Dielectric versus patch-based implementations of Risley Prism transmit-arrays in Ka-band

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***Abstract*—Many millimeter wave applications related with 5G and Satellite on the move (SoTM) communications rely on cost-effective high-gain antennas with wide beam scanning. Mechanical steering solutions can reduce the complexity and cost of the fully-electronic beam steering counterpart (e.g. phased arrays). Mechanical scanning with Transmit-array (TA) antennas can provide a balanced compromise between cost, size, and efficiency. TAs are usually associated with a thin metasurface composed by a tailored distribution of patch-based unit cells. However, fully-dielectric unit cells can also be used for the design of the aperture, which can be viewed as gradient index (GRIN) lenses. In this work we compare fully-dielectric and stacked patch-based implementations of the Risley Prism scanning concept. This configuration consists of two independent axially rotating TA that can provide elevation and azimuth mechanical scanning. The dielectric version can further reduce the cost of these antennas trading-off with some antenna efficiency degradation caused by material losses, free-space mismatch, and higher lens thicknesses. This work also includes the experimental validation of the dielectric Risley prism implementation, less explored in the state-of-the-art.**

***Index Terms*— Transmit-arrays, Risley Prism, Dieletric lens, Ka-band, Mechanical Scanning.**

I. INTRODUCTION

Cost-effective millimeter-wave antennas are an enabling technology for many applications associated with satellite and 5G communications. The trade-off between cost and performance must be properly balanced for achieving a commercially viable product. It has been shown that mechanical scanning approaches based on transmit-arrays can be a cost-effective solution [1]-[3]. Recently, a regained interest on the classical Risley prism scanning approach (see Figure 1), initially developed for optics using dielectric prisms, emerged in the microwave domain [4]. When combined with the design flexibility of transmitarrays, this scanning approach can be implemented in a more favorable planar geometry [3]. Moreover, several improvements have been proposed, such as merging the primary source and the first lens into a leaky-wave feed antenna placed in the vicinity of the transmit-array (the second "prism") [5]-[7]. All these works explore the use of metal inclusions in a dielectric host, which results in very thin meta-lenses. This work explores an alternative design using fully-dielectric TAs that can be simpler to fabricate, possibly reducing further the cost of the antenna [8]-[9]. The standard Risley Prism configuration can be implemented using simple Fuse Deposition Modelling (FDM) 3D printing. However, as far as the authors are aware, there is no such design reported in the literature as well as the assessment of its performance compared with the more conventional patch-based implementation.

In this work, we provide a comparative analysis of these two embodiments through full-wave simulations of a given design example. Experimental results for the dielectric implementation are also reported, validating the accuracy of the full-wave analysis.

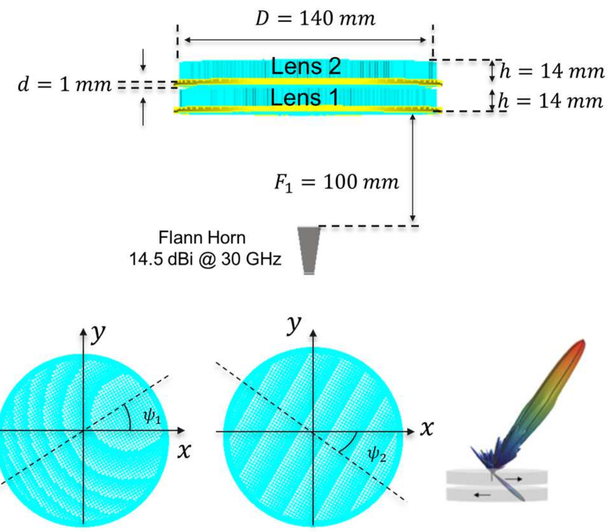


Figure 1 – Risley Prism working principle.

II. ANALYTICAL FORMULATION

The detailed design rules for a TA implementation of the Risley Prism concept can be found in [3]. In summary, for an incident spherical wave front (here, the feed is a 14.5 dBi gain horn antenna placed at $F = 100\ mm$, see Figure 1), scanning can be achieved through two independent axially rotating TA lenses with the following phase delay distributions

$$\phi_{lens1} = k_0\left(\sqrt{x^2+y^2+F_1^2}\right) - k_0\sin(\alpha_0)x \qquad (1)$$

$$\phi_{lens2} = -k_0\sin(\alpha_0)x \qquad (2)$$

The scanning direction is then defined by the rotation angle ψ_1 and ψ_2 (Figure 1) [3]. In our analysis, we analyze the scanning in the xz plane, corresponding to $\psi_1 = -\psi_2 = \psi$. In this case the beam zenith direction θ_{max} is given by

$$\sin\theta_{max} = \cos\psi\, 2\sin\alpha_0\, x \qquad (3)$$

In our design example, $\alpha_0 = 25°$.

