

A Cylindrical Mismatched Luneburg Lens Implemented on PCB at V-band

Vincent Kaschten^{*†}, Dimitri Lederer^{*}, Christophe Craeye^{*},

^{*}ICTEAM Institute, UCLouvain, Louvain-la-Neuve, Belgium,

vincent.kaschten@uclouvain.be, dimitri.lederer@uclouvain.be, christophe.craeye@uclouvain.be

[†]BEA Sensors Europe, Liège, Belgium

Abstract—We implement a cylindrical mismatched Luneburg lens at V-band, following the related theory and design rules. The lens has a relative dielectric permittivity of 2.6 at its edge, while the exterior medium is air. The implementation is done on a Printed Circuit Board, and includes the lens itself as well as Substrate-Integrated Waveguides acting as feeds and a transition from Grounded Co-planar Waveguide transmission lines to the feeds. The whole structure is fabricated as a single-piece board with standard processes. Measurements confirm that this design can produce a fan-shaped beam at multiple excitation points covering a 40 degrees angular range.

Index Terms—GRIN lenses, Luneburg lens, mismatched Luneburg lens, PCB, GCPW, SIW.

I. INTRODUCTION

The classical Luneburg lens [1] is one of the many examples of matched Gradient-Index (GRIN) lenses that one can find in the literature. GRIN lenses are spherical/cylindrical dielectric lenses featuring a radially varying dielectric permittivity. Implementations of cylindrical Luneburg lenses have been demonstrated based on metamaterials [2][3], PCB techniques [4]–[6], fully metallic structures [7][8], using pressed foam [9][10] or stacked materials [11]. Such lenses are capable of beam-switching over a wide angular range [3][5]–[7][10] with low scan losses and offer high gain performance. One challenging constraint frequently underlined [2][7] consists in covering the whole permittivity range required. To excite such a lens, different types of sources have been used: waveguides [3][4][7]–[9], transitions from microstrip lines [6][10], probes [2][11], as well as more sophisticated antennas [5]. Many implementations show that Substrate-Integrated Waveguides (SIW) [4][10] or standard rectangular ones [3][9] are a relevant choice for feeding cylindrical GRIN lenses, because of their natural geometrical compatibility. Most of the implementations listed above feature multiple pieces, while the cylindrical GRIN lens with its metallic plates can be fabricated as a single piece [2][10] or even the full antenna comprising the GRIN lens and the feeds [4][6]. Transitions from standard transmission lines to SIW have been designed on PCB [12][13] and LTCC [14] technologies. Transitions from Grounded Co-Planar Waveguide (GCPW) lines to SIW have been designed using coupling slots [13] with an identical height for the GCPW and the SIW. Microstrip to SIW transitions have also been proposed making use of a via probe diving into the SIW

located in buried layers [14], or using a tapered ridged SIW [12] allowing an SIW with a larger height than the microstrip.

In this paper, we implement a cylindrical mismatched Luneburg lens at V-band on a PCB, along with multiple feed elements, as a single piece. The mismatched distribution [15], allowing a relative dielectric permittivity value greater than 1 at the lens edge while maintaining the lens collimation effect, eases the realization of the permittivity range on PCB, as well as the integration of SIW feeds. A transition from GCPW to SIW with a large height ratio is also designed. This paper is organized as follows. Section II describes the implementation of a mismatched Luneburg lens on a PCB. Section III introduces a GCPW to SIW transition realized on PCB as well, which is used in Section IV as feed to obtain a GRIN lens antenna. Section V presents measurement results while Section VI provides a brief conclusion.

