

Article

An Ultra-Wide-Angle Mechanically Steered Reflectarray Antenna (RA) Based on Non-Specular Reflection

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Abstract

This paper presents a non-specular reflection-based mechanically steered reflectarray antenna (RA) that achieves ultra-wide beam steering up to 80° while preserving mainlobe integrity. Conventional mechanically steered RAs are fundamentally constrained by specular reflection, where the reflection angle follows the incident angle symmetrically. Consequently, large scan angles inherently require extreme incident angles, which exacerbate aperture projection loss, element angular instability, and beam distortion. To overcome this limitation, an asymmetric reflection phase distribution is engineered to decouple the reflection angle from the incident angle, thereby relaxing the incident angle requirement for wide-angle beam steering. By mitigating extreme angular excitation of the unit cells, the proposed approach enhances angular stability and improves beam robustness at large scan angles. Full-wave simulation and measurement demonstrate stable radiation patterns without mainlobe splitting up to a scan angle of 80°. Although a gain reduction of approximately 6 dB is observed at the maximum steering angle due to intrinsic aperture projection effects, the mainlobe characteristics remain well preserved. The proposed approach provides a physically grounded and practical pathway toward ultra-wide-angle beam steering in mechanically steered RAs.

Keywords: reflectarray antenna; non-specular reflection; ultra-wide beam steering; mechanical steering; angular stability

1. Introduction

Reflectarray antennas (RAs) have attracted significant attention due to their capability to combine the high-gain characteristics of parabolic reflectors with the low-profile and planar structure of phased arrays [1–10]. By engineering the reflection phase of subwavelength unit cells, RAs can synthesize desired radiation patterns while maintaining structural simplicity and reduced feeding complexity. These advantages make them attractive for satellite communications, radar systems, and high-frequency wireless applications. In addition to reflectarray antennas, transmitarray (TA) antennas have also attracted considerable attention as another representative space-fed architecture for high-gain beam-steering applications [11–14]. Similar to reflectarrays, transmitarrays employ a feed antenna to illuminate a planar aperture while controlling the transmitted phase through engineered unit cells.

Beam steering in RA can be achieved through electronic reconfiguration or mechanical tilting. Although electronically reconfigurable RA provide dynamic beam control,

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they often require complex biasing networks, active components, and increased fabrication cost [15–19]. In contrast, mechanically steered RA offer a simple and robust alternative, particularly in high-power or harsh-environment applications where reliability is critical [20–23]. In conventional mechanically steered RA, beam scanning is typically realized by tilting either the entire aperture or the feed source. Most reported designs rely on specular reflection behavior, where the reflection angle symmetrically follows the incident angle. Under this condition, the steering angle is directly determined by the geometrical relationship between the incident and reflected waves. However, such specular reflection inherently constrains wide-angle beam steering. As the desired scan angle increases, the required incident angle becomes correspondingly extreme. This leads to several fundamental challenges. First, aperture projection effects reduce the effective radiating area as the scan angle increases, resulting in unavoidable gain degradation proportional to the cosine of the steering angle. Second, extreme incident angles intensify angular instability in the reflectarray unit cells, causing reflection magnitude variation, nonlinear phase response, and polarization degradation. Third, large phase gradients across the aperture increase discretization errors and may induce beam distortion or elevated sidelobe levels. In addition, specular and undesired scattered reflections from the unit cells under oblique illumination can cause beam squint, gain degradation, and deviation of the main beam from the intended direction [24]. These effects become increasingly important in off-axis-fed reflectarrays and at large incident angles. Due to these combined effects, most mechanically steered RAs reported in the literature demonstrate scanning ranges limited to approximately $\pm 60^\circ$. Beyond this range, significant gain reduction and mainlobe distortion are commonly observed. In particular, at very large scan angles, the main beam may broaden, split, or become asymmetric due to the angular sensitivity of the elements and illumination imbalance. Metasurfaces have enabled versatile electromagnetic wave manipulation through engineered boundary conditions, including generalized reflection and refraction [25]. More recently, wide-angle wavefront manipulation has also been demonstrated using optical metalenses for large-angle beam control [26]. Although these studies employ different operating principles from horn-fed mechanically steered reflectarrays, they demonstrate the potential of engineered electromagnetic surfaces for wide-angle wave manipulation.

