar and target. Assuming the same measurement setup is employed for different distances, \(P_t, G_i, \text{RCS}_{\text{target}}\) remain constant. Thus, by dividing Eq. (14) for the two different distances of 0.3 m and 4 m, the following relation between the corresponding \(S_{11}\) is obtained:

$$|S_{11,0.3\text{ m}}|^2 = |S_{11,4\text{ m}}|^2 \cdot \left( \frac{4 \text{ m}}{0.3 \text{ m}} \right)^4,$$  \hspace{1cm} (15)$$

It should be pointed out that (15) is only accurate when (i) the measurement of the corner reflector is in line-of-sight, (ii) the distance at which the \(S_{11}\) is predicted is within the far field of the transmitting horn antenna, and (iii) the same monostatic radar setup is employed for both retroreflective lens and corner reflector measurements, which is our case.
The corresponding measurement setup for the corner reflector is shown in Fig. 25, whereas the received backscattered signals of the corner reflector are presented in Fig. 26. Empty room subtraction and time gating between 26 ns to 28 ns are employed to minimize the influence of the surrounding environment. The calculated RCSs at 40 GHz for the QCTO-based retroreflective lens with and without IML are presented in Fig. 27. It is shown that the QCTO retroreflective lens presents a maximum RCS of -20.05 dBsmq at the angle of -7°, whereas the QCTO retroreflective lens with IML has a maximum RCS of -15.78 dBsmq for the frontal incidence. Both values are 6.85 dB and 2.67 dB below the single coin’s RCS for the frontal incidence, respectively.

Furthermore, the retroreflective lenses also present a wide angular range where the backscattered power remains with relatively high magnitude. The operating angular range, defined between the angles in which the RCS decreases by 10 dB regarding the maximum value, is ±7° for the coin, ±37° for the lens and ±50° for the lens with IML. The retroreflective structures present less angular range than the maximum steerable angle of the designed lens. This is owing to the finite size of the metallic coin used as reflective layer. As the lens is rotated, the effective size of the coin is smaller, which in turn reflects less power.

The radar range equation (14) is used to calculate the maximum read-out range with our setup by solving it for the distance. In our measurements, $P_r$ is -5 dBm, $G_r$ is 18 dB, $\lambda_0$ is set to the vacuum wavelength at 40 GHz and $P_t$ is set to the minimum detectable power at the receiver, $P_{r,min}$, which is -70 dBm. With these values, the maximum read-out ranges are 48.63 cm and 62.18 cm for the retroreflective lens without and with IML, respectively.

**IV. CONCLUSION**

In this paper, we have proposed a novel 3D QCTO based Luneburg lens for Ka-band mm-wave self-localization systems, which has been manufactured from high permittivity alumina with the LCM 3D printing process. The maximum realized gain of the lens without an IML is 12.62 dB, and the lens with the exponential IML led to the maximum realized gain of 16.51 dB at 40 GHz with the maximum beam steering angles of 90° and 70°, respectively. The comparison with other related works is summarized in Table 3. The maximum RCS of the lens backed by a reflective layer, which is firstly evaluated for this kind of retroreflector, without and with the exponential IML is -20.05 dBsmq and -15.78 dBsmq at 40 GHz, respectively.

To the best of the authors’ knowledge, this is the first demonstration of a 3D and retroreflective ceramic QCTO Luneburg lens. The employment of ceramics such as alumina for the lens allows for the realization of wide-angle frequency-coded retroreflectors that can be used for mm-wave indoor localization in dynamic cluttered harsh and high-temperature environments, e.g., withstanding a fire. Future development will be focused on the integration of the lens with 3D photonic crystal-based frequency-coding particles into a monolithic block, and their placement along the lens’s bottom, with the objective of achieving angle-of-arrival identification.

**V. REFERENCES**

[1] D. Desai, I. Gatley, C. Bolton, L. Rizzo, S. Gatley, and J. F. Federici, “Terahertz Van Atta Retroreflecting Arrays,” in *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, pp. 997–1008, June 2020.

[2] A. B. Numan, J. F. Frigon, and J. J. Laurin, “Wide Field of View Retrodiffractive Millimeter Wave Antenna Array With Pulse Modulation and Orthogonal Polarization States,” in *IEEE Access*, vol. 8, pp. 221127-221137, 2020.

[3] A. Jiménez-Sáez, A. Allhaj-Abbas, M. Schüßler, A. Abuelhaia, M. El-Absi, M. Sakaki, N. Benson, M. Hoffmann, R. Jakoby, T. Kaiser, and K. Solbach, “Frequency-Coded mm-Wave Tags for Self-Localization System Using Dielectric Resonators,” in *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 40, pp. 908–925, June 2020.