II. MISMATCHED LUNEBURG LENS

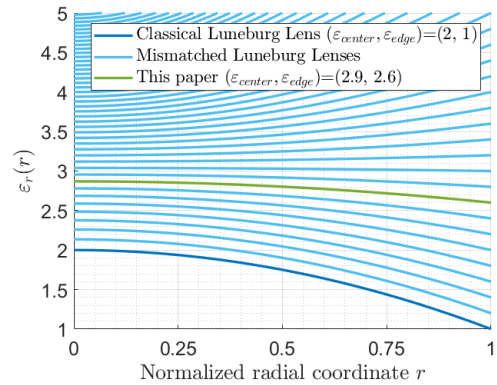


Fig. 1. Set of mismatched Luneburg distributions (1) obeying (2).

Recently, it was proposed to widen the scope of GRIN lenses by giving up the matching constraint at the lens edge: a comprehensive study was carried out [15] and optimal dielectric permittivity distributions were obtained through numerical analysis. They follow a square law along the radial coordinate,

$$\varepsilon_r(r) = \varepsilon_{center} - (\varepsilon_{center} - \varepsilon_{edge}) r^2 = 2.9 - 0.3 r^2 \quad (1)$$

between a value ε_{center} at the lens center and ε_{edge} at the lens edge, linked together by the following relationship:

$$\varepsilon_{center} = \sqrt{2} \sqrt{\varepsilon_{edge}} + (2 - \sqrt{2}) \quad (2)$$

We chose the combination $\varepsilon_{edge} = 2.6$ and $\varepsilon_{center} = 2.9$ according to (2), in order to avoid permittivities too close to that of air, and make the realization of such a lens feasible on PCB. The related distribution (1) is represented in green in Fig. 1, along with the classical Luneburg distribution and other mismatched Luneburg distributions.

In order to obtain a collimated beamwidth of about 10 degrees we chose a lens radius $R = 15$ mm (i.e., a diameter equal to $6\lambda_0$ at 60 GHz) that we discretized into 15 dielectric zones with a radial expansion of 1mm each, see Fig. 2. We chose to work with standard substrate and prepreg materials from Rogers, both with a relative dielectric permittivity $\varepsilon_{r,sub} = 3.66$ (dielectric and metallic losses, including metal roughness, were taken into account in the following simulations). By appropriate choice of the multi-layer PCB stack-up, the height h_{PCB} was fixed at about 2mm (i.e., $0.4\lambda_0$ at 60 GHz) as shown in Fig. 2(b), in order to obtain a beamwidth greater than 60 degrees in elevation.

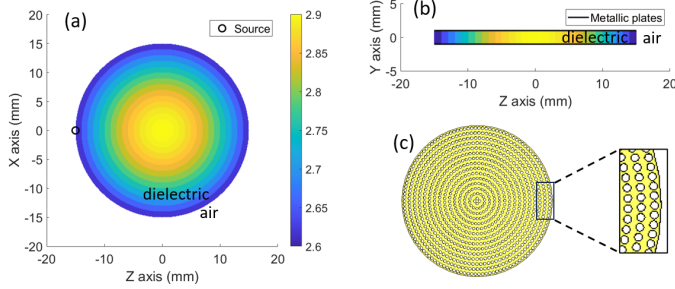


Fig. 2. GRIN lens implementing a mismatched Luneburg distribution discretized into 15 zones (a)-(b) on PCB, by drilling air holes (c).

The required lens profile (1) can be obtained by introducing small cylindrical air holes in the lens dielectric body [5], i.e. by drilling through-holes in the PCB. According to the effective medium theory, the effective permittivity of a zone $\varepsilon_{r,zone}$ is given in good approximation by the weighted average between $\varepsilon_{r,air}$ and $\varepsilon_{r,sub}$ with weights given by the fraction (f_{air} and $f_{sub} = 1 - f_{air}$) of each material in the zone [16]:

$$\varepsilon_{r,zone} = f_{air} \varepsilon_{r,air} + (1 - f_{air}) \varepsilon_{r,sub} \quad (3)$$

The required air fraction can be obtained from (3) and can be translated for each of the 15 zones into a certain number of holes with a given diameter, drilled over the whole height of the PCB lens, see Fig. 2(c). Their small size compared to the wavelength will guarantee that the waves perceive an effective medium as well as two virtually continuous metallic plates.

