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A Metal-Only Reflectarray Antenna Design Utilizing Split Ring Slot Cells

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Abstract
This paper introduces a compact, low-profile, low-loss, all-metal reflectarray antenna operating at 2.45 GHz. It features a novel unit cell with a triple split-ring slot configuration, where the reflection phase is controlled by adjusting sector angles. The design is etched onto a single metal plate, eliminating dielectric substrates and their losses. The 9×9 array, with a 540 × 540 mm² aperture and a height of 0.1225λ (15 mm), includes rim metallic walls to boost gain and radiation performance. A center-fed TE_{10} rectangular waveguide at a 335 mm focal distance illuminates the array, directing the main beam at broadside. Full-wave simulations show a 21.1 dB gain, 52.3% aperture efficiency, −14.6 dB sidelobe level, and 7.8% 3-dB gain bandwidth. Compared to dielectric-based reflectarrays, this metal-only design offers lower loss, higher radiation efficiency, and a compact manufacturable structure. Its robust construction enhances power-handling and thermal stability, making it ideal for high-power applications like wireless power transfer.

Keywords: Reflectarray, unit-cell, metal-only, low-profile, high efficiency

1. Introduction

Reflectarray antennas are gaining attention due to their ability to combine the advantages of both reflectors and phased arrays, offering high gain, beam-shaping capabilities, and cost-effective implementation. Traditional reflectarrays rely on dielectric substrates, but metal-only reflectarrays eliminate the need for such materials, reducing weight and improving thermal stability. Recent advances in Reflectarray antenna technology have introduced innovative solutions tailored for Ka-band and millimeter-wave applications. In study [1], a reflectarray using patch elements with position-adjustable metallic vias achieves full 360° phase control through via placement, enabling precise beam shaping for high-frequency operation. Work [2] demonstrates circular polarization using a low-profile, single-layer structure with optimized geometries of dissimilar elements, achieving high gain and robust axial ratio performance suitable for satellite systems. Complementing this, [3] presents a single-layer configuration supporting both circular polarization and efficient beam scanning while maintaining structural robustness.

For dielectric-based approaches, [4] features an element with two dielectric resonator sizes and variable slot loading, achieving full 360° phase coverage and approximately 10% gain-flatness bandwidth, particularly effective in offset-fed configurations. Additionally, research in millimeter-wave transmitarrays [5] shows advanced progress in high-frequency beamforming substrates, indicating broader trends in structured-metal systems.

However, many existing designs involve complex multi-element structures or retain dielectric materials, which can introduce losses and limit power handling. A simpler, all-metal design that retains precise phase tuning capabilities is therefore highly desirable for high-power applications. To address this need, this paper presents a novel metal-only reflectarray (MORA) employing triple split-ring slot cells. The design's innovation lies in its unique geometry and unified architecture, where reflection phase is controlled by varying sector angles within each cell. This approach eliminates dielectric substrates and complex interconnects. Fabricated as a single etched copper plate over an air spacer, the design achieves a unified structure offering mechanical robustness and minimal loss. Optimized for S-band applications, this low-profile architecture combines excellent thermal stability and power handling with precise phase control, demonstrating high efficiency suitable for demanding applications like wireless power transfer.

2. Unit Cell Design & Analysis

The unit cell configuration, as illustrated in Fig. 1, comprises three split ring slots carved on a copper sheet with 1 mm thickness, where the phase response is primarily governed by the slot sector

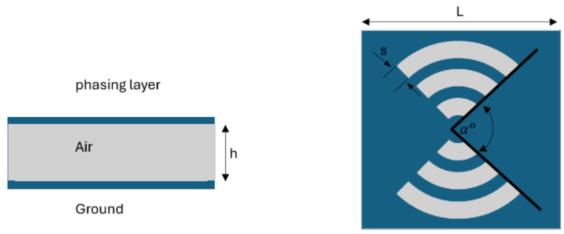

Fig. 1 Geometry of the proposed metal-only triple split-ring slot etched in a copper sheet unit cell. The blue region denotes copper.

