A Foldable and Reconfigurable Monolithic Reflectarray for Space Applications

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ABSTRACT An origami-based foldable and reconfigurable Reflectarray Antenna (RA) with multiple apertures is proposed for CubeSat applications. The proposed configuration consists of a central RA embedded in folding panels using Lamina Emergent Torsional (LET) joints based on compliant mechanisms. Depending on the folding direction of these panels (forward or backward), a new RA aperture is formed. The proposed RA along with its folding panels and hinges is fabricated using only a single PCB. A prototype of such an RA with two foldable panels is fabricated and measured. This RA operates in the Ku-band at 16 GHz and provides two pencil beams pointing at \((\theta = 30^\circ, \phi = 0^\circ)\) and \((\theta = -30^\circ, \phi = 0^\circ)\), and a dual-beam pointing at \((\theta = +27^\circ, \phi = 0^\circ)\) and \((\theta = -29^\circ, \phi = 0^\circ)\). The proposed RA provides a gain of 25 dB and 19 dB in its single- and dual-beam operations, respectively. For CubeSat applications, the key advantages of this RA are its small stowed volume, reconfigurable EM performance, beamsteering capabilities, monolithic construction, low fabrication cost, and reduced complexity.

INDEX TERMS CubeSat, reflectarray, surrogate fold, pattern reconfiguration, LET joint, compliant mechanisms, origami based.

I. INTRODUCTION Cubesat missions for low-earth orbit have seen significant growth over the last decade offering new opportunities to expand space exploration. Two of their main advantages are their short design time and low fabrication cost. Such space communication systems require High Gain Antennas (HGAs), including Reflectarray Antennas (RAs) [1], and parabolic reflectors [2]. Foldable panel RAs [3–8] are the most commonly used concept for CubeSat HGAs. Compared to fixed systems, one-time deployment foldable RAs offer small stowed volumes, low mass and low cost, but typically only radiate towards a single pre-defined direction.

Many applications require communications towards multiple directions, i.e. beam-scanning or radiation diversity. This is typically achieved through beamsteering. RAs can realize beamsteering electronically by controlling the phase of each unit-cell using pin-diodes [9], RF-MEMS [10], or varactors [11]. Beamsteering has also been realized by a mechanical displacement of the feed [12, 13] and by rotating individual elements of RAs using micromotors [14]. However, implementing these beamsteering techniques in CubeSat RAs is challenging, as it increases losses, cost, and power consumption.

Rather than electronically controlling the phase, mechanically displacing the feed, or actuating individual RA elements, a folding system can be used to mechanically replace the active RA panels with panels of entirely different properties. This could be achieved by using foldable RAs with multiple panels of varying beam configurations, i.e. pencil beams or dual-beams. In this paper, an origami-inspired reconfigurable monolithic RA with foldable panels and LET joint surrogate hinges is presented. The proposed design is shown in Fig. 1, and it consists of a combination of multiple
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The paper is organized as follows. A background review on previous foldable reflectarray designs is presented in Section II. The RA design is presented in Section III. The numerical analysis is carried out using ANSYS HFSS. The mechanical design of the hinge is presented in Section IV. The simulated and measured results are presented in Section V. Finally, conclusions are drawn in Section VI.

II. BACKGROUND
In order to better understand the work proposed in this paper, we review previous foldable reflectarray designs, and surrogate hinges.

A. FOLDABLE REFLECTARRAY DESIGNS
Folding has been used to efficiently pack arrays in small stowage compartments. To be used, such arrays unfold to deploy thereby increasing the operating aperture of the array. Likewise, our proposed RA has the advantage of compact stowage, while also providing reconfigurability since it uses foldable panels to form/change its radiating aperture.

Previously proposed foldable panels have been typically attached to one another using spring-loaded hinges [3], [4], which require longer assembly times and a larger number of components, thereby increasing the production cost of RAs. While these hinges allow for initial actuation and deployment via stored strain energy and may have locking mechanisms for the panels to maintain a flat surface, the metal hinges have the potential of interfering with the electromagnetic radiation of the arrays which degrade the performance. Alternatively, flexible PCBs can be used to replace hinges altogether. However, when flexible PCBs are creased to form hinges, they experience a deterioration of their mechanical integrity that can lead to cracking. Also, RAs on flexible PCBs must use supports for their structural integrity, which in turn increases their complexity and cost.