III. GCPW TO SIW TRANSITION

In order to excite the lens, we want feeds spaced 10 degrees from each other on the GRIN lens perimeter. An SIW implemented with vias of diameter d and spaced by a distance s from each other in each row, behaves like a classical rectangular waveguide with an effective width [17] given by

$$a_{SIW,eff} = a_{SIW,phys} - \frac{d^2}{0.95s} \quad (4)$$

where $a_{SIW,phys}$ is the SIW physical width. The SIW was implemented with $d = 300 \mu\text{m}$ and $s = 400 \mu\text{m}$. With the PCB height (along $\hat{y}$) fixed at $h_{PCB} = h_{SIW} \approx 2$ mm the TE_{01} mode (horizontally polarized) has a cutoff frequency of 39 GHz. We decided to fix the SIW physical width $a_{SIW,phys}$ at 1.70 mm (along $\hat{x}$), which yields a cutoff frequency of 53.5 GHz for the TE_{10} mode (vertically polarized) while the higher order modes have a cutoff frequency above 66 GHz.

A transition from a 50Ω GCPW to the SIW was designed. The coupling mechanism between both types of transmission lines was obtained using a blind via (see Fig. 3(c)), diving into the SIW, close to its mid-height. Through vias are used over the whole structure, for both the GCPW and the SIW parts, in particular for creating a metallic backplane [13].

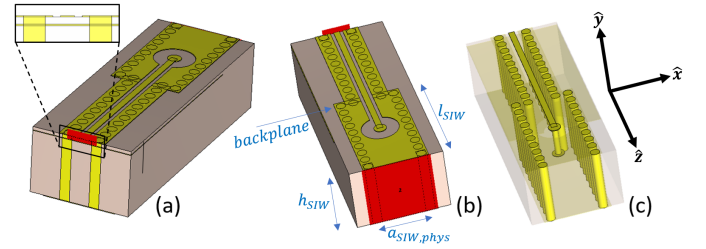


Fig. 3. GCPW to SIW transition seen from port 1 at the GCPW side (a), from port 2 at the SIW side (b) and with the blind via highlighted (c). Dielectric substrate is represented in grey, copper in yellow, simulations ports in red. For (b) and (c), axes ($\hat{x}, \hat{y}, \hat{z}$) represent the horizontal (width), vertical (height) and propagation (length) directions, respectively.

The structure was simulated using CST Studio Suite with port 1 at the GCPW side and port 2 at the SIW side, see Fig. 3(a)-(b). There is a ratio of about 20 between the GCPW height (signal line to buried ground, see zoom in Fig. 3(a)) and the SIW height. The SIW length l_{SIW} (along $\hat{z}$) was set to half a guided wavelength, and the blind via placed at a quarter wavelength both from the backplane [13] and from port 2. As the GCPW signal line reaches the blind via, the GCPW coplanar and buried ground planes open for the latter. Above the TE_{10} cutoff and below that of higher order modes, the vertical blind via only couples energy towards the vertically polarized TE_{10} mode in the SIW, while the TE_{01} mode, although above cutoff, is not excited due to the symmetry of the structure.

The simulated S-parameters of the optimized transition can be found in Fig. 4. Port 1 is matched from 56 GHz to 73 GHz. The S_{21} parameters, corresponding to the different modes that can be excited at port 2, show that only the desired TE_{10} mode in the SIW is significantly transmitted across the frequency range of interest, with a simulated $S_{21,TE_{10}}$ better than -2.5 dB between 57 GHz and 65 GHz. The matching at port 2 in the TE_{10} mode ($S_{22,TE_{10}}$) is achieved from 56 GHz to 66 GHz. To sum up, simulations show that this transition from GCPW to the TE_{10} mode in the SIW is matched at both ports with an insertion loss about 2 dB from 57 GHz to 65 GHz.

