Mechanical Beam Steering Reflectarray Antennas Using Focal Arc Geometries: Performance and Limitations

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***Abstract*—This paper presents a parametric study on passive, mechanically steerable reflectarray (RA) antennas using a tilted focal arc configuration. The objective is to examine the trade-offs in designing compact RA systems capable of steering beams over a wide angular range while minimizing scan losses. Multiple RA designs at 29.5 GHz are evaluated, featuring varying degrees of compactness and steering ranges with highly uniform gain across the steering range. Performance is assessed in terms of gain and aperture efficiency, highlighting the effects of focal ratio and steering range on these metrics. A prototype antenna is also manufactured and measured, validating the simulation results with a demonstrated scan loss of only 0.5 dB over a 90-degree range and a maximum gain of 28.2 dBi. The findings provide insights into the design compromises required for passive, mechanically steerable RA systems, offering guidelines for optimizing such antennas for mm-Wave applications.**

***Index Terms*—Reflectarray, Ka band, mechanical beam scanning.**

I. Introduction

There is an increasing demand for efficient and compact systems for mm-Wave satellite communications, requiring antennas capable of steering beams to maintain moving radio links. Traditional phased arrays are commonly used due to their high gain and beam agility, but their complex feeding networks and associated losses pose challenges [1], [2]. Reconfigurable spatially fed arrays (SFAs) such as reflectarrays (RRAs) and transmitarrays (RTAs) simplify the feeding network by using a single primary feed, reducing losses and cost. However, these designs rely on electronically tunable elements like PIN or varactor diodes [3], MEMS [4], or liquid crystals to dynamically adjust the antenna response [5]. The integration of these components and their control circuitry results in significant system complexity, limiting their viability for mass-produced solutions.

Mechanically steerable reflectarray (RA) and transmitarray (TA) antennas offer a more cost-effective alternative. These antennas steer the beam through feed or panel movements. They use passive panels to avoid the need for active electronic control, thereby reducing system complexity and cost. Common implementations involve moving the feed along a focal arc [6], [7], [8] or translating the panel in-plane [9], [10] to change the illuminated region. While these methods eliminate active components, they face challenges in achieving compact designs, such as feed blockage and beam distortions. Unlike actively reconfigurable systems, passive mechanically steerable RAs cannot dynamically tune the panel response to maximize collimation for each direction. Instead, they require a compromise that balances performance over the entire steering range. This trade-off results in lower gain and aperture efficiency compared to actively reconfigurable solutions.

The aperture efficiency in passive, mechanically steerable RAs is closely tied to the steering range. Achieving low scan losses across a broad range requires configuring the panel for diverse radiation scenarios, leading to a degradation in collimation. Additionally, compact antennas with low focal-to-diameter (F/D) ratios are more prone to phase aberrations, particularly with wide angular coverage. The sharper phase profile needed for collimation in such configurations makes finding an effective compromise challenging, requiring significant trade-offs to maintain consistent performance.

This paper presents a parametric study on beam steering RA antennas using feed translations along a focal arc. Its main purpose is to highlight the trade-offs that must be made when designing a passive RA capable of steering a beam over a wide angular range, while achieving extremely low scanning losses. For this purpose, multiple RA antennas are designed at 29.5 GHz featuring multiple angular steering ranges and levels of compactness. The Multi-Feed Phase Only Optimization (MF-POO) algorithm [8] is used to ensure highly uniform gain levels across the intended steering range for each configuration. Lastly, the equalized gain levels are compared across all the studied configurations. This comparison is meant to provide an intuition as to the beam steering performance and the aperture efficiency that could be expected from a passive, mechanically steerable RA antenna. Lastly, these simulated results are validated by means of a RA demonstrator that implements one of the presented compact antenna optics. This demonstrator achieves a 90-degree steering range with a measured scan loss of only 0.5 dB and a maximum gain of 28.2 dBi.