Another alternative to traditional hinges is the use of materials that are easily folded such as membranes. In [6], a folding and rolling membrane RA was proposed to achieve a high packing efficiency for large apertures, while reducing weight (since this RA was made from a membrane substrate and not printed on rigid PCBs). However, the design required a complex folding mechanism (folding and rolling).

A membrane RA was also proposed with an inflatable actuation mechanism in [7]. While this system is suitable for large RA apertures (≈11.9m²), and has high packing efficiency, it requires a three-step assembly (frame, membrane and suspension). Additionally, this design has large mass-to-area ratio (1.93 kg/m²), where the frame and suspension system represent 80% of the total weight of the reflectarray, which increases fabrication and launching costs. While RAs based on membrane structures offer many benefits, they are susceptible to the harsh space environment.

RAs ($RA_1$, $RA_2$, $RA_{12}$, and $RA_{21}$) that provide mechanically reconfigurable radiation properties (single and dual-beam) and beamsteering, while reducing the cost due to fewer parts, simplified manufacturing, and no need for maintenance. Notably, this work advances the designs of [3], [4] by: (a) enabling EM reconfigurability without requiring active RF components, (b) utilizing LET surrogate hinges instead of spring-loaded hinges, and (c) studying the performance of the proposed reflectarray for various panel misalignment conditions. Also, to the best of our knowledge, our work is the first to propose a monolithic space reflectarray antenna that incorporates built-in hinges and provides beam reconfigurability.
Moreover, the designs in [3], [4], [6] and [7] do not provide any EM reconfigurability. Additionally, traditional mechanical hinges and systems require maintenance (joint lubrication or replacement). The work in this paper builds upon this previous research to enable mechanical reconfigurability through the use of surrogate hinges.

## B. SURROGATE HINGES

In place of traditional hinges or flexible PCBs, surrogate folds can be used to make otherwise stiff PCBs foldable. A surrogate fold is a geometrically designed section between rigid panels used to locally reduce stiffness, resulting in a folding motion between panels similar to a paper crease. Many types of surrogate folds have been developed and designed for various motion and loading conditions [15]. Work has been done to characterize surrogate folds [15], [16]. In most applications it is desired that a surrogate fold has motion similar to a traditional pin-joint hinge, allowing rotation around one axis and restricting all other motion. However, introducing surrogate folds can introduce extra, undesired degrees of motion, referred to as parasitic motions.

A commonly used surrogate fold is the Lamina Emergent Torsional (LET) joint. The LET joint is compliant, meaning that its motion is enabled through the deflection of the material. In the case of a surrogate fold, the deflection allows pin-joint-like rotation for the two connected panels. This enables origami-based folding of patterned panels by allowing the needed rotation along the joint while minimizing the joint footprint on the panels. LET joints have been used in space applications [16], antennas arrays [17], [18], parabolic antenna design [19], precision adjustment target shrouds [20], and robotic surgical instrument design [21]. LET joint surrogate hinges can also be used to maintain electrical continuity across joints.

For this work, a LET joint surrogate fold was chosen for use in our foldable RA design for the following reasons:

- Allows 180° motion in both a forward and backward direction for array packing and EM reconfigurability
- Single-piece design that can be made straight into panel material (monolithic)
- Simple manufacturing process
- No assembly needed during manufacturing
- Low part count
- Lower weight due to lower part count
- No need for maintenance (joint lubrication or replacement)

This work utilizes a LET surrogate hinge design to enable a mechanically reconfigurable monolithic RA with foldable panels.

## III. REFLECTARRAY DESIGN

Multiple RA apertures were optimized to radiate towards a desired direction and were arranged so that when the panels are folded forward or backward a new RA aperture is illuminated. Each RA aperture is optimized with two foldable panels to provide three different combinations that correspond to three different radiation patterns: two single pencil beams \((RA_1\text{ and } RA_2)\) and one dual-beam \((RA_{12}\text{ or } RA_{21})\). The principle of the dual-beam radiation pattern is based on dividing the reflectarray surface into two sub-arrays, where each sub-array can radiate a beam toward a desired direction, [23].

