Multi-Spot Beam Reflectarrays for Satellite Telecommunication Applications in Ka-Band

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***Abstract*—This paper describes a reflectarray concept that can produce a full dual-band (transmit/receive) multiple spot beam coverage in Ka-band using only two main apertures while maintaining single-feed-per-beam operation. The proposed concept combines the capabilities of the reflectarray and a parabolic surface, enabling the antenna to radiate more than one beam types in the typical "4-color" frequency polarization re-use scheme. Preliminary results using single-band array elements are presented and confirm the potential of the proposed concept.**

***Index Terms*—reflectarrays, multiple spot beam, optimization, telecommunication, satellite applications**

I. Introduction

In the last decade, there has been an increased interest in the development of broadband satellite operating at Ka-band, utilizing multiple beam reflector antenna farms for High Throughput Satellites (HTS). Significant efforts has been on reducing the number of main apertures in order to cover a full transmit (Tx) and receive (Rx) multiple spot beam coverage. For the typical "4-color" frequency (F_1, F_2) and polarization (P_1, P_2) re-use scheme as shown in Fig. 1, the current state-of-the-art is to employ four dual-band (Tx/Rx) single-feed-per-beam (SFB) reflector antennas [1]–[3], one reflector for each of the beams A, B, C, and D. The mechanical complexity of accommodating four reflectors instead of two or three is of course high and any techniques for reducing the number of main apertures are of great interest.

Antenna configurations using three SFB reflectors have been reported and provides an interesting alternative but results in a slight degradation in performance compared to the conventional four reflector solution with similar aperture size [4]. Another interesting concept based on the SFB operation is proposed in [5]. Herein, a dual-band low-profile polarizer is used as the main reflector and could possibly be used to reduce the number of main apertures to only two main reflectors for full Tx/Rx operation. To maintain the SFB operation, gridded sub-reflectors are needed to separate the two orthogonal linear polarizations at the feed cluster level.

Recently, developments on feed systems for multiple-feed-per-beam (MFB) reflector antennas have demonstrated the capability of providing full Tx/Rx operation using only two main apertures. This can be achieved by using two single-band MFB reflectors, one for Tx and one for Rx [6]. Alternatively, the use of compact Tx/Rx feed chain designs has also been reported [7]. Finally, solutions to produce a full Tx/Rx multiple beam coverage using only one main aperture has also been

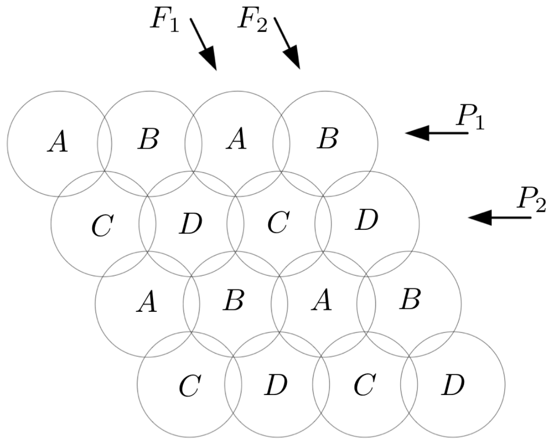


Fig. 1. Beam layout of the typical "4-color" frequency (F_1, F_2) and polarization (P_1, P_2) re-use scheme.

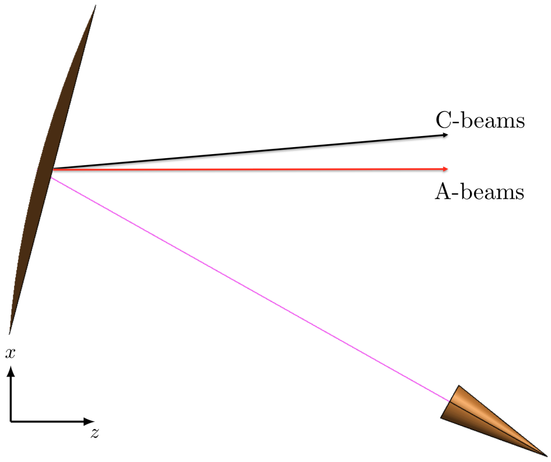
suggested by combining two single-band MFB feed systems through a frequency selective sub-reflector [8].

