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Dual Band Risley Prism Antenna for Satellite-on-the-move Applications

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***Abstract*— The development of the next generation of K/Ka band ground communication systems relies on cost-effective, compact terminals that provide high gain and wide-angle beam coverage while controlling the pointing direction in two widely separated frequency bands (20/30 GHz). The authors have been working on dual-band mechanical beam steering solutions based on a single aperture, eliminating the need of having separate Rx and Tx modules. In our previous works, the 2D beam steering control resulted from in-plane movements (rotation/translation) of a single aperture. A renewed interest has emerged on an alternative scanning solution based on the Risley Prism configuration (independent axial rotation of two TAs). However, until now the focus has been on single band solutions. In this work we present a dual-band Risley Prism antenna, enabled by an ultra-thin dual band TA design. A dedicated in-house full-wave solver was used for a more efficient search of the unit-cell solutions space, which allows reducing 70% of the TA thickness comparing with our previous designs. Full-wave simulations show that the TA has a maximum directivity of 23.8 dBi @ 19.5 GHz and 27.3 dBi at 30 GHz and can scan up to 47 degrees in elevation with scan loss below 2.6 dB.**

***Index Terms*— Satellite-on-themove, K/Ka-band, Mechanical steering, Risley Prism**

I. Introduction

The new generations of MEO and GEO satellite constellations are pushing the market of K/Ka-band satellite broadband communications [1]. One of the main challenges for the ground segment is to achieve cost-effective compact terminals capable of delivering high gain and wide-angle beam coverage while keeping the same pointing direction at K and Ka satellite Rx and Tx bands. The authors have been developing low-cost mechanical beam steering solutions based on transmit arrays (TAs) capable of achieving these requirements. Two complementary approaches for 2D beam scanning have been implemented: i) displacement (rotation and linear translation) of a single TA over a stationary aperture [2]; ii) axial rotation of two TAs, according to the Risley Prism working Principle [3]. A general framework for the design of TAs of any size capable of performing dual-band beam steering has also been proposed by the authors [4]. A proof-of-concept dual band design for configuration i) has been implemented. The devised dual-band unit cells end up having excessive height for being compatible with a Risley Prism configuration. It is worth mentioning that mechanical scanning based on metasurfaces operating as Risley Prisms are getting significant attention in the recent literature as a way of improving the scanning performance of mechanical steering solutions [5], [6]. In this work we present a new dual-band TA design dual-band compatible with a Risley Prism antenna allowing to demonstrate the potential of this solution for Satellite-on-the-move applications.

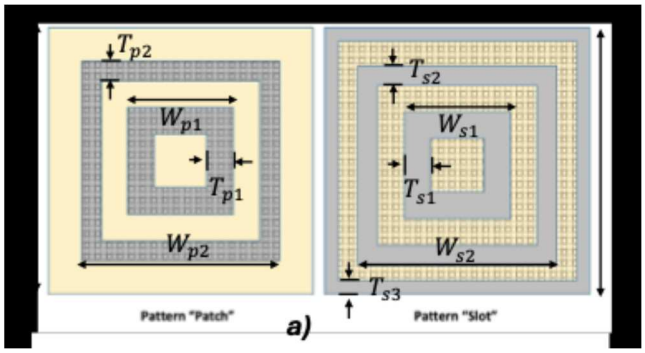
The first part of this work (Section II) focuses on the design of a new set of dual-band unit cells for designing a thin and high performant TA. The goal is to find a proper set of unit cells defined by our generalized framework [4] using a minimum number of metallic layers. The high number of degrees of freedom makes brute-force methods using general-purpose commercial software untreatable. In this work, an efficient in-house spectral domain method of moments (SD-MoM) [7],[8], that is two to four orders of magnitude faster than commercial software, was developed for this specific problem. Moreover, genetic-algorithm assisted search of unit-cell solutions help guiding the convergence of this search.

In the second part of this work (Section III), the design of a dual band Risley Prism configuration is presented. The first TA of the Risley TA antenna is designed to provide offset beam collimation. Finally, a second TA ("prism 2") is cascaded with the first TA, allowing to assess the performance of a dual-band Risley Prism antenna. Preliminary full-wave simulations show very promising results.