II. Defining the Antenna Optics

The use of feed translations along a focal arc is a common method to achieve mechanical beam steering with a passive RA panel. By having the feed point towards a fixed point on the RA surface along its entire translation path, there is a high overlap in the impinging fields among all possible feed positions, resulting in a fairly compact panel. Furthermore, the re-orientation of the feed along the arc means that the radiated

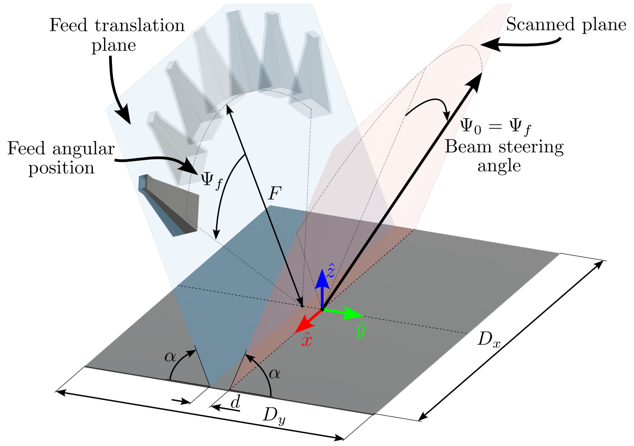

Fig. 1. Mechanically steering RA antenna optics based on a tilted focal arc. The feeding horn models are merely illustrative.

beam can always be pointed towards or close to the specular reflection direction. This exploits the natural phase distribution of the impinging fields on the RA surface and reduces beam squint within the operating band [11].

Typical focal arc implementations define a centered arc of feed positions which is contained on a plane perpendicular to the RA surface, with the center of the arc vertically aligned with the panel center [6], [7]. These implementations often suffer from notable beam distortions due to blockage of the feed and its support structure around the central feed positions. Furthermore, they do not support having multiple feed operating simultaneously along the arc to achieve multiple beams, as the feeds on one side of the focal arc severely block the beams generated by the feeds on the opposite side. To address this, [8] introduces a tilted focal arc geometry, shown in Fig. 1. This small modification introduces a small tilt α to the plane containing the focal arc, and an offset d from the panel center to adjust the illumination taper properly. By doing this, feed blockage can be largely negated while keeping most of the benefits of this geometry.

The position and orientation of the feed is defined by its angular position Ψ_f. For an arbitrary feed position within the intended steering range of the antenna, $|\Psi_f| \leq \Psi_{max}$, a collimated beam is generated on the specular reflection direction from the panel. As a result, moving the feed along the arc steers the beam within the scanned plane illustrated in Fig. 1, where the beam steering angle can be defined as $\Psi_0 = \Psi_f$. This angle can be related to the standard spherical angles (θ_0, φ_0) as shown in [8].

In order to design a RA panel capable of achieving a consistent beam level across its entire intended scanning range, the arc is first be discretized into a set of feed positions. The impinging fields on the RA surface associated to every one of these positions are calculated. For the purpose of this analysis, a simple linearly polarized feed model is used [12]:

$$\vec{E}(\vec{r}) = \begin{cases} E_0 \frac{e^{-jk_0 r}}{r} \cos^q \theta (\sin\varphi\hat{\theta} + \cos\varphi\hat{\varphi}), & \theta \leq \pi/2 \\ 0, & \text{otherwise} \end{cases}, \tag{1}$$

where the position vector $\vec{r}$, the spherical angles and the unit vectors are expressed in the coordinate system of the feed at a given angular position. This system is defined such that the H-plane of the feed coincides with the feed translation plane, and its z-axis aligns with its pointing direction as depicted in Fig. 1. This way, the E-plane of the feed contains the y-axis of the RA panel, and the impinging fields are mostly projected onto the E_y^i tangential field component.