Despite being able to reduce the number of main apertures, MFB reflectors require the need of beam forming networks, and the performance of the MFB reflectors when compared to SFB reflectors with similar aperture is inferior. Furthermore, the use of MFB reflectors for non-regular lattice beam spots with different beam sizes is not appropriate and is another shortcoming of the MFB concept.

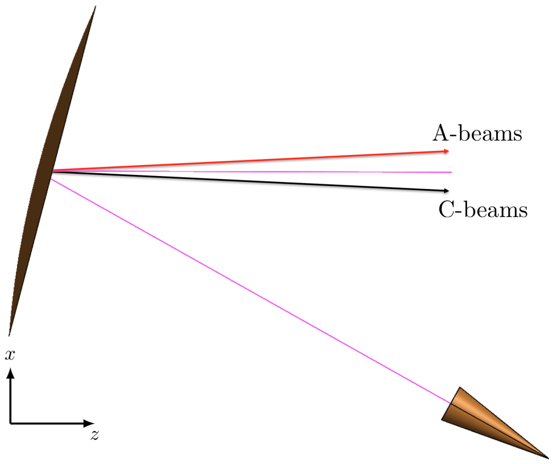
Printed reflectarrays can be designed to steer the reflected beam away from the specular direction or to shape it according to predefined requirements. Their properties can be tuned with respect to the frequency as well as polarization and the increased number of degrees of freedom in a reflectarray may provide a way to reduce the total number of main apertures. In this paper, we present a reflectarray concept where the number of main apertures may be reduced while maintaining the simplicity of the SFB operation (no beam forming networks) without the need of gridded sub-reflectors.

II. Parabolic Reflectarray

The concept of a reflectarray with array elements printed on a doubly curved surface was first suggested in [9] with the goal to enhance the bandwidth of contoured beam reflectarrays. The concept was later investigated in more detail in [10], [11] where it was shown that bandwidth can indeed be improved by using a doubly curved surface. For multiple spot beam applications, the curvature of the reflectarray can be used



(a) Configuration A



(b) Configuration B

Fig. 2. Different configurations where curved reflectarrays can be used to radiate two beam types in a multiple spot beam application using the 4-color re-use scheme: (a) the array elements steer the beam to radiate the C-beams and the parabolic surface is responsible for the A-beams, (b) the array elements steer the beams to radiate both the C- and A-beams. The purple ray follows the law of reflection.

for other advantages, namely to provide the capability of radiating more than one type of beams and thereby allowing the possibility of reducing the number of apertures. Two configurations are of interest and will be discussed in the following.

A. Configuration A

In the conventional four SFB reflector solution, consider one of the reflectors that is used to generate e.g. the A-beams in the 4-color re-use scheme. A feed cluster illuminates this reflector and the connection between feed placement and beam scan follows the law of reflection. Due to the spacing of the feeds in the cluster, this reflector will only radiate the A-beams.

Suppose identical reflectarray array elements (e.g. identical rectangular patches) are printed on the reflector surface, the curved reflectarray will operate like the solid reflector, regardless of the polarization, hence radiating the A-beams. However, it is possible to adjust the array elements to scan the reflected beam for one beamwidth for one polarization while fixing the reflected beam for the orthogonal polarization, hence enabling the parabolic reflectarray to radiate two beam types, e.g, A and C. This configuration is shown in Fig. 2a. For this to work, the array elements must be able to adjust the two orthogonal polarizations independently. To scan the reflected beam one beamwidth, a phase shift of 360° over the surface of the reflectarray is required.

Following this concept, a full Tx/Rx multiple spot beam coverage using the 4-color re-use scheme can be accomplished using either three or two reflectarrays, depending on the use of single-band or dual-band array elements.

1) Single-band array elements: Using single-band array elements, full Tx/Rx operation can be maintained using three reflectarrays:

Reflectarray 1: Beams A_{Tx}, C_{Tx}, and A_{Rx},
Reflectarray 2: Beams B_{Rx}, D_{Rx}, and B_{Tx},
Reflectarray 3: Beams D_{Tx} and C_{Rx}.