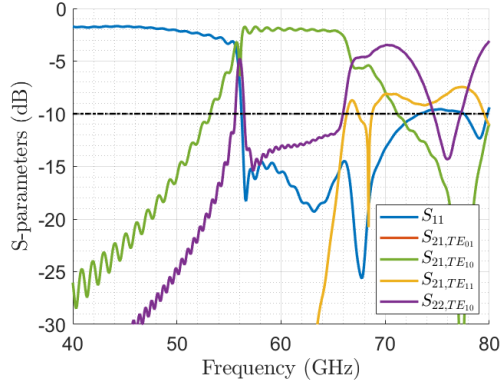


Fig. 4. Simulated S-parameters of the optimized GCPW to SIW transition.

IV. GRIN LENS ANTENNA

The transition detailed in Section III is now used as a feed for the GRIN lens detailed in Section II. Both have the same height as they were designed on the same PCB structure. A total of 5 feeds are added, with the SIW end (port 2 in Fig. 3(b)) placed tangent to the lens perimeter, see Fig. 5. The top and bottom metallic walls of the SIW naturally and continuously connect to the top and bottom plates of the cylindrical lens. The TE_{10} mode in the SIW naturally couples with the fundamental TM_0 mode in the lens, since both modes feature a vertical constant electric field.

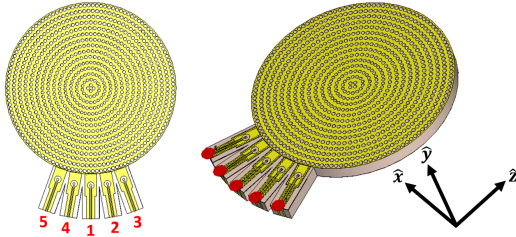


Fig. 5. Antenna consisting of a GRIN lens and 5 transitions acting as feeds on the lens perimeter. Dielectric substrate is represented in grey, copper in yellow, simulations ports (on the GCPW ends, numbered from 1 to 5) in red.

The optimized S_{ii} for ports 1 to 3 are shown in Fig. 6, along with the S_{11} of the transition for the sake of comparison. Simulations show that all ports are matched from 58.5 GHz to 71 GHz, which correlates with the S_{11} of the transition matched from 56 GHz to 73 GHz. Frequencies between 56 GHz and 58.5 GHz are above but close to cutoff, resulting in a large wave impedance of the SIW in TE_{10} mode, preventing proper wave impedance matching at the interface with the lens.

The simulated radiation patterns, at port 1 and for a set of frequencies from 50 GHz to 70 GHz, are shown in Fig. 7. Azimuth angle is defined in the XZ plane with respect to $\hat{z}$, positive towards $\hat{x}$, while elevation angle is defined in the YZ plane with respect to $\hat{z}$, positive towards $\hat{y}$. According to what was said before, the radiation pattern is rather noisy at 50 GHz because the transition does not correctly excite any of the modes in the SIW. The pattern then establishes into a stable and rather symmetric fan-shaped beam around 60 GHz (from

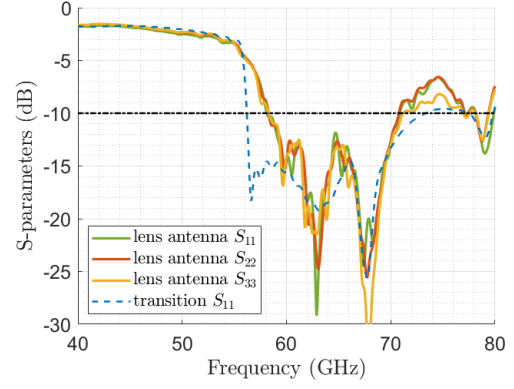


Fig. 6. Simulated S_{ii} parameters of the GRIN lens antenna, for ports 1-3.

59 GHz to 65 GHz), while the higher-order modes perturb the fan shape at higher frequencies such as 70 GHz, even though the impedance is matched.

