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Ultralight Deployable Multi-Modular Faced Reflectarray

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***Abstract*—This paper proposes a multi-modular and multi-faceted reflectarray antenna solution that reduces the weight and complexity of implementation. The antenna consists of multiple facets, not aligned among them, and following an equivalent parabolic reflector profile. The supporting structure of the antenna is stowed and deployed in several parts to accommodate the facets of the structure. Each facet consists of one or several modules with ultrathin and flexible surface that are independently deployed to conform the surface of each facet. The use of multi-faceted topologies enhances the electrical performance of the antenna compared to planar apertures and relax the accuracy constraints imposed in the reflector surface, compared to parabolic reflectors. A modular approach from mechanical and RF point of view is a more robust solution to overcome bandwidth limitations and deployment failures of large reflectarrays.**

***Index Terms*—antennas, reflectarrays, modular, faceted, deployable**

I. INTRODUCTION

The tendency to achieve higher data rates to fulfill the demanding services like those for telecom applications is to use larger antenna apertures to increase the directivity and fulfil the specifications of the mission in terms of throughput or measurement resolution. Accommodating larger aperture antennas on already quite loaded spacecrafts is a challenging task. Normally large parabolic reflectors are folded and stowed on the spacecraft body during launch, then they are deployed once the satellite is in orbit. The current commercial known solutions are based on ultralight mesh grid reflectors. This technology is difficult to apply to reflectarrays, where multifaceted techniques are considered to overcome the intrinsic bandwidth limitations of this technology, without having to consider curved reflectarrays which would be more difficult to implement, model and analyze.

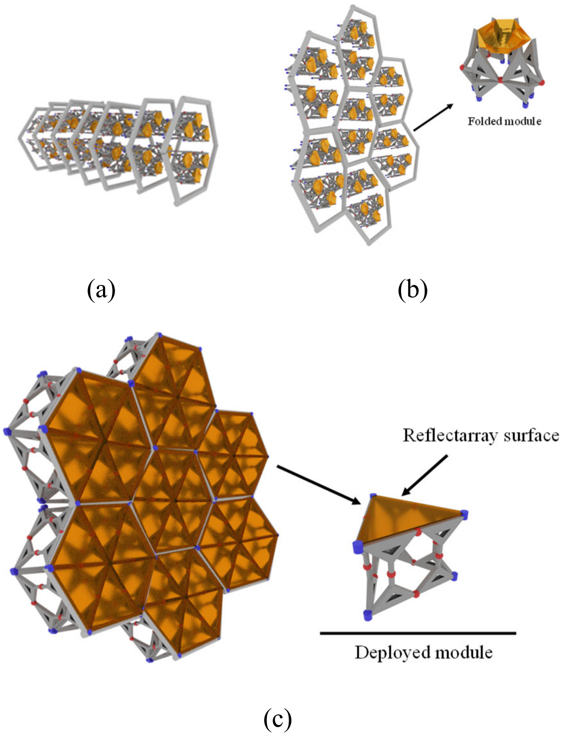

Fig. 1. Example of the proposed deployable structure: (a) antenna structure folded; (b) supporting structure deployed, faceted modules folded; (c) full antenna deployed.

Multifaceted technique is an approach where several flat panels with printed patches are used to emulate the behavior of a parabolic metallic surface, these apertures are based on reflectarrays technology. Flat reflectarrays have been used in several space missions such as [1], [2], where the aperture is divided in several flat panels that are aligned in the same plane. These antennas were deployed using a similar mechanism as solar panels. Although the concept was implemented successfully, using flat panels aligned in the same plane, exhibits an inherent narrow bandwidth which could not cover the specifications of other satellite mission, like those that provide telecom services.

