Low-Cost 3-D Printed Lens Antenna for Ka-Band Connectivity Applications

Kamil Trzebiatowski[#1], Weronika Kalista[#2], Mateusz Rzymowski[#3], Lukasz Kulas[#4] and Krzysztof Nyka[#5]

[#]Department of Microwave and Antenna Engineering,
Faculty of Electronics, Telecommunications and Informatics,
Gdansk University of Technology,
Gdansk, Poland

{[1]kamil.trzebiatowski, [2]weronika.kalista, [3]mateusz.rzymowski, [4]lukasz.kulas, [5]krzysztof.nyka}@pg.edu.pl,

Abstract — **This paper discusses the use of low-cost 3-D printing technology to fabricate dielectric lenses for Ka-band wireless networks. A low-cost FDM alternative to previously presented 3-D printed lens in SLA technology with high performance resin is presented. The presented approach has been demonstrated for a 39 GHz MU-MIMO antenna array modified to realize multibeam or switched-beam antenna that can support demanding energy-efficient applications in millimeter waves. The impact of different 3-D printing settings on the lens performance is also investigated. The results demonstrate that with proper printing settings, low-cost 3-D printed lenses created using FDM process are a viable alternative for high-frequency applications.**

Keywords — **3-D printing, PLA, FDM, additive manufacturing, fifth-generation (5G) communication, Internet-of-Things, millimeter-wave antenna, passive multibeam antennas, switched-beam antennas.**

I. INTRODUCTION

The increasing demand for high-speed and reliable communication systems, such as fifth-generation (5G) networks, has driven the development of new antenna technologies for various applications. Among these, lens antennas have gained attention due to their superior performance in terms of gain, beamwidth, and sidelobe levels [1-3]. These antennas are suitable for a range of applications, including satellite communications [1, 3], radar systems [4], and wireless networks [5-8].

Apart from the above applications, such lens antennas can also be used as low-cost switched-beam reconfigurable antennas in 5G systems. In available millimeter-wave (mm-wave) antennas having a single RF port fed and beam-switching circuit that can be steered using a single microcontroller, due to many unwanted effects present at mm-wave frequencies, beam-steering capabilities are usually limited. The most severe limitations are the main beam steering, which can usually be steered by a few degrees only [9], and difficulty to control radiation pattern shape while changing its direction [10], [11], which is crucial for direction-of-arrival (DoA) estimation accuracy [12].

One of the key features of dielectric lenses is the possibility to couple them with antenna arrays to realize a single RF port fed passive multibeam or active switched-beam antennas [1-8]. In our previous work, we presented such an antenna designed for CubeSat connectivity and capable of selecting the main beam between 16 directions. The lens was printed in stereolithography (SLA) process using high-performance resin [1,13].

Unfortunately, SLA technology can be expensive and time-consuming, limiting its wider use for mass production. Especially, when lens antennas are planned to be used in low-cost wireless sensor networks applications, in which hundreds or thousands of sensors can be deployed. One of the alternatives is the fused deposition modelling (FDM) printing which offers several advantages, including a lower cost and easier and faster fabrication, especially with the polylactic acid (PLA) filament material [13, 14]. However, to the authors best knowledge, there are no publications available in the literature that show how such PLA-based lens antennas can successfully be produced to be used in practical low-cost switched-beam reconfigurable antennas.

In this paper, we investigate the feasibility of using low-cost PLA material for the fabrication of the lens, in contrast to the high-performance resin typically used in SLA technology. The performance of the proposed lenses is compared for several samples with varying manufacturing settings, providing valuable information on how these settings can affect the performance of the antenna. The PLA lenses are compared with a reference lens previously printed in SLA technology [1]. The results demonstrate how inexpensive PLA printing techniques together with low-cost filament can be used to achieve multibeam/beam-switching in Ka-band 39 GHz antenna used in 5G applications, showcasing the potential of the low-cost 3-D printed lens antenna as a viable option for high-frequency applications.

II. ANTENNA AND LENS DESIGN

A. Antenna design

The antenna array used in this study was previously presented in [1, 15], and consists of 16 dual-polarized aperture-coupled circular patches as presented in Fig. 1. The patches are on a 0.254 mm CuClad217 substrate with a relative permittivity of 2.17 and a loss tangent of 0.002. The feeding network is designed on a RT/duroid 5880 substrate with ε_r = 2.20 and tanδ = 0.001. Each patch is fed through a pair of miniature

SMPS connectors (exciting two orthogonal linear polarizations) soldered to feeding microstrip lines on the bottom layer. The array elements are placed with a spacing of 0.75 λ_0, where λ_0 is the free space wavelength at the resonance frequency (39 GHz). The manufactured array is encased in a 3-D printed casing as seen in Fig. 2.