[4] J. Sánchez-Pastor, A. Jiménez-Sáez, M. Schüßler, and R. Jakoby, “Gridded Square-Ring Frequency Selective Surface for Angular-Stable Response on Chipless Indoor Localization Tag Landmarks,” in

---

**TABLE 3. 3D printed ceramic Luneburg lens antennas.**

| Ref. | Frequency [GHz] | Max. beam steering angle [°] / lens type | Max. gain @ Freq. [dB] | Dimensions [mm] (w x h) |
|------|-----------------|----------------------------------------|------------------------|------------------------|
| [59] | 28–38           | fixed at 0 / 3D                         | 26 (33)                | 54 x 54                |
| [62] | 12–18           | ±20 / 2D                               | 19.1 (18)              | 70.9 x 7.9             |
| [63] | 12–18           | ±15 / 2D                               | 16.5 (13)              | 70.04 x 7.9            |
| [68] | 12–18           | fixed at 0 / 2D                        | 18 (n/a)               | 70 x 8                 |
| This work | 26.5–40           | ±70 / 3D                               | 16.51 (40)             | 29.9 x 23.2            |

---

**FIGURE 26. Measured and adjusted reflection coefficient for the corner reflector.**

**FIGURE 27. Measured and simulated RCS over angle at a frequency of 40 GHz.**
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3166509, IEEE Access
Stereolithographic additive manufacturing of antennas: Why limit the bandwidth with metamaterials?, in *Scientific Reports*, vol. 3, Art. no. 1903, May 2013.

J. M. Poyanco, F. Pizzaro, and E. Rajo-Iglesias, “Wideband Hyperbolic Flat Lens in the Ka-Band based on 3D-Printing and Transformation Optics,” in *Applied Physics Letters*, vol. 118, Art. no. 123503, March 2021.

D. H. Kwon, “Quasi-Conformal Transformation Optics Lenses for Conformal Arrays,” in *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 1125–1128, Sep. 2012.

H. F. Ma, and T. J. Cui, “Three-Dimensional Broadband and Broad-Angle Transformation-Optics Lens,” in *Nature Communications*, vol. 1, iss. 8, Art. no. 124, Nov. 2010.

H. Eskandari, M. S. Majedi, A. R. Attari, and O. Quevedo-Teruel, “Elliptical Generalized Maxwell Fish-Eye Lens Using Conformal Mapping,” in *New Journal of Physics*, vol. 21, Art. no. 063010, June 2019.

C. Mateo-Segura, M. Lorente-Crespo, and Y. Hao, “All Dielectric Conformal Luneburg Lens Based Antenna,” in *The 5th European Conference on Antennas and Propagation (EuCAP 2014)*, The Hague, Netherlands, 2014, pp. 3001–3004.

Q. Liao, N. J. G. Fonseca, and O. Quevedo-Teruel, “Compact Multibeam Fully Metallic Geodesic Luneburg Lens Antenna Based on Non-Euclidean Transformation Optics,” in *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7383–7388, Dec. 2018.

M. Ebrahimipour and O. Quevedo-Teruel, “Bespoke Lenses Based on Quasi-Conformal Transformation Optics Technique,” in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2256–2264, May 2017.

O. Quevedo-Teruel, and Y. Hao, “Directive Radiation from a Diffuse Luneburg Lens,” in *Optics Letters*, vol. 38, no. 4, pp. 392–394, Feb. 2013.

T. Driscoll, G. Lipworth, J. Hunt, N. Kundtz, D. N. Basov, and D. R. Smith, “Performance of a Three Dimensional Transformation-Optical-Flattened Lüneburg Lens,” in *Optics Express*, vol. 20, no. 12, pp. 13262–13273, June 2012.

O. Quevedo-Teruel, W. Tang, and Y. Hao, “Isotropic and Nondispersive Planar Fed Luneburg Lens from Hamiltonian Transformation Optics,” in *Optics Letters*, vol. 37, no. 23, pp. 4850–4852, Dec. 2012.

S. Biswas, and M. Mirozniak, “High Gain, Wide-Angle QCTO-Enabled Modified Luneburg Lens Antenna with Broadband Anti-Reflective Layer,” in *Scientific reports*, vol. 10, Art. no. 12646, July 2020.

L. Wu, X. Tian, M. Yin, D. Li, and Y. Tang, “Three-Dimensional Liquid Flattened Luneburg Lens with Ultra-Wide-Viewing Angle and Frequency Band,” in *Applied Physics Letters*, vol. 103, iss. 8, Art. no. 084102, Aug. 2013.

R. K. Luneburg, and M. Herzberger, *Mathematical Theory of Optics* (University of California Press, Berkeley, CA, 1964), pp. 182–188.