To extend the achievable steering range while preserving radiation performance, it is necessary to reconsider the fundamental reflection mechanism employed in conventional designs. Instead of relying on the conventional specular reflection characteristic, the proposed reflectarray is synthesized to exhibit a non-specular reflection behavior, where the reflected beam is redirected toward a desired direction that does not satisfy the conventional specular reflection relationship. This non-specular reflection characteristic is realized through the synthesized reflection phase distribution of the reflectarray. By decoupling the reflection angle from the incident angle, it becomes possible to achieve large output steering angles without requiring extreme angular excitation of the unit cells. Motivated by this observation, this paper proposes a non-specular reflection-based mechanically steered RA. An asymmetric reflection phase distribution is synthesized to redirect oblique incident waves toward desired radiation directions without adhering to the conventional symmetric reflection constraint. Through this approach, the incident angle required for wide-angle beam steering is effectively relaxed, mitigating angular sensitivity of the elements and improving beam robustness. Unlike prior works that focus primarily on extending the steering angle through larger mechanical tilting, the proposed method fundamentally modifies the reflection mechanism at the aperture level. By reducing extreme angular excitation, the design alleviates reflection magnitude degradation and phase distortion associated with large incidence. Multifocal reflectarray synthesis has also been investigated to improve the scanning performance of mechanically steered

reflectarrays by optimizing the aperture phase distribution for multiple feed positions. Although such approaches effectively reduce scan loss over multiple feed locations, they rely on multi-position aperture synthesis. In contrast, the proposed method preserves the conventional single-focus reflectarray configuration and extends the achievable steering range through a non-specular reflection mechanism rather than multi-position optimization. As a result, stable radiation patterns can be maintained even at very large scan angles. Full-wave simulation and measurement demonstrate that the proposed RA achieves beam steering up to 80° while preserving mainlobe integrity. No beam splitting or severe distortion is observed within the investigated range. Although a gain reduction of approximately 6 dB occurs at the maximum scan angle due to intrinsic aperture projection effects, the radiation characteristics remain well defined and stable. This performance significantly exceeds the typical scanning range reported for conventional specular-based mechanically steered RAs.

This paper is organized as follows. Section 2 describes the design procedure and simulation results of the ultra-wide-angle steered RA. Section 3 details experimental results and discussion of the proposed RA. In the final section, the concluding remarks are given.

2. Design of Proposed Ultra-Wide-Angle Steered Reflectarray Antenna (RA)

Figure 1 illustrates the resulting reflection behavior of the proposed reflectarray concept and is intended only to provide a conceptual explanation of the non-specular reflection characteristic rather than the underlying reflectarray synthesis procedure. Conventional high-gain reflectarray antennas (RAs) are typically synthesized under normal (0°) incidence, where the metasurface phase distribution is tailored such that a normal incident wave is redirected broadside. In this configuration, the RA operates analogously to a parabolic reflector, producing a beam that is symmetric with respect to the incident angle. Consequently, when the feed is tilted by $-\theta$, the main beam is steered toward $+\theta$, resulting in an inherently symmetric angular mapping governed by specular reflection, as shown in Figure 1a. This symmetry fundamentally limits the achievable beam-scanning range in mechanically steered systems because large steering angles inevitably introduce severe scan loss and pattern degradation. As the beam is driven away from broadside, the effective projected aperture decreases, reducing the attainable directivity and realized gain. Simultaneously, the incidence across the reflectarray becomes highly nonuniform and increasingly oblique, which amplifies element-level phase and amplitude errors relative to the broadside-optimized phase model. These effects are further compounded by feed-related degradations at wide angles, including increased spillover and blockage, reduced illumination efficiency, and stronger phase curvature across the aperture. Consequently, wide-angle mechanical steering in conventional specular designs is typically accompanied by noticeable gain roll-off, beam broadening, elevated sidelobe levels, and increased susceptibility to undesired lobes.

In contrast, the proposed RA is synthesized under a predefined oblique feed condition such that the spherical wave radiated by the horn is coherently reflected toward broadside. The proposed reflectarray is synthesized using the conventional horn-fed reflectarray phase synthesis procedure under spherical-wave illumination and is not based on the generalized Snell's law or a linear phase-gradient metasurface formulation. Specifically, the phase distribution is engineered so that an incident wave arriving at $+30^\circ$ is reflected toward 0° . The selected $+30^\circ$ design condition was not determined through mathematical optimization and is not intended to represent a globally optimal solution. Instead, it was chosen as a representative proof-of-concept design point based on engineering considerations. A smaller angular offset would provide only a limited improvement in the achievable steering range, whereas a larger offset could further extend the steering