Curved reflectors with a parabolic profile can provide advance performance in terms of bandwidth. The typical solution to deploy parabolic reflectors onboard satellites are the use of large deployable truss structure supported by tensioned cables [3] or the use of deployable mesh reflectors [4]. To approximate accurately the parabolic surface, both solutions require typically complex mechanical systems of tensioned cables. In addition, they are not modular, so the

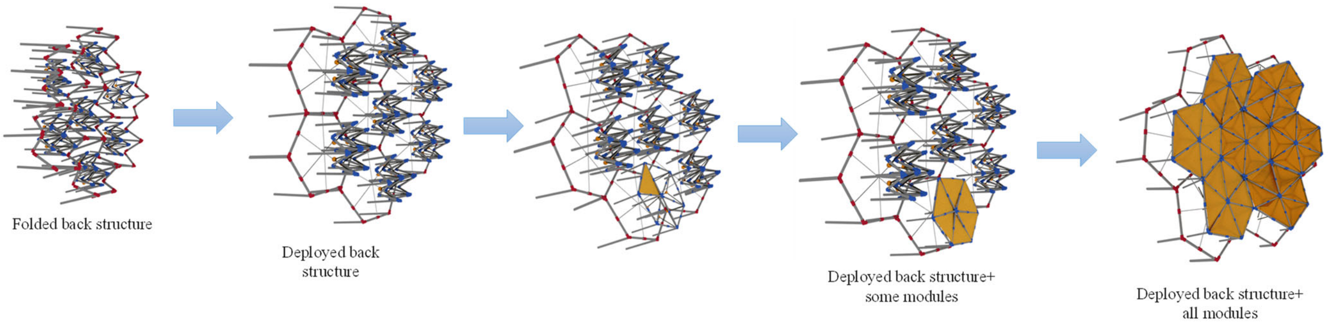

Fig. 2. Deployable mechanism step by step of the multi-modular and multi-faceted structure.

operation of the antenna is conditioned to the correct deployment of the entire supporting structure.

As an intermediate solution between parabolic and planar apertures, multi-faceted topologies can achieve acceptable antenna performance satisfying the electrical specifications of the satellite mission while simplifying the deployable mechanism using a modular approach. These structures, detailed in [5], are comprised of a plurality of not-aligned panels, assembled following an equivalent parabolic reflector. The panels are designed to introduce a phase in the ray path of the electric field similar to the one got in the ray path using a parabolic reflector, so the antenna can achieve acceptable in-band performance using several non-aligned panels. The supporting structure of the multi-faceted antenna is simpler than the one used in a conventional parabolic reflector. The multi-faceted antenna still requires supporting structures of truss and tensioned cables as parabolic reflectors [3], however the modularity approach requires simpler structures that would be more robust against deployment malfunctioning.

This contribution presents a multi-modular and ultrathin antenna structure composed by multiple and not aligned facets, suitable for multi-faceted reflectarray antennas. The topology is based on a supporting structure that allocates and helds each facet to provide a performance similar to the equivalent parabolic reflector. The proposed structure has been analyzed electrically, evaluating the features of using reflectarray technology in these surfaces over other type of materials. The proposed antenna concept is amenable for deployment on different aerospace platforms, such as for mm-wave terrestrial communications [6], and holds even greater potential for satellite communications.

II. DESCRIPTION OF THE MODULAR DEPLOYABLE MULTI-FACETED CONCEPT

Each facet of the structure is comprised by one or several deployment modules, integrated in the supporting structure. The modules can be polyhedral structures based on triangular prisms. The deployment mechanism of each module is independent from other modules and the supporting structure itself. The modules contain an ultrathin surface that can be stowed inside the module. After the deployment, the surface is tensioned by the back structure of the module, forming one facet of the antenna or part of it.

The thin surface could be made of a flexible ultrathin material that can conform a planar or curved facet. Alternatively, the surface can be composed of reflecting elements, designed properly, to compensate electronically the difference between the assembled antenna structure and the equivalent surface, i.e. the parabolic reflector surface.

The proposed antenna solution is modular since each facet is independently deployed to the supporting structure. The deployment modules are smaller and simpler, thus reducing the possible deployable errors. In addition, the proposed solution is more robust than other current alternatives to deployment failures. If one or several modules fail, the antenna can still work with some slight performance degradation.

An example of the structure is presented in Fig. 1. The antenna proposed consists of a multi-faceted aperture and a primary feed that illuminates the surface (see Fig. 1(c)). The multi-faceted surface consists of a multi-modular structure of multiple hexagonal segments, which can be folded in the spacecraft (see the grey truss in Fig. 1(a)). They can be thin fiber carbon and can be stowed following a similar concept as the one described in [3]. In a first step, a deployment mechanism of the segments is carried out, obtaining the mechanical approach presented in Fig. 1(b), which acts as the supporting structure of the surface. The mechanical structure locates each one of the hexagonal facets properly to follow a parabolic profile. To do this, a system similar to the one described in [3] can be used. A back network of tensioned cables, truss, and interlayer vertical pillars can be used instead.