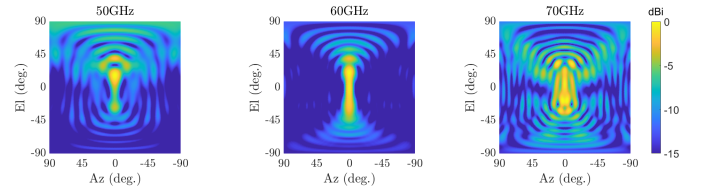


Fig. 7. Normalized radiation patterns for port 1, obtained with CST.

V. MEASUREMENTS

Prototypes were fabricated, and measured at the "Wallonia Electronics and Communications Measurements" (WEL-COME) facility at UCLouvain. All prototypes were excited from a 1.85mm SMA edge launch connector *ELF67* from *Signal Microwave*. The GCPW and SIW transmission lines were characterized with the *mTRL* method up to 67 GHz using the VNA *N5247A PNA-X, 67GHz* from *Keysight*.

Then, two GCPW to SIW transitions in a back-to-back configuration were characterized. The measured S-parameters are shown in Fig. 8 along with simulated ones.

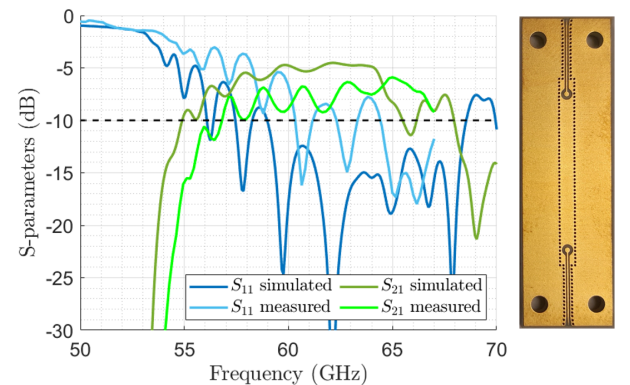


Fig. 8. Simulated and measured S-parameters (left) of the two GCPW to SIW transitions in a back-to-back configuration (right).

A 1 GHz shift in both S_{11} and S_{21} is observed. It can be related to a shifted cutoff frequency $f_{c,TE_{10}}$ of the SIW, that we can explain by a slightly lower permittivity of the substrate than the value used in simulations (5% variation of $\epsilon_{r,sub}$ is sufficient to explain such a shift). The S_{21} also features 1.5 dB of additional losses compared to simulations, which we link to increased losses in the transition (0.5 dB, to count twice) partially related to matching issues, as well as increased losses in the long SIW part (0.5 dB). The measured insertion loss of the transition alone is thus estimated at 2.5 dB.

Prototypes of the GRIN lens antenna were also printed and are shown in Fig. 9. Each time, a connector footprint was placed at one of the ports, while the other ports were matched with a 50 Ω RF resistor from Vishay.

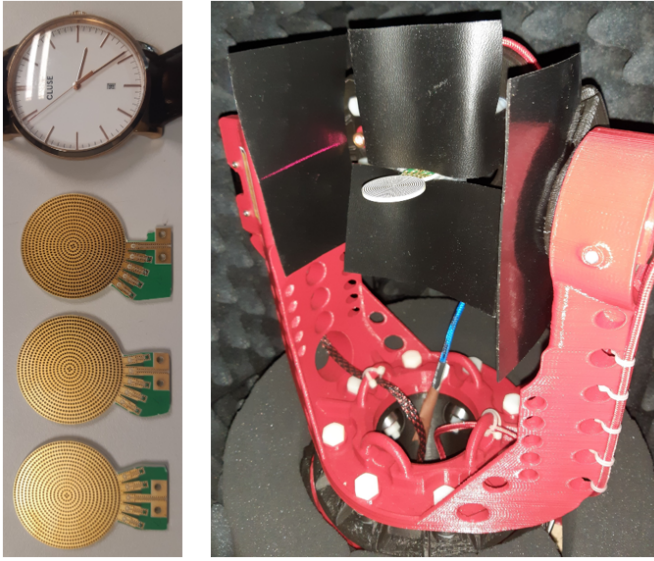


Fig. 9. Fabricated antenna prototypes (left) and measurement setup (right).

