Reflectarray Unit Cell Based on a SIW Cavity Resonator

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***Abstract*- We introduce a novel reflectarray unit cell based on a SIW cavity resonator, designed for operation at 18.7 GHz. It can achieve a full phase cycle of phase shifting and low losses, while keeping manufacturing requirements simple. Furthermore, by relying on a resonant cavity instead of open elements, inter-cell coupling effects are reduced. This can lower the approximation errors resulting from using the cell response under a fully periodic environment during the design process.**

I. INTRODUCTION

In recent years, climate change has been a significant cause for concern. Its detrimental effects extend to coastal and fluvial regions, manifesting in sea level rise and alteration in storm frequency, intensity, and patterns. Essential tools for assessing and predicting climate change include Earth observation missions employing satellite-borne radiometers. Traditionally, three narrow-band frequency channels have been utilized for these purposes: 18.7 GHz for observing surface emissivity, 23.8 GHz for monitoring atmospheric water vapor content, and a higher frequency channel around 36.5 GHz for observing cloud water liquid content [1], [2].

Antennas utilized for such missions typically necessitate high gain and demand precise modeling and manufacturing techniques. Reflector antennas have been employed in recent missions to meet these specifications [3]. However, the large apertures required for achieving the desired gain renders parabolic reflectors bulky, thereby increasing mission costs and potentially posing challenges for stowage and in-orbit deployment. Reflectarray (RA) antennas present an appealing alternative due to their low-profile planar structure, cost-effectiveness, and adaptability [4]. They also include several challenges, such as ensuring a low insertion loss, polarization purity and accurate control and modelling of every element of the array.

By tuning the local phase shift that every individual cells within a RA introduces to the incident fields, arbitrary phase distributions can be attained in the reflected fields on the panel surface. Such capability has been used both in high-gain [5]-[7] and contoured beam [8] antennas for space applications. The influence of each cell in the incident fields in the RA is commonly assessed through a modal Floquet analysis of the structure. This method hinges on a local periodicity (LP) approximation, treating each cell as if it were embedded in an infinite periodic array [9].

Ensuring that an RA antenna meets the stringent requirements typical of space missions necessitates an accurate model of the unit cell. Factors such as the angle of incidence from the feeding element to each cell must be considered in the cell analysis to achieve maximum precision [10]-[12]. However, Floquet analysis falls short in predicting changes in inter-cell coupling in finite non-periodic arrays, which can lead to distortions, especially in Ras with rapidly varying cell designs. Efforts have been made to address these effects by considering each cell's actual surroundings when predicting its response [13]. Nevertheless, this approach is only practical when evaluating a finalized design due to its high computational demand. A more accessible strategy involves utilizing cells with similar geometries across the RA surface, aiming to minimize changes in inter-cell coupling compared to the fully periodic scenario [14].

In this work, we introduce a reflectarray unit cell operating at 18.7 GHz, which utilizes a slot-coupled substrate-integrated waveguide (SIW) resonant cavity. The resonance frequency of each cell, and consequently its phase shift, is adjusted by incorporating a via within the cavity. This concept, initially proposed in [15], suggests that SIW-based cells are promising candidates for reflectarray cells, where inter-cavity coupling occurs solely through similar slots on the substrate surface. As a result, LP approximation errors could be reduced. We substantiate this hypothesis by examining how alterations in neighboring cells affect the response of the proposed SIW cell. The findings are compared with those obtained from a more conventional cell design, such as varying-size printed patches.

II. UNIT CELL DESIGN

The examined RA unit cell comprises an SIW-based square cavity coupled through a curved slot, illustrated in Fig. 1. Both sides are sized at $p = 6.477$ mm, or $0.4\lambda_0$ at the design frequency of 18.7 GHz. It is fabricated on a Rogers RO3003 substrate with a thickness of $h = 0.762$ mm (30 mil) and dielectric properties $\epsilon_r = 2.97$ and $\tan\delta = 0.0013$. Vias with a diameter of $v_d = 0.6$ mm serve as the cavity side walls. Before a slot is added, the fundamental resonance of this cavity can be calculated as [16]:

$$f_0 = \frac{c_0}{p_{eff}\sqrt{2\epsilon_r}} \tag{1}$$

$$p_{eff} = p + \frac{v_d^2}{0.95\ \ s}, \tag{2}$$

or 20.08 GHz with the selected parameters. Next, a rectangular slot measuring $s_l = 5.2$ mm by $s_w = 1.0$ mm is introduced, with a distance $s_c = 0.65$ mm from the edge of the cell. The

