Design of Dual-Band Dual-Polarized Reflectarray for Future Multiple Spot Beam Applications in Ka-band

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***Abstract*—The design of a parabolic polarization selective reflectarray for dual-band dual-circular polarization for multiple beam applications in Ka-band is presented. The reflectarray has a diameter of 0.65 m and is a single-layer design consisting of rotated split hexagonal-loop dipole elements. For RHCP, the reflectarray scans the reflected beam half a beamwidth in one direction, and for LHCP, the reflectarray scans the reflected beam half a beamwidth in the opposite direction. This is achieved in both Tx (19 GHz) and Rx (29 GHz). Using a feedarray of 27 feeds, 54 beams can be generated. With this concept, a full multiple beam coverage employing the 4-color frequency/polarization re-use scheme can be covered using only two reflectarrays while maintaining the single-feed-per-beam operation.**

***Index Terms*—Reflectarrays, satellite applications, optimization**

I. INTRODUCTION

Multiple beam reflector antennas are becoming more and more popular for telecommunication applications due to their capability of delivering high capacity for high-throughput satellites (HTS). Currently, the state-of-the-art is to employ four dual-band (Tx/Rx) single-feed-per-beam (SFB) reflectors to cover a contiguous spot beam coverage using the 4-color re-use scheme, one reflector for each of the colors [1]. Recently, significant efforts have been made on reducing the number of main apertures onboard these HTS. The in-flight demonstration of the MEDUSA multiple-feeds-per-beam (MFB) [2] has paved the way to cover the multiple beam coverage using only two main apertures [3]. Solutions to produce a full Tx/Rx multiple beam coverage using only one main aperture has also been suggested by combining two single-band MFB feed systems through a frequency selective sub-reflector [4]. However, despite being able to reduce the number of main apertures, MFB reflectors require advanced beam forming networks.

ESA has recently promoted activities on polarizing and polarization selective surfaces [5]–[7] with the aim to reduce the number of apertures required for HTS missions while maintaining SFB operations. However, these concepts rely on the use of dual-reflector systems which increase the complexity of the antenna system.

In [8], we proposed an innovative reflectarray concept to reduce the number of apertures, while considering a single offset antenna system and maintaining SFB operation. The idea is to use a parabolic polarization selective reflectarray that can radiate two of the beams in the 4-color re-use scheme. The two beam types shall discriminate in polarization, meaning that for one polarization, the reflectarray needs to scan the beam in one direction, and in the orthogonal polarization, the reflectarray needs to scan the beam in the opposite direction. In this way, a single reflectarray can generate two of the four colors in the 4-color re-use scheme and another reflectarray can generate the remaining colors resulting in a total of two apertures to cover the full multiple beam coverage.

In [8], the concept was demonstrated for the Tx-band (20 GHz) only. However, in a real Ka-band mission, the reflectarray must operate in both Tx (20 GHz) and Rx (30 GHz) In this paper, we present the design of a Ka-band polarization selective reflectarray operating in both Tx and Rx bands. The reflectarray is based on a single-layer design and uses the variable rotation technique to control the reflection phase in Tx/Rx. As array element, the split hexagonal-loop dipole element is used and the reflectarray is designed for global coverage.

II. REFLECTARRAY DESIGN

Although the proposed concept has several advantages compared to existing solutions, there are several major challenges that need to be solved.

First, the design of a dual-band reflectarray with separated beams for the two orthogonal CP is not an easy task. To fulfill the stringent RF requirements of a real flight mission is challenging and demands designs with high complexity. Second, the manufacturing of a doubly curved reflectarray is not a straightforward task as it is with planar reflectarrays. There are no standard manufacturing technologies for the production of curved reflectarrays and a first breadboard is yet to be demonstrated. Finally, once the reflectarray has been manufactured and tested, a good correlation between simulations and measurements is needed to verify the accuracy of the design and the modelling tools.

A complex RF design may fulfill the RF requirements, but can significantly complicate the manufacturing process and this can have a strong impact on the quality of the manufactured antenna. As a result, we have selected to proceed with a pragmatic approach, making sure that the reflectarray design has a complexity that can be manufactured with a certain confidence, hence increasing the likelihood of a good agreement between simulations and measurements.