The array elements are modeled as ideal phase shifters, with $\rho_{yy} \approx e^{j\phi_y}$ being the direct reflection coefficient that relates the main incident and reflected field components, E_y^i and E_y^r respectively. For every one of the selected feed positions Ψ_f along the arc, a different distribution of phase shifts ϕ_y can be calculated to achieve maximum collimation in the specular direction Ψ_0. This results in as many phase shift distributions as discrete feed positions in the system, each one of them being tailored for a single feed position with rapid degradation when the feed is moved away from it.

A single phase response needs to be selected for the RA elements that achieves a balanced compromise among the radiation requirements for all the feeds. MF-POO is selected for this purpose, as it was shown to be able to achieve highly equalized beams in previous works [8]. MF-POO is a weighted multi-objective optimization technique where the phase shift to be introduced by each element on the array is selected based on multiple colliding radiation requirements. To find a balance among all of them, the impinging field amplitude from each feed position onto each cell is accounted for when selecting its phase response. Furthermore, the weight of each feed position in the optimization process can be tuned. This is used to prioritize certain beams (typically the more oblique ones) to achieve a highly uniform gain across the entire steering range.

III. Parametric Comparison

When designing a passive RA panel capable of mechanical steering, the collimation performance of the panel is tightly tied to the steering range that it is optimized for. A broad steering range means the panel needs to provide a balanced performance across a more diverse set of radiation directions, which limits its collimation capabilities compared to being optimized for a single configuration. The compactness of the antenna optics also plays a big role in the drop in antenna gain from a panel designed for a single beam direction to one optimized for beam steering. Large focal ratios require moderately directive feeding, which offsets part of the collimating requirements from the RA panel to the feeding elements. In contrast, low focal ratios with low-directivity feeds have the RA panel responsible for most of the beam collimation. This requires phase shift distributions on the RA elements that change rapidly along the RA surface, which result in larger phase aberrations when the RA response is balanced for multiple radiation requirements.