For Reflectarray 1, the array elements are designed at the Tx frequency such that for one polarization, they scan the reflected beams to radiate the C_{Tx}-beams. For the orthogonal polarization, the beams need to be unaffected by the array elements such that the reflectarray behaves like a solid reflector, thus generating the A_{Tx}-beams. At the Rx frequency, the array elements are non-resonant and the parabolic reflectarray behaves like a solid reflector and generates therefore the A_{Rx}-beams, regardless of the polarization.

Reflectarray 2 is similar to Reflectarray 1, expect that the array elements are designed to work at Rx and inactive at Tx. Reflectarray 3 radiates the remaining beams with array elements working at either Rx or Tx.

2) Dual-band array elements: Using dual-band array elements, full Tx/Rx operation can be accomplished using two reflectarrays:

Reflectarray 1: Beams A_{Tx}, C_{Tx}, A_{Rx}, and C_{Rx},
Reflectarray 2: Beams B_{Rx}, D_{Rx}, B_{Tx}, and D_{Tx}.

The operation of these two reflectarrays is similar to that described above, except that dual-band array elements that can be adjusted independently for the two bands are required.

Configuration A is well suited for linear polarization due to the existing work published on single- and dual-band array elements that can adjust the two orthogonal polarizations independently.

B. Configuration B

In this configuration, which is shown in Fig. 2b, the parabolic reflectarray also radiates two beam types, e.g., A and C. The idea is similar to that of Configuration A, however, the array elements are designed such that the reflected beams are scanned half a beamwidth for one polarization and another half towards the opposite direction for the orthogonal polarization. Again, the array elements must be able to adjust the two orthogonal polarizations independently.

To scan the reflected beam half a beamwidth, a phase shift of only 180° over the surface of the reflectarray is required. Although the array elements are responsible for scanning two beams, whereas only one beam is required in Configuration A, the two beams in Configuration B are only scanned one half beamwidth. This puts less constraints on the array elements and reduces scan losses.

Single-band array elements can not be used in this configuration to reduce the number of apertures. The reason for this is that in the frequency band where the array elements are inactive, the reflected beams will follow the law of reflection, resulting in spot beams in between the two desired beam types, see Fig. 2b. Consequently, full Tx/Rx operation can only be accomplished using two reflectarrays with dual-band array elements:

Reflectarray 1: Beams A_{Tx}, C_{Tx}, A_{Rx}, and C_{Rx}

Reflectarray 2: Beams B_{Rx}, D_{Rx}, B_{Tx}, and D_{Tx}.

Configuration B is particular suitable for circular polarization using the variable rotation technique [12] as will be more clear later in the paper.

III. Concept Demonstration

To illustrate the proposed concept and to provide some quantitative analysis of the expected performance, we present here some preliminary results for a global coverage mission in Ka-band considering Configuration B. For demonstration purposes, we consider a reflectarray using single-band array elements that can radiate the beams A_{Tx} and C_{Tx}. For the beam specifications, the 3 dB beamwidth should be 2.2° with the characteristics as listed in Table I.

TABLE I
Beam Specifications

Beam type	Frequency	Polarization
A_{Tx}	20 GHz	RHCP
C_{Tx}	20 GHz	LHCP

A. Reflectarray Analysis and Optimization

For the design of the reflectarray, the direct optimization technique (DOT) from [13] is applied. The analysis method used in the DOT is based on a spectral domain method of moments assuming local periodicity (LP-SDMoM). The optimization engine uses a gradient-based non-linear minimax optimization algorithm. In [13], the DOT is validated and described in detail for planar reflectarrays and the reader is referred hereto for additional details.

For curved reflectarrays, the LP-SDMoM can not be directly applied due to the curvature of the array elements and the ground plane. Consequently, an equivalent planar configuration has to be defined to approximate locally the curvature of each array element. This extension of the LP-SDMoM algorithm for curved reflectarrays is described in [11]. Herein, the LP-SDMoM is applied on a curved contoured beam reflectarray and the results are compared to the full-wave higher-order method of moments solver in GRASP [14]. The comparison shows that the LP-SDMoM is very accurate, also for curved reflectarrays. Details of the LP-SDMoM for curved reflectarrays will not be provided here and the reader is referred to [11] for more information.

B. Variable Rotation Technique

The reflectarray needs to operate in dual circular polarization. Must conventional array elements for circular polarization, e.g., circular loops, works in dual circular polarization, but the two orthogonal polarization can not be adjusted independently of each other which is required here.