According to Fig. 1(b), each segment or facet is comprised by several folded modules. The modules can be polyhedral units with small volume and high stowage capacity. The units can be tetrahedral mechanical units as the one shown in Fig. 1(b) or another polyhedral topology as the one proposed in [7]. Each unit contains a flexible material, which could be Kapton. In a variant, the flexible surface can be rolled around the module unit and follow a deployment mechanism as detailed in [8].

Following an independent deployment mechanism, each module is deployed, tensioned the flexible material as shown in the detailed sketch of Fig. 1(c) and Fig. 2. After this process, the entire surface is deployed as shown in Fig. 2.

III. TECHNICAL RESULTS

Some preliminary investigations have been conducted for the EM characterization of the deployed multi-modular structure, focusing on the electrical performance of the topology, once it is fully deployed in the satellite platform, as shown in Fig. 1.

A. *Analysis of ultrathin reflectarray cells on Kapton*

As aforementioned, the mechanical specifications required for the modular structure demand the use of a space-qualified dielectric substrate for flexible printed circuits, which could be Kapton. Kapton laminates are thin substrates, with a typical thickness below 1 mm, a dielectric constant about 3.5 and a loss tangent of 0.002. The limited thickness of Kapton results in single-layer narrowband reflectarray cells with abrupt phase variations and small phase ranges. However, the multifaceted design approach reduces the complexity of the reflectarray phase distribution, makes it more robust against cells limited in phase, and improves the overall antenna bandwidth. Thus, the implementation of this modular antenna structure can make it feasible to use Kapton as a substrate.

In this section, four single-layer reflectarry cells based on Kapton have been analysed to check the phase performance of the cell, with a period (p) of 5 mm, corresponding to half the wavelength in free space at 30 GHz. The analysis considers two different thicknesses for the Kapton sheets: h=0.25 mm and h=0.5 mm, and two different resonant elements: a single patch (or dipole) and a multi-resonant element based on 5 parallel dipoles, as shown in Fig. 3. The multi-resonant element maintains the symmetry with respect to the central dipole. The width of the central and lateral dipoles is 0.5 mm and 0.3 mm, respectively. The distance between the centre of the central dipole and the centre of the lateral dipoles is 0.8 mm and 1.4 mm. After a parametric study of the cell, the scale factors that relate the lengths of the lateral dipoles with the length of the central dipole have been defined as 0.98 and 0.96 for the 0.25 mm Kapton cell, and 0.93 and 0.89 for the 0.5 mm Kapton cell.

The phase curves of the single-resonant (SR) and multi-resonant (MR) cells when the lengths of the dipoles are increased are shown in Fig. 4, considering a periodic environment. The phase curves show fast phase variations for the 0.25 mm Kapton cell, which can be slightly smoothed by the MR configuration. Note that the MR element has been proposed to smooth the phase-shift associated with the first resonance of the cell, as the extremely thin Kapton prevents a typical linear phase response based on the combination of the multiple resonances. As a first solution, the use of a thicker substrate (0.5 mm) improves the phase response in both SR and MR configurations, practically achieving a complete 360º phase range. The MR cell with 0.5 mm Kapton substrate presents the most linear phase curve. Fig. 4 includes a yellow area indicating the zone of operation of the dipoles for the 0.5mm Kapton MR cell.

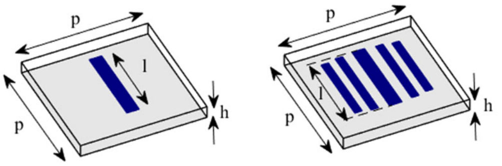

Fig. 3. Single-resonant cell (left) and multi-resonant cell based on 5 parallel dipoles (rigth).

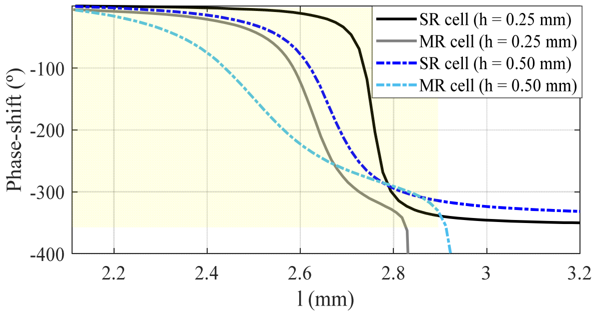

Fig. 4. Phase-curves of the proposed reflectarray cells.

