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Gain-Enhanced Ultra Broadband Millimeter-Wave Reflectarray Design with Varied Square Minkowski Units for CubeSat Space Applications

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***Abstract*—This paper introduces a novel millimeter-wave reflectarray antenna designed for ultra-broadband frequency operation, specifically tailored for CubeSat space applications. The proposed reflectarray antenna features a circular aperture with a diameter of 310 mm. The proposed design comprises square-based cross-Minkowski unit antenna elements of varied sizes distributed across the circular aperture. The proposed reflectarray design achieves an absolute peak gain of 32.6 dBi with a half-power beamwidth (HPBW) of 2.9 degrees at 60 GHz. The proposed design maintains an overall gain exceeding 24 dBi across an ultra-broad frequency operation range from 30 GHz to 110 GHz. The simulated and measured S-parameter results portrayed $S_{11} \leq -10\,\text{dB}$ for the frequency of operation ranging from 30 GHz to 110 GHz. The significant high gain and extensive frequency band coverage, spanning the Ka, V, and W bands, highlight the suitability of the proposed design for CubeSat-based space applications.**

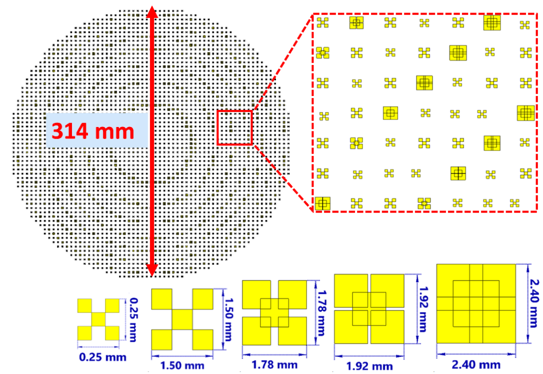

Fig. 1. Proposed reflectarray design.

I. Introduction

In recent years, numerous studies have explored reflectarray and mmWave phased antenna array configurations, yet limitations persist in achieving high gain and ultra-broadband frequency coverage that is critical for CubeSat missions [1], [2]. This paper introduces an innovative millimeter-wave reflectarray design strategically crafted to surpass these constraints. Addressing the specific demands of CubeSat missions, prior attempts often struggled to strike the delicate balance between high gain and ultra-broadband coverage, hindering their suitability for these compact satellites. Such compromises impact the reliability and efficiency of communication and sensing systems in a challenging space environment. As CubeSats play an increasingly vital role in space exploration, overcoming these constraints becomes imperative. This paper presents a novel reflectarray design optimized for both high gain and ultra-broadband coverage, addressing shortcomings in earlier endeavors and advancing the field [3]–[5].

The subsequent sections of the paper unfold as follows: Section II details the antenna design approach. Subsequently, Section III extensively investigates the simulation results and engages in discussions concerning the proposed reflectarray antenna. The paper concludes in Section IV, providing final remarks and outlining potential avenues for future research.

II. Antenna Design Approach

The proposed millimeter wave reflectarray is presented in Fig. 1. The design and performance optimization were carried out through the integration of the computer simulation technology (CST) suite and MATLAB software. The proposed design comprises modified square Minkowski units spread across a circular aperture that has a diameter (D) of 310 mm (62λ). The feed horn antenna (DRH110) model is designed and utilized to feed the reflectarray structure as portrayed in Fig. 2. The focal distance (F) between the feed horn and reflectarray aperture is 155 mm (31λ), which is half the reflectarray aperture diameter. The optimum F/D ratio is analyzed and obtained as 0.5 with an iterative approach varying the aforementioned focal distance (F). The single element of the reflectarray is designed by modifying the conventional square patch-based reflectarray design. Four square patches, each placed at the four corners of an imaginary square, and one at the center, making it a Minkowski type of cross shape. The other versions of this single unit were designed by varying the distance between the corner square units, along with variations in size. These variations were all incorporated into the reflectarray and are responsible for achieving the ultra-broadband frequency operation. The smallest unit is $0.25(0.05\lambda) \times 0.25(0.05\lambda)$ mm^2 and the largest unit is $2.4(0.48\lambda) \times 2.4(0.48\lambda)$ mm^2. Where λ is 4.99 mm for 60 GHz center frequency.