The S-parameters of the fabricated GRIN lens antennas were measured and are compared with simulations in Fig. 10. Measurements show that the ports are matched for frequencies higher than 60.5 – 61.5 GHz (while matching started from 58.5 GHz in simulations) and up to 67 GHz. The observed frequency shift with respect to simulations is now larger, about 2 to 3 GHz. This is not surprising, given the previous 1 GHz shift in SIW cutoff frequency, which impacts the wave impedance $Z_{TE_{10}}$ in the SIW working in the TE_{10} mode in a nonlinear way, resulting here in an amplified effect.

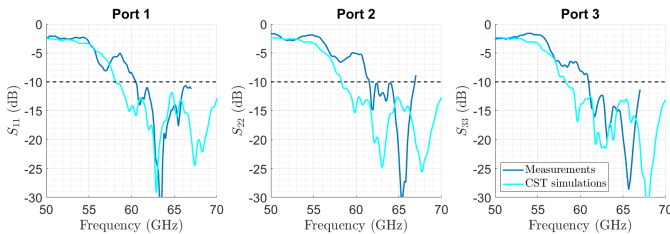


Fig. 10. Simulated and measured S-parameters of the GRIN lens antenna.

Radiation patterns were measured up to 70 GHz in an anechoic chamber *Millibox3* with the VNA *N5291A*, 125GHz from *Keysight*, using a 1.85mm-to-1mm SMA adapter. In addition to placing absorbing sheets around the antenna under test (see Fig. 9), time gating was performed on the data to filter strong secondary peaks observed in the time domain, linked to reflections on objects (e.g., the mechanical structure holding the antenna) inside the chamber. Eventually, a Gaussian filter (window size $\Delta\theta = 6$ degrees) was applied over the angular range of each cut, to remove perturbations coming from objects located further than $\Delta L = \lambda_0(60GHz) / \Delta\theta(rad) \approx 5$ cm away from the antenna under test. The radiation patterns obtained at port 1 are shown in Fig. 11 at multiple frequencies.

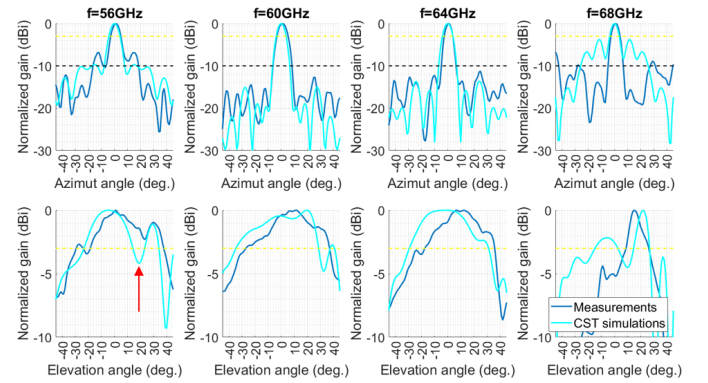


Fig. 11. Simulated and measured radiation patterns for port 1 (H-plane cuts above, E-plane cuts below) at multiple frequencies.

We observe a good agreement with simulated patterns in the H-plane, where the beamwidth values are very close and side lobes remain below -10 dB between 60 GHz and 64 GHz. In comparison, measurements in the E-plane are slightly less consistent with simulations, but we nevertheless observe a similar behavior, with a large beamwidth and a maximum slightly displaced with respect to the 0 degree elevation. As expected, the fan shape is not correctly formed below 60 GHz because of the transition blocking all modes, nor above 64 GHz because of the presence of higher order modes.

