REFLECTARRAYS FOR BEAM SQUINT COMPENSATION OF ORTHOGONALLY POLARIZED TX/RX OFFSET ANTENNA SYSTEMS

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Abstract – **Beam squint in single offset reflector antennas with circularly polarized feeds is well known. For applications where single offset reflectors operate in orthogonal circular polarizations in Tx/Rx, the beams in the two bands squint in opposite directions resulting in incongruent beams in Tx and Rx. This paper presents the use of reflectarrays to compensate for the beam squint in offset antenna systems. The proposed concept combines the phasing capabilities of the reflectarray and a parabolic surface, enabling the antenna to compensate the beam squint in one band without affecting the beam in the other band, resulting in congruent beams in Tx and Rx. Preliminary results are presented which demonstrate the proposed concept.**

I. INTRODUCTION

Printed reflectarrays have existed for several decades and provide a way to realize low-cost high-gain antennas [1]. Recently, research and development of reflectarrays have gained momentum and a large number of reflectarrays with advanced capabilities have been designed [2-4]. Despite their advanced capabilities, reflectarrays have not yet gained widespread acceptance for space applications. However, with the increased interest for SmallSats, e.g., CubeSats, reflectarrays are gaining popularity and the first spaceborne reflectarray designed for a deep space mission is scheduled to launch in 2018 [5]. Other applications of reflectarrays in space, which are currently planned, include Earth observation, e.g., the SWOT mission [6].

For other satellite applications, e.g., telecommunication and broadcasting applications, where stringent requirements need to be fulfilled, the reflector technology is still the preferred choice due to its maturity, both in terms of performance, manufacturing, and modelling capabilities. Recently, the European Space Agency (ESA) has promoted several activities to improve and extend the applicability of reflectarrays for satellite applications with particular emphasis on contoured beam missions [2,3]. One way to enhance the performance of contoured beam reflectarrays is to consider reflectarrays with array elements printed on a doubly curved surface. Although considered before [7], the concept of a curved reflectarray is relatively new and is the topic of an on-going ESA activity. The results on contoured beams obtained here are promising and indicate that curved reflectarrays can, for certain missions, surpass the performance of that of a shaped reflector [8].

In addition to contoured beams, curved reflectarrays can also provide other attractive solutions compared to conventional reflector antennas. One of them is the multiple spot beam reflector antenna farms for High Throughput Satellites (HTS) that utilize the typical 4-color frequency and polarization re-use scheme [9]. Currently, the state-of-the-art is to employ four dual-band (Tx/Rx) single-feed-per-beam (SFB) reflector antennas [10], one reflector for each of the four beams. Using curved reflectarrays, the number of apertures could be reduced from four to two while maintaining SFB operation [11].

Another interesting application is to use a reflectarray to compensate for beam squint of orthogonally polarized Tx/Rx offset antennas systems. The beam-squint phenomenon which is observed when an offset reflector is illuminated by a circularly polarized feed is well known [12]. The squint occurs in a direction orthogonal to the principal offset plane and the squint direction depends on the polarization of the reflected field. This beam-squint affects the beam pointing and must be taken into account for advanced reflector applications, e.g., satellite communications, deep-space applications, etc. For certain applications, beam-squint can be alleviated by means of proper feed positioning or by using dual-reflector systems [13]. However, for applications where single offset reflectors operating in orthogonal circular polarizations in Tx/Rx are needed, no easy solution exists. One example is the SFB reflector farms for HTS in Ka-band. Due to the orthogonal polarizations in Tx and Rx, the beams in the two bands squint in opposite directions (see Figure 1) resulting in incongruent beams in Tx and Rx and degraded communication performance over the service area.