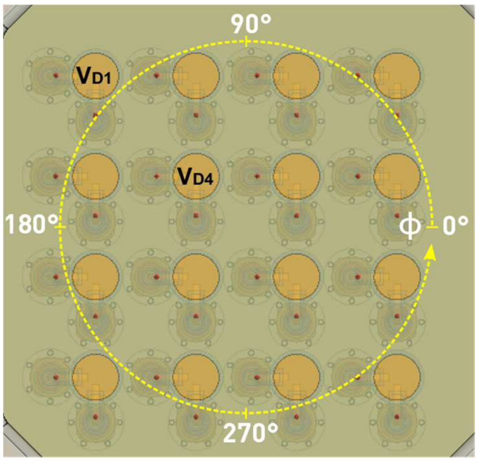


Fig. 1. The antenna array view (top) with the labels of the excited antenna elements corresponding to the beams [1].

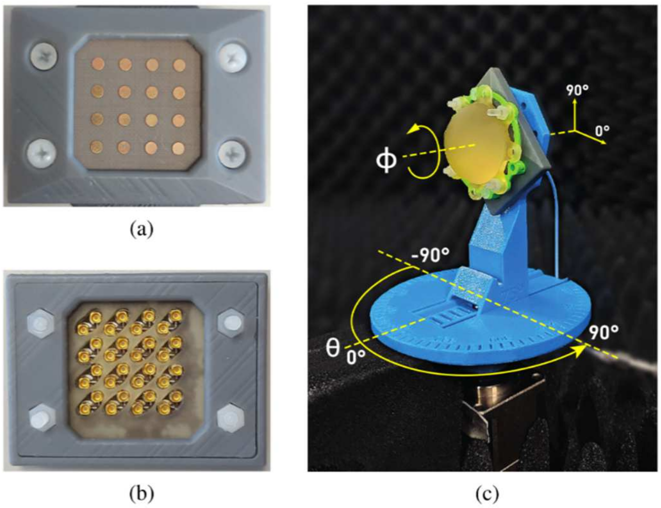


Fig. 2. Fabricated antenna. (a) Array top view. (b) Array bottom view. (c) Array with the 3-D printed SLA lens mounted on a turntable in an anechoic chamber [1] (see text for explanations).

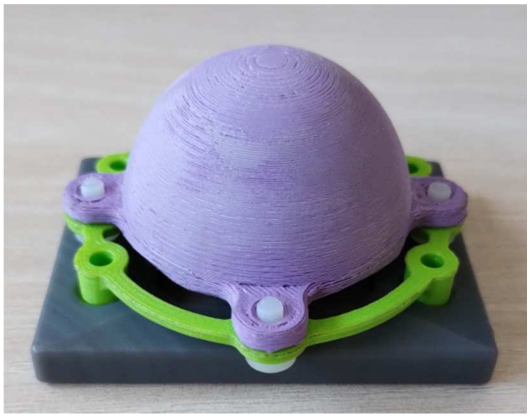


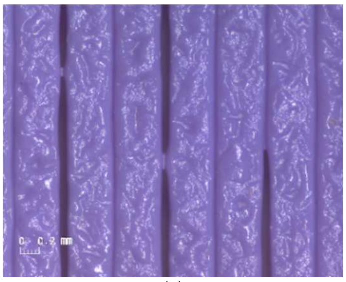
Fig. 3. The antenna array with the 3-D printed PLA lens.

B. Lens design

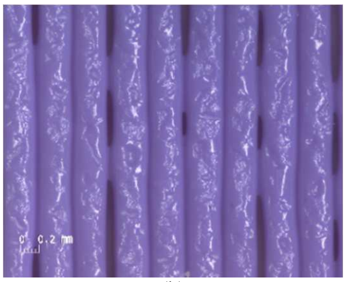
The lens used in this study is a homogeneous all-dielectric half-ellipsoid shaped lens. The selection of this shape was based on its capability to generate a narrow beam and low sidelobe levels. The lens dimensions and dielectric constant were optimised to provide the largest area coverage with 3 dB beams of 16 antennas. The lens has a diameter of 18.5 mm and height of 21 mm and is placed at a distance 5 mm from the antenna array (Fig. 3).