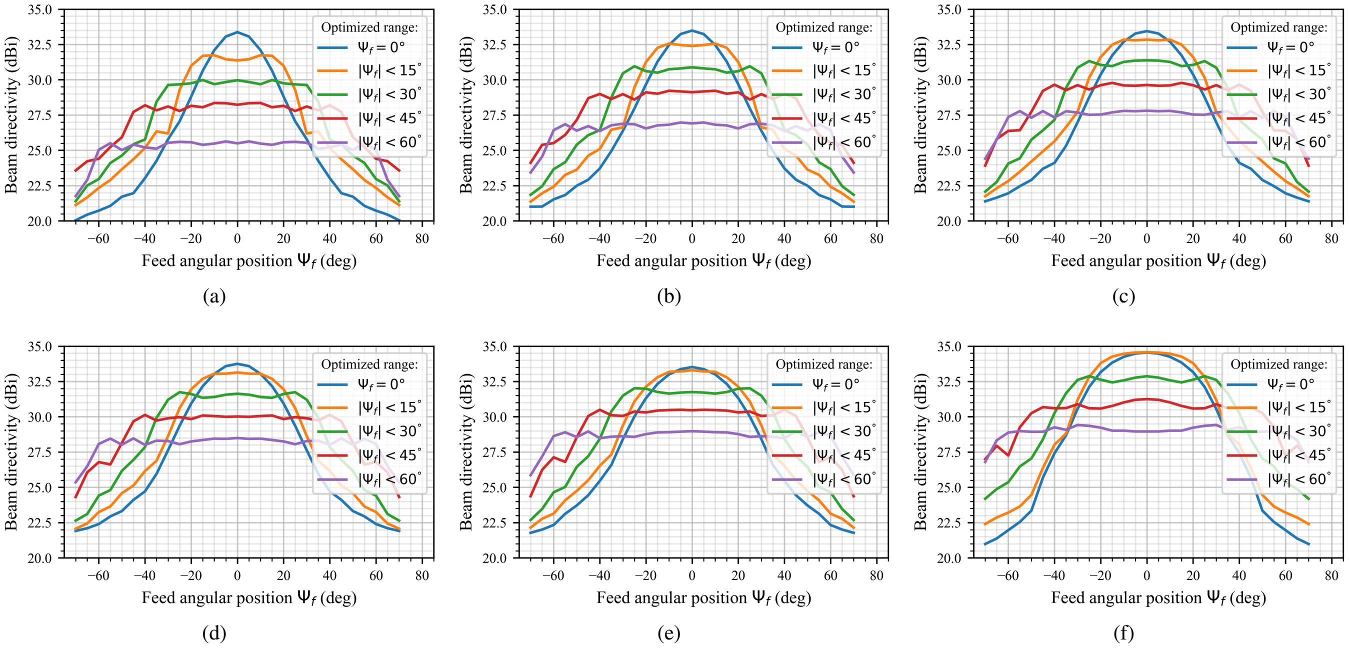

Fig. 2. Estimated steered beam directivity for multiple compactness levels and steering ranges. (a) through (e) represent the beam steering performance for tilted focal arcs of radi $F = \{0.55, 0.7, 0.85, 1, 1.15\}D_y$, respectively. (f) presents the same results for a centered arc configuration (i.e., $\alpha = 0°$ and $d = 0$ mm) with $F = D_y$.

In order to test these claims, multiple mechanically steering RA antenna designs are compared at 29.5 GHz, all of which are based on the tilted focal arc configuration shown in Fig. 1. A fixed panel size D_y of 175 mm is selected, and the tilt of the feed plane is set to $\alpha = 68°$ to largely avoid feed blockage effects. The array cell size is set to $0.4\lambda_0$, or 4.07 mm, to prevent grating lobes and to ensure a fine discretization of the phase profile. Five focal ratios ranging from $F = 0.55D_y$ to $F = 1.15D_y$ are considered. For each case, the offset d and the feed directivity are adjusted to ensure an illumination taper of -10 dB at the longer panel edges (i.e., $y = \pm D_y/2$). An additional reference configuration using a centered focal arc and a focal ratio of $F = D_y$ is also considered for completeness. For every antenna optics, five different RA designs are calculated, targeting beam steering ranges starting from 0° (i.e., single-focus designs) up until ±60°. The panel size D_x is adjusted for every steering range and optics to ensure the illumination taper on the shorter panel edge (i.e., $x = \pm D_x/2$) is also about -10 dB even on the most oblique feed positions. This is done to ensure that the aperture efficiency estimations presented below account for the real aperture size required for each antenna geometry and radiation objective.

A total of 30 combinations of antenna optics and beam steering ranges is studied. To ensure a smooth and controlled beam steering performance, the focal arc is discretized into angular steps of 5°. Then, a different RA phase response is calculated using MF-POO for each of these cases. The optimization process is tuned to ensure a highly uniform steering performance, achieving scanning losses below 0.5 dB within the intended steering ranges. Lastly, the radiation pattern associated to the resulting RA phase responses is evaluated over a wide range of feed positions, both within and outside of the optimized angular range.

TABLE I
MAXIMUM APERTURE EFFICIENCY AMONG OPTIMIZED BEAM DIRECTIONS

	Steering range (deg)				
	0°	±15°	±30°	±45°	±60°
$F = 0.55D_y$	61.2%	37.4%	21.7%	13.4%	7.2%
$F = 0.70D_y$	62.8%	45.2%	26.6%	14.8%	7.9%
$F = 0.85D_y$	63.8%	49.3%	29.9%	16.4%	8.5%
$F = 1.00D_y$	63.6%	52.8%	32.5%	17.7%	9.2%
$F = 1.15D_y$	64.9%	54.8%	34.6%	19.0%	9.7%