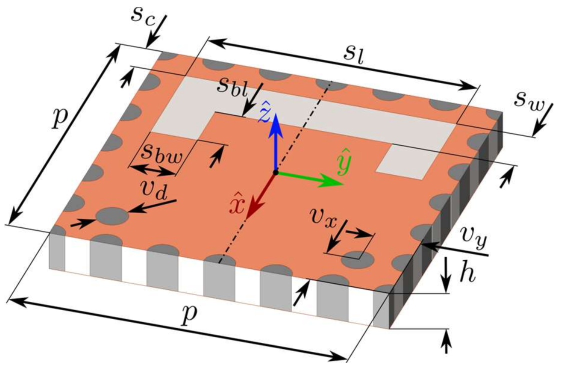

Fig. 1. SIW-based unit cell geometry

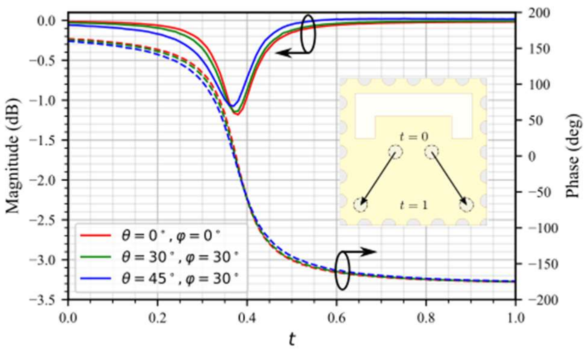

Fig. 2. SIW unit cell, reflection coefficient ρ_{xx} at 18.7 GHz.

slot has a strong effect on the resonant fields inside the cavity, and it can be approximated as a perfect magnetic conductor (PMC) or a magnetic wall following the study from [15]: This magnetic wall acts as a symmetry plane, leading to a half-mode resonance that effectively doubles the apparent size of the cavity along the x-axis. Consequently, the resonance frequency of the cavity with the rectangular slot is lowered to 17.55 GHz.

The operational concept of this cell relies on modifying the resonance frequency of the cavity through the introduction of shorting vias inside the cavity. By deliberately each cell's resonance slightly below or above the design frequency, it is feasible to tune the phase of the reflected fields within a range of up to 360 degrees. To achieve this broad phase-shifting capability, it's essential for the resonance of the cavity without vias to be significantly below the desired operating frequency, since the shorting vias can only increase it. However, this is not fully achieved by using a simple rectangular slot. In order to further reduce the cavity resonance frequency, the slot is curved and extended by $s_{bl} = 1.0$ mm with a width of $s_{bw} = 0.9$ mm. This adjustment results in a final baseline resonance at 15.4 GHz.

Finally, two symmetric tuning vias are introduced, their positions defined by (v_x, v_y). When positioned close to the cavity corners, their impact on the cavity is minimal. However, when positioned near the center, they can shift the resonance frequency beyond 25 GHz. For analytical convenience, a linear range of via positions is defined as:

$$v_x = v_{x,max} - t(v_{x,max} - v_{x,min}) \quad (3)$$

$$v_y = v_{y,max} - t(v_{y,max} - v_{y,min}), \quad (4)$$

where $t \in [0, 1]$ is the single variable parameter among cells.

The cell's response under Floquet analysis is depicted in Fig. 2 at 18.7 GHz. The magnitude and phase of the ρ_{xx} direct reflection coefficient are presented for both normal and oblique incidences. Notably, the phase shifting range spans 338 degrees, while losses remain mostly below 1 dB. Furthermore, the analysis reveals high angular stability.

With its straightforward geometry and easily attainable manufacturing tolerances (such as via diameter and via-to-slot tolerances), this unit cell achieves nearly a complete cycle of phase shifting. Consequently, it serves as the fundamental component for SIW-based resonant cavity unit cells in RA antennas. This characteristic renders it a favorable option for cost-effective terminals with modest bandwidth requirements.

III. LOCAL PERIODICITY ANALYSIS

When designing a RA, the geometry of each cell is chosen based on its behavior in an infinite periodic environment. This approach is adopted because analyzing and optimizing each individual cell while considering the effects of all others, each with its unique geometry, is computationally impractical. Consequently, there exists an inherent discrepancy between the actual response of each cell and the predictions made during the design process. These discrepancies arise due to variations in inter-cell coupling effects, with each cell primarily influenced by its closest neighbors (i.e., the cells directly surrounding it).

The impact of errors stemming from the LP approximation on the final antenna performance is highly dependent on the particular design. Reflectarray layout with aggressive or rapidly changing phase shift distributions tend to exhibit poor cell uniformity, thereby exacerbating errors associated with the LP assumption. However, such issues can be alleviated by opting for a unit cell where inter-cell coupling effects are minimized. In cavity-based structures, as illustrated here, these effects are expected to be considerably reduced compared to open structures like printed resonators. This is attributed to the partial isolation of the cavities by the SIW walls.

To investigate the influence of inter-cell coupling in the cell responses, an infinite array with an extended periodicity unit is examined, as depicted in Fig. 3. A 4-cell structure is analyzed using periodic boundary conditions (PBC), where 3 out of the 4 cells (highlighted in red) are identical. The response of the isolated (blue) cell can then be assessed for a given geometry, when all of its direct neighbors are simultaneously altered. The focus is on the isolated cell's response rather than the collective effect of the infinite array of 4-cell blocks, and therefore Floquet modal analysis is not applicable. Instead, the extended unit cell is excited by a normally incident plane wave under PBC. The effective reflection coefficient of the blue cell can then be calculated by integrating the reflected fields over the surface of exclusively the blue cell and relating the amplitude and phase of the reflected wave to those of the incident wave.