MATLAB. [Online]. Available: https://www.mathworks.com/products/matlab.html

Comsol Multiphysics. [Online]. Available: https://www.comsol.com/

S. Biswas, “Design and additive manufacturing of broadband beamforming lensed antennas and load bearing conformal antennas,” PhD dissertation, University of Delaware, Department of Electrical and Computer Engineering, Newark, USA, 2019.

E. B. Graan, M. G. Moharam, and D. A. Pommet, “Optimal design for antireflective tapered two-dimensional subwavelength grating structures,” in *Journal Optical Society America*, vol. 12, no. 2, Feb. 1995.

K. F. Brakora, J. Halloran, and K. Sarabandi, “Design of 3-D Monolithic MMW Antennas Using Ceramic Spherolithography,” in *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 3, pp. 790–797, March 2007.

E. Burden, Y. Oh, B. MummaReddy, D. Negro, P. Cortes, A. D. Plessis, E. MacDonald, J. Adams, F. Li, and R. Rojas, “Unit cell estimation of volumetrically-varying permittivity in additively-manufactured ceramic lattices with X-ray computed tomography,” in *Materials & Design*, vol. 210, Art. no. 110032, 2021.

Y. Oh, V. T. Bhardambe, J. J. Adams, D. Negro, and E. MacDonald, “Design of a 3D Printed Gradient Index Lens Using High Permittivity Ceramic,” in *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, Montreal, QC, Canada, 2020, pp. 1431–1432.

Y. -H. Lou, Y. -X. Zhu, G. -F. Fan, W. Lei, W. -Z. Lu, and X. -C. Wang, “Design of Ku-Band Flat Luneburg Lens Using Ceramic 3-D Printing,” in *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 2, pp. 234–238, Feb. 2021.

F. Wang, Z. Li, Y. Lou, F. Zeng, M. Hao, W. Lei, X. Wang, X. Wang, G. Fan, and W. Lu, “Stereolithographic additive manufacturing of Luneburg lens using Al2O3-based low sintering temperature ceramics for 5G MIMO antenna,” in *Additive Manufacturing*, vol. 47, Art. no. 102244, Nov. 2021.

P. Kadera, J. Lacik, and H. Arthaber, “Effective Relative Permittivity Determination of 3D Printed Artificial Dielectric Substrates Based on a Cross Unit Cell,” in *Radioengineering*, vol. 30, iss. 4, pp. 595–610, Dec. 2021.

M. Schwenkewijen, and J. Homa, “Additive Manufacturing of Dense Alumina Ceramics,” in *International Journal of Applied Ceramic Technology*, vol. 12, iss. 1, pp. 1–7, Jan. 2015.

M. Schwenkewijen, P. Chmeidei, and J. Homa, “Lithography-Based Ceramic Manufacturing: A Novel Technique for Additive Manufacturing of High-Performance Ceramics,” in *Advances in Science and Technology*, vol. 88, pp. 60–64, Oct. 2014.

Lithoz. [Online]. Available: https://www.lithoz.com/

Y. Lou, F. Wang, Z. Li, Z. Zou, G. Fan, X. Wang, W. Lei, and W. Lu, “Fabrication of high-performance MgTiO3–CaTiO3 microwave oven ceramics through a stereolithography-based 3D printing,” in *Ceramics International*, vol. 46, iss. 10, part B, pp. 16979–16986, July 2020.

*Sideways Cross Section Handbook – Volume 2*, G. T. Ruck, New York, NY, USA: Plenum Publishing Corporation, 1970.

PETR KADERA was born in Čeladná, Czech Republic, in 1994. He received the M. Sc. degree in electronics and communications from the Brno University of Technology, Brno, Czech Republic, in 2018, where he is currently pursuing the Ph.D. degree with the Department of Radio Electronics. His current research interests include 3D printing, artificial dielectrics, lens antennas, material characterization and transformation optics in microwave and millimeter-wave frequencies. In 2020 and 2021 he has been a visiting PhD student at TU Darmstadt, and at KTH Royal Institute of Technology, Darmstadt, Germany, and Stockholm, Sweden.

JESÚS SÁNCHEZ-PASTOR received the double master’s degree in telecommunications engineering from the Polytechnic University of Valencia, Spain, and in information and communication engineering from the Technische Universität Darmstadt, Germany, in 2020. He is currently pursuing the Ph.D. degree with the Institute of Microwave Engineering and Photonics, TU Darmstadt. His current research interests include chipless RFID applied to indoor localization and sensing, high-Q photonic crystal cavities, and frequency selective surfaces.
HOSSEIN ESKANDARI received his B.Sc. in electrical engineering, M.Sc., and Ph.D. in telecommunication engineering (field and waves) from the Ferdowsi University of Mashhad, Iran in 2012, 2014, and 2020 respectively. His research interests cover transformation-optical design of devices in microwave and photonics, antenna and phased array design, and all-dielectric lens design and fabrication.