Table 1 Geometrical Parameters of the Proposed Element

Parameter	Description	Value
L	Element spacing	60 mm
α	Sector angle range	1° - 100°
t	Copper thickness	1 mm
R1	Inner radius	13 mm
R2	middle radius	20.5 mm
R3	outer radius	28 mm
S	Slot width	3 mm

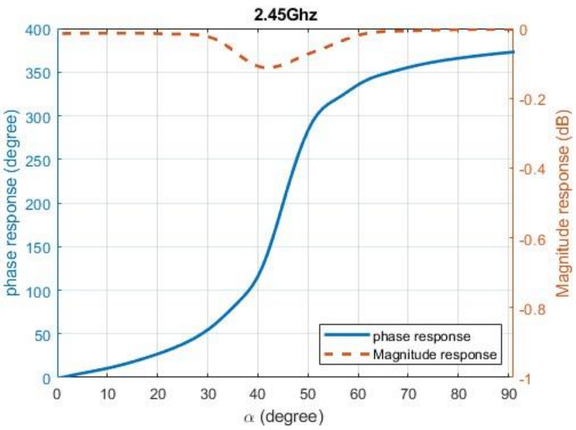

Fig. 2 Simulated phase and amplitude responses of the reflectarray unit cell.

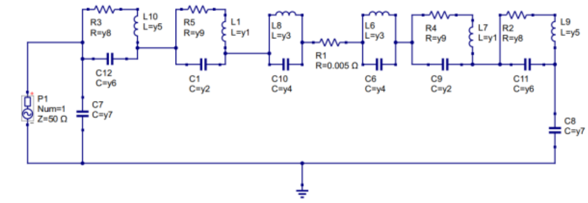

Fig. 3 Equivalent Circuit model for the unit cell

angles that modulate the phase shift across the aperture. An air layer thickness of 15 mm has been chosen to strike a balance between phase stability and a compact profile, while a periodic element spacing of 60 mm with height of 0.1225λ contributes to its low-profile design. Notably, the magnitude response does not exceed –0.12 dB, indicating low losses in the structure and efficient reflection characteristics over the operating band. The phase control mechanism is achieved by adjusting the slot sector angles, as shown in Fig. 2. This approach enables flexible phase tuning without relying on dielectric loading or multilayer structures. The design was optimized to achieve a near-linear phase response, low loss, and a compact form factor with a cell spacing of 60 mm (~λ/2) to suppress grating

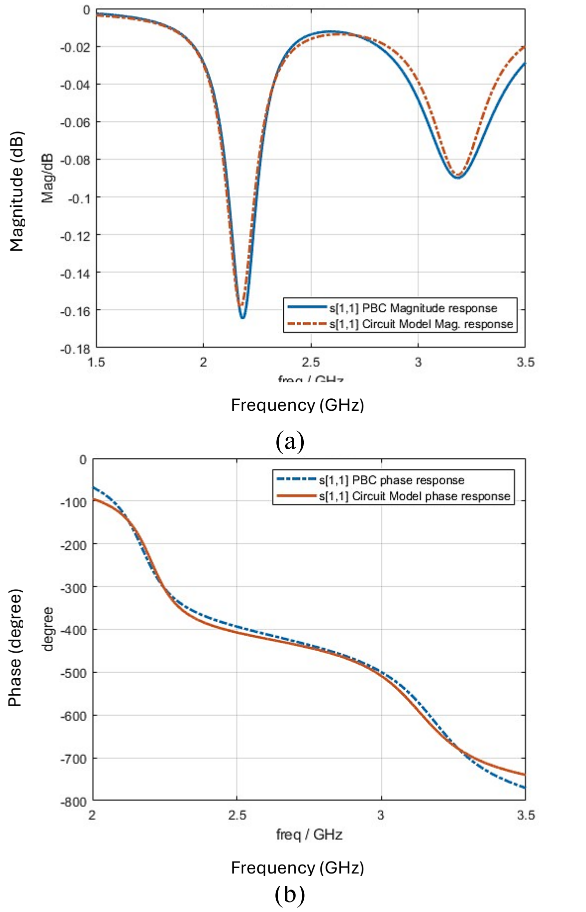

Fig. 4 Comparison between periodic boundary condition (PBC) method and circuit model method: (a) magnitude response, (b) phase response at certain angle

lobes. Table 1 summarizes the key geometrical dimensions of the unit cell, including slot radius, slot width, and other critical parameters

3. Equivalent Circuit Modeling

To validate the electromagnetic behavior of the unit cell, an equivalent circuit model was developed, as shown in Fig. 3. This model offers a simplified analytical representation while providing good insight into the physical characteristics of the element. Following the element analysis method in [6]