In summary, the proposed design consists of a combination of multiple RAs that can be packed into a single RA in an efficient manner, as shown in Fig. 1. The folding abilities of the RA may also be used to achieve electromagnetic reconfigurability (e.g., beamsteering, polarization reconfigurability and/or frequency reconfigurability). Additionally, these multiple arrays are packed into a single reflectarray to save space, as shown in Fig. 1. This monolithic design can be manufactured in a single process and provides the capability of on-site manufacturing (i.e., can be made in space or other planets), which is a highly desirable feature in space exploration applications. The proposed RA exhibits better performance, lower losses, and lower cost compared to state-of-the-art CubeSat RAs. In addition, our RA uses LET joint surrogate hinges to allow the needed folding motions using a simple, and low-cost reflectarray structure, which enables multiple beam configurations, i.e., pencil beams or dual-beams. These hinges will be detailed further in Section III.

### A. UNIT CELL

The simulations of the proposed RA unit cell element were performed using ANSYS HFSS with master-slave boundaries, as shown in Fig. 2(a). The unit-cell was designed to operate in the Ku band with a center frequency of 16 GHz and inter-element spacing of 18.75 mm \((0.5\lambda_0)\). The unit
cell is a square patch on a Rogers RO5870 substrate ($\varepsilon_r = 2.33$, $\tan \delta = 0.0013$, thickness = 30 mil). The phase and amplitude responses of the unit cell for various patch sizes were simulated for normal incidence as well as for incident angle of $\theta = 30^\circ$ at 16 GHz, as shown in Fig. 2. It is seen that a $310^\circ$ range of reflection phase response can be achieved with a maximum loss of 0.4 dB.

**B. REFLECTARRAY SYNTHESIS**

To simplify the design and prove the concept, only two foldable panels are used, attached on either side to a larger stationary panel (see Fig.1). This RA configuration provides four different sub-configurations of RA apertures, each with 20 × 20 elements. Namely, $RA_1$ and $RA_2$ with independent single pencil beams, and $RA_{12}$ and $RA_{21}$ with dual-beams. Specifically, $RA_{12}$ and $RA_{21}$ are obtained by using a panel from $RA_1$ and a panel from $RA_2$. The four apertures along with their LET joint surrogate hinges are shown in Fig. 1. These hinges enable the RA panels to fold and unfold in order to change the RA’s aperture between the four configurations.

A linearly polarized horn with a gain of 14 dB is placed at 8.42 from the center of the RA with an offset of $20^\circ$ in the $yz$-plane, which corresponds to a $f / D$ of 0.8. The required phase shift $\phi_i^j$ for the $i$th element on each aperture is calculated using the ray-tracing method, as follows

$$\phi_i^j = k (-\vec{r}_i \cdot \hat{u}_0 + r_f) + \Delta \phi_0$$  \hspace{1cm} (1)

where $r_f$ is the distance between the $i$th element and the phase center of the feed, $\hat{u}_0$ is the unit vector in the observed main beam direction, $\vec{r}_i$ is the position vector of the element, $k$ is the wavenumber and $\Delta \phi_0$ is a constant reference phase, which is set to zero in the calculations.

Apertures $RA_1$ and $RA_2$ are designed to provide pencil beams towards directions ($\theta = 30^\circ$, $\varphi = 0^\circ$) and ($\theta = -30^\circ$, $\varphi = 0^\circ$), respectively. Notably, these two beam-directions are chosen arbitrarily for demonstration purposes. Also, as explained above aperture $RA_{12}$ is formed when the right panel of $RA_2$ is folded forward and the left panel backward and vice versa for aperture $RA_{21}$ as shown in Fig.1. Apertures $RA_{12}$ and $RA_{21}$ provide dual beams as will be shown below. The phase distributions of the four apertures are calculated using (1) and plotted in Fig. 3.

**C. ARRAY THEORY RESULTS**

The radiation patterns are calculated using array theory and are shown in Fig. 4(a) for the four sub-configurations of the folding panels. It is clearly seen that $RA_1$ and $RA_2$ provide single pencil beams toward the intended directions while exhibiting a low side-lobe level of $-21$ dB. Also, $RA_{12}$ and $RA_{21}$ provide dual-beam radiation patterns with peaks towards the intended directions. However, in the dual-beam configurations, the beam at $\theta = -30^\circ$ is 2 dB and 0.6 dB higher than the beam at $\theta = +30^\circ$ for $RA_{12}$, and $RA_{21}$, respectively.

