Design and Analysis of a Reflector Antenna System Based on Doubly Curved Circular Polarization Selective Surfaces

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***Abstract*—This paper discusses the design and analysis of a reflector antenna system combining two doubly-curved Circular Polarization Selective Surfaces to provide a functionality equivalent to that of a dual gridded reflector but in circular polarization. The key feature of this design is to use a non-resonant CPSS design to avoid the bandwidth limitation of most CPSS designs previously discussed in the literature. A specific design at Ku-band is investigated and promising results are demonstrated, providing a cross-polarization discrimination higher than 25 dB over the full band.**

***Index Terms*—reflector antenna, circular polarization selective surface, doubly curved surface.**

I. INTRODUCTION

Dual gridded reflectors (DGR) for linear polarization (LP) have found widespread use for satellite communication antennas in geostationary orbit. They have the advantage to combine two independent reflector geometries on a same antenna configuration, thereby facilitating performance optimization and spacecraft accommodation. They also eliminate the cross-polarization due to offset geometries.

DGRs are mostly considered for contoured beams at Ku band. Current and future satcom applications require more bandwidth and bring the need to develop antenna solutions at higher frequency bands, such as Ka-band, at which circular polarization (CP) is the standard. The lack of antenna technologies offering the properties of DGR's in circular polarization was addressed in [1]. Several possible solutions were identified, but none was shown to be competitive both commercially and with respect to performances. Also, CPSS (circularly polarized selective surface) solutions were not addressed. For these reasons, further investigations were deemed necessary considering that the CP-equivalent of a DGR would enable potential reduction of mass, envelope and cost as compared to two separate reflector antennas for the same mission.

Two groups of potential solutions can be found in the literature:

a) The first one is given by CPSS solutions, which are the CP-equivalent of dual gridded surfaces. An ideal CPSS is able to reflect one CP and transmit the orthogonal one. Properties of reciprocal CPSS are described in [2] and suggestions on how to implement them are provided in [3]-[7], some including practical demonstration at sample level.

b) The second group of solutions consists of polarizers, typically from linear to circular polarization, which can either be placed in front of the linearly polarized feeds or located in front of the DGR.

Antenna geometries based on CPSS solutions use two distinct surfaces to independently reflect the two circularly polarized waves. The surface in the front has to be transparent to the polarized wave reflected by the surface in the back. The properties of the back-surface are dependent on the characteristics of the CPSS in the front. In order to do that, two configurations can be considered, as illustrated in Fig. 1. The first configuration uses two reciprocal symmetrical CPSS with orthogonal patterns (the CPSS is labelled according to the reflected incident polarization). The second uses a non-reciprocal CPSS (either symmetrical or asymmetrical) with a perfect reflector as back-surface. A third configuration could be to combine a reciprocal and symmetrical CPSS with a back-reflector, but this was discarded as it would generate multiple reflections for the signal going through the front surface.

The technical solutions described in the literature, [2]-[7], are all reciprocal-symmetrical CPSS. These solutions are usually resonant structures and consequently have limited bandwidth. Their performances are also optimized to incidence angles close to the normal of the surface and practical demonstration was only performed on flat samples. The elementary resonant patterns usually require a 3-dimensional design, asking for further mechanical investigations to produce non-planar surface shapes (such as a parabolic shape).

It was therefore the purpose of the ESA contract No. 4000108854/13/NL/MH "Circular Polarization Dual-Optics Proof-of-Concept" started in 2013 to study and develop a new doubly curved CPSS technology that could be used in future communication reflector systems. This paper discusses a promising broadband CPSS concept and its implementation in a dual-doubly-curved reflector geometry with particular emphasize on the modelling approach retained to accurately analyze the performance of the antenna system.