A comparison of the scanning performance of the studied configurations is presented on Fig. 2. Most notably, there is a significant drop in maximum antenna directivity in all configurations as the steering range grows larger. This is to be expected, as balancing the RA panel performance over larger set of feed positions means that it can be less specialized for any single one of them. It is also remarkable that all antenna optics using a tilted focal arc achieve a similar maximum directivity for the single-focus designs. However, the more compact optics suffer a more severe gain drop at higher steering ranges. With a focal ratio of $F = 0.55D_y$ a drop of 7.8 dB is observed from the single-focus to the 120° steering design, whereas with a focal ratio of $F = 1.15D_y$ the drop is reduced to 4.5 dB. As introduced before, this difference

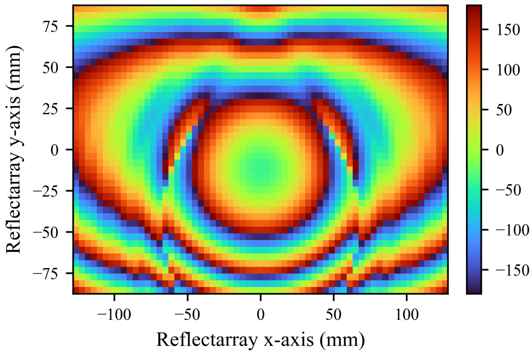

Fig. 3. Selected phase shift distribution for the manufactured antenna prototype.

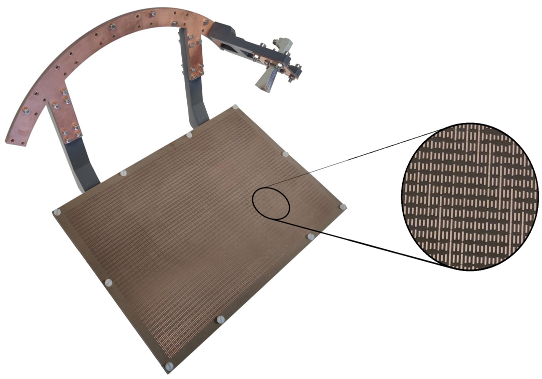

Fig. 4. Reflectarray antenna demonstrator with beam steering using a tilted focal arc.

is caused by the difference in the feed directivity: the most compact configuration requires a feed model with a low directivity of 11.9 dBi, but for a focal ratio of $F/D_y = 1.15$ this is increased to 17.9 dBi. Having a more directive feeding element relaxes the collimating requirements on the passive panel, reducing the compromises required to balance multiple radiation requirements.

Finally, the aperture efficiency is compared across all the presented cases. To do so, the highest directivity within the optimized steering range for each case is compared to that of a uniformly illuminated aperture, given by $4\pi A/\lambda_0^2$ with A being the aperture area. This comparison is presented in Table I. Notice that a similar trend is observed, with bulkier setups typically achieving higher aperture efficiencies. However, the differences among focal ratios are not as significant in terms of aperture efficiency as one may expect from the difference in achieved directivity presented above. The reason is that with a higher focal ratio, a significantly longer panel is required along the x-axis to have an adequate illumination taper. The larger panel largely compensates the differences in the estimated antenna directivity over broad steering ranges, bringing the final aperture efficiency to comparable levels.

IV. Experimental validation

To validate the presented results, a RA antenna demonstrator using one of the showcased antenna optics is manufactured and

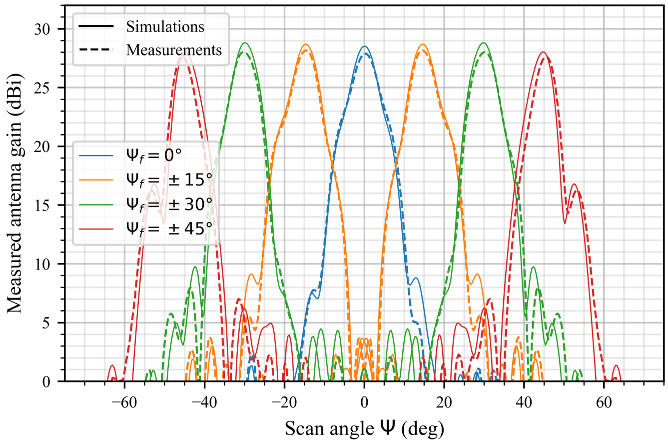

Fig. 5. Measured antenna gain within the scanned plane for multiple feed positions.