In order to explain this degradation in the beam at $\theta = +30^\circ$, Fig. 4(b) shows the reflected waves on $RA_{12}$ and $RA_{21}$. It can be seen, that in $RA_{12}$ the reflected waves interfere with each other whereas in $RA_{21}$ this interference is not present. Notably, the better performance of $RA_{21}$ is due to each panel reflecting the incidence wave towards different directions, not by constructive interference.

In addition, the radiating elements from $RA_2$ are closer to the feed by 4 mm than the radiating elements of $RA_1$, where this difference is contributed by the offset of the hinge when $RA_2$ panels fold forwards. Thus, the radiating elements from $RA_1$ have a slightly lower spillover efficiency since they are farther from the feed; this contributes to a 0.6 dB drop at $\theta = +30^\circ$. Assuming a similar gain drop occurs in $RA_{12}$ for the same reason, it can be deduced that the reflected wave interference in $RA_{12}$ (explained above) is the cause of the additional 1.4 dB gain drop towards $\theta = +30^\circ$. In the case
that our proposed RA needs to provide dual beams, RA_{21} is chosen as the aperture of choice since it provides higher gain than RA_{12}. Therefore, for the rest of this paper, the performance of our proposed RA will be studied only for its three optimal states RA_1, RA_2, and RA_{21}, whereas RA_{12} will not be considered as it is not optimal.

Moreover, both RA_{12} and RA_{21} sub-configurations exhibit a high SLL of $-9$ dB. The level of these side lobes can be reduced by increasing the number of elements in the sub-arrays RA_{12} and RA_{21}, as shown in Fig. 5. Figure 5 compares the beams of RA_{21} with a different number of elements. It is also seen that RA_{21} arrays with a larger number of elements have narrower beams.

IV. SURROGATE HINGES

Two surrogate hinges are introduced in the design to make the RA foldable as shown in Fig. 1. These surrogate hinges are realized by making slots on a single piece of thick, rigid material (in this case, PCB). The slots create LET joints that allow the rigid structure to rotate around the axis of the hinges by placing the long segments of the joints into torsion. The hinges are appropriately designed to bend $\pm 180^\circ$, while maintaining mechanical integrity. Placing these surrogate hinges on either side of a solid PCB panel enables the spatial reconfiguration of the RA into the four folding states shown in Fig. 1.

The exact dimensions of the LET joint hinge are dependent on the thickness of the panel, desired total angle of panel rotation, desired stiffness, and the mechanical properties of the material. For this work, 0.787 mm thick Rogers 5880 RA high frequency laminate with 0.5 oz copper cladding was used in this foldable RA. It is important to note that this design could be adjusted for different materials and thicknesses to achieve various ranges of motion and stiffnesses.

An example of a LET array surrogate hinge is shown in Fig. 1(b), with several individual LET joints placed in series and in parallel. A detailed diagram of the LET joint dimensions used in this design is shown in Fig. 6.

The rotational stiffness of a LET array in the out-of-plane ($x$-direction) is

$$k_{eq,x} = \frac{P k_T k_B}{S(k_B + (\frac{2p+1}{p+1}) k_T)} + k_l$$

where $k_T$ is the stiffness of the torsional sections, $k_B$ is the stiffness of the bending sections, and where $P$ and $S$ are the amount of LETs in parallel and series, respectively [16]. The in-plane rotational stiffness ($y$-direction) is given by

$$k_{eq,y} = \frac{\delta M_y}{\delta \beta}$$

where $M_y$ is the bending moment about the $y$-axis and $\beta$ is the rotational displacement. Unlike the stiffness about the $x$-axis (Eqn. 2), the stiffness about the $y$-axis is nonlinear and requires an iterative solution. Ref. [16] describes the algorithm to determine the stiffness about the $y$-axis. DeFigueiredo [22] showed that the maximum Von Mises equivalent stress in an S-series LET array is

$$\sigma_{max} = \frac{2 k_T k_B \theta}{S(k_T + 2k_B)} \sqrt{\frac{9}{w_B^4} + \frac{3}{4Q^2}}$$

where $\theta$ is the angle of rotation of the whole array in radians, $t$ is the thickness of the array, and $Q$ is a geometry dependent parameter defined as

$$Q = \frac{w_T^2 t^2}{3w_T + 1.8t}$$

A. LET ARRAY DESIGN OPTIMIZATION

An optimization routine was performed to define dimensions for the LET array joint. While the desired motion of the LET joint is an out-of-plane rotation, other undesirable “parasitic” motions can also occur as the joint has 6 degrees of freedom (DOF). Researchers have characterized LET joints according to many of these DOF [16], [22], [24]. The surrogate joint is used to simulate a pin-joint and precise motion of the joint is important. For these reasons, the purpose of the optimization was to maximize the resistance to in-plane rotation (parasitic motion) in comparison to out-of-plane rotation (desired folding) of the array. These motions are shown in Fig. 7. This was quantified by using the ratio of the stiffnesses ($k_y/k_x$) as defined in [16].