Consequently, to ease the manufacturing process, we will only consider single layer designs using substrate materials where the RF characteristics are well controlled to reduce the number of uncertainties.

A. Analysis and Optimization

For the design of the curved reflectarray, we follow the direct optimization design procedure described in [9].

First, the reflectarray array element with the necessary properties is selected. Second, an appropriate starting point for the direct optimization is identified. The optimization algorithm is a gradient-based minimax algorithm which is specially tailored to large-scale optimization problems. Since it is gradient-based, a good starting point is needed to avoid that the optimization ends up in a local minimum. A design obtained using a phase-only approach is often a good choice, but identical array elements have also proven to provide good results. The local periodicity assumption is used for the analysis of the reflectarray during the optimization.

For additional details, the reader is referred to [9].

B. Reflectarray Geometry

For the breadboard design, we consider a single offset configuration as shown in Fig. 1. The reflectarray surface is a paraboloid surface with a focal length of $f = 1,000$ mm. The projected aperture diameter is 650 mm with an aperture center offset of 600 mm

As feed, we use an existing horn designed for a flight mission in Ka-band. It has a diameter of 66 mm and operates at Tx: 18.8-19.3 GHz and Rx: 28.7-28.9 GHz.

C. Array Element

As shown in [8], the variable rotation techcnique (VRT) can be used for controlling the phase of the elements for circular polarization (CP). Many types of single-layer dual-band elements using the VRT have been studied in the literature, e.g., concentric dual split loop [10].

In our case, we use the split hexagonal-loop dipole element shown in Fig. 2 which will be printed on a single layer Duroid substrate with a dielectric constant of 3.66, loss tangent of 0.0037, and a thickness of 1.524 mm. Similar to many other dual-band VRT elements, the idea of this element is that the outer loop controls the phase in the Tx band where the inner dipole is too small to have any effect. Similarly, it is assumed that the inner dipole is dominating in the higher frequencies and controls the phase in the Rx band. In this way, the reflected phase can be adjusted independently in the two frequency bands by the rotations angles ψ_l and ψ_d. For each combination of these angles, the other parameters are optimized to ensure low cross polarization.

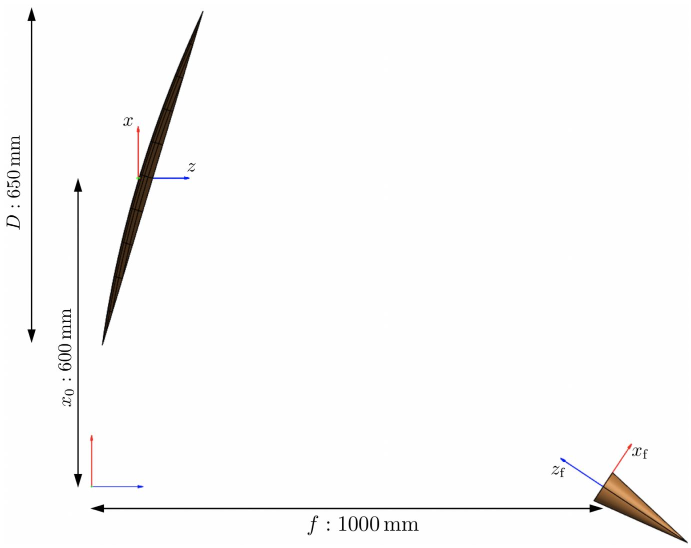


Fig. 1. Reflectarray configuration. The xyz-coordinate system represents the reflectarray coordinate system and the $x_\mathrm{f}y_\mathrm{f}z_\mathrm{f}$-coordinate system the feed coordinate system.

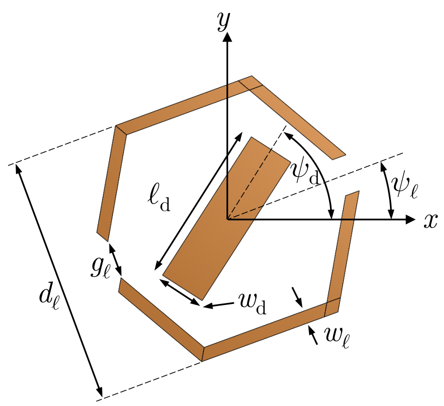


Fig. 2. Split hexagonal-loop dipole element.