To this end, the variable rotation technique (VRT) [12] is a suitable way to achieve this. The VRT uses identical array elements with different angular rotations to achieve a given far-field beam. When an array element is illuminated by a circularly polarized wave, a rotation of the array element by an angle ψ gives the reflected field a phase shift of 2ψ. As a result, by rotating the array elements, the phase distribution over the reflectarray surface can be controlled thus radiating a specified far-field beam.

The VRT requires that the reflection coefficients of the two orthogonal linear components are of equal magnitude and 180° out of phase, in which case the reflected field has the same sense of circular polarization as the incident field with a phase shift of $\pm 2\psi$ depending on the polarization of the incident field [15]. The VRT is a well known concept and have been applied on many planar reflectarrays, and the reader is referred to [12], [15] for more information.

The use of VRT has to the best of the authors knowledge never been applied on a curved reflectarray. When used on a curved reflectarray, there are features which makes the technique particularly useful for the proposed reflectarray concept. To illustrate this, consider a simple dipole element printed on a single-layer dielectric with substrate thickness $h = 0.762$ mm and dielectric constant $\epsilon_{\mathrm{r}} = 3.66$ with a unit cell size of $5.25 \times 5.25\,\mathrm{mm}^2$. If the length and width of the dipole are $L = 4.1$ mm and $w = 0.1L$, respectively, the reflection coefficients of the two orthogonal linear components (at normal incidence) are 180° out of phase at 20 GHz. Thus by optimizing the rotation of the dipoles the reflected beam can be scanned.

The dipole element is used in a single offset parabolic reflectarray. The reflectarray surface is a paraboloid surface with a focal length of $f = 60$ cm and has a circular projected aperture of $D = 44.5$ cm. This gives a focal length to diameter ratio of $f/D = 1.34$. As feed, a dual circular polarized conical horn model with an aperture diameter of 50 mm is used. The configuration is actually the one shown in Fig. 2b.

Using the DOT, the rotation angles of the dipoles are optimized to scan the reflected beam toward $(\theta, \phi) = (1.1°, 0°)$ in RHCP. The angles are given with respect to the coordinate system in Fig. 2. Once the rotation angles have been obtained, the lengths of all the dipoles are optimized to compensate for the different incidence angles. This is necessary to maintain a low cross-polar radiation. The optimized reflectarray layout is shown in Fig. 3.

In Fig. 4, the radiation pattern of the optimized reflectarray is shown. Illumination of the reflectarray with a RHCP incident field yields the radiation pattern shown in black where solid and dashed lines indicate co-polar and cross-polar components, respectively. It is seen that the co-polar (RHCP) main beam is

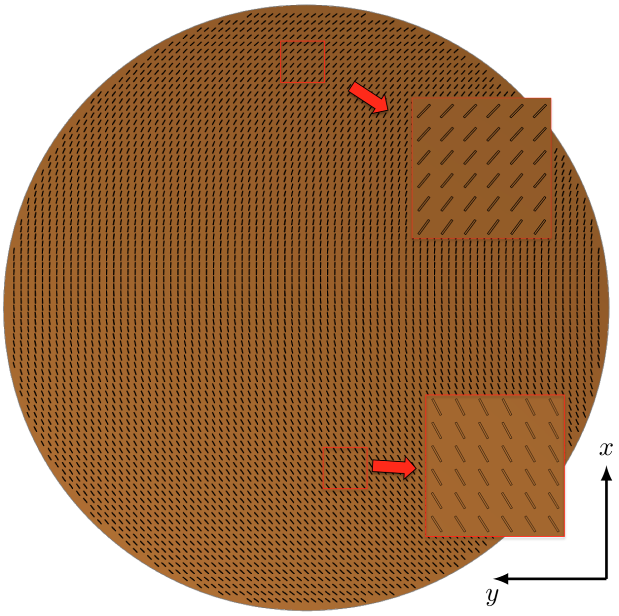


Fig. 3. The layout of the optimized reflectarray seen in the xy-plane with respect to the coordinate system in Fig. 2