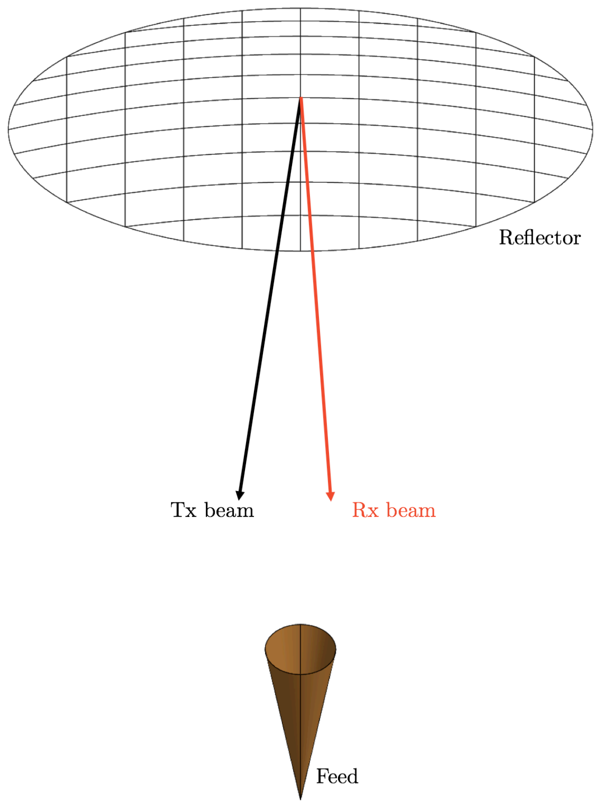

Figure 1: Beam squint in a single offset parabolic reflector seen from a plane orthogonal to the offset plane. Due to the orthogonal polarizations in Tx and Rx, the beams in the two bands squint in opposite directions as shown with black and red, respectively. Note that the Tx and Rx squint are slightly different since the squint depends on the wavelength.

Curved reflectarrays can be used to compensate for the beam-squint issue mentioned above, which is the topic of this paper. Taking outset in Ka-band (Tx 17.8-20.2 GHz and Rx 27.5-30.0 GHz), preliminary results on the design of reflectarrays for beam squint compensation of orthogonally polarized Tx/Rx offset antenna systems will be presented, demonstrating the proposed concept.

II. BEAM SQUINT COMPENSATION

There are several approaches to compensate for the beam squint of orthogonally polarized Tx/Rx antenna systems using curved reflectarrays. Although the concepts are quite intuitive as one will see below, no one has to the best of the authors' knowledge considered this before.

Approach I: Optimize the reflectarray elements such that they compensate for the beam squint in Rx. The reflectarrays elements are active at Rx and passive at Tx such that the reflectarray operates like a solid reflector in this band. In this way, the Rx squint needs to be inverted such that it matches the Tx. This approach is illustrated in Figure 2a.

Approach II: Similarly, one could optimize the reflectarray elements to compensate for the beam squint in Tx, such that the array elements are active at Tx and passive at Rx. This approach is illustrated in Figure 2b.

Approach III: In the above, one uses single-band reflectarray elements (active at either Tx or Rx). The same can be achieved using dual-band elements to compensate for beam squints in Tx and Rx independently. This approach is illustrated in Figure 2c.

Of the two bands (Tx 17.8-20.2 GHz and Rx 27.5-30.0 GHz) compensating the beam squint in Rx instead of Tx is easier since the fractional bandwidth that the array elements need to operate is narrower. Hence from a bandwidth point of view, compensating in Rx is the easiest. Compensating in Rx also has the advantage that it is easy to ensure that the array elements are passive in Tx. If one considers cells <0.5 wavelengths at Rx, which is customary to avoid grating lobes, the array elements would usually be too small in Tx to provide any phase change and will therefore be passive. To compensate in Tx, one needs to ensure that an appropriate cell is selected for compensation in Tx without changing the response in Rx. However, manufacturing tolerances are better since the array elements operate at a lower frequency.

If one wants to compensate in both Tx and Rx, all the drawbacks mentioned above are present, e.g., wider fractional bandwidth in Tx, smaller manufacturing tolerances in Rx, etc. In addition, one needs to use dual-band elements which puts additional constraints on the bandwidth performance. However, the required beam scan is less since both the Tx and Rx beams are being compensated.

Overall by comparing the different methods, approach No. I seems most appropriate and is therefore the method that will be considered in this paper to demonstrate the proposed concept.

III. REFLECTARRAY ANALYSIS AND DESIGN

For the design of the reflectarray, the direct optimization technique (DOT) from [14] is used. The analysis method is based on a spectral domain method of moments assuming local periodicity (LP-SDMoM), and the optimization engine uses a gradient-based non-linear minimax optimization algorithm.