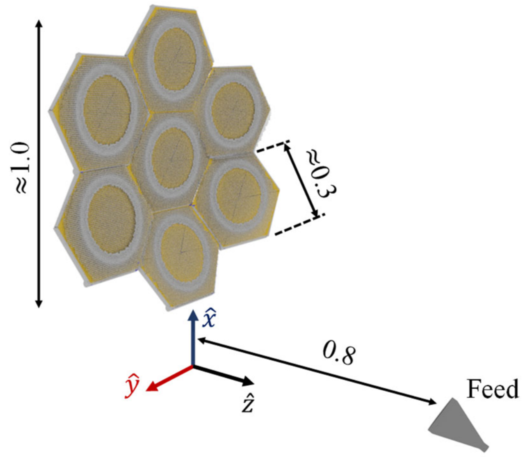

Fig. 5. Perspective view and antenna optics of the deployed multi-modular structure considered for the EM analysis. All dimensions in m.

B. *Analysis of a multi-modular and multi-faceted structure based on reflectarray technology*

The following section is devoted to the EM characterization of a deployed multi-faceted reflectarray based on the proposed multi-modular approach. The antenna example is designed at 30 GHz to provide a directive beam in the broadside direction of the antenna system.

Fig. 5 presents the optics of the proposed structure: it comprises by 7 hexagonal flat surfaces of 335 x 335 mm (they can be formed by multiple tetrahedrons that the ones illustrated in Figs. 1 and 2). Each facet is properly tilted following an equivalent parabolic reflector in several planes. The total aperture of the structure is about 1.0 m.

The multi-modular structure is spatially feeding by a primary feed in the focus of a single-offset configuration. This source is modelled as a $\cos^q$ function adapted to the radiation pattern of a 15 dBi horn antenna. At 30 GHz, the q factors in the E- and H-plane are 5.4 and 5.8 respectively. The subtended

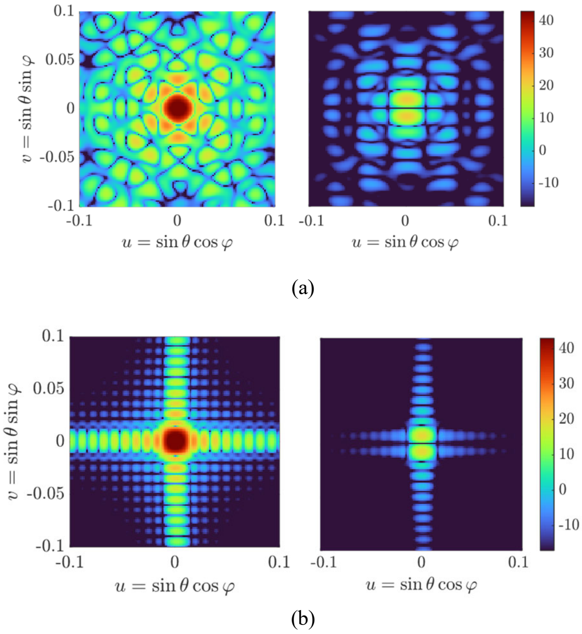

Fig. 6. Simulated co-polar and cross-polar radiation pattern [dBi] in (u, v) coordinates at 30 GHz of (a) the multi-modular structure and (b) its equivalent parabolic reflector.