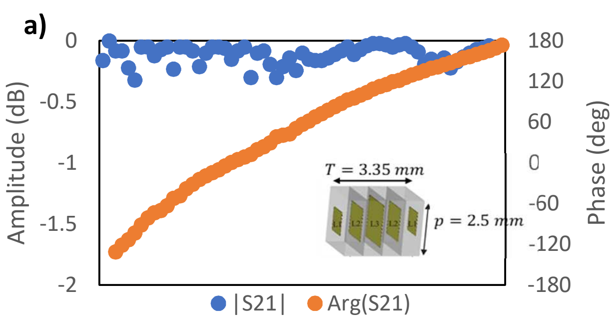
III. Unit cells

For the purpose of this comparative study, two types of unit cells are considered:

i) a 5-layer stack of metallic patches separated by Duroid 5880 dielectric layers ($\varepsilon_r = 2.2$ *and* $\tan\delta = 0.0009$) with 0.787 mm thickness as used in [2]. The in-plane dimension of the unit cell is $p = 2.5$ mm ($\lambda/4$ at 30 GHz);

ii) a hollow square prism with height 14 mm and side 2.5 mm of polylactic acid (PLA) ($\epsilon_r = 2.98$ and $\tan\delta = 0.0148$). We use PLA because it is readily available in our lab for FDM 3D printing.

The performances of these two types of unit cells are show in Figure 2. The thin stacked patch configuration (3.35 mm of thickness) provides higher transmission (>-0.32 dB) for a 310º of phase span at 30 GHz. As for the full-dielectric case, the PLA unit cells need to be thicker (14 mm) to ensure an equivalent phase delay variation range (304º). The dielectric losses and free-space mismatch result in a poor transmission (>-1.7 dB). On the other hand, dielectric cells are inherent broadband and less complex to implement (which includes the use of FDM 3D printing). The dielectric losses could have been minimized if other low loss 3D printing filaments, such as Teflon or Polystyrene, were used. For a more fair comparison between these two types of TAs, we assess in Section IV the directivities of both implementations instead of gain.



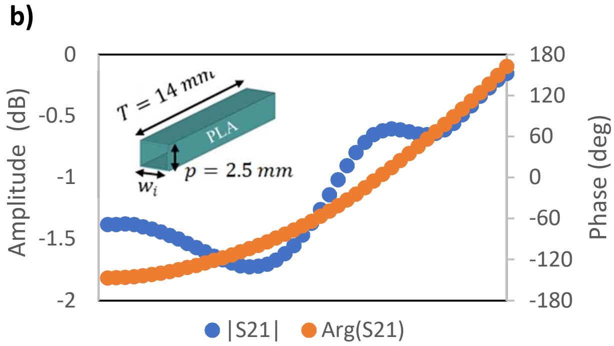


Figure 2 – Amplitude and phase response of the patch-based (a) and full-dielectric (b) unit cells at 30 GHz.

IV. Full-wave analyses

A. *Lens 1 Comparison*

In this Section, the two implementations of the phase correction (1), corresponding to lens 1 in Figure 3, are compared. In , the gain of the dieletric implementation is compared with the patch-based TA. For both cases, the beam points to the same prescribed offset angle $\alpha_0 = 25°$, but the directivity is lower for the dieletric TA (28.7 dBi) than in the patch-based case (29.6 dBi). This 1 dB reduction can be justified by the higher reflection (free-space missmatch) and additional aberrations resulting from the use of a thicker lens. The losses of PLA lead to a lower radiation efficiency (-0.7 dB), which in the patch-based case are approximately -0.1 dB.

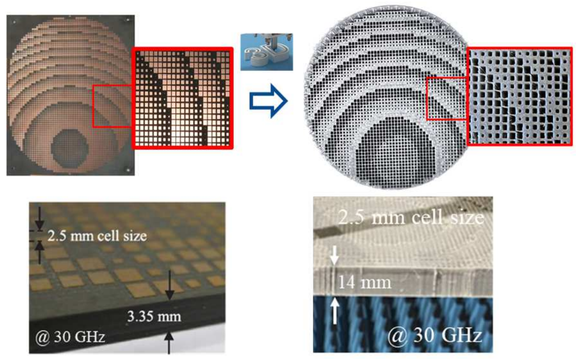


Figure 3 –Comparison of an offset Fresnel corrections implemented in full-dielectric (Lens 1 of Figure 1) and patch-based [2] TAs.