Radiation patterns were also measured for all three ports. The H-plane cuts are shown in Fig. 12 at 62 GHz, confirming the collimation effect. We observe very good agreement for the collimated beamwidth equal to 8 degrees at 62 GHz, as well as good agreement for the SLL.

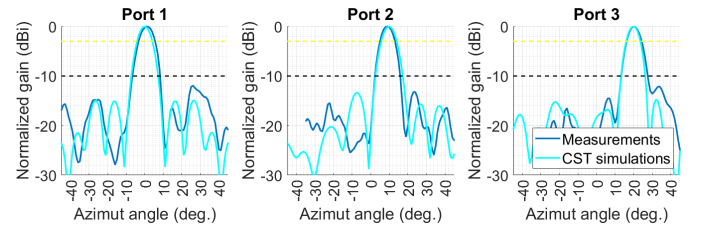


Fig. 12. Simulated and measured radiation patterns for ports 1-3 (H-plane cuts) at 62 GHz.

Eventually, the evolution of key performance indicators over frequency was calculated for port 1 and is shown in Fig. 13. A Gaussian filter (window size $\Delta f = 1\text{GHz}$) was applied over the frequency range to smoothen the measured indicators and ease observations.

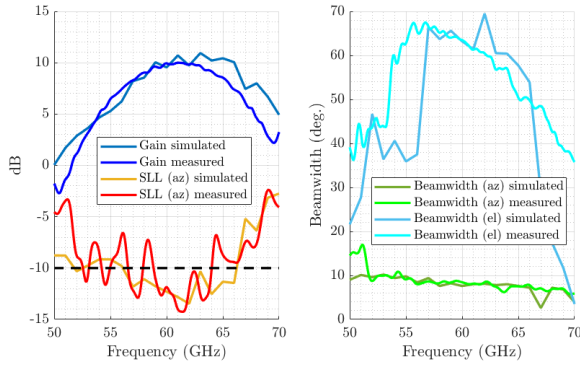


Fig. 13. Simulated and measured key performance indicators at port 1.

In the H-plane (az), the measured beamwidth is stable and very close to simulated values, while side lobes remain below -10 dB between 59 GHz and 64 GHz. In the E-plane (el), the measured beamwidth is large and follows the simulated tendency, however with a sharp increase (related to the TE_{10} cutoff) around 54 GHz, earlier than expected in simulations. The simulated main beam is split in two (i.e., the drop between the two peaks is greater than 3 dB) for frequencies below or close to cutoff, for example at 56 GHz (see the red arrow in Fig. 11), and then gradually becomes a single fan-shaped beam. Our measurements show that the split beams merge earlier in frequency, which we can explain by our measurement setup: both the increased insertion loss of the transition and the presence of the SMA connector result in some undesired energy radiated towards positive elevation angles, which we believe helps mitigating the gain drop between both peaks. The last indicator is the measured gain, which is normalized to a maximum of 10 dBi for the sake of comparison with the simulated gain. The tendency shows good agreement with an increase up to 62 GHz. While it then stays rather constant up to 66 GHz in the simulations, it decreases in the measurements. This can be due some frequency-dependent behavior of the connecting parts, for example the 1.85mm-to-1mm adapter, that we did not correctly de-embed in post-processing. The same explanation applies to the measured E-plane (el) beamwidth which slightly deviates from simulated values after 62 GHz.

VI. CONCLUSION

We put in practice the mismatched Luneburg lens theory and showed that such a lens could be successfully manufactured, along with feeding elements, as a single-piece multi-layer PCB with standard fabrication processes including through and blind vias. Measurements show that the GRIN lens antenna is matched above 61.5 GHz and up to 67 GHz at all ports, and radiates a beam that is collimated in one plane with an 8

degrees beamwidth. The fan-shaped beam is formed between 59 GHz and 64 GHz with side lobes below -10dB in the H-plane. Such an antenna could be fed through its GCPW lines from RF electronic components, e.g. a radar chip, soldered directly on the same PCB. Impedance matching could be improved and the bandwidth could be increased, for example thanks to a different choice of dimensions for the SIW whose cutoff frequencies are the main contributor to the GRIN lens antenna bandwidth.