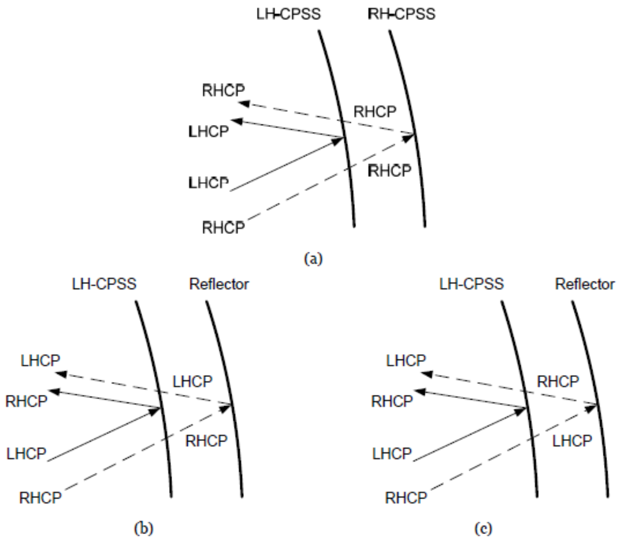

Fig. 1. Dual reflector CPSS geometries equivalen to DGR in CP: in (a) a reciprocal and symmetrical CPSS, in (b) a non-reciprocal and symmetric CPSS with a solid reflector and in (c) a non-reciprocal and asymmetric CPSS with a solid reflector.

II. THE CPSS TECHNOLOGY

The circular polarization selective surface developed in this work is based on a non-resonant concept of operation, consisting of five layers of anisotropic sheets realized by metal meander lines on thin substrates, interspaced by low permittivity materials as shown in Fig. 2. Each meander line axis is rotated 45 degrees with respect to the neighboring substrate, and each spacer has a thickness of $\lambda_0/8$, where λ_0 is the center wavelength of operation. This causes the meander lines to align with the electric field of a LHCP wave, which leads to strong interaction and reflection, whereas a RHCP wave interacts very weakly with the meander lines and is transmitted. In order to increase the bandwidth of the CPSS, the thickness of the spacers and the geometry parameters of the meander lines of each sheet have been optimized using full wave simulations in CST Microwave Studio. A detailed description of the design procedure, optimization, and performance of the structure is presented in [8]. The CPSS is modeled as a planar structure of infinite extent, and an exploded view of the unit cell is presented in Fig. 3. The meander lines are printed on thin substrates with thickness 0.1 mm, relative permittivity 2.62, and a loss tangent of 0.0114. The substrates are separated by low permittivity spacers with relative permittivity 1.1 and a loss tangent of 0.002, and the spacers and the substrates are glued together using thin bond films. When curving the structure, the individual meander line sheets will be shifted laterally with respect to each other, which causes changes in the unit cell geometry. This effect was simulated in the planar geometry and found to be of minor importance.

The resulting reflection and transmission coefficients were computed using CST for both polarizations and all angles of incidence from both sides. The data were then transformed into the tep-format used in GRASP to enable the analysis of a curved reflector in Section III.

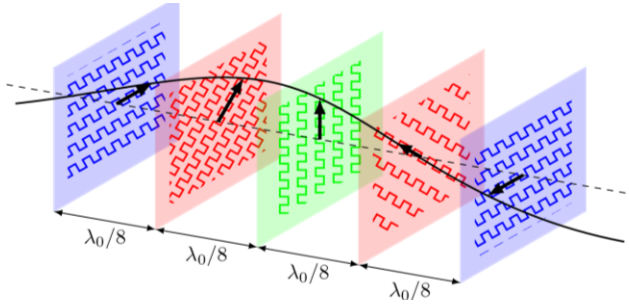

Fig. 2. Principal design of the CPSS. Metal meander line sheets separated by $\lambda_0/8$ are rotated 45 degrees with respect to the neighboring sheet. The electric field of a LHCP wave has been indicated at each sheet. In the final design, the sheet separation and meander line parameters are optimized using full wave simulations.