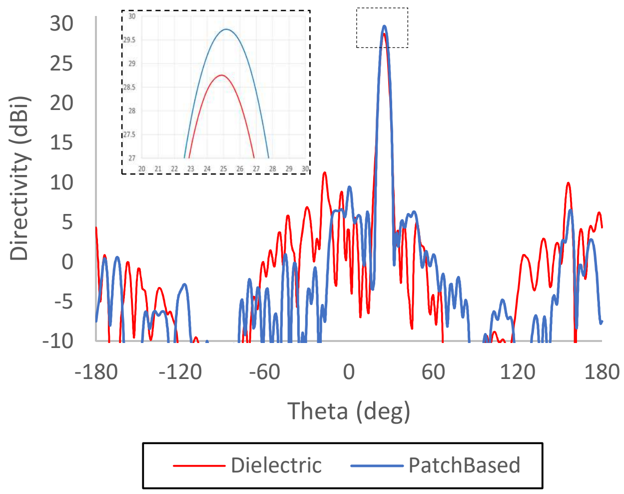


Figure 4 – Radiation pattern of lens 1 considering the ideal case, patch-based and full-dielectric implementations.

B. Risley Prism Configuration (lens 1 and 2)

In Figure 6 we compare both implementations in terms of directivity to avoid accounting the dielectric losses, as mentioned previously. The patch-based solution performs better (0.7 to 2 dB higher directivity) which is consistent with the result shown in the previous section. Nevertheless, the wide beam scanning (47 degrees) is achieved in both implementations. The dielectric Risley Prism TA as the additional advantage of having higher bandwidth (which will not be analyzed herein due to space constrains) and a simpler realization.

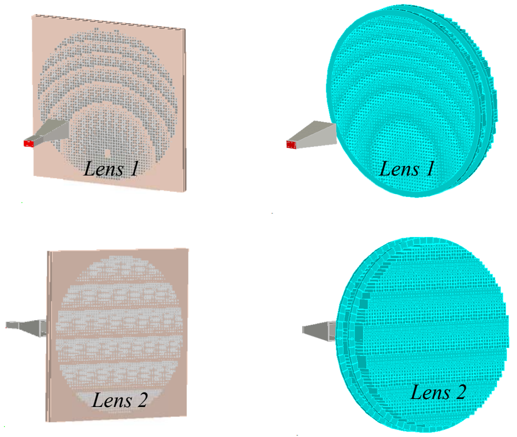


Figure 5 – Models of the Dielectric and a patch-based implementations of Risley Prism.

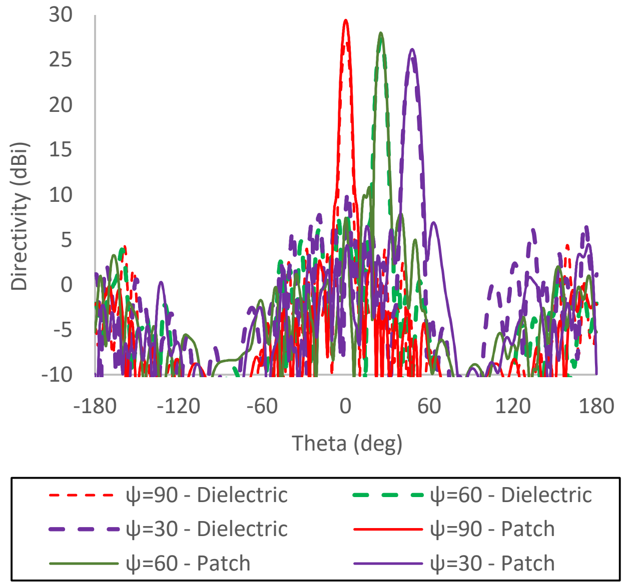


Figure 6 – Comparison of the scanning performance of a dielectric and a patch-based implementation of Risley Prism

V. Experimental Validation of Dielectric TAs

The full-dielectric version of the Risley prism was fabricated using FDM 3D printing (inset of Figure 7). In Figure 7 we show that wide beam scanning is achieved (47 degrees) with low scan loss, confirming that the Risley Prism TA configuration still holds even for thicker lens. There is a good agreement between measurements and simulations. The 1dB gain difference between measurements and simulations can be accounted by the manufacture inaccuracies associated with the low-cost fabrication process that was used.