range but at the expense of reduced broadside gain and increasingly asymmetric steering characteristics. Therefore, an angular offset of $+30^\circ$ was adopted as a practical compromise for demonstrating the feasibility of the proposed non-specular reflection concept. This design strategy embeds a fixed spatial phase gradient into the metasurface, effectively pre-tilting the reflected phase front by a constant angular offset. Due to this built-in phase gradient, the angular mapping between the incident and reflected waves no longer follows a symmetric relation. Rather than mirroring the incident direction, the metasurface reconstructs a spatially shifted phase front, resulting in a constant angular offset in the reflection response. As a consequence, if $+30^\circ$ incidence produces a 0° reflection, then 0° incidence yields $+30^\circ$ reflection, and -30° incidence results in $+60^\circ$ reflection. This asymmetric behavior originates from the non-specular phase transformation imposed by the engineered metasurface and enables extended beam displacement without requiring active phase tuning elements. Although the proposed non-specular reflectarray significantly extends the achievable steering range, beam steering is inherently limited to one angular direction because of the fixed asymmetric phase distribution. Unlike conventional specular reflectarrays, where steering toward the opposite direction can be achieved by relocating the feed, the proposed design requires mechanical rotation of the entire reflectarray to realize opposite-direction beam steering. This represents a trade-off between steering range and bidirectional scanning capability. As shown in Figure 2a, the reflectarray is implemented using a planar metasurface composed of periodically arranged unit cells with dimensions of $15\text{ mm} \times 15\text{ mm}$, designed to operate at 8.2 GHz. Each unit cell consists of a circular ring metallic structure. The metasurface is implemented on ZYF 450 substrate with a relative permittivity of 4.5 and a thickness of 3.2 mm. The unit-cell geometry is characterized by a strip width of 0.4 mm. The geometrical symmetry of the unit cell further mitigates polarization sensitivity and ensures consistent performance under oblique incidence. The electromagnetic characteristics of the unit cell were analyzed using full-wave simulations with periodic boundary conditions. As shown in Figure 2b, the magnitude of the reflection coefficient exhibits low loss as the ring radius varies from 0.5 mm to 7 mm. In addition, the reflection phase response provides a sufficiently wide phase compensation range, enabling effective phase correction and ensuring adequate phase coverage for reflectarray synthesis. It is well known that the reflection phase of a reflectarray unit cell progressively deviates from its normal-incidence characteristic as the incident angle increases, resulting in larger phase errors under wide-angle illumination. Although this angular dependence can be partially compensated by incorporating the incident-angle characteristics of individual unit cells into the reflectarray synthesis, no significant improvement in antenna performance was observed. Therefore, rather than compensating for the angular dependence of individual unit cells, the proposed approach reduces the maximum incident angle required for a given steering direction through the non-specular reflection mechanism. Consequently, the unit cells operate under less severe angular excitation, inherently reducing the phase errors associated with large-angle incidence while employing the same unit-cell geometry as the conventional reflectarray. To verify the proposed non-specular beam-steering concept, two reflectarray phase distributions were synthesized and compared. Because the feed horn operates in the radiating near-field region of the reflectarray, the aperture phase distribution was not determined solely from a point-source distance approximation. Instead, the feed horn was simulated independently, and the phase distribution of the linearly polarized electric field was extracted at each unit-cell location on the reflectarray aperture plane. The required reflection phase of each unit cell was then obtained from the difference between the extracted feed phase and the target aperture phase for the desired beam direction. The reflectarray antenna is fed by a rectangular horn antenna with a gain of 9 dBi. The horn antenna is positioned with the focal-length-to-diameter ratio (F/D) ratio of 0.5. The overall dimension of the