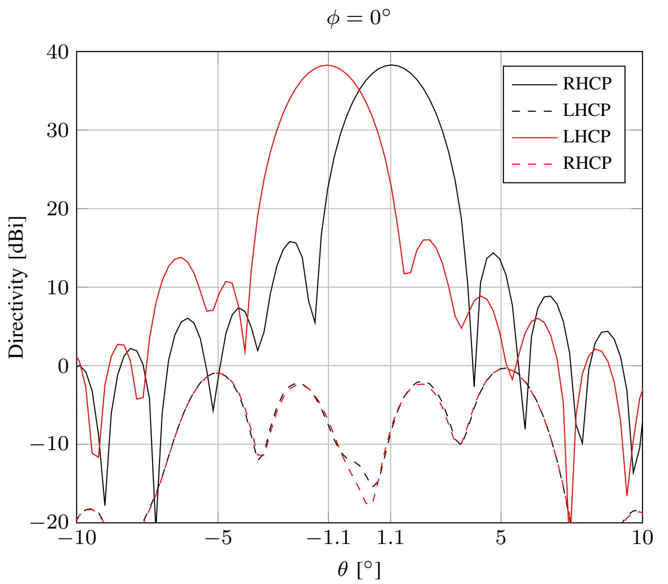


Fig. 4. The radiation pattern of the optimized reflectarray when illuminated by RHCP incident field (black curves) and LHCP incident field (red curves). The co-polar components are shown with solid lines whereas the cross-polar components are shown with dashed lines. The radiation pattern are shown with respect to the coordinate system in Fig. 2.

scanned towards $\theta = 1.1°$, i.e., the A_{Tx}-beam. Furthermore, the cross-polar (LHCP) radiation is low, below 0 dBi.

Now, if one illuminates the reflectarray with a LHCP incident field, shown in red in Fig. 4, it is seen that the reflectarray automatically scans the co-polar (LHCP) main beam towards $\theta = -1.1°$, i.e., the C_{Tx}-beam. This is a unique feature of the VRT when applied to a parabolic reflectarray to scan a spot beam in a given direction. Although the reflectarray is optimized to radiate a RHCP-to-RHCP beam in a given direction, it will automatically scan the LHCP-to-LHCP beam in the opposite direction. This is a consequence of the natural phase symmetry that is obtained when using the VRT on a parabolic reflectarray. It is furthermore exactly what is required in Configuration B. A similar symmetry can not be obtained when using planar reflectarrays, thus the use of a curved reflectarray is a necessity.

C. Multiple Spot Beam Results

In Fig. 4, it is shown that the optimized parabolic reflectarray is capable of radiating two types of beams. In this section the performance when a feed cluster is used to illuminate the optimized reflectarray is shown. To this end, we consider 9 dual circularly polarized conical horns, similar to that used in the previous example. The spacing of the feed centers is set equal to the diameter of the feeds and arranged in a hexagonal lattice, see Fig. 5.

In Fig. 6, the radiation pattern of the parabolic reflectarray at 20 GHz is shown. The blue and black beams correspond to the A_{Tx} and C_{Tx} beams, respectively. In the figure, the -2 and -3 dB contours and the peak of each beam are shown. It is seen that using the 9 feeds, a total number of 18 beams can be generated. Some scan loss is observed at the beams at the edge of the earth. These losses are due to aberrations and are comparable to that of a solid reflector. The cross-polarization of the beams are not shown, but they are below 0 dBi for all beams. The only exception is the beam at the top right $(u, v) = (-0.13, 0.07)$, where the peak cross-polar component is 2.9 dBi and outside the edge of the earth. Using additional feeds, the remaining A_{Tx} and C_{Tx} beams over the earth can be covered.

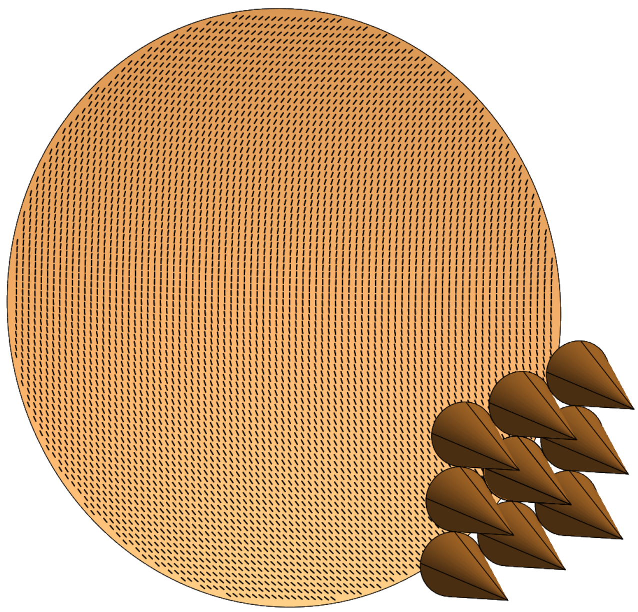


Fig. 5. Optimized parabolic multiple spot beam reflectarray.