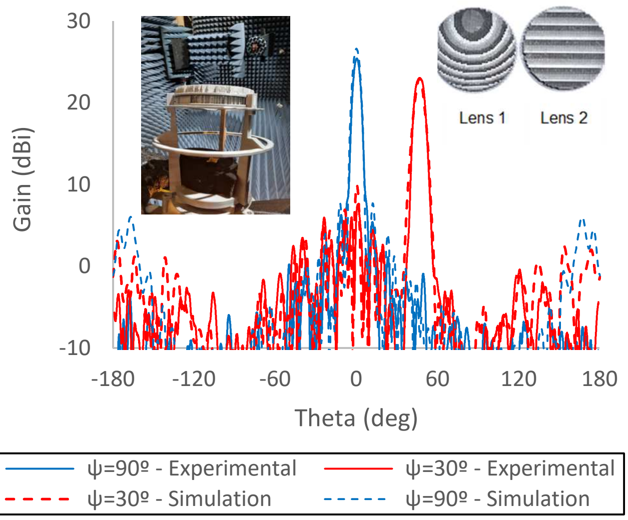


Figure 7 – Experimental validation of the scanning performance of full-dielectric TAs implementation (Vertical polarization)

VI. CONCLUSIONS

A comparison between fully-dielectric and patch-based TAs implementation of the Risley prism scanning approach was conducted. Despite some degradation of the antenna gain, dielectric TAs realization can still perform wide beam scanning. Experimental results show that conventional FDM 3D printing can be a viable way of fabricating these lenses, which can lead to significant cost savings. Future work includes redesign the dielectric TAs using low loss 3D printing materials (such as Teflon or Polystyrene), which would allow improving the radiation efficiency of the antenna.

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REFERENCES

[1] Mirmozafari, M.; Zhang, Z.; Gao, M.; Zhao, J.; Honari, M.M.; Booske, J.H.; Behdad, N. Mechanically Reconfigurable, "Beam-Scanning Reflectarray and Transmitarray Antennas: A Review." Appl. Sci., vol. 11, p. 6890, 2021..

[2] E. B. Lima, S. A. Matos, J. R. Costa, C. A. Fernandes and N. J. G. Fonseca, "Circular Polarization Wide-Angle Beam Steering at Ka-Band by In-Plane Translation of a Plate Lens Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 12, pp. 5443-5455, Dec. 2015.

[3] N. Gagnon and A. Petosa, "Using Rotatable Planar Phase Shifting Surfaces to Steer a High-Gain Beam," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 6, pp. 3086-3092, June 2013,.

[4] Y. Lu, Y. Zhou, M. Hei, and D. Fan, "Theoretical and experimental determination of steering mechanism for Risley prism systems," Appl. Opt. 52, 1389-1398 (2013)

[5] M. U. Afzal, K. P. Esselle and M. N. Y. Koli, "A Beam-Steering Solution With Highly Transmitting Hybrid Metasurfaces and Circularly Polarized High-Gain Radial-Line Slot Array Antennas," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 1, pp. 365-377, Jan. 2022.

[6] Z. Zhang, Y. C. Zhong, H. Luyen, J. H. Booske and N. Behdad, "A Low-Profile, Risley-Prism-Based, Beam-Steerable Antenna Employing a Single Flat Prism," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 8, pp. 6646-6658, Aug. 2022, doi: 10.1109/TAP.2022.3161562.

[7] J. Wang and Y. Rahmat-Samii, "A Simplified Configuration of Beam Steerable Risley Prism Antennas: Principles and Validation," *IEEE Antennas and Wireless Propagation Letters*, 2022.

[8] S. A. Matos et al., "3-D-Printed Transmit-Array Antenna for Broadband Backhaul 5G Links at V-Band," in IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 6, pp. 977-981, June 2020.

[9] J. Teixeira, S. A. Matos, J. R. Costa, J. M. Felício and C. A. Fernandes, "Assessing different monoblock dielectric implementations of a low profile beam steering Transmitarray for 3D printing," 2022 Microwave Mediterranean Symposium (MMS), 2022, pp. 1-3.