In practice, this is not entirely true. At Tx, it is correct that the reflected phase can be controlled by ψ_l and is nearly independent of ψ_d. However at Rx, there is a significant coupling between the outer loop and the dipole, resulting in a more complicated relation between the reflected phase and the rotation angle ψ_d. This effect is well-known [10] and solutions to reduce the coupling involves for instance the use of multiple layers and FSS backing [11], which is not a solution of relevance in our case.

In addition to the coupling between the outer loop and the inner dipole that needs to be taken into account during the design, we also need to consider the fact that the beams need to be scanned in opposite directions for the two orthogonal polarizations. On top of this, most multiple spot beam missions

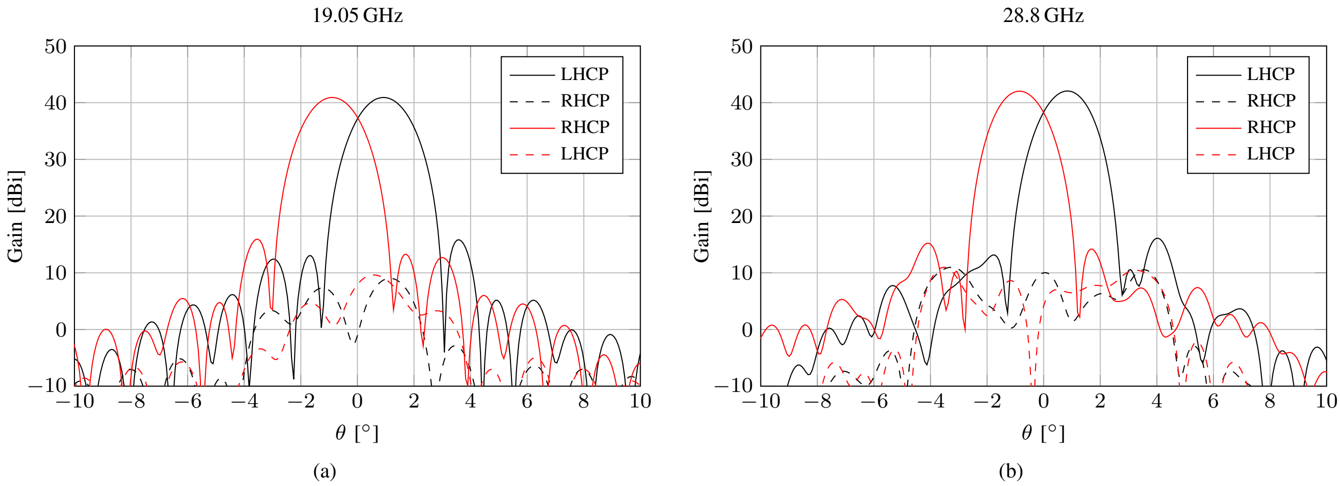


Fig. 3. Radiation pattern of Tx and Rx beams when illuminated by LHCP (black) and RHCP (red) incident field with the feed in the focal point at the center Tx/Rx frequencies. The $\phi = 90°$ cut is shown, i.e., the cut orthogonal to the offset plane.

require orthogonal polarizations in Tx and Rx. This means for example that the A beams in Tx and Rx must have opposite polarizations, implying that $\psi_l = -\psi_\mathrm{d}$, and this complicates the element design even further due to the coupling effects.

During the design stage, we optimized the reflectarray to ensure orthogonality in Tx and Rx. This increased the complexity of the design as the orthogonality constraint in Tx/Rx seems to be an unnatural characteristic for the reflectarray. This resulted in designs that was rather narrow-banded and sensitive to manufacturing errors. If the orthogonality constraint in Tx/Rx is removed, allowing the reflectarray to operate in the same polarization in Tx/Rx, we obtained designs with improved performance, both in terms of cross-polarization, scan performance, bandwidth, and robustness to manufacturing errors.