The optimization was constrained to design a LET array that would not fail due to stresses when folded as defined in [22]. Other constraints imposed were that the width, $W$, of the LET array had to be equal to the width of the panels, $w_{array}$, and that the LET array length, $L$, needed to be less than or equal to a specified length, $l$, see Fig. 6. Concisely,
FIGURE 7. Two modes of motion for a LET array: (a) the desired folding panel motion (applied moment around x-axis), and (b) the undesired in-plane parasitic motion (applied moment around y-axis).

the objective of the optimization was to

Minimize $-k_y$ with respect to $w_t, l_t, w_b, l_b, P, S$

subject to $\sigma_{max} \leq \frac{\sigma_T}{n}$

$L \leq \alpha$

$W = W_{array}$

$P, S \in \mathbb{Z}^+$

Lower bounds were chosen based on the smallest dimensions that could be manufactured without greatly increasing the expense of manufacturing. Upper bounds were chosen based on the upper limits of the space (length and width) that the LET array was required to fit in. A constrained optimization algorithm using the ‘fmincon’ function in MATLAB was initially run. This algorithm was used because of the need for constraints. Code from [16] was modified and used as the objective function. Additionally, because the parallel and series values ($P$ and $S$ respectively) determined in the optimization need to be integers, the initial optimization was refined using a branch and bound approach until satisfactory results were achieved. The optimized dimensions of the LET array are shown in Table 1. The resulting parameters of the surrogate fold are presented in Table 2.

TABLE 1. Optimized LET joint design.

| Design Variable | Quantity | Units | Optimized Value |
|-----------------|----------|-------|-----------------|
| $w_t$           | Width of torsion segment | mm    | 0.79            |
| $l_t$           | Length of torsion segment | mm    | 26.83           |
| $w_b$           | Width of bending segment | mm    | 3.79            |
| $l_b$           | Length of bending segment | mm    | 0.79            |
| $P$             | Number of parallel elements | #     | 3               |
| $S$             | Number of series elements | #     | 2               |

B. FINITE ELEMENT ANALYSIS (FEA)

Using the defined dimensions from the optimization results, an FEA analysis was performed on the joint using ANSYS Workbench. To expedite the FEA calculations, and for simplicity, a single parallel LET joint of the array was analyzed. Since parallel LET joints undergo the same angular displacement, stresses and deflections are the same across the entire joint due to symmetry.

A fixed constraint was placed on the face of one connecting bending segment, and a ramped remote displacement rotation of $180^\circ$ was placed on the opposite connecting bending segment face. Stress results are shown in Fig. 8 and show a maximum Von Mises stress of 22.97 MPa. As expected from torsion theory, the maximum stress is located along the edges of the beams in torsion. The arrows in Fig. 8 show example locations of where the maximum stress is located. In addition, a $180^\circ$ angular deformation results in a panel displacement of 4.591 mm along the y-axis.

TABLE 2. Resulting surrogate fold parameters.

| Parameter | Quantity | Units | Optimized Value |
|-----------|----------|-------|-----------------|
| $k_{eqx}$ | Out-of-plane rotational stiffness | N-mm | 1.1             |
| $k_{eqy}$ | In-plane rotational stiffness | N-mm | 236.7           |
| $k_{eqx}$ | Stiffness ratio | - | 215.2           |
| $M_s$     | Moment to actuate 180° | N-mm | 3.6             |
| $\sigma_{max}$ | Maximum stress | MPa | 22.92            |

C. MATERIAL PROPERTIES

Material properties were obtained from Rogers’ Corporation [25] and are presented in Table 3. These properties were provided for the x- and z-directions. However, since the equations presented in [16] and [22] are for isotropic materials, the worst-case directional properties ($E_x, \nu_{xz}, \sigma_{T_2}$) were used. While this introduces some error, a safety factor of 1.2 was added to the optimization stress constraints to account for the possible error.