In [14], 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 also be used, albeit an extension is required. This extension is described in [15] and validated by comparison with the full-wave higher-order

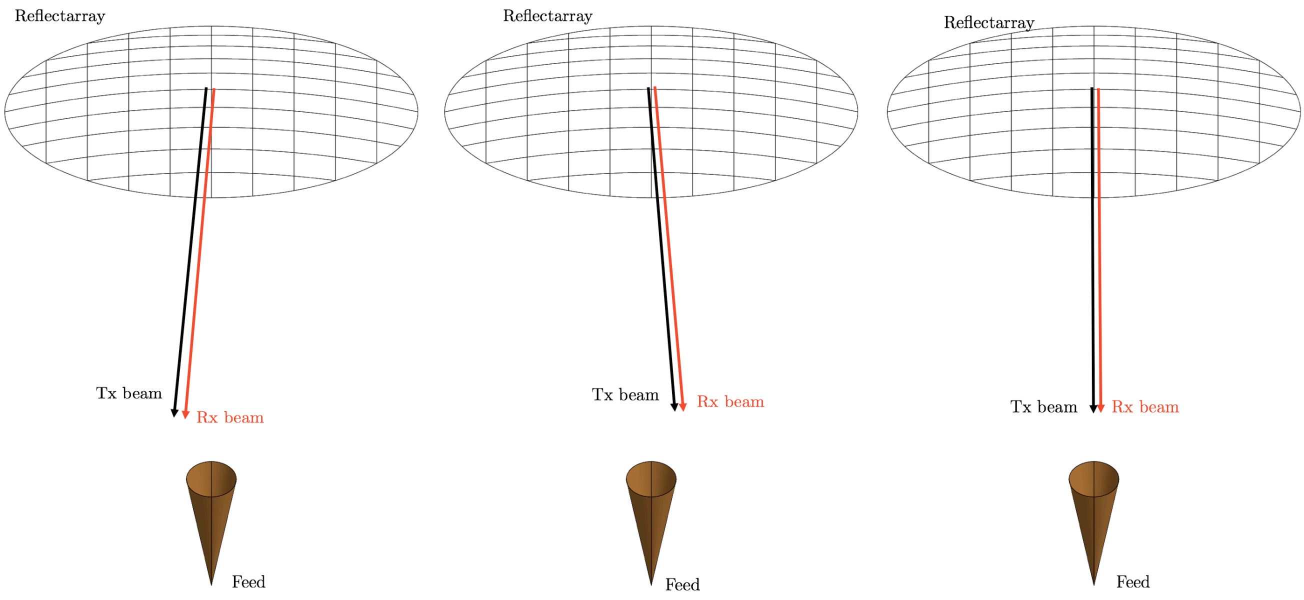

Figure 2: Different approaches to compensate beam squint using curved reflectarrays: a) compensate in Rx, b) compensate in Tx, and c) compensate in both Tx and Rx.

method of moments solver in GRASP [16]. The results show that the extended LP-SDMoM is very accurate for curved reflectarrays. Details of the extended LP-SDMoM will not be provided here and the reader is referred to [15] for more information.

IV. Concept Demonstration

A. Reflectarray Configuration

To illustrate the proposed concept, we consider Ka-band with Tx 17.8-20.2 GHz operating in LHCP and Rx 27.5-30.0 GHz in RHCP. As antenna configuration, we consider the offset reflector setup shown in Figure 3. The reflector surface is a paraboloid surface with a focal length of f = 0.722m and has a circular projected aperture of D = 0.633m. As feed, a dual circular polarized conical horn model with an aperture diameter of 56mm is used and provides with the reflector a 3dB beam width of approximately 1.9 degrees.

In Figure 4, the beams radiated by the reflector at 19.3 GHz (dotted) and 28.75 GHz (solid) are shown in an *uv*-grid. The contours show 0.5, 1.0, and 3.0dB below peak. As one can see, the beams squint in opposite directions in Tx and Rx, respectively, resulting in incongruent beams in the two bands.

B. Reflectarray Design

The conventional methods to construct reflectarrays that operate in circular polarization (CP) are using array elements with varying sizes [17] or array elements with varying rotations [18]. Although both methods generate CP, they work fundamentally different. If we consider only surfaces that reflect CP to CP, such surfaces can be classified according to their reflection properties:

1) The reflected field has the opposite sense of CP as the incident field (RHCP to LHCP and LHCP to RHCP),

2) The reflected field has the same sense of CP as the incident field (LHCP to LHCP and RHCP to RHCP).