The proposed reflectarray design incorporates single antenna elements with variations in the dimensions, ranging from 0.25 mm to 2.4 mm. This deliberate variation addresses the operational bandwidth, with larger antenna units covering the lower frequencies from 30 GHz, and smaller units extending coverage to the higher frequencies, reaching up to 110 GHz. The resonant frequencies corresponding to these antenna element sizes were determined utilizing $f \approx \frac{c}{2\sqrt{\varepsilon_r}L}$, where L is the characteristic dimension, c is the speed of light

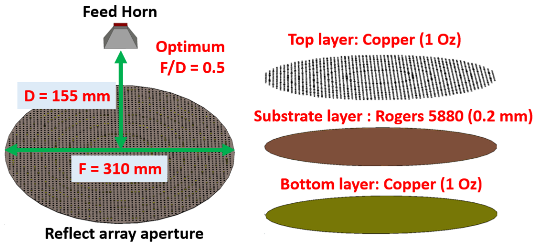

Fig. 2. Simulation setup of the proposed reflectarray antenna.

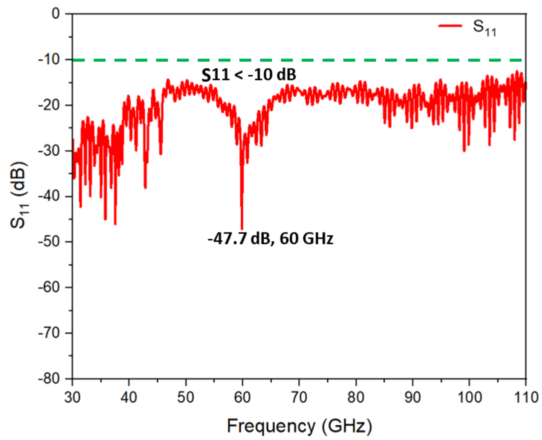

Fig. 3. S_{11} versus frequency plot.

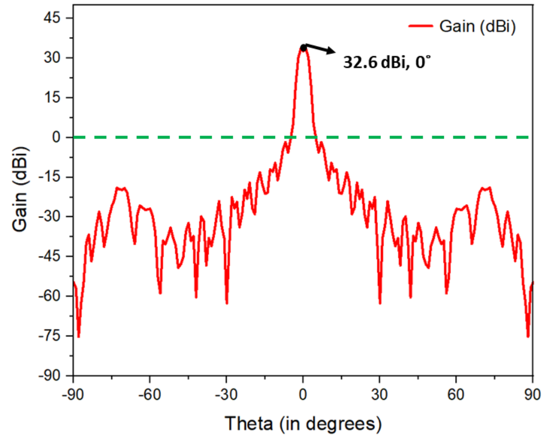

Fig. 4. Radiation pattern plot with gain versus theta at 60 GHz.

(3×10^8 m/s), and ε_r is the dielectric constant of the substrate on which the antenna is built. This results in an estimated frequency range of approximately 29.9 GHz to 151.7 GHz, showcasing the versatility of the reflectarray in covering a wide frequency band. It is noteworthy that our frequency of interest is constrained to 30 GHz to 110 GHz, within which the Ka, V, and W bands are effectively covered.

III. Results and Discussion

The simulated return loss vs. frequency result is presented in Fig. 3. It is observed that the magnitude of S_{11} is well below the -10 dB reference and is observed to be -47.7 dB at 60 GHz. The proposed reflectarray's radiation pattern with gain vs. theta plot, as shown in Fig. 4, has portrayed an absolute gain of 32.6 dBi and a half-power beamwidth (HPBW) of 2.9 degrees at 60 GHz. These exceptional performance characteristics highlight the suitability of the proposed reflectarray for CubeSat applications. Table I provides a comparative analysis between the present study and prior works. The proposed work demonstrates superior performance in terms of relatively small aperture size, with an absolute gain of 32.6 dBi, and broadband operational bandwidth ranging from 30 GHz to 110 GHz, covering the desired Ka, V, and W bands.

TABLE I
Comparison with Prior Works

	[3]	[4]	[5]	This Work*
Antenna diameter (mm)	110	80	380	310
Gain (dBi)	25.6	23	36	32.6
Frequency bands covered	X, Ku, and Ka	Partial Ka	K and partial Ka	Ka, V, and W
HPBW (in degrees)	30°	15°	6°	2.9°

* This work is based on simulation

IV. Conclusion

In conclusion, this work presented a millimeter-wave reflectarray antenna with a high gain of 32.6 dBi and sustained gain above 24 dB across a broad 30 GHz to 110 GHz frequency range. The proposed reflectarray establishes a new paradigm for high-performance antennas in CubeSat-based space applications. Its coverage of the Ka, V, and W bands positions it as an ideal choice for CubeSat communication and sensing. Future work involves fabricating the design and conducting comprehensive measurements, focusing on parameters like far-field radiation patterns, realized gain, half-power beamwidth, and return loss for practical validation and refinement.

Acknowledgment

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