D. DISCUSSION OF RESULTS

Analytical and FEA analyses show that the individual elements of the LET array will not exceed the ultimate stress of
TABLE 3. Material properties of Rogers 5880.

| Parameter | Quantity | Units | Value |
|-----------|----------|-------|-------|
| $E_x$     | Modulus of elasticity in x-direction | MPa  | 2482  |
| $\nu_{xx}$ | Poisson’s ratio in x-direction with applied force in z-direction | -    | 0.48  |
| $\sigma_{tx}$ | Tensile strength in x-direction | MPa  | 27.5  |
| $E_z$     | Modulus of elasticity in z-direction | MPa  | 2206  |
| $\nu_{xz}$ | Poisson’s ratio in z-direction with applied force in x-direction | -    | 0.44  |
| $\sigma_{tz}$ | Tensile strength in z-direction | MPa  | 26.2  |

the Rogers 5880 material when deformed 180° with a pure moment in either direction. Similarly, the fold can also be cycled many times without failure. The actuating moment was solved to be approximately 3.6 N-mm, which is well within the range of standard motor actuators.

Integrating the LET joint into the RA design provides many benefits. First, the surrogate hinge allows the mechanical rotation of the panels ±180° thereby enabling mechanical reconfigurability of the RA. Furthermore, all components of this folding RA design are manufactured from a single planar PCB material. This monolithic design can be made using planar fabrication processes such as micro-milling, stamping, or laser cutting. This is attractive for on-site fabrication in space applications. In addition, since the RA is made from a single planar piece of material, part count and assembly times are greatly reduced. The lower part count also decreases the weight and cost of the RA while the simple manufacturing and little assembly time reduce its production cost. Moreover, since there is no contact between components in the joint, there is no need for lubrication or maintenance considering that this compliant system can be designed to never fatigue.

As mentioned above, the dimensions of the LET array depend on the thickness and stiffness of the panel material. As the thickness or stiffness of the material increases, the LET array will become longer and/or wider, taking up more of the array’s usable area. In addition, the resulting moment from the deformation in the LET array may deform the RA enough to affect RA performance. In some configurations with different materials, stress relaxation may become a problem. However, work done by Obaid et al. has showed that the fibers in a composite material may slow the process of stress relaxation [26].

V. FABRICATION AND MEASUREMENTS
A. REFLECTARRAY FABRICATION
To validate the proposed RA design, a prototype was manufactured in a single step using standard PCB fabrication. Fig. 9 shows our prototyped RA at its three different folding states $RA_1$, $RA_2$, and $RA_{21}$, which were defined in Fig. 1. Also, magnified views of the surrogate hinge at its flat and folded states are shown in Fig. 9(f).

B. PERFORMANCE OF REFLECTARRAY
The proposed RA was simulated in ANSYS HFSS. Also, the performance of the fabricated RA was measured using an MVG Starlab system. Fig. 10 shows the measurement setup of the proposed foldable RA at its $RA_2$ sub-configuration inside the MVG Starlab system. In this work, an MVG SH2000 (commercially available) dual-ridge horn is used as the feed antenna. It is challenging to model this feed antenna in ANSYS HFSS since all its design details are not known. Therefore, the feed was first measured in the MVG Starlab and its equivalent near-field source was calculated using MVG Insight software. This near-field source is imported...
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FIGURE 10. Measurement setup of the proposed foldable reflectarray at its RA₂ configuration in an MVG Starlab system.

FIGURE 11. Measured realized gain pattern of the feed antenna at 16 GHz.

into ANSYS HFSS and used as the exciting source of our proposed RA. Fig. 11 shows the measured realized gain pattern of the feed at 16 GHz. The feed exhibits a maximum gain of 13.7 dB, and its radiation patterns are not identically symmetrical in both $\varphi = 0^\circ$ and $\varphi = 90^\circ$ elevation planes.