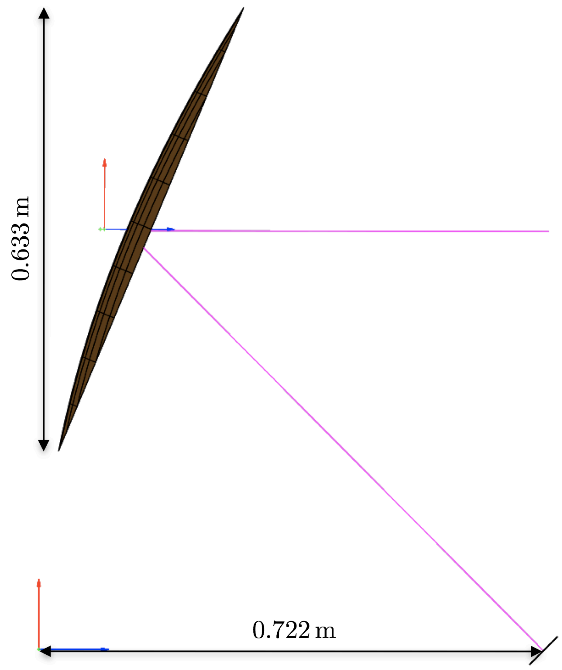

Figure 3: Offset reflector configuration

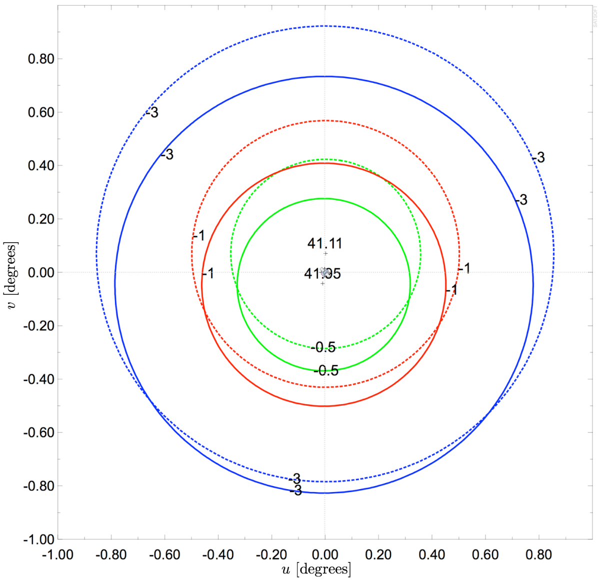

Figure 4: Radiation pattern of the reflector at 19.3 GHz (dotted) and 28.75 GHz (solid). The contours show 0.5 (green), 1.0 (red), and 3.0 dB (blue) below peak. The beams squint in opposite directions in Tx and Rx, respectively, resulting in incongruent beams in the two bands

Array elements with varying sizes belong to the first type, just like a solid conducting surface, whereas array elements with varying rotations belong to the second type. The choice of method is dictated by the feed. A conventional dual-band feed that operates in orthogonal polarizations in Tx and Rx needs array elements with varying sizes to ensure beams with orthogonal polarizations. In our case, for demonstration purposes, we will consider simple square patches as array elements.

Another important factor that needs to be considered is the choice of substrate of the reflectarray. When a reflector is coated by dielectrics, cross-polarization is generated in CP due to depolarization effects. This is particularly the case using solid dielectric materials, e.g., Rogers substrate. It is possible to optimize the array elements to compensate for this cross-polarization, but the cross-polarization will still be present in Tx unless dual-band elements are needed. This would, however, increase the complexity significantly and degrade performance, even if advanced elements are used.

To ensure low cross-polarization, RF transparent substrates should be used. This reduces the depolarization effects generated by the substrate and maintains the cross-polarization at a low level. To this end, RF transparent honeycombs with dielectric constants close to one are the best candidates as the support core and all bonding and structural reinforcement layers should have low permittivity and kept as thin as possible.

One possible layer composition is shown in Figure 5 which is also the sandwich configuration used for the reflectarray design in this paper. Such sandwich configurations are actually preferred for space applications to reduce mass and to avoid excessive RF losses. The sandwich also provides structural stability. For simplicity, the adhesives in the sandwich configuration are not included in the model since the modelling of these types of structures can be difficult due to ill-defined characteristics, e.g., thickness, air bubble, etc.