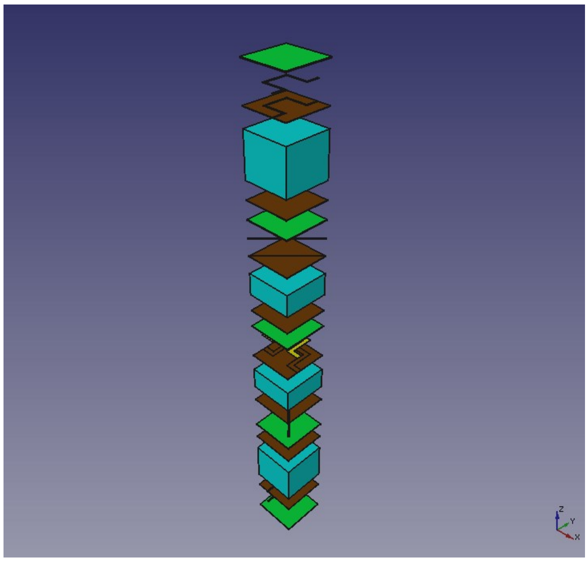

Fig. 3. Exploded view of the CPSS unit cell. Substrates are green, metal structures are yellow, bond films are brown, and spacers are cyan. The metal structures are embedded in the bond films, leaving an imprint.

The target frequency band was 10.75-14.5 GHz. Throughout this band, the final design achieved return loss and insertion loss better than 0.5 dB for all planes of incidence for an angle of incidence up to 30 degrees with respect to the normal direction. The axial ratio in reflection and transmission was better than 0.77 dB for almost all planes of incidence for an angle of incidence up to 20 degree. In some planes of incidence up to 30 degree angle of incidence slightly degraded performance can be tolerated. This is confirmed by the analyses presented in the following section. The performances achieved over the full band

[10.75-14.5] GHz by this CPSS technology surpass the ones found in the literature.

III. THE RECIPROCAL AND SYMMETRICAL CPSS REFLECTOR

The mission selected for the study is the CP-equivalent of a dual gridded reflector shaped in Ku band to illuminate the Australian coverage. The antenna is implemented in a reciprocal configuration, i.e. with two CPSS surfaces, according to Fig. 4. The front reflector is a reciprocal symmetric LH-CPSS reflector, which reflects an LHCP field to an LHCP field while an RHCP field passes through. The rear reflector is also reciprocal symmetric and is a RH-CPSS reflector, which reflects the RHCP field to an RHCP field, while a LHCP field passes through. By this set-up the field of an LHCP feed (the front feed) will, ideally, be reflected by the front reflector to an LHCP far field, and the field of an RHCP feed (the rear feed) will pass through the front reflector and will be reflected by the rear reflector to an RHCP far field, which again will pass through the front reflector to the far field.

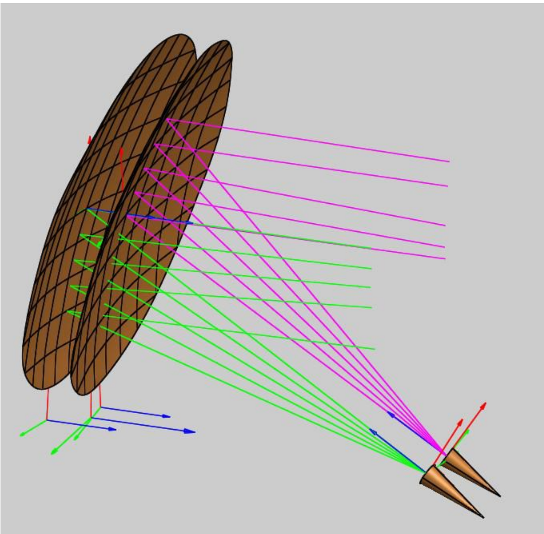

Fig. 4. The reciprocal CPSS reflector designed for the study: rays from the LHCP (in pink) and RCHCP (in green) feed are highlighted, as well as the rays reflected and transmitted by the CPSS surfaces.

The two reflectors have a circular rim, are 1 m in diameter and are displaced 0.6 m from the axis of the parabolic antenna. The parabolic surfaces have focal lengths of 1.0 m and 1.1 m for the front and rear reflector, respectively. The antenna is designed for the frequency band 10.75 – 14.5 GHz. The feeds are modelled as Gaussian beams with -12 dB taper at the edge of the front and rear reflectors.

