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Deposited version:
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Peer-review status of attached file:
Peer-reviewed

Citation for published item:
Matos, S., Fonseca, N. J. G., Felício, J., Fernandes, C. A. & Costa, J. R. (2025). Ultra-compact Risley-prism design with a 3D-printed transmit-array fed by a radial line slot antenna. In 2025 19th European Conference on Antennas and Propagation (EuCAP). Estocolmo: IEEE.

Further information on publisher's website:
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Ultra-compact Risley-Prism Design with a 3D-printed Transmit-array fed by a Radial Line Slot Antenna

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***Abstract*— Satellite-on-the-move systems based on mechanical beam steering can be a cost-effective alternative to phased-arrays. However, these solutions tend to be bulky for accommodating the mechanical displacements and the focal distance of the system (intrinsic to spatially fed array configurations). The Risley Prism mechanical scanning approach, based on the axial rotation of two transmit-arrays (TAs), can overcome some of these shortcomings. In particular, the profile of the lens can be dramatically reduced by integrating the primary source with the first TA ("Prims 1") into a single leaky wave antenna. In this work we present a low-cost implementation of this concept, consisting of a Radial Line Slot Antenna (RLSA) and a fully dielectric TA. This choice reduces the complexity of the system, as well as, facilitating the integration of these two components. The developed antenna has a profile of $2\lambda_0$ (at 29 GHz) and can scan up to 48 degrees with a maximum directivity of 31 dBi.**

***Index Terms*— Satellite communications, K/Ka-band, Ridge Waveguide Transition, Wideband Power Divider**

I. INTRODUCTION

Wide-angle beam steering is a fundamental requirement for satellite-on-the-move applications. Electronic beam scanning, widely accepted by the industry, combines good RF performance with ultra-compact terminals [1]. However, the associated complexity and fabrication cost still represent a bottleneck for the massification of this technology. Mechanical beam steering approaches can be a cost-effective alternative. However, these solutions tend to be bulky [2]. One of the main design challenges is the reduction of the system focal distance (i.e., the distance between the primary source and the TA) without compromising the antenna scanning performance. The authors have used the concepts of virtual focus [3] and multifocal TA [4] for reducing the antenna focal distance, reaching satisfactory performances with *F/D* as low as 0.34. However, these solutions are still considerably thicker than phased arrays.

A renewed interest on the Risley Prism antennas based on TAs [5]-[7] have emerged (Fig. 1). It has been shown, [6]-[7], that the antenna height can be significantly reduced using a leaky-wave feeding system, instead of a spatially fed array configuration. The leaky-wave feeder provides the near-field distribution required at the aperture for generating a tilted pencil beam (functioning as the first prism). The second "prism" is a TA with the same linear tilt than the first aperture. The scanning control is then achieved by independent axial rotation of the two surfaces, as detailed in [5]. The focus of this work is to highlight that the expected performance of a Risley Prism antenna can be accommodate in a compact terminal (only $2\lambda_0$) exploring simpler designs than the ones found in the recent literature [7]. We use a Radial Slot Line Antenna (RLSA) [8], [9] as the leaky wave feed, and a fully dielectric TA [5]. This choice aims to reduce the antenna complexity/cost as well as improving the integration of the two components. The final design is shown in Fig.1, attesting for the extremely compact profile of the antenna.

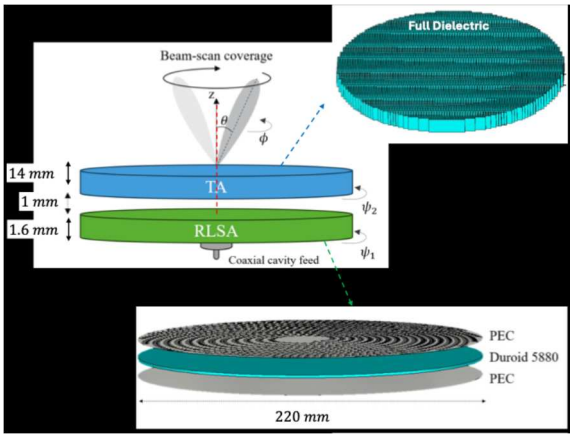


Fig.1 – Designed RLSA Risley Prism antenna

II. RLSA DESIGN

A RLSA consists of a radial parallel plate waveguide (PPW), where the top metal plate has the proper distribution of half-wavelength slots to form a leaky-wave aperture with controlled field distribution [9]. The general working principle of this leaky-wave antenna relies on a traveling radial mode ($TM^z_{0,0}$, described by a first-order Hankel function of the second kind) that leaks electric fields through the top part of the PPW with orthogonal slots pairs to produce circular polarization. Each slot acts as a local magnetic dipole source that collectively form the outgoing wave with the prescribed phase profile. The following simplifications are

assumed in the RLSA design process: i) The phase of the cylindrical propagation mode is given by $k\rho = 2\pi\rho/\lambda_g$, under the asymptotic large argument expansion of the Hankel function; ii) all slots have the same dimensions, which allows to account for the corresponding phase variation with the slot's axial position ϕ. Under these assumptions, the locus of the slot on the PPW, $\rho(\phi)$, is given by

$$\frac{2\pi}{\lambda_g}\rho(\phi) = \frac{\phi}{1 - \cos\phi\,\frac{\sin\alpha_0}{\sqrt{\epsilon_r}}}, \quad \rho_0 < \rho < R \qquad (1)$$