metasurface with unit cells of 10×10 is $150 \text{ mm} \times 150 \text{ mm}$. Figure 3a illustrates the conventional phase distribution designed for specular reflection, where the reflected beam direction follows the symmetric angular relationship dictated by the law of reflection. Under this configuration, the metasurface compensates only for the feed phase delay, resulting in a reflected wavefront whose steering direction is directly determined by the feed orientation. Consequently, the reflected beam exhibits a one-to-one symmetric mapping with respect to the incident angle. In contrast, Figure 3b presents the phase distribution of the proposed non-specular reflectarray. In addition to the conventional feed phase compensation, an additional phase term is incorporated such that an incident wave arriving from -30° is redirected broadside. As a result, the reflected beam no longer follows the symmetric angular relationship associated with specular reflection. Instead, a fixed angular offset is embedded into the reflection response, enabling non-specular beam steering without requiring active phase-control elements. The beam-steering performance of both reflectarray configurations was evaluated using full-wave simulations in the commercial ANSYS Electronics Desktop (HFSS) 2024 R1. During the optimization process, F/D was adjusted for each steering condition to maximize the realized gain while maintaining stable aperture illumination. Figure 4 compares the simulated far-field radiation patterns of the conventional specular reflectarray and the proposed non-specular reflectarray under various steering conditions. For the conventional design, acceptable beam quality is maintained at moderate steering angles. However, as the steering angle exceeds approximately 60° , severe pattern degradation becomes evident. The main beam gradually broadens and eventually splits into multiple lobes due to the combined effects of aperture projection loss, nonuniform illumination, and the increased angular sensitivity of the unit cells under extreme oblique incidence. In contrast, the proposed non-specular reflectarray exhibits significantly improved beam robustness across the entire steering range. Owing to the built-in phase gradient, the required incident angles remain substantially lower than those of the conventional specular configuration for the same reflected beam direction. Consequently, the unit cells operate within a more stable angular regime, reducing phase errors across the aperture. As shown in Figure 4, the proposed design preserves a well-defined main beam without noticeable beam splitting up to a steering angle of 80° . Although a gradual gain reduction is observed at large steering angles due to the inherent aperture projection effect, the mainlobe characteristics remain well preserved throughout the entire scanning range. Although the proposed design successfully extends the achievable steering range, slightly elevated sidelobe levels can be observed in the opposite angular region. This behavior is mainly attributed to the asymmetric aperture phase profile required for non-specular reflection, which redistributes a portion of the reflected energy away from the desired beam direction. Nevertheless, the increase in sidelobe levels is relatively small compared with the substantial improvement in the achievable steering range and the preservation of mainlobe integrity. Tables 1 and 2 summarize the optimized F/D values together with the corresponding steering angles and realized gains for the conventional specular reflectarray and the proposed non-specular reflectarray, respectively. For each steering condition, an identical parametric sweep of the F/D ratio from 0.3 to 0.7 was performed independently for both the conventional specular reflectarray and the proposed non-specular reflectarray. The F/D value yielding the maximum realized gain was selected for each antenna configuration and steering angle. The same optimized F/D conditions were subsequently employed in the corresponding measurements. Therefore, the results in Tables 1 and 2 represent the best achievable performance of both reflectarrays under equivalent F/D optimization constraints, rather than a comparison between an optimized proposed design and a non-optimized conventional design. The results quantitatively confirm the superior wide-angle beam-steering capability of the proposed non-specular reflectarray compared with the conventional specular design.

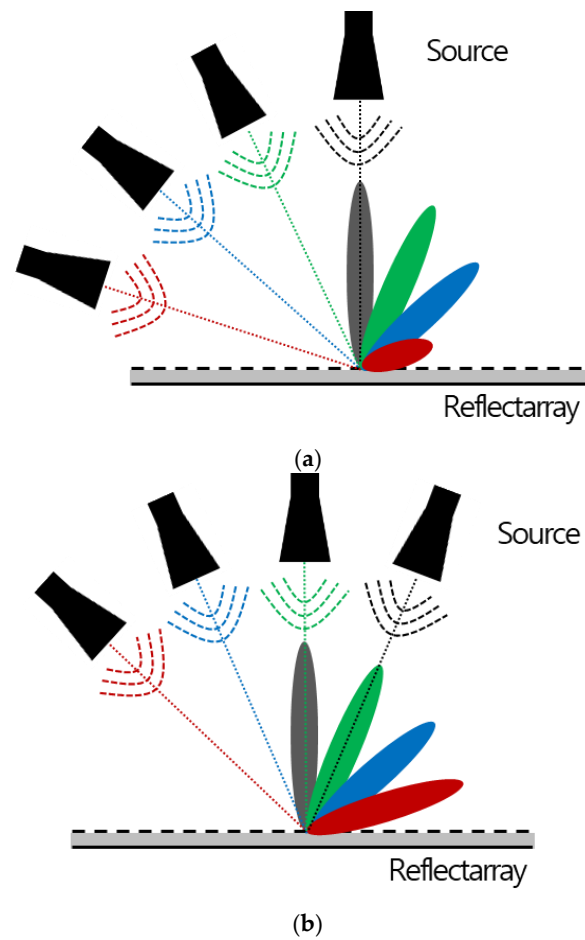
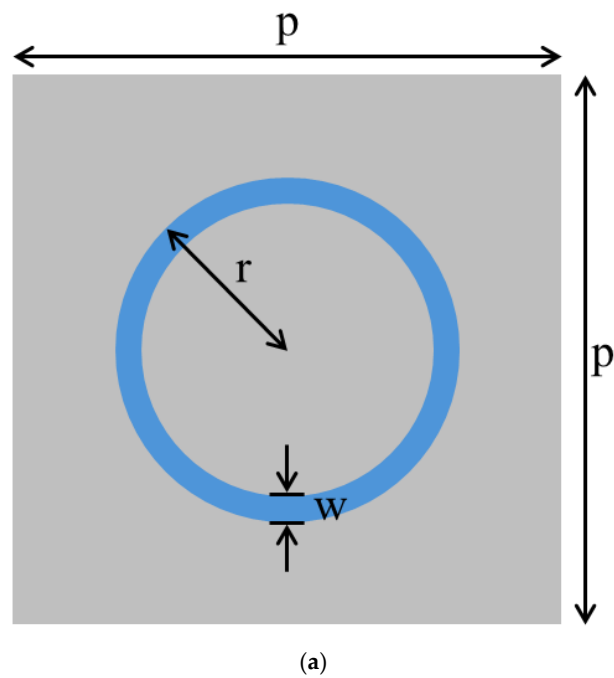


Figure 1. Conceptual comparison of conventional and proposed reflectarray antenna (RA). (a) Conventional specular-based RA. (b) Proposed non-specular-based RA.