Fig. 12 compares the simulated and measured realized gain patterns of the three sub-configurations. RA₁ and RA₂ exhibit a maximum measured gain of 25.5 dBi at $(\theta = 0^\circ, \varphi = 0^\circ)$ and 24.36 dBi at $(\theta = -30^\circ, \varphi = 0^\circ)$, respectively. Also, RA₁ and RA₂ have side-lobe levels below $-18$ dB. The gain difference between simulations and measurements for RA₁ and RA₂ is $1.2$ dB and $2.4$ dB, respectively. For RA₁, we attribute this difference to fabrication and measurement errors (e.g., the expected accuracy of the Starlab for high gain antennas is $\pm 1$ dB). We estimate that the same difference of approximately $1$ dB contributes towards the $2.4$ dB difference between the measured and simulated gain of RA₂ for the same reasons. The rest of the difference between the measured and simulated gain of RA₂ is attributed to possible slight misalignment of the two foldable panels (in RA₂ both panels fold forward to form its aperture). Notably, as the foldable panels of RA₂ fold forward they most likely form a concave shape due to gravity as they are not supported in our prototype by any highly accurate control mechanism (see detailed explanation about the effects of misalignment in Section IV.C). In summary, our results show a good agreement between simulations and measurements considering some of the associated errors.

The simulated realized gain patterns of the dual-beam sub-configuration RA₂₁ exhibit a gain of $21.7$ dBi and $20.8$ dBi at $\theta = 27^\circ$ and $\theta = -29^\circ$, respectively. However, in measurements, aperture RA₂₁ exhibits a gain of $19$ dBi and $19.43$ dBi at $\theta = 27^\circ$ and $\theta = -32^\circ$, respectively. The difference in gain between the two beams is associated with interference of RA₁ beneath the folded panel. This gain loss is not observed in RA₂ due to both panels being folded forward and closely aligned, thereby completely blocking aperture RA₁ from illumination. In fact, the interference of RA₁ in the performance of RA₂₁ causes a progressive phase error as the required phase at the inner edge of the aperture is not ideal for the second beam. Furthermore, the beam at $\theta = -29^\circ$ in simulation is shifted in measurements to $\theta = -32^\circ$, which is most likely due to a misalignment of the RA₂ panel. This misalignment also affects the gain of both beams and its influence is discussed in detail in Section IV.C.

The measured realized gains of RA₁ and RA₂ versus frequency are depicted in Fig. 13. The 1-dB gain bandwidth of RA₁ and RA₂ are $5.4\%$ (from $15.4$ GHz to $16.25$ GHz) and
FIGURE 13. Measured realized gain of RA1 and RA2.

3.9% (from 15.36 GHz to 15.97 GHz), respectively. Notably, the measured center frequency of this 1-dB gain bandwidth is approximately 15.82 GHz, which slightly deviates from the intended center frequency of 16 GHz. This deviation is attributed to phase center errors of the feed (i.e., horn), phase errors for large incidence angles, fabrication tolerances, and testing errors.

C. FOLDABLE PANEL MISALIGNMENT

To better understand the effects of the foldable panels’ misalignment, apertures RA2 and RA21 were simulated for different cases of misalignment: (a) perfectly aligned panels that provide a planar aperture, (b) under folded panels (that provides a convex aperture), and (c) over-folded panels (that provides a concave aperture) where θm is the folding angle. These cases of misalignment for both RA2 and RA21 are shown in Figs. 14(a) and 14(b), respectively. Notably, due to the width of the surrogate hinge, the folded panels in the concave case can only over-fold up to θm = 2°. The simulated realized gain patterns of RA2 for the different misalignment cases are presented in Fig. 15(a). These results show that the misalignment of the folding panels in both convex and concave cases eventually causes (for θm > 4°) the main beam of the planar aperture to split into two separate beams. The splitting of the main beam is due to the lateral displacement of the feed illumination. In addition, in the concave case, a gain drop of 1.2 dB occurs for θm = 1°, which validates that the difference between the measured and simulated gain of RA2 is due to misalignment (which was mentioned in Section IV.B). The results of Fig. 15(a) also clearly show that a misalignment of θm = 2° causes more significant beam distortion and drop in maximum gain in the concave case than the convex case. This distortion is explained by the presence of strong interference between the two foldable panels in the concave case compared to the convex. Fig. 16 clearly explains this interference by showing the reflected waves on RA2 for the planar, convex and concave configurations. It can be seen that in RA2 the reflected waves interfere with each other in the concave case whereas in the convex case, such interference is not present.

Similarly, the simulated gain patterns of RA21 are shown in Fig. 15(b) for the different misalignment cases. These results show that the misalignment of the panels in aperture RA21 causes beam distortion and lowers the maximum gain (similarly to the results for the aperture RA2). In the convex cases, the beam at θ = −29° shifts to θ = −31°, −37° and −46° for a misalignment angle θm of 2°, 4°, and 8°, respectively.