This analysis method is applied to the SIW cell introduced in this study. The effective reflection coefficient of the isolated cell is assessed for two configurations: below resonance ($t_c = 0$) and above resonance ($t_c = 1$). For each scenario, the neighboring cells are systematically modified across their entire tuning range of $t \in [0, 1]$. Fig. 4 illustrates the

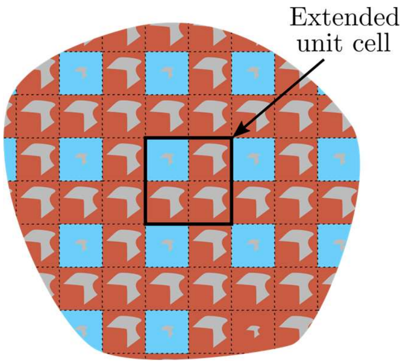

Fig. 3. Periodic lattice with extended unit cell.

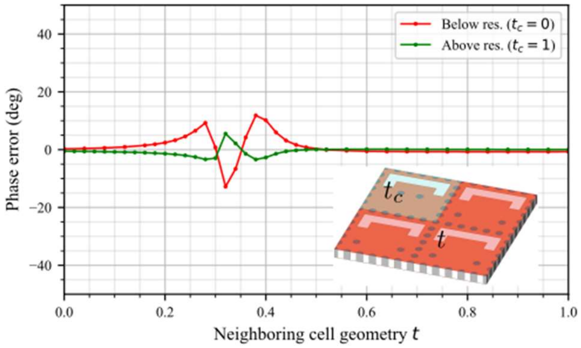

Fig. 4. Aperiodicity errors in SIW-based unit cell at 18.7 GHz.

discrepancies in the effective phase shift of the cell when compared to the values predicted by Floquet analysis for a fully periodic environment. It is noteworthy that no error is observed when $t = t_c$, since in those cases all cells are identical in the lattice.

For comparison, a similar analysis is conducted on a cell based on a varying size printed patch. The substrate and periodicity remain consistent with the SIW cell, while the resonant cavity is substituted with a resonant square patch. This cell geometry is commonly employed in the literature for low-cost narrowband reflectarray designs due to its simple characteristics and ease of manufacture. The response of this patch-based cell is depicted in Fig. 5. Compared to the SIW cell, the phase shifting range is slightly reduced to approximately 310 degrees, and losses are also lowered to below 0.5 dB.

The outcomes of the periodicity analysis for the square-patch unit cell are illustrated in Fig. 6. Compared to the SIW cavity, notably higher phase errors can be observed. This suggests a more pronounced coupling among neighbors, which leads to the electromagnetic fields above any one cell being largely influenced by its surroundings. Both cell designs show the maximum level of distortion when nearby cells have strongly resonant geometries. The SIW cavities demonstrate a rapid reduction in these distortions, with errors. In contrast, the square patch cell continues to exhibit errors upwards of 20 degrees in some cases even when its surrounding cells are operating far from resonance.

IV. CONCLUSIONS

A novel SIW-based unit cell geometry has been introduced for reflectarray antennas, showcasing the competitiveness of

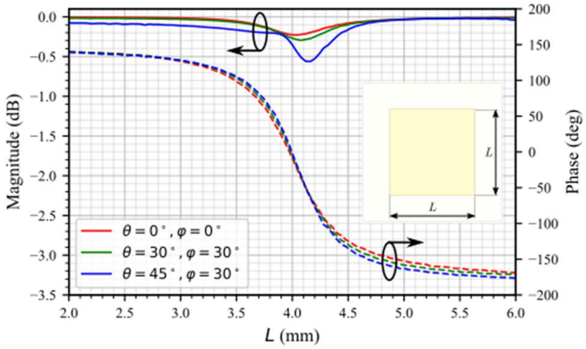

Fig. 5. Printed square patch unit cell, direct reflection coefficient ρ_{xx} at 18.7 GHz.

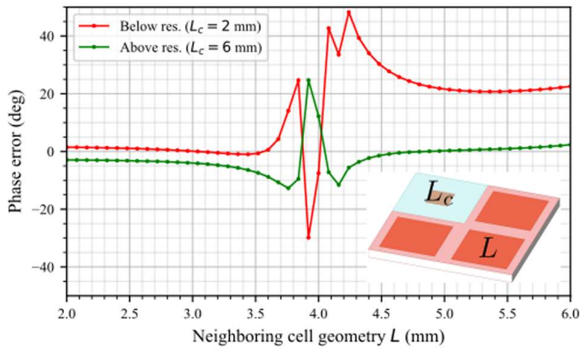

Fig. 6. Aperiodicity errors in square patch unit cell at 18.7 GHz.

SIW cavity-based structures at the K band. This design offers low losses and an adequate phase shifting range within a compact size. Furthermore, the cell's response was studied in semi-periodic environments, where it was compared to the fully periodic case. The study revealed that the proposed cavity-based cell exhibits resilience to phase distortions stemming from the typical local periodicity approximation. In contrast, an alternative popular cell based on varying size patch revealed significantly higher distortions under the same analyses, as a result of a stronger inter-cell coupling.

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