ACKNOWLEDGMENT

This work was conducted thanks to the collaboration between the ICTTEAM Research Group and BEA Sensors Europe, and was funded by the Région Wallonne under the "Doctorat en entreprise" framework of the SPW EER.

REFERENCES

- [1] R. K. Luneburg, *Mathematical theory of optics*, Berkeley, CA, USA: Univ. California Press, 1964.
- [2] H. Chen et al., "Modified Luneburg lens based on metamaterials", *International Journal of Antennas and Propagation*, vol. 2015, 2015.
- [3] J. -W. Lian et al., "Wideband and high-efficiency parallel-plate Luneburg lens employing all-metal metamaterial for multibeam antenna applications," *IEEE Trans. Antennas Propag.*, vol. 71, no. 4, pp. 3193-3203, April 2023.
- [4] B. Hu et al., "A novel metamaterial-based planar integrated Luneburg lens antenna with wide bandwidth and high gain," *IEEE Access*, vol. 8, pp. 4708-4713, 2020.
- [5] X. Wang, Y. Pan, and Y. Dong, "An E-plane-focused triple-layer multi-beam Luneburg lens antenna for 5G millimeter-wave applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 2, pp. 227-231, Feb. 2022.
- [6] C. Pfeiffer, and A. Grbic, "A printed, broadband Luneburg lens antenna," *IEEE Trans. Antennas Propag.*, vol. 58, no. 9, pp. 3055-3059, Sept. 2010.
- [7] O. Zetterstrom et al., "V-band fully metallic geodesic Luneburg lens antenna," *IEEE Trans. Antennas Propag.*, vol. 71, no. 2, pp. 1965-1970, Feb. 2023.
- [8] D. Pérez-Quintana et al., "Fully metallic Luneburg metalens antenna in gap waveguide technology at V-band," *IEEE Trans. Antennas Propag.*, vol. 71, no. 4, pp. 2930-2937, April 2023.
- [9] J. Bor et al., "Foam based Luneburg lens antenna at 60 GHz," *Progress In Electromagnetics Research Letters*, vol. 44, pp. 1-7, 2014.
- [10] M. K. Saleem et al., "Lens antenna for wide angle beam scanning at 79 GHz for automotive short range radar applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 2041-2046, April 2017.
- [11] H. T. Chou, and Z. D. Yan, "Parallel-plate Luneburg lens antenna for broadband multi-beam radiation at millimeter wave frequencies with design optimization," *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 5794-5804, Nov. 2018.
- [12] Y. Ding, and K. Wu, "Substrate integrated waveguide-to-microstrip transition in multilayer substrate," 2007 IEEE/MTT-S International Microwave Symposium, Honolulu, HI, USA, 2007, pp. 1555-1558.
- [13] R. Kazemi et al., "Development of an ultra wide band GCPW to SIW transition," 2012 IEEE Radio and Wireless Symposium, Santa Clara, CA, USA, 2012, pp. 171-174.
- [14] T.-H. Yang et al., "A 60GHz LTCC transition between microstrip line and substrate integrated waveguide," 2005 Asia-Pacific Microwave Conference Proceedings, Suzhou, China, 2005.
- [15] V. Kaschten et al., "Mismatched Luneburg lenses: numerical analysis and design rules," submitted to *IEEE Trans. Antennas Propag.*
- [16] F. Maggiorelli et al., "Profile inversion and closed form formulation of compact GRIN lenses," *IEEE Open Journal of Antennas and Propagation*, vol. 2, pp. 315-325, Feb. 2021.
- [17] Y. Cassivi et al., "Dispersion characteristics of substrate integrated rectangular waveguide," *IEEE Microwave and Wireless Components Letters*, vol. 12, no. 9, pp. 333-335, Sept. 2002.