,the unit cell was analyzed using both the Periodic Boundary Condition (PBC) method and the circuit model approach. As shown in Fig. 4, both methods yield closely matching results in terms of magnitude and phase response at a specific incident angle. However, slight discrepancies are observed, primarily attributable to inherent limitations of the circuit model. The lumped-element approximation neglects distributed electromagnetic effects, while the assumption of infinite periodicity in the model does not account for mutual coupling variations and edge effects present in practical finite arrays. Furthermore, higher-order modes excited by the split-ring slots are not captured in the simplified circuit representation. Despite these limitations, the overall trend remains consistent, confirming the accuracy and reliability of the proposed design for preliminary analysis. This dual approach ensures coherence between full-wave simulations and circuit-level predictions, while highlighting the importance of full-wave simulation for final validation of the unit cell performance in reflectarray applications.

4. Reflectarray Antenna Design and simulation

The proposed metal-only reflectarray is designed with an aperture size of 540 × 540 mm, comprising a 9×9 element array, and utilizing a center-fed configuration with the feed positioned 335 mm above the aperture as shown in Fig. 5. This feed distance creates an amplitude taper of approximately -10 dB at the aperture edges, ensuring optimal illumination efficiency while minimizing spillover losses.

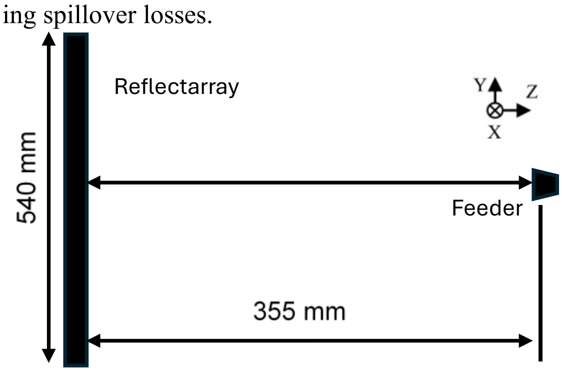

Fig. 5 Center feed configuration of proposed reflectarray

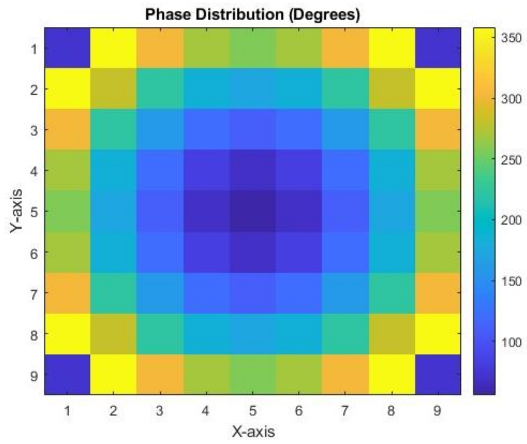

Fig. 6 Reflectarray cells phase distribution.

An integral feature of the design is the electrical wall connecting the element layer to the ground layer. This wall enhances gain by reducing surface wave losses and suppressing unwanted reflections through improved electromagnetic confinement at the array boundaries. The wall structure minimizes edge diffraction effects and improves current distribution uniformity, ultimately enhancing radiation efficiency, directivity, and phase coherence across the aperture while maintaining a low-profile.

The required phase distribution for each unit cell is calculated using the conventional path compensation equation [6]:

$$\emptyset(x_i, y_i) = k_o(R_i - (x_i \cos(\phi_d) + y_i \sin(\phi_d))\sin(\theta_d)) \quad (1)$$

where $\emptyset(x_i, y_i)$ is the required reflection phase for the unit cell at position (x_i, y_i), k_o is the free-space wave number, R_i is the distance between feeder phase center and unit cell, and (θ_d, ϕ_d) is the beam

direction in elevation and azimuth, respectively. Fig. 6 presents the phase distribution required for each cell, illustrating how the calculated phase response compensates for the different optical path lengths from the feed to ensure coherent beamforming at 2.45 GHz.