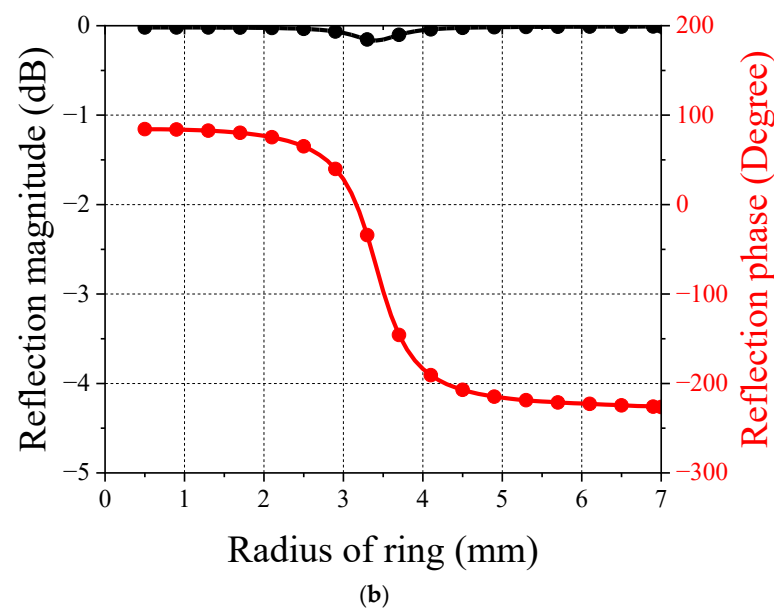


Figure 2. Designed metasurface unit cell (Top view) and its reflection characteristics. (a) Geometry of the unit cell consisting of a circular ring. (b) Full-wave simulated reflection responses at 8.2 GHz.

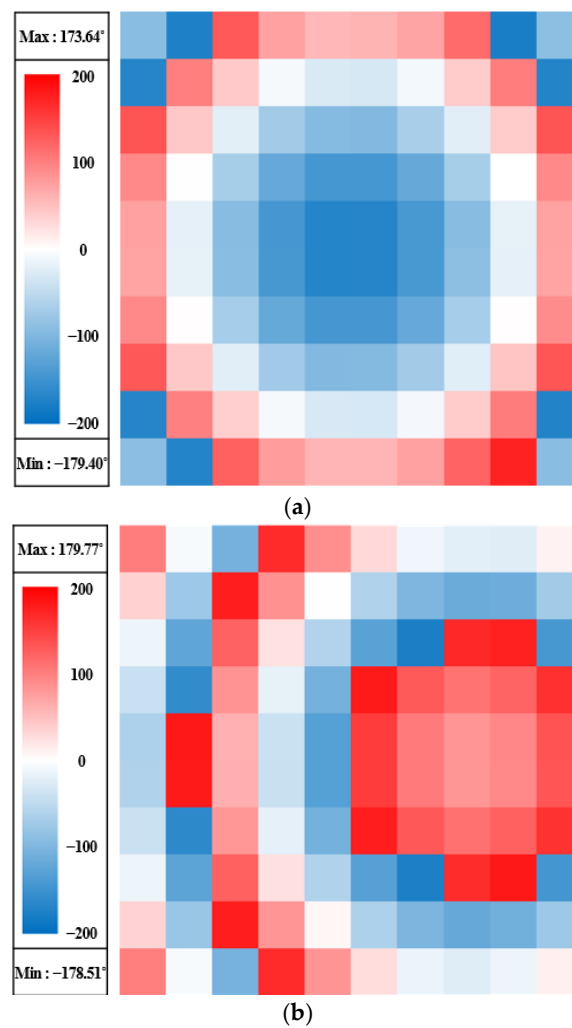


Figure 3. Reflection phase of the metasurface. (a) Specular reflection. (b) Non-specular reflection (30°).