Note that the thickness of the sandwich is almost 2mm. This corresponds to approximately 0.2 wavelength at the Rx-band which is relatively thick. Usually, square patches used in conjunction with a thick substrate do not provide sufficient phase range to be used in practical reflectarray designs. However, for the application at hand, the reflectarray only needs to scan the beam a fraction of the beamwidth. With the assistance of the curvature of the reflectarray, this means that a reflection phase variation much less than 360º is needed. Using a thick substrate instead of a thin one, the bandwidth is also enhanced and ensures that the entire Rx-band can be covered.

When identical patches are deployed periodically over the surface of the reflector, the patches themselves causes a beam squint of a small fraction of the beam width. Thus, the patches need to be optimized to compensate for both the squint caused by the offset, but also the squint from the patches themselves.

Using a cell size of 4mm, the DOT is used to optimize the sizes of all the patches to compensate the beam squint in the entire Rx-band. Simulated results are presented in the following.

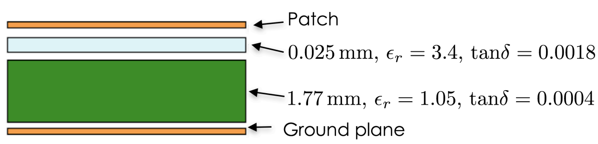

Figure 5: Reflectarray sandwich configuration.

C. Simulation Results

In Figure 6, the radiation patterns of the optimized reflectarray at the extreme and centre frequencies of the Tx and Rx-bands are shown. The contours show 0.5, 1.0, and 3.0dB below peak. The dotted curves show the Tx beams whereas the solid curves show the Rx beams. It is seen that the beam squint has been corrected and that the beams are now aligned in Tx and Rx.

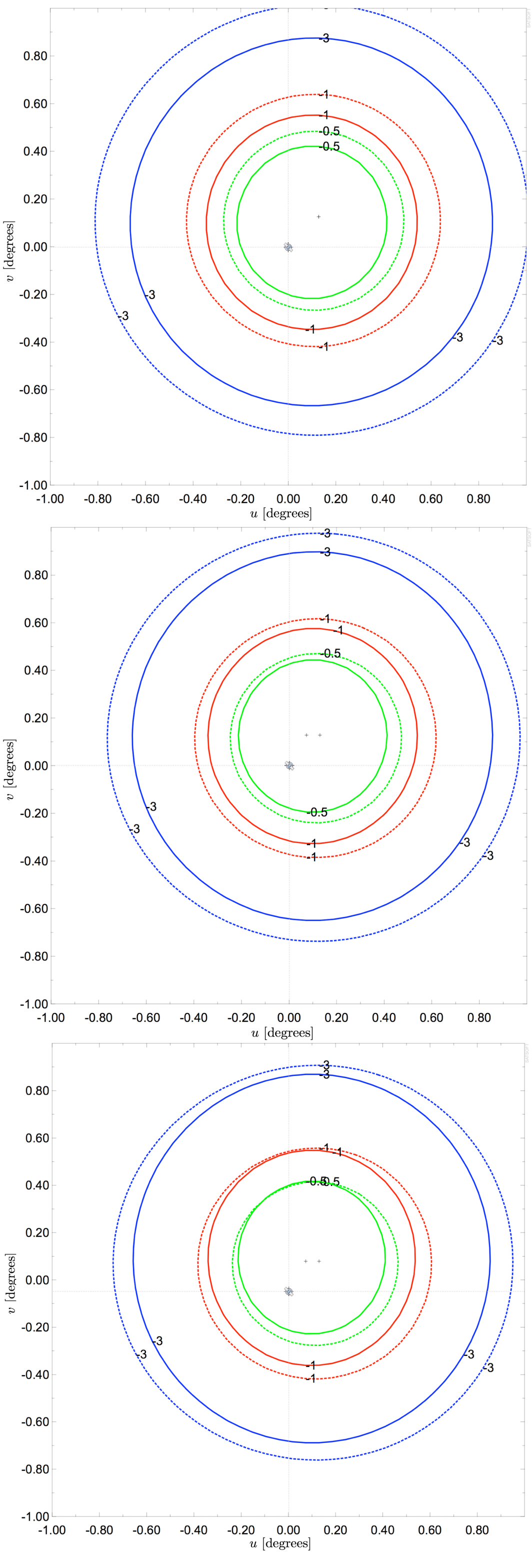

Figure 6: Radiation pattern of the optimized reflectarray. Top: 17.8GHz (dotted) and 27.5GHz (solid), middle: 19.3GHz (dotted) and 28.75GHz (solid), bottom: 20.2GHz (dotted) and 30.0GHz (solid). The contours show 0.5 (green), 1.0 (red), and 3.0 dB (blue) below peak. It is seen that the beam squint is compensated throughout the frequency bands.