To verify the performance of the reflectarray, full-wave simulations were conducted using both the time-domain (TD) and frequency-domain (FD) solvers in CST Studio Suite. This dual-solver approach ensures comprehensive electromagnetic analysis and allows cross-validation of key performance parameters. The reflection coefficient (S_{11}) results obtained from both solvers are shown in Fig. 7, demonstrating close agreement across the operational frequency range. Both the time-domain and frequency-domain solvers predict similar resonance behavior and return loss characteristics, indicating

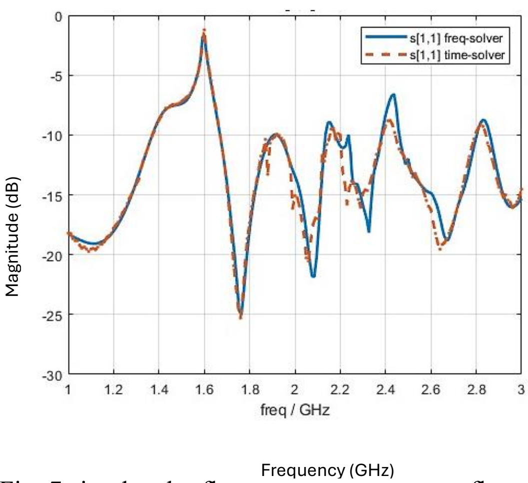

Fig. 7 simulated reflection coefficient for reflectarray antenna using time-domain solver and frequency-domain solver

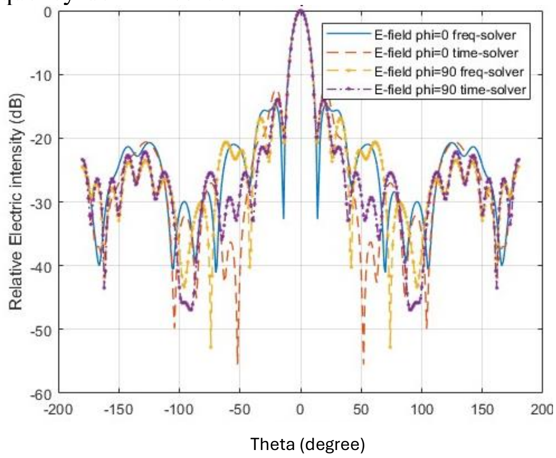

Fig. 8 Simulated radiation pattern at 2.45 GHz, E-plane (phi = 0), H-plane (phi = 90) for time-domain solver and frequency-domain solver

proper impedance matching and validating the stability of the design under different solver techniques.

The reflectarray was analyzed using full-wave simulations, achieving a realized gain of 21.1 dB, aperture efficiency of 52.3%, and a 3-dB gain bandwidth of 7.8% at 2.45 GHz. As shown in Fig. 8, the simulated .radiation patterns for both E-plane and H-plane exhibit a beamwidth of 11.7° and a sidelobe level of 14.6 dB, with strong agreement between the time-domain and frequency-domain solvers.

The consistency across gain, reflection coefficient, and radiation pattern confirms the accuracy and reliability of the proposed design.

The realized gain obtained from both solvers is presented in Fig. 9, showing good overall agreement across the frequency band. However, a slight difference is observed in the peak gain frequency, which occurs at 2.475 GHz for the frequency-domain solver and at 2.45 GHz for the time-domain solver. This variation is attributed to the inherent differences in solver algorithms and meshing techniques. Despite this shift, the consistency in gain magnitude and bandwidth confirms the reliability of the design across both simulation methods. The gain-vs-frequency response is shown in Fig. 10, while aperture efficiency versus frequency is plotted in Fig. 11 and shows maximum aperture efficiency about 56.3% at 2.475 GHz using FD solver.

Finally, the comparison in Table 2 highlights the strengths and trade-offs of the proposed metal-only Reflectarray. Operating at 2.45 GHz, it achieves a high aperture efficiency of 52.3%, surpassing [7], [9] and [10], with a compact unit cell height of 0.1225λ₀ smaller than [7], [8] and [10]. Despite a narrower 3-dB gain bandwidth of 7.8%, the design benefits from low unit loss (0.1 dB), ensuring minimal insertion losses. This makes the Reflectarray a compact, efficient, and low-cost solution such as

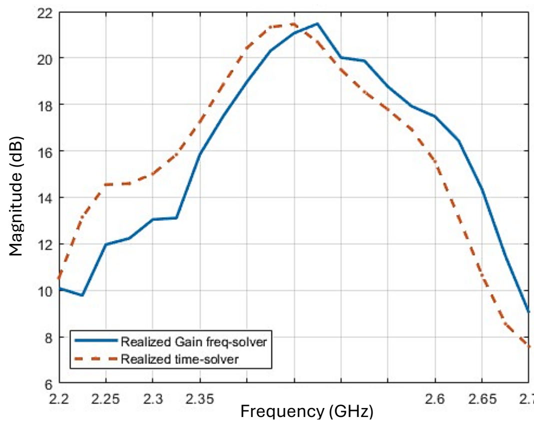

Fig. 9 realized gain comparison using time-domain solver and frequency-domain solver.