Where $\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_r}}$ is the guided wavelength, ϵ_r is the relative permittivity of the material inside the PPW, λ_0 the free-space wavelength, and α_0 is the Risley Prism tilting angle. There is a wide range of works on the design of RLSA for boresight collimation ($\alpha_0 = 0$), showing aperture efficiencies in the order of 60% [9]. However, the implementation of the Risley Prism principle requires a tilted collimated beam ([5]). RLSA antennas for this type of design are less frequent in the literature [10]. In this case, the slot distribution in the aperture becomes sparser, limiting the RLSA aperture efficiency, although it can still reach 30% [10].

The considered PPW has a diameter of $D = 110\ mm$ and is filled with a 60 mills Rogers 5880 substrate ($\epsilon_r = 2.2, \tan\delta = 0.0009$). In this work, we present an innovative cavity feeding mechanism. The optimized cylindrical cavity allows having a wideband transition from a standard coaxial cable to the PPW, as shown in Figs. 2 and 3. We obtain a 10-dB bandwidth of 13% (28 to 32 GHz). It worth mentioned that the overall antenna bandwidth (around 1 GHz) is limited by the PPW slots. The crafting of the slot in the PPW follows from Eq. (1) considering $\alpha_0 = 24°$, according to the designed rules summarized in Fig. 4 and Table I. The radiation pattern and bandwidth of the RLSA are shown in Fig 5 and Fig. 6, which achieves the expected performance for this type of antenna.

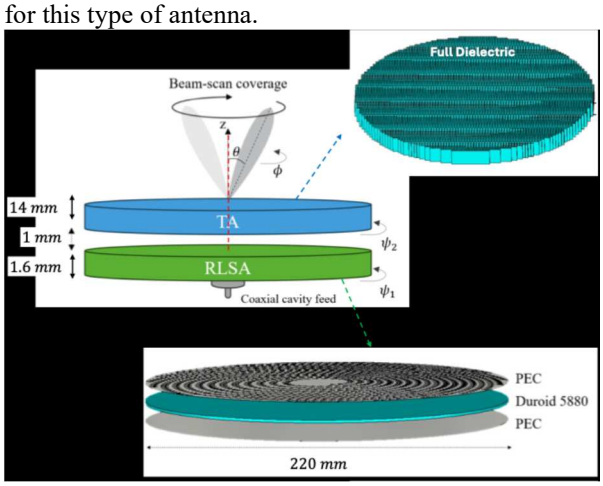


Fig.1 – Designed RLSA Risley Prism antenna

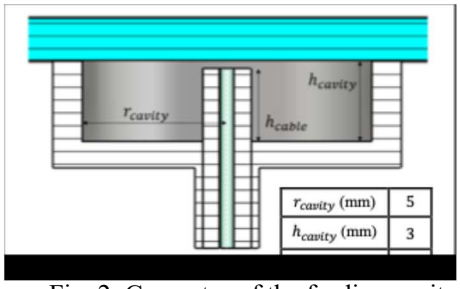


Fig. 2. Geometry of the feeding cavity of the RLSA.

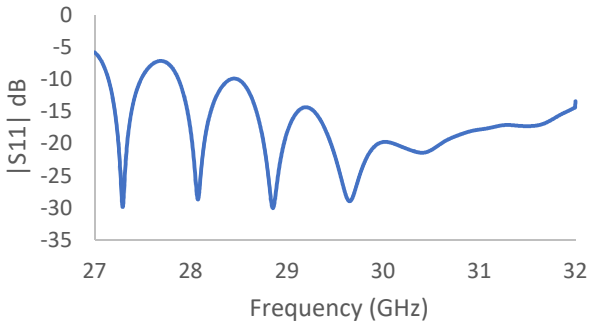


Fig. 3. Return loss of design antenna shown in Fig. 1.