The lens was 3-D printed using FDM technology and PLA filament. The measured dielectric properties of samples with maximum infill are ε_r = 2.65 and tanδ = 0.01. Since FDM allows for thinning the material, relative average permittivity of arbitrary value within the range from 1 to 2.65 could be realised, and the value chosen in our design was 2.2. The structure was fabricated using a 3-D printer with a 0.4 mm nozzle and printed with a layer height of 0.27 mm. Electric permittivity of PLA samples with different infills was measured before printing the lenses. To investigate the impact of different manufacturing settings on the lens performance, three different samples of the lens with 76% infill were fabricated with varying path width settings (0.4 mm, 0.3 mm, and 0.2 mm). Apart from these three samples, a PLA lens with 100% infill and relative permittivity of 2.65 was printed to directly compare it to the SLA resin lens presented in [1] with ε_r = 2.66. The photomicrographs of the printed structures are presented in Fig. 4.

The antenna array operates as a multibeam antenna when integrated with the lens and is capable of deflecting the main beam into 16 different directions due to the diversity of patch positions relative to the lens axis. The beam selection is realized by choosing the excited port, which means the antenna could be alternatively treated as a switched-beam antenna when coupled with an external switching network [1].

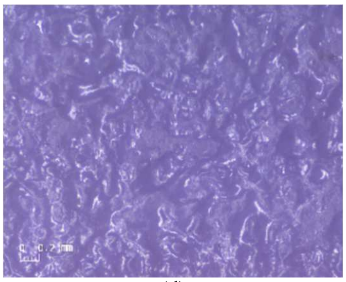


(a)



(b)

(c)



(d)

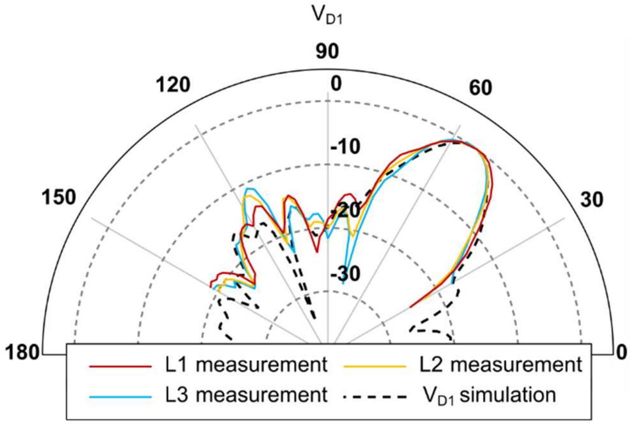
Fig. 4. Structures printed with a) 76% infill and 0.4 mm path width, b) 76% infill and 0.3 mm path width, c) 76% infill and 0.2 mm path width, d) 100% infill and 0.2 mm path width.

III. Simulation and Measurement Results

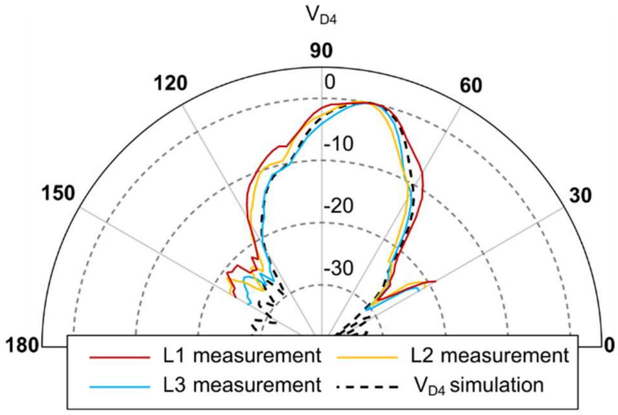
A. Simulation and measurement results

The radiation patterns of the fabricated lens antenna were measured in an anechoic chamber with a vector network analyser. The antenna was measured in the $\varphi = 315°$ plane. The radiation patterns corresponding to the V_{D1} and V_{D4} patches were measured and compared as they deflect the beam in the measurement plane, so the results can easily be compared with those provided using SLA technology in [1].

The measured results were compared with the simulated results. Fig. 5. shows comparison of the radiation patterns obtained with three lenses that were printed with different path width settings. The results for 0.2 mm path width are closest to the simulation. The effect of the surface roughness on the radiation pattern is shown in Fig. 6, where grinded and non-grinded lenses are compared. Fig. 7. shows that, while the discrepancies are visible, the FDM printed lenses can be used in the same character as the SLA printed lenses.



(a)



(b)

Fig. 5. Simulated and measured normalized radiation patterns (dB) of the lens antenna ($\varepsilon_r = 2.20$) at 39 GHz in vertical plane (theta) in $\varphi = 315°$ cut with varying path width setting (L1 = 0.4 mm, L2 = 0.3 mm, L3 = 0.2 mm) of the 3-D printer, (a) V_{D1} beam (b) V_{D4} beam.