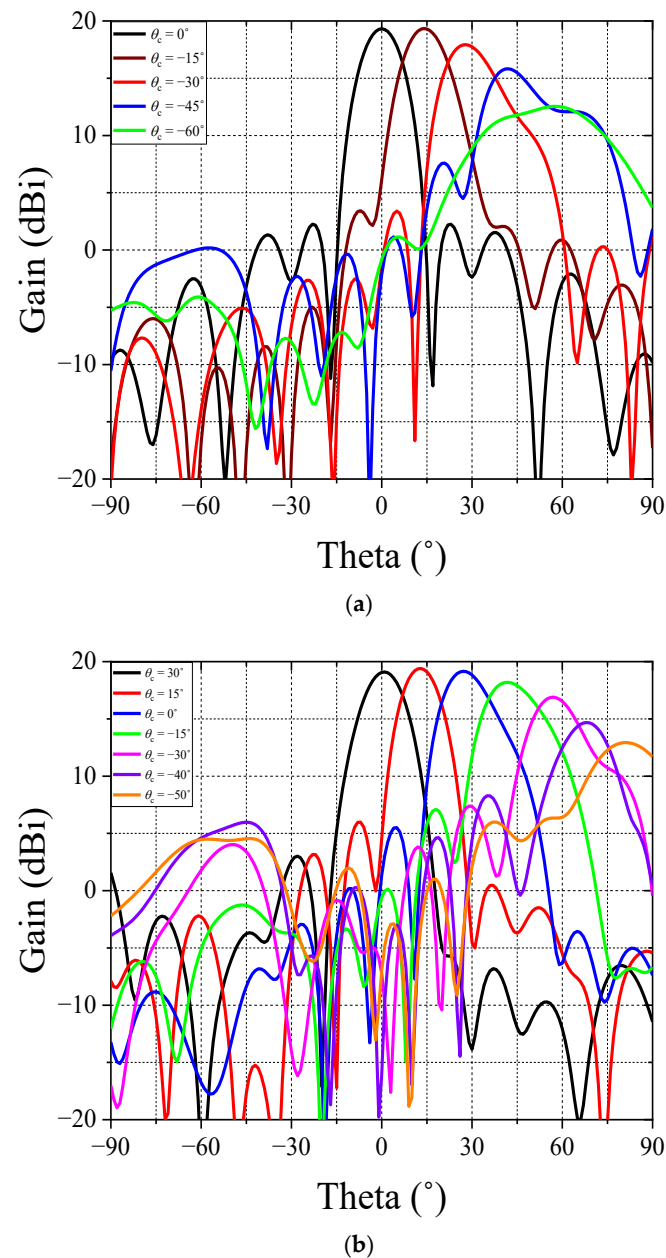


Figure 4. Full-wave simulated far-field radiation patterns (y - z plane). (a) Conventional specular reflectarray. (b) Proposed non-specular reflectarray.

Table 1. Beam-steering performance of the conventional specular reflectarray.

	Incident Angle (0°)	Incident Angle (-15°)	Incident Angle (-30°)	Incident Angle (-45°)	Incident Angle (-60°)
F/D	0.5	0.5	0.5	0.55	0.45
Maximum gain (dBi)	19.32	19.34	17.93	15.82	12.54
Beam steering angle	0°	14°	28°	42°	58°

Table 2. Beam-steering performance of the proposed non-specular reflectarray.

	Incident Angle (30°)	Incident Angle (15°)	Incident Angle (0°)	Incident Angle (-15°)	Incident Angle (-30°)	Incident Angle (-40°)	Incident Angle (-50°)
F/D	0.5	0.6	0.5	0.5	0.6	0.6	0.5
Maximum gain (dBi)	19.10	19.40	19.15	18.19	16.89	14.68	12.93
Beam steering angle	1°	13°	27°	42°	57°	68°	81°