II. Unit Cell Design

The proposed unit cells have an in-plane periodicity of 3.5 mm × 3.5 mm and consist of three stacked substrate layers (thickness = 0.787 mm each) Rogers Duroid 5880 (dielectric constant = 2.2, loss tangent = 0.0009) with corresponding four metallized interfaces. At each n-th interface ($n = 1, \ldots, 4$) two concentric square ring patches are printed. Two distinct patterns of the layers are considered (Fig.1a). For each pattern there are multiple degrees of freedom ($T_{s,p}^{i}, W_{s,p}^{i}$)

that will define our search space. An exhaustive search by brute force methods is not feasible in this case. We have developed a fast search algorithm based on a combination of genetic algorithms with an in-house SD-MoM. The efficient computation of the MoM matrix entries based on the Non Uniform Fast Fourier Transform [8] is carried out to achieve a computational speedup with respect to general-purpose three- dimensional methods (i.e., the ones in commercial software as CST Microwave Studio) from two to four orders of magnitude. Combining this fast algorithm with proper bounding criteria for the space of solution search, we were able to populate the required phase combinations at 20 and 30 GHz according to the design rules defined in [4] (Fig. 1b), with transmission above -1.5 dB in both bands. It should also be highlighted that the new solution allows to improve significantly our previous designs [4], where 6 substrate layers (1.575 mm thick each), with corresponding 7 metallized interfaces, were considered for the same target design as this work. We refer to [7] for further details on the optimization process. This innovative approach allowed finding a new set of thin dual band unit cells (70% height reduction relative to the previous design [4], with only 4 metallic layers instead of 7). The wideband response of some designed unit cells (ID20 to ID24) is shown in Fig. 1c, where the desired dual-band performance can be checked.



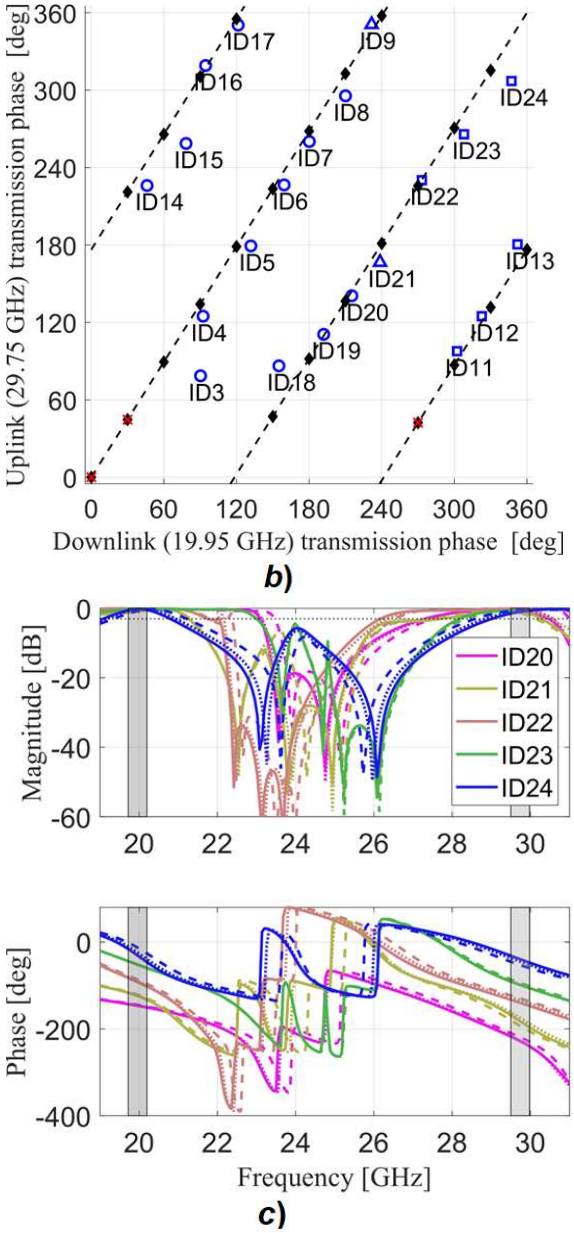


Fig. 1. a) Unit cell Geometry; b) final set of unit cell selection according to [4] general design procedure; c) wideband response of unit cells ID20 to ID24.

III. DUAL BAND RISLEY PRISM

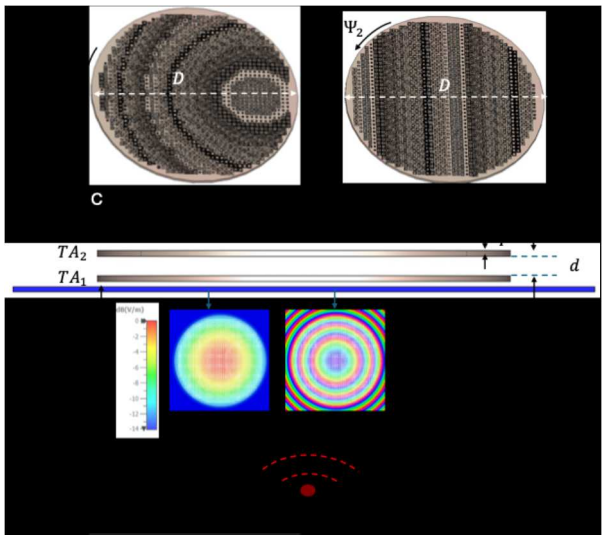


Fig. 2 Schematics of the Risley Prism TA antenna

The Risley Prism design principle with planar antennas [9], implies cascading two TAs with independent axial rotations (ψ_1, ψ_2 in inset of Fig. 2). The first TA converts an impinging spherical wave into an outgoing tilted plane wave, corresponding to the phase distribution [2] (see TA_1 in inset of Fig. 2)

$$\phi_{TA_1} = \frac{2\pi}{\lambda_0}\left(\sqrt{x^2 + y^2 + F^2} - \sin\alpha_0\, x\right) \qquad (1)$$