D. Design Specifications

The reflectarray is designed to radiate the two beam types in the 4-color re-use scheme that are discriminated in polarization (P_1 and P_2) and operate in one of the sub-bands. The design specifications are listed in Table I. The θ and ϕ angles stated in the beam scan are defined in the reflectarray coordinate system in Fig. 1. Thus the reflectarray needs to scan the beam in the plane orthogonal to the offset plane, i.e., the yz-plane in Fig. 1. The beam is scanned -0.9° for one polarization and 0.9° for the orthogonal polarization.

For many ground terminals, it is customary to have Tx and Rx in orthogonal polarizations due to the practicality of building the antenna, and this is one of the main reasons that current multiple spot beam missions operate in orthogonal polarizations in Tx and Rx. For modern/future HTS where the ground terminal already has dual polarization capability, the reason to maintain orthogonal polarization for Tx and Rx is less important. For this reason, we have decided to design the reflectarray to operate in the same polarization in Tx/Rx, i.e., the P_1 is RHCP in both Tx/Rx and the P_2 is LHCP in both Tx/Rx.

TABLE I
DESIGN SPECIFICATIONS.

Freq.	Polarization P_1	Polarization P_2	Beam spacing	Beam scan
Tx	RHCP	LHCP	1.8°	$\theta = \pm 0.9°, \phi = 90°$
Rx	RHCP	LHCP	1.8°	$\theta = \pm 0.9°, \phi = 90°$

E. RF Design

The split hexagonal-loop dipole element has seven parameters that can be optimized. Including all of them in the direct optimization would add unnecessary complexity to the optimization problem. It is a better approach to include fewer, but the most dominant parameters in the optimization.

As explained in Section II-C, the rotation of the loop/dipole (ψ_ℓ and ψ_d) controls the phasing and the remaining five parameters $(d_\ell, g_\ell, w_\ell, \ell_\mathrm{d}, w_\mathrm{d})$ are used to ensure good CP to CP conversion. This means that the ψ_ℓ and ψ_d must be included in the optimization. To identify the influence of the remaining parameters, a parametric investigation at the unit-cell level was performed. In this investigation, the element is optimized for its performance in both Tx and Rx for various combinations of the loop/dipole rotation. Based on a comparison of the optimized unit-cells, it was observed that the dipole length ℓ_d and the loop gap g_ℓ had the largest percentage variations. We interpret this result as an indication that these two parameters have the largest influence on the element performance. Thus, it was decided that in addition to ψ_ℓ and ψ_d also ℓ_d and g_ℓ are included in the optimization giving a total of four parameters per element.

In Fig. 3, the radiation patterns of the Tx and Rx beams when illuminated by LHCP and RHCP incident at the center Tx and Rx frequencies are shown. Herein, the feed is positioned in the focal point of the reflector. It is seen that when