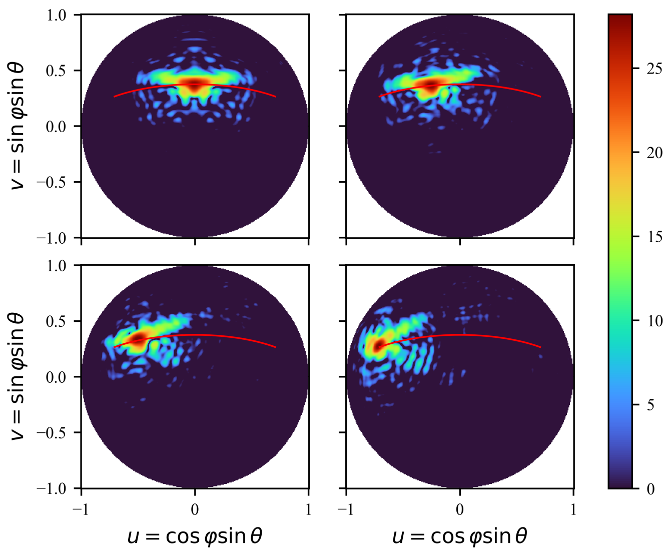

Fig. 6. 3D measured gain patterns for beam positions $\Psi_0 = 0°$ (top left), $\Psi_0 = 15°$ (top right), $\Psi_0 = 30°$ (bottom left) and $\Psi_0 = 45°$ (bottom right). The red line represents the projection of the scanned plane.

measured. The final antenna geometry features a focal ratio of $F/D_y = 0.7$ and an offset of $d = 12$ mm, with an intended 90-degree beam steering range. The calculated RA phase response is shown in Fig. 3. It is implemented on a unit cell consisting on 3 coplanar dipoles on DiClad 880 substrate ($\epsilon_r = 2.3$, $\tan\delta = 0.005$) at 0.762 mm thickness. The resulting antenna prototype and the unit cell are shown in Fig. 4.

The measured radiation pattern cuts along the scanned plane are shown in Fig. 5 for feed positions $\Psi_f = \{0, \pm 15, \pm 30, \pm 45\}^{\circ}$. An excellent match is observed between simulation and measurements. The 3D gain patterns are also shown in Fig. 6, where a collimated beam can be seen being steered within the scanned plane, represented as a red line in the diagram. The manufactured prototype achieves a maximum gain of 28.2 dBi and a measured scan loss of 0.5 dB across the measured positions. In-band measurements between 28 and 31

GHz show a 1.2 dB variation in maximum gain and a scan loss consistently below 1.5 dB. More details about this prototype can be found on [8].

V. Conclusion

The study demonstrates that while passive, mechanically steerable RA antennas using a tilted focal arc configuration can achieve broad beam-steering capabilities, they inherently face performance trade-offs related to compactness and steering range. Antenna designs with lower focal ratios exhibit more severe gain reductions as they attempt to balance collimation across diverse feed positions. Conversely, increasing the focal ratio improves gain and aperture efficiency but demands a larger antenna volume and a longer panel. The results from the fabricated prototype align well with the simulations, validating the approach and illustrating that the MF-POO technique can effectively equalize gain across wide steering ranges with minimal scan loss. These findings highlight the potential of mechanically steerable RAs for low-cost, compact solutions in mm-Wave communications while providing practical guidelines for optimizing their design.

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