This beam dependence on the alignment of the panels can be used to achieve beamsteering, if this is desired, i.e., the folded panels can be intentionally misaligned to slightly shift the beam. Notably, this beamsteering would be controlled by an actuation system that can control the angle of the foldable panels. In addition, the beamsteering range also depends on the size of the reflectarray and its panels. Such beamsteering can be particularly useful for fine-tuning the beam direction of CubeSat antennas in deep space applications. In addition, Fig. 15(b) shows that the misalignment of the panels in aperture RA21 causes the gain of the beam towards θ = +27° to...
TABLE 4. Performance comparison of the proposed and the reference antennas.

| Reference foldable RA designs | Folding mechanism | Features in reference design not available in proposed design | Enhancements in proposed design not available in reference design |
|-------------------------------|-------------------|-----------------------------------------------------------|-------------------------------------------------------|
| [3],[4]                       | Panels with spring-loaded hinges | • Locking panel system  
• Spring-loaded hinges do not require additional engineering design to implement in different patterns | EM Reconfigurability  
• Enables two operating states: single-beam, dual-beam  
Manufacturing  
• Single piece design that is manufactured with its hinges directly on panel materials  
• Simpler manufacturing process  
• No assembly needed during manufacturing  
• Low part count  
• Low cost  
Weight  
• Lightweight due to lower part count  
Actuation  
• Simpler actuation mechanisms than [6],[7]. Simpler complexity to [3],[4].  
Robustness  
• More resistant to harsh space environments that membranes  
• No need for maintenance (joint lubrication or replacement)  
Other Design Considerations  
• Hinges made from non-metal parts (does not interfere with EM properties) |
| [6]                           | Folding and rolling membrane reflectarray | • Locks in desired position  
• Large reflectarray aperture (4 m²)  
• High packing efficiency | |
| [7]                           | Inflatable membrane reflectarray | • Large reflectarray aperture (~11.9 m²)  
• High packing efficiency | |

In summary, the results in this section illustrate that the performance of the proposed reflectarray depends on the alignment of its foldable panels. Therefore, an accurate control and actuation system should be used in practice to achieve optimal performance.

D. KEY CONTRIBUTIONS

Building upon the work of previous RA designs [3]–[7], the key advantages of our proposed RA include (1) mechanical reconfigurability into multiple states, and (2) a surrogate hinge design that offers advantages over current folding mechanisms used in RA designs. More specifically, the proposed RA design is mechanically reconfigurable, meaning that by folding or unfolding its sub-arrays it supports (a) three operating states: two single-beam states and one dual-beam state, and (b) beamsteering capabilities through accurate actuation of its sub-array panels.

While mechanical reconfigurability can be achieved through standard hinges, this paper presents a surrogate hinge that offers a number of additional advantages. The surrogate hinge incorporated into the proposed RA is fabricated straight into the RA material, is easy to manufacture using a single process, requires no assembly, has a low part count, requires no maintenance, and has a reduced overall weight. The monolithic RA establishes a new type of RA that is well-suited for on-site manufacturing in space exploration missions, i.e., they can be made using simple and additive manufacturing processes. Furthermore, this surrogate hinge enables RAs to be robotically manufactured in space.

In addition to the proposed RA, this paper presents a detailed study of the misalignment effects of the foldable panels to the radiation performance of the RA. Notably, our proposed configuration is suitable for small satellites, such as CubeSats, FemtoSats and PicoSats. Table 4 summarizes the differences between RA configurations, and outlines the added enhancements offered by the proposed RA.

VI. CONCLUSION

A novel reconfigurable and monolithic reflectarray (RA) with foldable panels, which is suitable for CubeSat applications, was presented. The proposed RA has extremely low fabrication cost, reconfigurable EM performance, beamsteering capabilities, efficient stowage, and excellent compatibility with CubeSat geometries. The performance of the foldable RA was investigated using simulations and measurements. By folding and unfolding its panels, this high-gain RA can
support three different aperture sub-configurations with three different patterns, namely, two single-beam patterns and one dual-beam pattern. One unique advantage of the RA is that it can be entirely manufactured along with its hinges out of a single PCB. Such a monolithic configuration is very attractive for space missions that need to use on-site manufacturing of components.

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