It is noted that the beam peaks are slightly shifted with respect to the Tx beam peak in Figure 4. This is due to the aforementioned squint caused by the presence of the patches.

Concerning the cross-polarization levels, the radiation patterns in different planes are shown in Figure 7. It is seen that the cross-polarization is approximately 50dB below peak in Tx, whereas it is higher in Rx, approximately 30dB below peak. This cross-polarization is not generated by the reflectarray, but rather the feed model used in the design. If one plotted the radiation pattern of the nominal reflector without the patches, similar cross-polarization level is observed. If one uses an idealized Gaussian beam as the feed, the cross-polarization is approximately 40dB below peak. Similar patterns are observed for the other frequencies in the Tx and Rx band and are therefore not shown here. Consequently, it is safe to conclude that the cross-polarization from the reflectarray itself is very low.

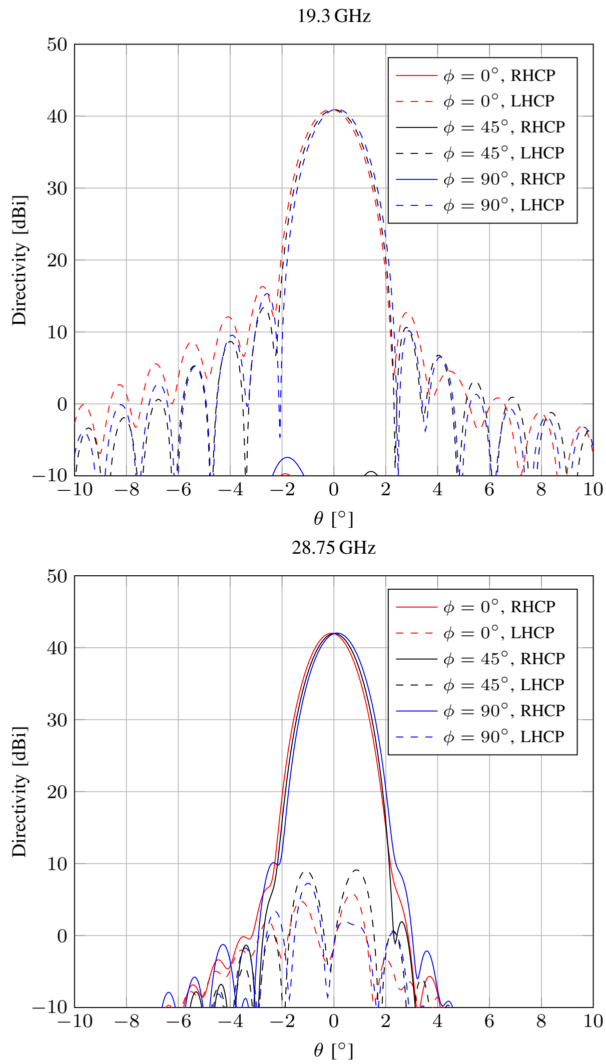

Figure 7: Radiation pattern of the optimized reflectarray shown in different planes.

The results presented in this paper demonstrate that curved reflectarrays can be used to compensate the beam squint of orthogonally polarized Tx/Rx offset antenna systems. The concept is very promising, but further investigations are still required to assess its potential for space applications, e.g., scan performance. Very simple array elements are used in this work. It is expected that improvements can be obtained if advanced array elements are utilized. This would also provide additional degrees of freedom to perhaps slightly enlarge the beams in Rx to have them coincide with the larger beams generated in Tx. Finally, the array elements need to be printed on a doubly curved surface and non-conventional manufacturing approaches are needed and require further investigations. Work in this direction is currently on-going.

V. CONCLUSIONS

We present in this paper a new application of reflectarrays for space. Using a curved reflectarray, it is possible to compensate for the beam squint that occurs in orthogonally polarized Tx/Rx offset antenna systems. Several approaches to achieve this are described. The idea is to use the reflectarray's phasing capabilities to compensate the beam squint in one band without affecting the beam in the other band, thereby making the beams in Tx and Rx coincide. Preliminary results using simple square patches have been presented. The results show that the optimized design compensates the beam squint, hence demonstrating the proposed concept. Further investigation on the topic is currently on-going.

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