3. Experimental Results and Discussion

To experimentally verify the proposed ultra-wide-angle beam-steering concept, both the conventional specular reflectarray and the proposed non-specular reflectarray were fabricated and measured. Figure 5 shows the synthesized metasurface layouts of the conventional specular reflectarray and the proposed non-specular reflectarray. Both antennas employ identical aperture dimensions, substrate, unit-cell geometry, and feed configuration, with the synthesized metasurface arrangement being the only difference between the two designs. The horn antenna (HS-090-UBR-10A, 8.2–12.4 GHz) with a gain of 9 dBi at 8.2 GHz is employed as the feed antenna. A custom 3D-printed jig is fabricated to provide adjustable height and incident angle, allowing precise positioning and alignment of the horn antenna during the measurement process. Both reflectarrays are implemented using identical unit-cell geometries and substrate materials, with the only difference being the synthesized aperture phase distribution. This configuration enables a direct comparison of the beam-steering characteristics resulting from the specular and non-specular reflection mechanisms. The radiation characteristics of the fabricated reflectarrays were measured in a full anechoic chamber at 5-degree intervals. Figure 6 compares the simulated and measured radiation patterns for both the conventional specular reflectarray and the proposed non-specular reflectarray under various steering conditions. Overall, good agreement is observed between the simulation and measurement results, confirming the accuracy of the design methodology and the validity of the full-wave simulation model. Slight discrepancies between the simulated and measured results are mainly attributed to fabrication tolerances, feed-position alignment errors, and measurement uncertainties. In addition, the measured gains are approximately 3 dB lower than the simulated values because practical implementation factors, including the horn-support structure, the waveguide adapter, and their associated insertion losses, were not included in the full-wave simulation model. The conventional specular reflectarray achieved a measured peak gain of 16.1 dBi at broadside, with beam steering limited to 62°. In comparison, the proposed non-specular reflectarray extends the maximum steering angle to 81° while maintaining a measured peak gain of 11.7 dBi at the largest steering angle. Although the gain decreases at extremely large steering angles, this behavior is mainly attributed to the intrinsic aperture projection effect. As the radiation direction approaches grazing, the effective projected aperture decreases approximately according to the cosine of the steering angle. Accordingly, aperture projection losses of approximately 3 dB at 60° and 7.6 dB at 80° are expected even for an ideal aperture antenna. It should also be noted that the proposed reflectarray is synthesized to exhibit a non-specular reflection characteristic; therefore, the broadside direction does not correspond to the maximum-gain condition. The simulated and measured gain difference between the broadside direction and the maximum steering angle is approximately 6 dB, which is comparable to the gain degradation expected for extremely wide-angle radiation. Despite this unavoidable reduction in effective aperture, the proposed reflectarray maintains a measured gain of 11.7 dBi and a well-defined main beam at 81°, demonstrating the practical significance of the proposed wide-angle steering concept. It should also be noted that the measured broadside gain of the conventional reflectarray is slightly underestimated due to partial blockage by the feed horn, making the measured gain variation appear smaller than its intrinsic value. Moreover, the measured radiation patterns of the proposed reflectarray maintained a well-defined main beam without significant beam splitting or mainlobe distortion, even at the maximum steering angle. Moreover, the measured peak sidelobe levels of the conventional reflectarray are approximately −15.4 dB, −15.5 dB, −14 dB, −8.3 dB, and −12.2 dB at steering angles of 0°, 15°, 30°, 45°, and 60°, respectively. For the proposed non-specular reflectarray, the corresponding peak sidelobe levels are approximately −14.8 dB, −12.9 dB, −13.6 dB, −10.6 dB, and −9 dB, respectively. As expected, the proposed reflectarray exhibits slightly higher

sidelobe levels because the asymmetric aperture phase distribution required to realize the non-specular reflection characteristic introduces additional diffraction effects, particularly at large steering angles. Nevertheless, the main beam remains clearly dominant throughout the investigated steering range without significant beam splitting. A preliminary study further confirmed that reducing the unit-cell size from 15 mm to 10 mm can improve the peak sidelobe level while preserving the proposed non-specular steering mechanism. Further optimization of the unit-cell design for sidelobe reduction will be presented in future work. These results confirm that the proposed non-specular phase synthesis enables a significantly wider steering range while preserving stable radiation characteristics. In particular, the proposed approach extends the achievable steering angle from 62° to 81° , corresponding to about 30% increase in steering capability compared with the conventional specular reflectarray. The close agreement between the simulated and measured results verifies that the proposed non-specular phase synthesis effectively mitigates the angular limitations associated with conventional mechanically steered reflectarrays. Furthermore, the experimental results demonstrate that the proposed approach successfully extends the achievable beam-steering range while preserving mainlobe integrity. These observations indicate that the steering limitation of conventional mechanically rotated reflectarrays is fundamentally associated with the specular reflection mechanism and highlight the effectiveness of the proposed non-specular phase synthesis for ultra-wide-angle beam steering. Table 3 summarizes the performance of the proposed reflectarray and previously reported mechanically steered reflectarrays. The proposed antenna maintains a well-defined main beam up to $\pm 81^\circ$ while achieving an aperture efficiency comparable to existing designs.

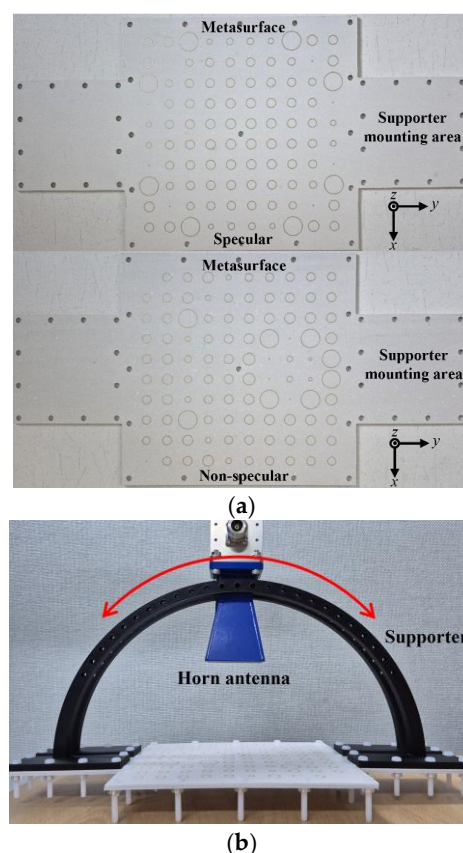


Figure 5. Photographs of the fabricated prototype of reflectarray. (a) Top view of metasurfaces for specular and non-specular. (b) Non-specular reflectarray antenna.