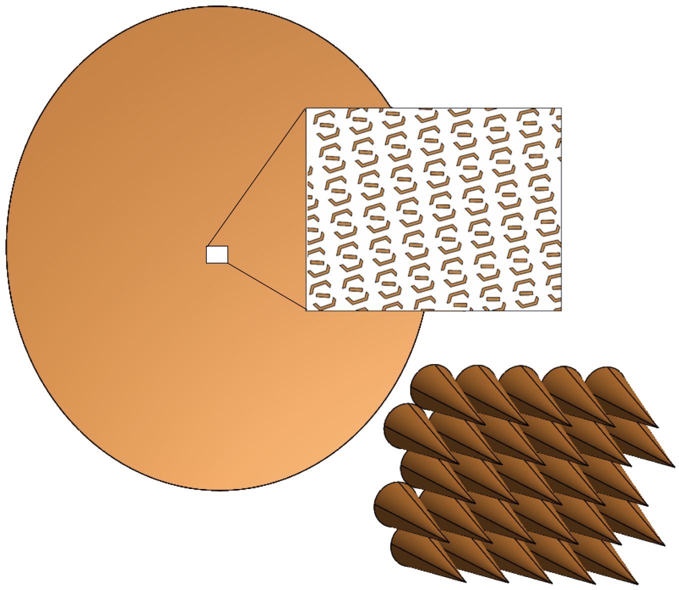
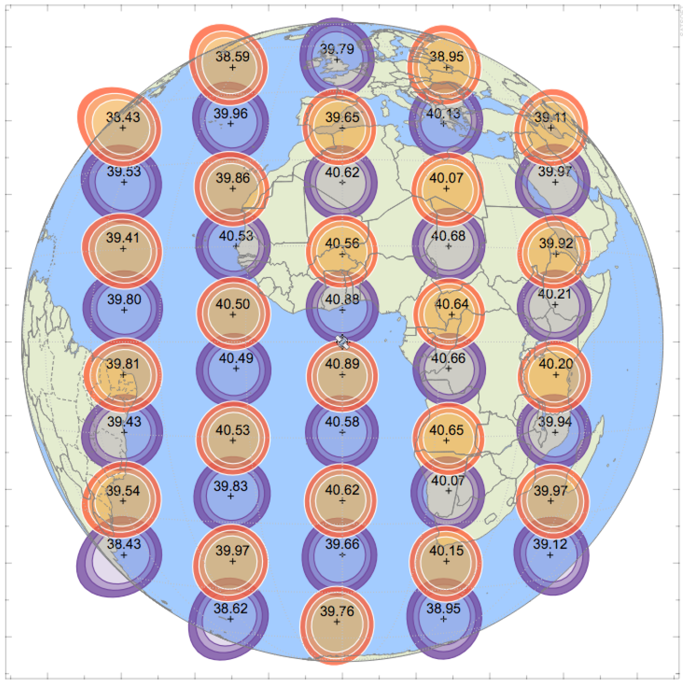
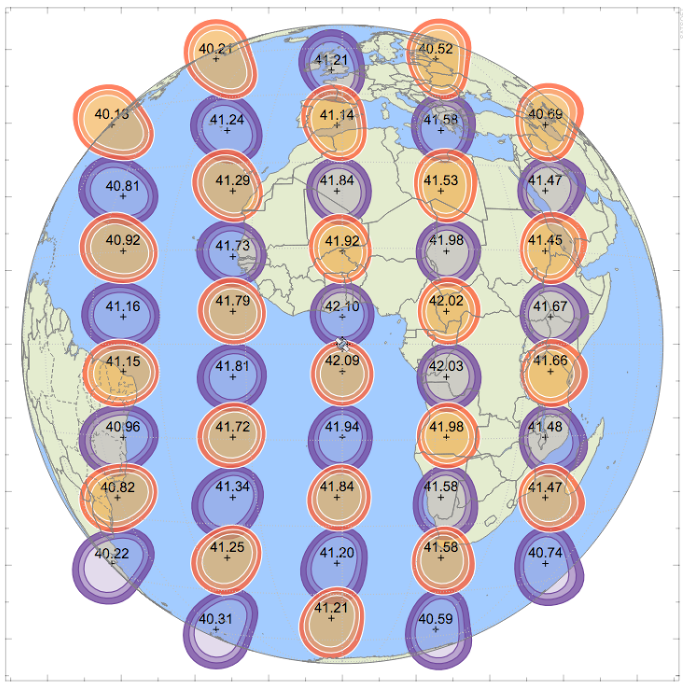


Fig. 4. Reflectarray illuminated by a feedarray consisting of 27 feeds in a hexagonal grid.



(a) Tx: 18.8 GHz



(b) Rx: 28.7 GHz

Fig. 5. Beams generated by the reflectarray when illuminated by the feedarray. The two colors represent the two polarization P_1 and P_2. The peak position of the beams are indicated by a cross (+) with associated peak value, and different contours show -2, -3, and -4.3 dB below peak.

the reflectarray is illuminated in LHCP the beam is scanned towards $\theta = 0.9°$ whereas when it is illuminated in RHCP the beam is scanned towards $\theta = -0.9°$. This is the case in both Tx and Rx. Furthermore, the beam shapes in both Tx and Rx are rather good with low side-lobes. The cross-polar peak is around 10.0 dBi in both Tx and Rx and is comparable to that of the nominal reflector pattern which is around 8.5 dBi. The patterns for the lower and higher Tx/Rx frequencies resemble those at the center frequencies and is therefore not shown.