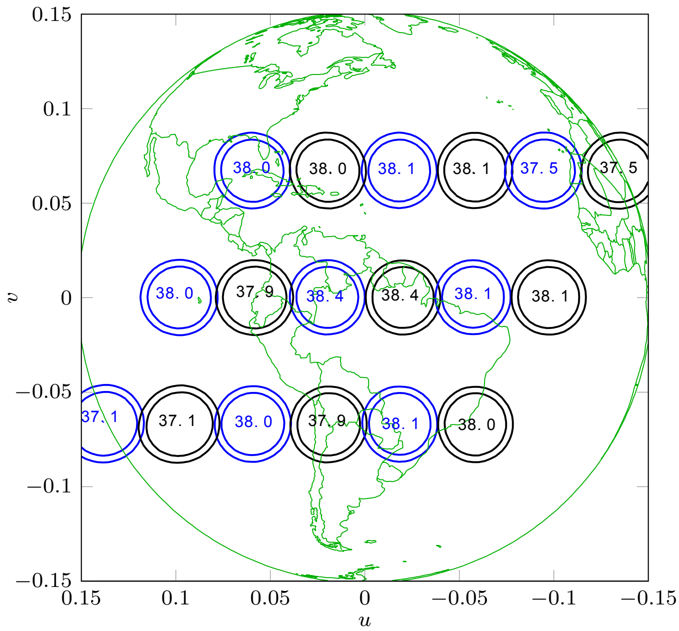


Fig. 6. The radiation pattern of the optimized parabolic reflectarray at 20 GHz. The blue and black beams correspond to the A_{Tx} and C_{Tx} beams, respectively. The plot shows the -2 and -3 dB contours and the peak of each beam.

This reflectarray, used together with another reflectarray that radiates the B_{Tx} and D_{Tx} beams can cover the entire earth in Tx.

D. Full Tx/Rx Operation

The reflectarray presented above uses single-band array elements and can not be used to cover the full Tx/Rx coverage. In Ka-band, the final objective is the generation of multiple spot beams in dual circular polarization, where orthogonal polarizations in Tx and Rx are usually used. To achieve the goal of reducing the number of main apertures from four to two, the use of a dual-band (20/30 GHz) circularly polarized reflectarray element operating in orthogonal polarizations in the two bands is needed.

A promising element candidate is proposed in [15]. The reflectarray element is a concentric dual split-loop element. The outer loops can be rotated such that they generate the phase-shift at Tx whereas the inner loops generate the phase-shift at Rx. Since the two loops can be rotated independently, it is possible to design a reflectarray that generates orthogonal polarizations in the two frequency bands. This array element is suitable for the proposed parabolic reflectarray concept since it is based on the VRT.

The use of the concentric dual split-loop element, and other similar element types, in conjunction with a parabolic reflectarray is currently being investigated in an on-going ESA-funded activity where the proposed concept is being further developed.

IV. Conclusion

We show in this paper that parabolic reflectarrays can be used to reduce the number of main apertures in a multiple spot beam mission based on the typical "4-color" frequency and polarization re-use scheme in Ka-band. Using a parabolic reflectarray, it is possible for the reflectarray to radiate more than one beam types in the re-use scheme, enabling the possibility of reducing the number of main apertures from four to two for both transmit/receive operations. For this to work, dual-band array elements where the two orthogonal polarizations can be adjusted independently are required.

In this paper, the proposed concept is demonstrated using single-band array elements. The use of dual-band array elements together with the parabolic reflectarray concept is currently on-going.

Acknowledgment

The work presented in this paper is partially funded by the European Space Agency (ESTEC contract No. 4000115345/15/UK/ND).

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