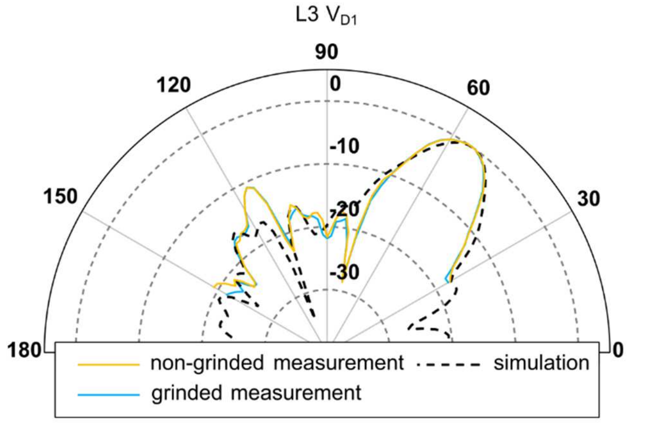
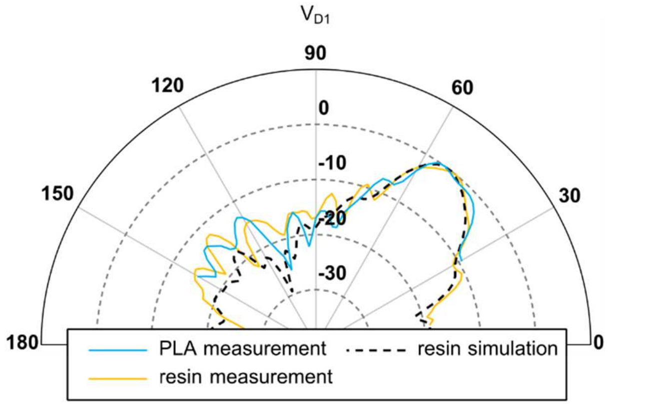
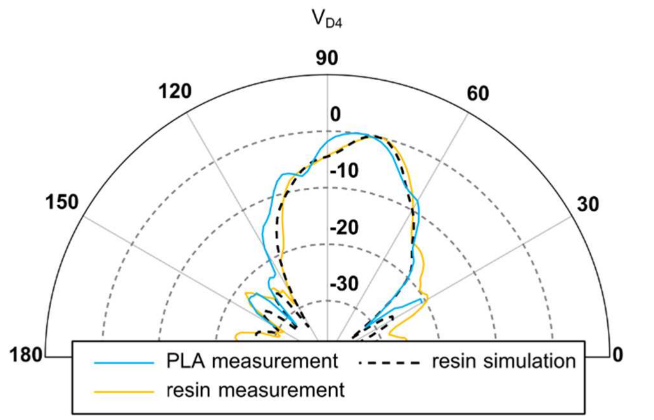


Fig. 6. Simulated and measured normalized radiation patterns (dB) of the lens antenna ($\varepsilon_r = 2.20$) at 39 GHz in with the PLA lenses that have been grinded to increase smoothness of the surface.



(a)



(b)

Fig. 7. Comparison of the measured and simulated radiation patterns of the antenna with PLA (FDM-printed, $\varepsilon_r = 2.65$) and resin (SLA-printed, $\varepsilon_r = 2.66$) lens: (a) V_{D1} beam (b) V_{D4} beam.

IV. Conclusion

We have demonstrated that an inexpensive 3D printing technique using PLA filament can be used to fabricate a multibeam Ka-band antenna for 5G applications. Our results show that the use of PLA filament, when employed in a proper 3-D printing set-up, does not significantly compromise the performance of the antenna, as the radiation patterns obtained with PLA are close to those obtained with more expensive SLA printing techniques using high-performance resin. The estimated cost of materials used to fabricate one resin lens was approximately 3.0€, whereas the cost of one PLA lens is around 0.42€. The printing time for PLA lenses depends on the path width and was 48, 60, and 83 minutes for lenses L1, L2, and L3, respectively. In contrast, the printing time of the resin lens is considerably longer and in this case was 8 h 39 min. It means that low-cost FDM printing can be a viable alternative to SLA printing for the production of high-performance millimeter wave lens antennas. In consequence, it opens up a future possibility to develop new low-cost and energy-efficient millimeter wave sensors having DoA estimation functionality.