TOMÁŠ TYC received the M.Sc. and the Ph.D. degrees in theoretical physics from Masaryk University, Brno, in 1996 and 1999, respectively. In 2006, he obtained habilitation and in 2009 full professorship, both from Masaryk University. He was a Research Fellow or Visiting Professor at University of Vienna (2000), Macquarie University Sydney (2001 and 2002), University of Calgary (2004), University of St. Andrews (2007, 2008, 2010, 2011 and 2012), and University of Dundee (2013 and 2014). He is currently with the Institute of Theoretical Physics and Astrophysics, Masaryk University. He was initially involved in quantum mechanics, quantum optics and quantum information theory. Since 2007 his focus has been optics, in particular theory of invisible cloaking, transformation optics and geodesic lenses.

MASOUD SAKAKI received the Ph.D. degree in materials science and engineering in 2010. His main expertise is synthesis, characterization, and sintering of ceramic compounds via different routes. He was an Assistant Professor with Malayer University, Iran, from 2010 to 2014, and a Postdoctoral Researcher with Kochi University, Japan, from 2014 to 2019. He is currently a Postdoctoral Researcher with Duisburg-Essen University. His research is focused on the additive manufacturing of ceramics for THz applications.

MARTIN SCHÜBLER received the Dipl.Ing. and Ph.D. degrees from the Technische Universität Darmstadt, Germany, in 1992 and 1998, respectively, where he has been a Staff Member of the Institute for Microwave engineering and Photonics, since 1998. During his career, he worked in the fields of III-V semiconductor technology, microwave sensors for industrial applications, RFID, and small antennas. His current research interests include microwave biosensors and passive chipless RFID.

ROLF JAKOBY was born in Kinheim, Germany, in 1958. He received the Dipl.Ing. and Dr.Ing. degrees in electrical engineering from the University of Siegen, Germany, in 1985 and 1990, respectively. In 1991, he joined the Research Center of Deutsche Telekom, Darmstadt, Germany. Since 1997, he has been a Full Professor with the Technische Universität Darmstadt. He is a Co-Founder of ALCAN Systems GmbH, author of more than 320 publications and holds 20 patents. His current research interests include tunable passive microwave devices, beam-steering antennas, chipless RFID sensor tags and biomedical applicators, using metamaterial, ferroelectric, and liquid crystal technologies. He received an award from CCI Siegen for his excellent Ph.D., in 1992 and the ITG-Prize, in 1997 for an excellent publication in the IEEE AP Transactions. His group received 23 awards and prizes for best papers and doctoral dissertations. He was the Chairman of the EuMC in 2007 and GeMiC in 2011 and was Treasurer of the EuMW in 2013 and 2017. He is Editor-in-Chief of FREQUENZ, DeGruyter, and member of VDE/ITG and of IEEE/MTT/AP societies.

NIELS BENSON received the Dipl.-Ing. degree in electrical engineering from the University of Stuttgart, in 2004, and the Dr.-Ing. degree in materials science from the Technische Universität Darmstadt, in 2009. Since 2008, he was a Senior Scientist for polymer vision on rollable active matrix displays. In 2010, he joined the University of Duisburg-Essen as a Research Group Leader on thin film photovoltaics and electronics. In 2018, he was appointed a W1-Professor with the University of Duisburg-Essen on printable materials for signal processing systems. His current research interests include charge carrier transport in disordered semiconductor, passive chipless RFID systems, and additive manufactured ceramic components for sub-mm and mm-wave signal processing applications.

ALEJANDRO JIMÉNEZ-SÁEZ received the double master’s degree (Hons.) in telecommunications engineering from the Polytechnic University of Valencia, Spain, and in electrical engineering from the Technische Universität Darmstadt, Germany, in 2017. He received the Dr.-Ing. degree (summa cum laude) from the TU Darmstadt in 2021, and the award Freunde der TU Darmstadt to the best dissertation in Elektrotechnik und Informationstechnik at TU Darmstadt in 2021. He currently leads the Smart RF Systems based on Artificial and Functional Materials research group at the institute of microwave engineering and photonics, TU Darmstadt. His current research interests include chipless RFID, high-Q resonators, electromagnetic bandgap structures, liquid crystals, and reconfigurable intelligent surfaces at sub-mm and mm-wave frequencies.

JAROSLAV LÁČÍK received the M.Sc. and Ph.D. degrees from Brno University of Technology, Brno, Czech Republic, in 2002 and 2007, respectively. He is currently an Associate Professor at Brno University of Technology. His research interests are antennas, body-centric wireless communication, computational electromagnetics, and measurement.