The parabolic reflectors are shaped by POS at 12 GHz to an Australian coverage for a geostationary satellite at 130 deg East resulting in the non-parabolic surfaces seen in Fig. 4. The design goal for the CPSS material is that the antenna pattern shall have polarization purity – or cross polarization discrimination (XPD) – of at least 27 dB. The same goal applies for the CPSS material but a relaxation to an XPD of 25 dB is accepted for high angles of incidence.

The antenna properties were determined both when the reflectors are ideal CPSS reflectors, as well as when the reflectors are made by the CPSS technology described in Section II and optimized by Lund University. The CPSS surface is described in GRASP by a .tep file in which the transmission and reflection coefficients of the surface are given in a regular grid in the angles θ, the angle of incidence, and φ, the azimuth angle. The properties shall be given for incidence from the front side as well as from the back side. The antenna radiation is then computed by Physical Optics. The transmission and reflection coefficients for the ideal CPSS surfaces were computed analytically and do not depend on the angle of incidence. The coefficients provided by Lund for the CPSS structure of Section II were computed by CST with a 5 deg sampling in theta and phi. We will focus in the following mainly on the performances of the front reflector, i.e. the reciprocal symmetric LH-CPSS reflector.

For an ideal CPSS structure, the minimum co-polar gain within the coverage region is 29.4 dBi and 29.3 dBi at the centre frequency, 12.625 GHz, for the RHCP beam and the LHCP beam, respectively. By decreasing the frequency to the low end of the band, 10.75 GHz, the minimum gain decreases about 0.8 dB for both beams while the gain at the highest frequency, 14.5 GHz, decreases by 2.3 dB for both beams. The cross-polar fields are negligible when using the ideal CPSS surfaces and thus the XPD is not relevant. A plot of the antenna pattern for the LHCP coverage obtained from the LHCP front feed is shown in Fig. 5. Contours levels are in black at -1, -3, -5, -7 and -9 dB relative to the pattern peak. The green lines shows a map over the Australian region and the red polygon shows the coverage within which the field shall be evaluated.

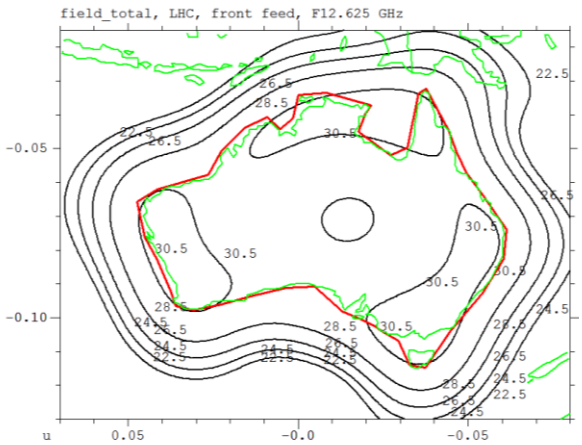

Fig. 5. Antenna pattern in dBi with ideal CPSS reflector surfaces at 12.625 GHz: LHCP coverage obtained from the LHCP front feed, the field is reflected in the front reflector, which is an ideal LH-CPSS.

For the real CPSS structure of Section II and a phi=45 deg orientation, that turned out to give the best cross-polar performances, the cross-polar pattern reaches levels between -3.81 dBi and 2.96 dBi within the coverage region, while the co-polar pattern is between 29.19 dBi and 31.29 dBi, at the centre frequency 12.625 GHz for the LHCP beam. The minimum value of the XPD is found to be 26.44 dB within the coverage region.

It was found that the cross-polar levels of Fig. 6 are due to the RHCP component reflected by the front LH-CPSS reflector. It is thus the reflection in the front reflector which causes the cross-polarization of the total field. In general, the cross polarisation in the total pattern arises from the scattering in the reflector which reflects the co-polarization (the front reflector for the front feed and the rear reflector for the rear feed). It is also seen that the cross-polar pattern has an overall shape which is the same as that for the co-polar pattern. This implies that it will not be possible to reduce the cross polarization by an additional shaping of the reflectors. Neither it will be possible to find a reduced cross polarization by moving or re-orientate the feeds. Any attempt to reduce the cross polar-pattern will change the co-polar pattern comparably and the XPD will not be improved.