Acknowledgment

This work is a result of the BEYOND5 (www.beyond5.eu) project, which has received funding from the ECSEL Joint Undertaking (JU) under Grant 876124. The JU receives support from the European Union's Horizon 2020 research and innovation programme and from France, Germany, Turkey, Sweden, Belgium, Poland, Netherland, Israel, Switzerland, and Romania. The document reflects only the authors' view, and the Commission is not responsible for any use that may be made of the information it contains.

References

[1] K. Trzebiatowski, W. Kalista, M. Rzymowski, Ł. Kulas and K. Nyka, "Multibeam antenna for Ka-band CubeSat connectivity using 3-D printed lens and antenna array," in *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 11, pp. 2244-2248, Nov. 2022, doi: 10.1109/LAWP.2022.3189073.

[2] B. T. Malik, V. Doychinov, S. A. R. Zaidi, I. D. Robertson, and N. Somjit, "Antenna gain enhancement by using low-infill 3D-printed dielectric lens antennas," in *IEEE Access*, vol. 7, pp. 102467-102476, 2019, doi: 10.1109/ACCESS.2019.2931772.

[3] J. R. Costa, C. A. Fernandes, G. Godi, R. Sauleau, L. Le Coq and H. Legay, "Compact Ka-band lens antennas for LEO satellites," in *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 5, pp. 1251-1258, May 2008, doi: 10.1109/TAP.2008.922690.

[4] M. K. Saleem, H. Vettikaladi, M. A. S. Alkanhal and M. Himdi, "Lens antenna for wide angle beam scanning at 79 GHz for automotive short range radar applications," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 4, pp. 2041-2046, April 2017, doi: 10.1109/TAP.2017.2669726.

[5] J. Ala-Laurinaho et al., "2-D beam-steerable integrated lens antenna system for 5G E-band access and backhaul," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2244-2255, July 2016, doi: 10.1109/TMTT.2016.2574317.

[6] A. Artemenko, A. Maltsev, A. Mozharovskiy, A. Sevastyanov, V. Ssorin, and R. Maslennikov, "Millimeter-wave electronically steerable integrated lens antennas for WLAN/WPAN applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1665–1671, Apr. 2013.

[7] W. Kalista, L. Leszkowska, M. Rzymowski, K. Nyka and L. Kulas, "Low-cost 3D printed dielectric lens antennas for 5.9 GHz frequency band V2X applications," *2022 24th International Microwave and Radar Conference (MIKON)*, Gdansk, Poland, 2022, pp. 1-4, doi: 10.23919/MIKON54314.2022.9924842.

[8] H. Yi, S. -W. Qu, K. -B. Ng, C. H. Chan, and X. Bai, "3-D printed millimeter-wave and terahertz lenses with fixed and frequency scanned beam," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 2, pp. 442-449, Feb. 2016, doi: 10.1109/TAP.2015.2505703.

[9] A. Bondarik and D. Sjoberg, "Investigation of reconfigurability for a stacked microstrip patch antenna pattern targeting 5G applications," *2015 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC),* Turin, 2015, pp. 1202-1205.

[10] W.-S. Chang, C. Yang, C.-K. Chang, W.-J. Liao, L. Cho, and W.-S. Chen, "Pattern reconfigurable millimeter-wave antenna design for 5G handset applications," *2016 10th European Conference on Antennas and Propagation (EuCAP)*, Davos, 2016, pp. 1-3.

[11] A. N'gom et al., "A reconfigurable beam dual polarized microstrip cross patch antenna," *2017 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, 2017, pp. 3135-3139.

[12] M. Rzymowski and L. Kulas, "Influence of ESPAR antenna radiation patterns shape on PPCC-based DoA estimation accuracy," *2018 22nd International Microwave and Radar Conference (MIKON)*, Poznan, 2018, pp. 69-72.

[13] C. M. Choudhari., and V. D. Patil. "Product development and its comparative analysis by SLA, SLS and FDM rapid prototyping processes." *IOP Conference Series: Materials Science and Engineering*. Vol. 149. No. 1. IOP Publishing, 2016.

[14] C. Ballesteros, M. Maestre, M. C. Santos, J. Romeu, and L. Jofre, “A 3D printed lens antenna for 5G applications,” in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting*, 2019, pp. 1985–1986.

[15] K. Trzebiatowski, J. Fromme, D. Duraj, L. Kulas and K. Nyka, "A dual-polarized 39 GHz 4x4 microstrip antenna array for 5G MU-MIMO airflight cabin connectivity," *2022 24th International Microwave and Radar Conference (MIKON),* Gdansk, Poland, 2022, pp. 1-4, doi: 10.23919/MIKON54314.2022.9924929.