To investigate the scan performance when displacing the feed, the reflectarray is illuminated using a feed array consisting of 27 feeds positioned in a hexagonal grid, see Fig. 4. Using these 27 feeds, it is possible to generate 54 beams, of which 8 are outside the Earth coverage, hence resulting in a total of 46 beams over the Earth as shown in Fig. 5. The Tx beams scan well with very little beam distortion, whereas the distortions for the Rx beams are more visible. Compared to the nominal reflector radiation pattern, the beam shapes are quite similar, indicating that the degradation in peak value and the beam distortion for the scanned beams is mainly due to scan aberrations.

The results presented here demonstrate that a curved polarization selective reflectarray can indeed radiate two of the beam types in the 4-color re-use scheme in both Tx and Rx. Using another reflectarray that generates the P_1 and P_2 in the other sub-bands, global coverage can be achieved.

F. Manufacturing

For the breadboard, an aluminimum reflector will be used as the mold on which the printed boards will be conformed and cured.

Three manufacturing techniques were initially considered: hot forming, vacuum forming, and cold forming. Because an aluminum reflector mold was chosen as a base to bond the boards, it was decided to use a room temperature cured epoxy adhesive using a vacuum forming technique for the boards to the aluminum surface. The use of room temperature adhesives eliminates temperature induced deformations due to

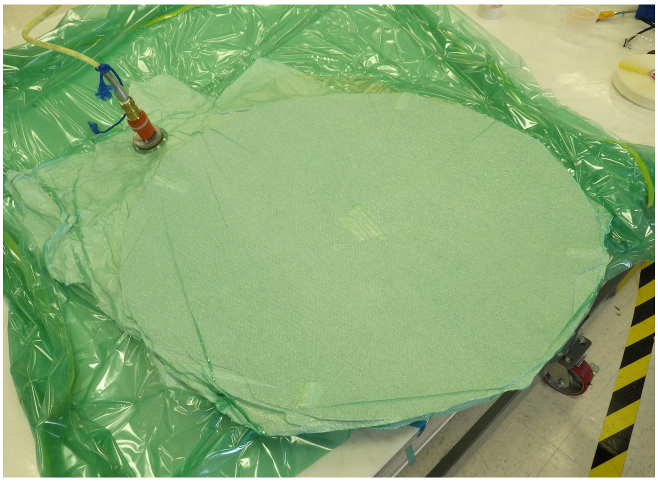


Fig. 6. Vacuum bagged reflector mold assembly during ambient curing.

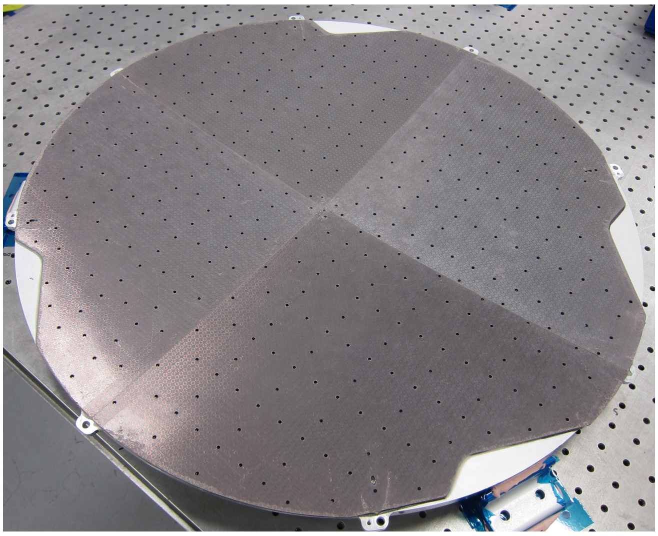


Fig. 7. Conformed test pie slices bonded to the aluminum reflector mold.

the material CTE mismatches. Cold forming was not required on the boards beforehand as the curvature of the aluminum surface was small.