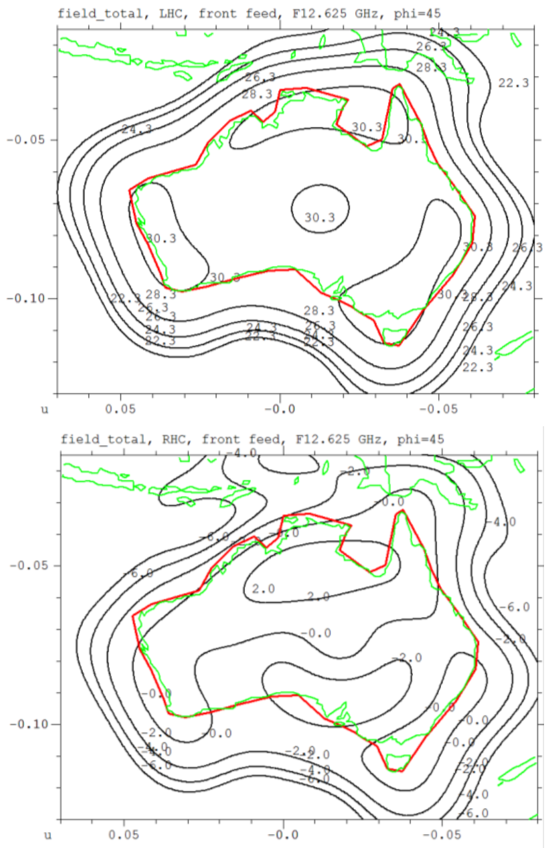

Fig. 6. Antenna patterns, total field, for the real CPSS reflectors at 12.625 GHz: LHCP coverage obtained from the LHCP front feed, CPSS orientation phi=45 deg. Above is the co-polar LHCP component, below the cross-polar RHCP component.

To summarize, when the ideal reflectors surfaces are replaced with the real CPSS, the minimum directivity of the co-polar field decreases up to 1.1 dB at the centre and the low end frequency for the RHCP beam. For the LHCP beam the decay is low, i.e. 0.2 dB or less. These values are practically independent of the orientation of the CPSS upon the reflector surface.

The minimum XPD within the coverage region for the left beam ranges from 25.5 dB at 14.5 GHz, to 26 dB at the centre frequency and 30 dB at 10.75 GHz. For the right beam, the XPD is slightly better, and equal to 29 dB at 14.5 GHz, 26.1 dB at the center frequency and 28.6 dB at 10.75 GHz. The relaxed goal at 25 dB is thus well fulfilled above the full Ku band for both beams.

IV. CONCLUSIONS AND PERSPECTIVES

This paper described the design and analysis of a reflector system combining two doubly-curved CPSS's. The proposed modelling approach enables to accurately evaluate the performance of the antenna system, taking into account the local angle of incidence. These results indicate that a CP-equivalent of a DGR may be feasible and compatible with demanding space application requirements, particularly in terms of frequency bandwidth.

The main difficulty lies obviously in the manufacturing of such a doubly-curved surface. Two main manufacturing techniques were envisaged for a demonstrator. One is to deposit metallic traces directly on a doubly-curved assembly of dielectric supports and spacers. The alternative one, more conventional, is to etch the metallic traces on flat thin dielectric surfaces (e.g. kapton) which are then conformed with an adequate stack of dielectric supports and spacers to reach the doubly curved shape. The first approach is quite attractive but limitations in the maximum size of the area that may be produced exist. The main challenge in the second approach is to find an adequate process to conform the layers' assembly. This second approach was selected as it had less constraints on the maximum size that could be manufactured. A doubly-curved CPSS demonstrator with a diameter of 750 mm and a Focal over projected Diameter ratio (F/D) of 1 has been manufactured and is currently under test. Further details on this demonstrator will be provided at the conference.

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