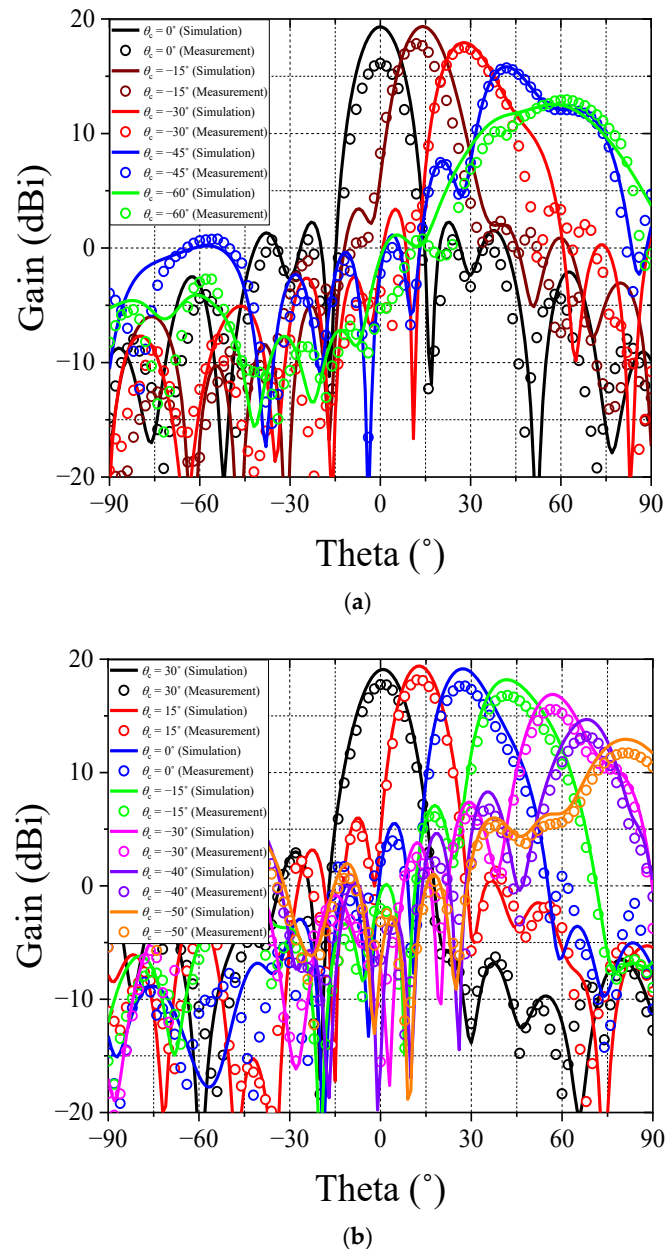


Figure 6. Full-wave simulated and measured far-field radiation patterns (y - z plane). (a) Conventional specular reflectarray. (b) Proposed non-specular reflectarray.

Table 3. Comparative analysis of mechanical RAs.

Reference	Operation Frequency (GHz)	3 dB Beam Steering Range	Aperture Efficiency
[27]	11.6~12.7	$\pm 55^\circ$	43.1%
[28]	NA	$\pm 27^\circ$	24.5%
[29]	31.6~33.2	$\pm 30^\circ$	40%
		$\pm 63^\circ$	
This work	8.2	Steering angle with well-defined main beam ($\pm 81^\circ$)	41.3%

4. Conclusions

This paper presented a non-specular reflection-based mechanically steered reflectarray antenna for ultra-wide-angle beam steering. By introducing an asymmetric phase

distribution, the proposed reflectarray redirects an incident wave arriving from -30° toward broadside, thereby reducing the incident-angle requirement associated with conventional specular reflection. As a result, the angular limitations of mechanically steered reflectarrays can be effectively mitigated. A reflectarray operating at 8.2 GHz was designed, fabricated, and experimentally validated. Both simulation and measurement results showed excellent agreement. While the conventional specular reflectarray exhibited severe pattern degradation beyond approximately 60° , the proposed non-specular reflectarray maintained a stable main beam up to a steering angle of 80° . These results demonstrate that non-specular phase synthesis provides an effective and practical approach for realizing ultra-wide-angle beam steering in high-gain reflectarray antenna systems.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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