Table 1 – RLSA design parameters

Design Frequency (GHz)	29
RLSA dimensions	
Height (mm)	1.6
Radius, R (mm)	110
Relative dielectric constant (Roger 5880), ϵ_r	2.2
Metal plate thickness, mm	0.017
RLSA Slots	
Position of the first slot, ρ_0 (mm)	20
Slot dimensions (mm^2)	3.1 × 0.31
Spacing between slot pairs along the locus (mm)	4.2
Spacing between the center of the two slow pairs	2.3
Orientation relative to the radial direction (°)	±45

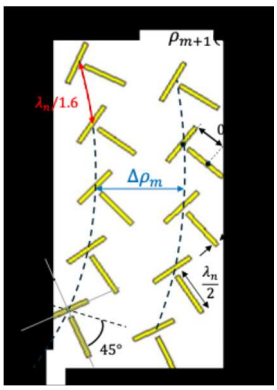


Fig 4. RLSA slot geometry along the prescribed loci $\rho(\phi)$ - Eq.1

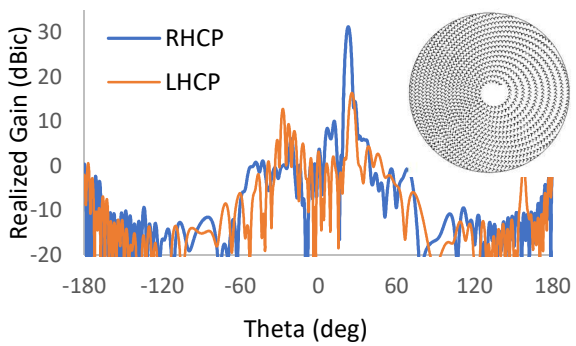


Fig. 5. Realized gain (RHCP) and X-Pol at 29 GHz of offset RLSA.

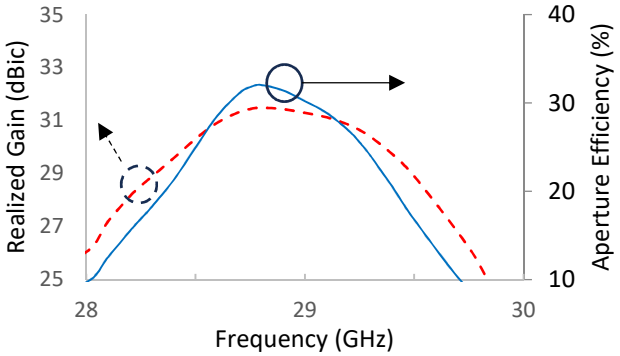


Fig. 6. RHCP Realized Gain (dashed curves) and Aperture efficiency (solid curves) as function of frequency for a beam tilt of 24º.

III. Compact Risley Prism Antenna

The TA unit cell was consider to be a hollow square prism with 14-mm height and 2.5-mm side made of polylactic acid (PLA) ($\epsilon_r = 2.98$ and $\tan\delta = 0.0148$). PLA unit cells need to be 14-mm thick to ensure a 304º phase delay span. Both the dielectric losses and the contrast to free space sets a limit to the maximum transmission of the unit cells, which is always above -1.7 dB. The high dielectric losses of PLA will account for -1.5 dB gain drop. Other lower loss dielectric material can employ instead (e.g. PEEK $\epsilon_r = 3.2$, $\tan\delta = 0.006$). Further details on the unit cell can be found in [5]. The directivity of the antenna is shown in Fig. 7. A maximum directivity of 31 dBi is achieved and scanning up to 48º with 3.4 dB of scan loss. Without accounting the dielectric loss, the antenna is expected to have a maximum of aperture efficiency of 27%, which is a promising value paving the way for further developments of this technology.

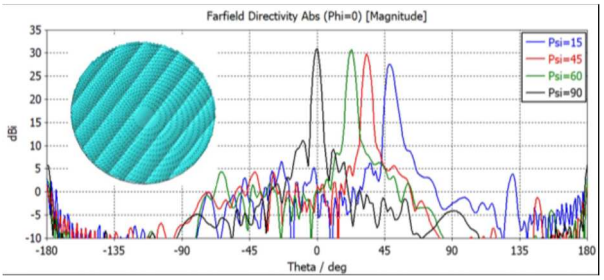


Fig 7. – Radiation patterns of the complete antenna setup for four scanning positions corresponding to the rotation angle of $\{15°, 45°, 60°, 90°\}$.

IV. Conclusions

We present an ultra-low profile Risley Prism antenna ($2\lambda_0$) consisting of a RLSA and a 3D printed TA. The combination of these two simple structures simplifies the complexity of the antenna, without compromising its performance. Moreover, the use of dielectric TA allows placing the two elements very close (1mm apart), further contributing to the height reduction. Finally, a cavity feeding system was also developed for the RLSA to have low return losses in a wider bandwidth, simplifying the design of the antenna. Further optimization and experimental implementation are in preparation.

Acknowledgment

This work was supported by FCT - Fundação para a Ciência e Tecnologia, I.P. by project reference UIDB/50008/2020, and DOI identifier https://doi.org/10.54499/UIDB/50008/2020, SNS JU project TERRAMETA under the EU's Horizon Europe research and by innovation programme under Grant Agreement No 101097101, including top-up funding by UKRI under the UK government's Horizon Europe funding guarantee, and the Spanish Government under grants TED2021-130650B-C21 (ANT4CLIM) and PID2023-146246OB-C31 (ANT4IT), funded by MCIN/AEI/10.13039/501100011033 (Agencia Estatal de Investigación), by UE (European Union) "NextGenerationEU"/PRTR

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