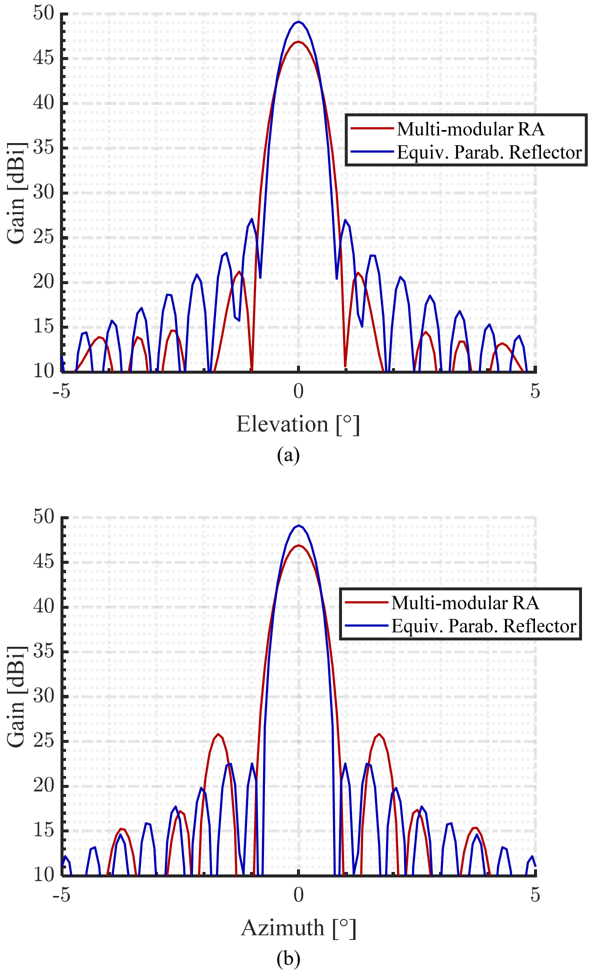

Fig. 7. Simulated co-polar radiation pattern at 30 GHz of the multi-modular structure (red line) compared with an equivalent parabolic reflector (blue line).

angle between feed and multi-modular approach is roughly 36º and the f/D ratio is about 0.8.

Based on this antenna optics, each module is comprised of 765 radiating elements that could be similar to the unit-cell presented in the above-mentioned section. In this analysis, the radiating elements are modelled as an ideal phase-shifters (i.e. they reflect perfectly the wave that impinges the cell and introduce a certain phase-shift on it [9]). The required phase distributions in each facet have been obtained using the analytical expression reported in [10]. Here, it is applied to generate a high-gain beam pattern in the broadside direction$(\theta_0, \varphi_0) = (0.0, 0.0)°$, according to the coordinate system shown in Fig. 1.

The radiation pattern of the multi-modular structure is obtained using an electromagnetic simulation, whose procedure is described in [10]. Figs. 6 and 7 depict the radiation pattern of the proposed multi-modular structure compared with the one provided by an ideal parabolic reflector with equivalent projected aperture. The reflectarray-based structure generates a high-gain pencil beam pattern with a half power beamwidth (HPBW) of 0.7º x 0.7º and a side lobe level 21 dB lower than its maximum. Compared to its equivalent parabolic reflector, the multi-faceted approach features a gain reduction, that could be attributed to the higher side radiation and cross-polar values observed in Fig. 6(a), compared to the pattern obtained for the equivalent reflector (see Fig. 6(b)). Including an optimization technique during the design process, could reduce the difference between these two patterns.

IV. CONCLUSIONS

In this work, authors propose a multi-modular and multi-faceted structure suitable for reflector antennas, especially the ones based on reflectarray technology. The mechanical scheme comprises several modules integrated with a back supporting structure, which allocates each one with the proper tilt and location. The modules consist of a thin material, which could be flexible, a priori folded in the system. Each module has a deployment mechanism independent from the supporting structure or other modules, so this mechanical concept exhibits higher robustness against possible failures.

To evaluate the electrical performance of antennas supported by this structure, some studies based on electromagnetic simulations have been carried out. In the former, an example of multi-modular and multi-faceted structure has been designed and numerically assessed. The proposed structure comprises several modules that conforms seven hexagonal facets, distributed following a parabolic profile. A comparison between the use of metal and reflectarray technology in the module has been performed. Such investigations demonstrate that the use of surfaces with reflectarray technology could generate directive beam patterns, using a lower number of modules (and therefore facets) compared to the use of surfaces based on metal. Also, the multifaceted antenna configuration reduces the complexity of the antenna phase distribution, making it possible the use of ultrathin flexible dielectrics for the unit-cell.

The result of this study demonstrates the potential of multi-faceted structures to provide advanced electrical performance that meet the constraints of different space missions. These topologies can be folded and deployed using a simplify modular deployable mechanism like the one proposed here, they show high stowage capacity reducing the cost of conventional deployable reflectors systems, to fulfil the volume constraints that typically exists onboard satellites.

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