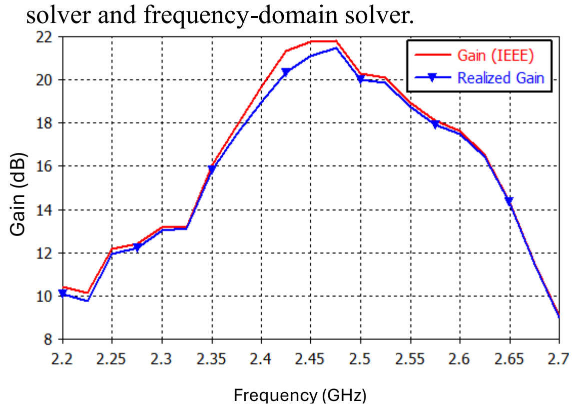

Fig. 10 Simulated and realized gain within the frequency band of interest using frequency-domain solver

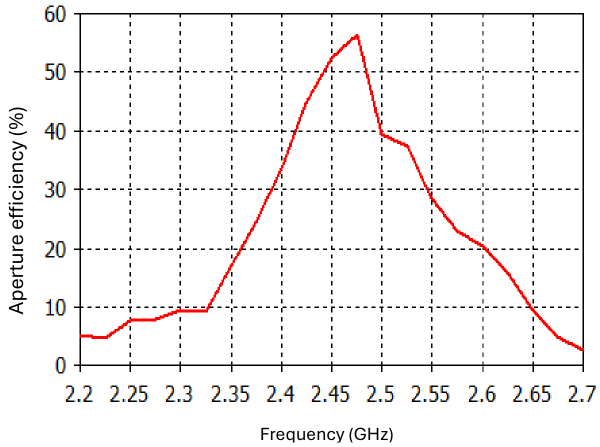

Fig. 11 Aperture efficiency within the frequency band of interest.

satellite systems and radar, and high-power applications wireless power transfer

Table 2 Comparison with Previous Works on Metal-Only Reflectarray

	This work	[7]	[8]	[9]	[10]
Center frequency (GHz)	2.45	12.5	12.5	12.5	20
Gain (dB)	21.1	25.9	33.9	32.5	30.2
Aperture efficiency (%)	52.3	44.6	53.8	39	49.3
Cell Height (λ_o)	0.1225	0.173	0.17	0.08	0.4
Aperture size (λ_o)	4.41	6.66	21.5	21.5	13
Unit loss (dB)	0.1	0.15	0.1	0.42	-
3-dB Gain Bandwidth (%)	7.8	20	12.8	8.3	17.5

6. Conclusion

This paper presents a compact, metal-only reflectarray antenna utilizing a triple split-ring slot unit cell, optimized for high-gain and low-profile applications. An integrated electrical wall minimizes surface wave losses, boosting radiation efficiency and gain. Performance was assessed using time-domain and frequency-domain solvers, with consistent results for gain, reflection coefficient, and radiation patterns. At 2.45 GHz, the antenna achieves a peak gain of 21.1 dB, a sidelobe level of −14.6 dB, and an aperture efficiency of 52.3%, validating the design's effectiveness. An equivalent circuit model was developed to analytically confirm the unit cell's behavior, aligning well with full-wave simulations. These results highlight the reflectarray's suitability for efficient, broadband, and thermally stable operation in modern communication ,radar systems and high-power application, particularly wireless power transfer.

Author Contributions

Mohammed M. Azab: Performed the simulation design and implementation, analyzed the results, and prepared the initial draft of the manuscript under the supervision of the co-authors.
Maha R. Abdel-Haleem: Supervised the simulation work and provided technical guidance
Abdelhady M. Abdelhady: Supervised the simulation work ,provided technical guidance, provided scientific supervision, guided the analysis and interpretation of results, contributed to the revision and editing of the manuscript and reviewed the manuscript for intellectual content.
All authors read and approved the final version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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