The second TA phase profile is a linear phase gradient, according to (see TA_2 in inset of Fig. 2)

$$\phi_{TA_2} = -\frac{2\pi}{\lambda_0}\sin\alpha_0\, x \qquad (2)$$

Where λ_0 is the design wavelength, α_0 is the tilting angle (same value for both TAs) and F is the focal distance. We have considered $\alpha_0 = 25°$ as in [3].

For a dual band solution, it is necessary that (1) and (2) are verified for the two design frequencies (20/30GHz). As shown in [4], a generalized phase wrapping method can be used to simplify the process of finding a set of re-usable unit cells capable of mapping all the required phase combinations in both bands. The solution to this problem can be summarized in the finding of a set of unit cells that can populate the 2D phase map shown in Fig. 1b along the solid lines.

The TAs have a diameter $D = 150\ mm$ and a thickness $T = 2.36\ mm$, and are distanced by $d = 7.5\ mm$. Without loss of generality, the rotation angles of the TAs are considered symmetric ($\psi_1 = -\psi_2 = \psi$) to provide scanning along the main plane [9]. In this work, we are focusing on assessing the performance of the cascade of the two dual-band TAs. For this reason, we emulate the dual-band feed with an analytical near-field source (method validated in previous works). This approach also reduces the simulation complexity of this antenna, which nevertheless requires a high-end server solution. All simulations were performed in CST Microwave Studio using the time domain solver and GPU acceleration.

A. *Assessment of the first TA*

To validate the unit cell design we first consider only TA_1. The full-wave results (Fig. 3) show that TA_1 is performing as expected, providing the same beam tilt at the two frequencies with remarkable aperture efficiencies: 40% and 43% at 30GHz and 20 GHz, respectively.

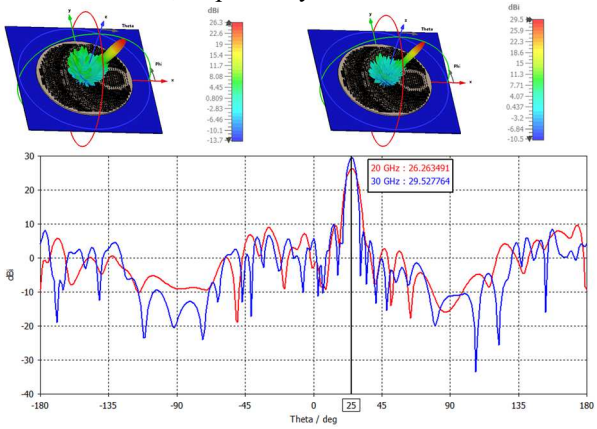


Fig. 3 Directivity at 20 GHz (red curve) and 30 GHz (blue curve) for TA1.

B. *Scanning with two metasurfaces*

In Fig.4 we present the radiation patterns of a complete Risley Prism configuration ($TA_1 + TA_2$) considering three rotation positions: $\psi = \{30°, 60°, 90°\}$, providing scanning up to 48 degrees, with a scan loss of 2.5 dB. As future work, the distance between the two lenses can be optimized to further compensate the coupling between the two TAs, responsible for reducing the gain by 2 dBi. Nevertheless, this work clearly shows the path in order to achieve a simple design of a dual-band steerable antenna for ground terminal.

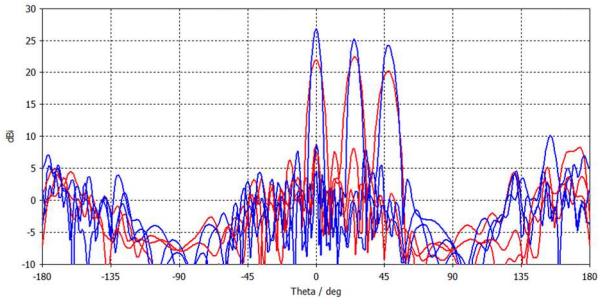


Fig. 4 Directivity at 20 GHz (red curve) and 29.5 GHz

IV. CONCLUSIONS

We presented for the first time (as far as the authors are aware) a Risley Prism TA antenna with dual-band operation at K and Ka satellite communication Rx and Tx bands. The stacking of two TAs requires the use of thin apertures that for dual-band operation can be quite challenging to achieve. For this

purpose, an in-house efficient full-wave method (SD-MoM) was developed, allowing to fully explore the space of possible geometries for multi-layered stacked square-ring patch unit cells. These results pave the way for future developments on this now popular mechanical beam steering solution.

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