The boards will cut in quadrants in order to help conform to the curved surface; a pin and slot feature was included on each of the four boards to precisely locate them on the reflector surface. Vacuum was applied during the entire curing phase of the adhesive to help keep the boards bonded as closely as possible to the surface of the reflector with a constant pressure.

The actual breadboard is currently being manufactured. Prior to this, a test board was manufactured. Fig. 6 shows the reflector mold in the vacuum bag during the curing phase of the epoxy adhesive. In Fig. 7, the bonded test pie-slices on the reflector mold are shown. The small holes on the boards are measurements points to confirm the deformations of the test boards. The breadboard will be measured and results will be presented at the conference.

III. Conclusions

We shown in this paper that a parabolic polarization selective reflectarray can be used to reduce the number of main apertures in multiple beam antenna applications in Ka-band. Using array elements printed on a parabolic surface, it is possible to radiate beams that are discriminated in polarization, resulting in an antenna that can radiate two of the beam types in the 4-color re-use scheme. Consequently, using two reflectarrays, it is possible to cover a full multiple beam coverage.

To demonstrate the concept, a reflectarray has been designed to operate in both Tx and Rx in Ka-band. The reflectarray is based on a single-layer design consisting of rotated split hexagonal-loop dipole elements. Using a feedarray of 27 feeds, it is shown that the reflectarray generates 46 beams over the Earth in both Tx and Rx. A breadboard is currently being manufactured to verify the simulation results and measurement results will be presented at the conference.

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References

[1] E. Amyotte, Y. Demers, L. Hildebrand, M. Forest, S. Riendeau, S. Sierra-Garcia, and J. Uher, "Recent developments in Ka-band satellite antennas for broadband communications," in *Proc. EuCAP*, 2010.

[2] M. Schneider, C. Hartwanger, E. Sommer, and H. Wolf, "The multiple spot beam antenna project "Medusa"," in *Proc. EuCAP*, 2009.

[3] J. C. Lafond, E. Vourch, F. Delepaux, P. Lepeltier, P. Bosshard, F. Dubos, C. Feat, C. Labourdette, G. Navarre, and J. M. Bassaler, "Thales Alenia Space multiple beam antennas for telecommunication satellites," in *Proc. EuCAP*, 2014.

[4] N. J. G. Fonseca, "Dual-band (Tx/Rx) multiple-beam reflector antenna using a frequency selective sub-reflector for Ka-band applications," in *Proc. EuCAP*, Lisbon, Portugal, 2015.

[5] N. J. G. Fonseca and C. Mangenot, "High-performance electrically thin dual-band polarizing reflective surface for broadband satellite applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 640–649, 2016.

[6] W. Tang, S. Mercader-Pellicer, G. Goussetis, H. Legay, and N. J. G. Fonseca, "Low-profile compact dual-band unit-cell for polarizing surfaces operating in orthogonal polarizations," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1472–1477, 2018.

[7] C. Cappellin, D. Sjöberg, A. Ericsson, P. Balling, G. Gerini, N. J. G. Fonseca, and P. D. Maagt, "Design and analysis of a reflector antenna system based on doubly curved circular polarization selective surfaces," in *Proc. EuCAP*, Davos, Switzerland, 2016.

[8] M. Zhou and S. B. Sørensen, "Multi-spot beam reflectarrays for satellite telecommunications applications in Ka-band," in *Proc. EuCAP*, Davos, Switzerland, 2016.

[9] M. Zhou, E. Jørgensen, N. Vesterdal, O. Borries, S. B. Sørensen, P. Meincke, M. Simeoni, and G. Toso, "Design of high-performance antenna systems with quasi-periodic surfaces," in *Proc. EuCAP*, London, UK, 2018.

[10] T. Smith, U. Gothelf, O. S. Kim, and O. Breinbjerg, "Design, manufacturing, and testing of a 20/30-GHz dual-band circularly polarized reflectarray antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1480–1483, 2013.

[11] R. Deng, F. Yang, S. Xu, and M. Li, "An FSS-backed 20/30-GHz dual-band circularly polarized reflectarray with suppressed mutual coupling and enhanced performance," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 926–931, 2017.