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Evaluation of the Beam-Scanning Performance of Curved Transmitarrays

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***Abstract*—This work presents mechanical wide-angle beam steering antennas based on transmitarrays for mm-Wave communication systems. Elevation steering is achieved by translating the feeder, while azimuth scanning is done by rotating the transmitarray 360°. Traditional methods use planar surfaces and advanced techniques to enhance scan range. This study introduces a convex curved surface to improve performance by reducing scan loss at high tilt angles, achieving nearly 80° of scanning. It examines bifocal phase correction for curved surfaces and compares it with planar designs, emphasizing the benefits of the curved shape. A manufactured bifocal design demonstrates effective scan performance with minimal loss and sidelobe levels, showing that curved surfaces enhance performance beyond what analytical phase correction can achieve on planar surfaces.**

***Index Terms*—antennas, electormagnetidcs, propagation, measurements.**

I. Introduction

Recent research in high-performance antenna design for mm-Wave communication systems has focused on enhancing performance metrics like latency, data rate, and bandwidth. Beam steering antennas are a preferred solution due to their ability to provide interference-free, secure communications and user tracking [1], [2]. Additionally, high-gain antennas are essential for reducing propagation losses at mm-Wave frequencies and directing beams toward targets, whether stationary or mobile. These features can be integrated into a cost-effective, lightweight, low-power antenna front-end suitable for various platforms, including satellites, base stations, and small spacecraft [3], [4].

Standard beam scanning solutions, such as phased-array antennas, offer excellent beam agility, scalability, and flexibility [5], [6]. However, they rely on electronically controlled beam scanning, which necessitates complex active circuitry integration, results in high losses from the feeding network, and consumes significant power.

Quasi-periodic surfaces using spatial feeding (SFA) have been proposed for beam steering [7]. Transmitarray antennas offer excellent scanning performance and compact geometries, with F/D ratios of 0.34 [8]–[10], making them a viable alternative to phased arrays by balancing scan performance, cost, and compactness. This passive surface design achieves beam steering through mechanical displacement of the feeder, like parabolic reflectors [11]. Two main approaches are used: one involves moving the feeder along a parabolic trajectory while always pointing to the aperture's center, and the other involves linear in-plane displacement, which is more compact and simplifies the mechanical structure.

The mechanical displacement of the feed in transmitarrays can lead to defocusing and phase aberrations that degrade scan performance and side lobe levels (SLL). To address these issues, some methods involve blind optimization or multifocal techniques, as discussed in [10]. However, these approaches are limited by the planar surfaces they use, which restrict the effective aperture area and its performance according to the cosine law. Consequently, planar apertures only effectively adhere to this law up to 50°; beyond this angle, scan losses are significantly greater than expected.

This work presents a novel transmitarray configuration for ultra-wide beam scanning in the mm-Wave band, utilizing analytical bifocal phase correction and a new degree of freedom. By employing a convex curved surface instead of a planar one, the design extends the scanning range and reduces scan loss associated with planar apertures. The bifocal phase correction is tailored for curved surfaces, accommodating the new element positions. A detailed comparison highlights the advantages of curved surfaces over planar ones. The transmitarray, designed with a unit cell comprising five layers of stacked patches, achieved excellent scanning performance with a 3dB scan of 70° and maintained the cosine law up to 80° at 30 GHz. The unit cell supports both dual-linear and circular polarization. These results indicate a significant improvement in scanning performance compared to previous methods, especially with the use of only analytical bifocal phase correction.

II. Bifocal Approach on Curved Surfaces

This section introduces the bifocal approach [9] applied for curved apertures, which formulation is related with the parameters shown in Fig. 1. The scanning performance of the curved aperture is achieved likewise planar apertures. Thus, beam steering in the elevation plane is obtained through

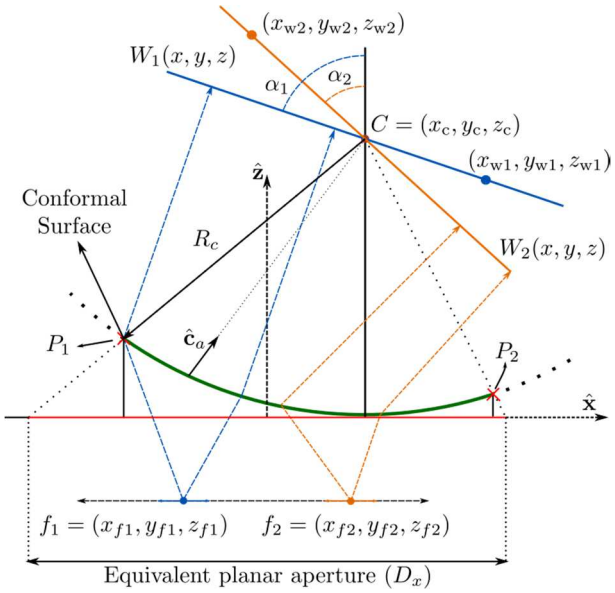


Fig. 1. Description of the curved transmitarray and its main parameters considering an xz-plane.

the mechanical displacement of the feed, while the scanning in azimuth is reached by the antenna rotation around the z-axis. Firstly, an equivalent aperture of size $D'_x \times D'_y$ is defined, which is symmetrical around the y-axis and have two foci at $f_i = (x_{fi}, y_{fi}, z_{fi})$ with $i = 1,2$. Second, the planar aperture is bended to reach the curved surface using a cylinder of radius R_c and centre $(x_c, 0, z_c)$, therefore the aperture is bended in the xz-plane. Now, the new aperture is limited by P_1 and P_2, which are the projection of the edge of the equivalent aperture onto the cylinder.

Now, the computation of the phase distribution of the transmitarray must consider the position of the elements, which are no longer in a planar xy-plane. To do so, we consider that the curved transmitarray for each focus should radiate a different wavefront, so that f_1 is associated with W_1 while f_2 with W_2 (see Fig. 1). The phase correction for each focus is computed by the analytical approach for a unifocal phase correction [9], given by Geometrical Optics (GO) and expressed by

$$\phi_i^u(x_a, y_a, z_a) = k_0(l_{ia} + d_{ai}) \tag{1}$$

where k_0 is the wavenumber in free-space, (x_a, y_a, z_a) is the position of the a-th element, l_{fa} is the distance from the i-th feeder to the a-th element, and d_{ai} is the Euclidean distance travelled by the ray from the a-th element to the i-th point of the wavefront W_i. This ray is perpendicular to the wavefront W_i. Now, (3) can be re-written as

$$\phi_i^u(x_a, y_a, z_a) = k_0\left[\sqrt{(x_{fi} - x_a)^2 + (y_{fi} - y_a)^2 + (z_{fi} - z_a)^2} + \sqrt{(x_{wi} - x_a)^2 + (y_{wi} - y_a)^2 + (z_{wi} - z_a)^2}\right] \tag{2}$$

The coordinates of the elements are no longer distributed in a planar xy surface, thus (x_a, y_a, z_a) refers to their projections onto the cylinder. In the case of the wavefront W_i, the (x_{wi}, y_{wi}, z_{wi}) can be expressed as

$$x_{wi} = \sin(2\alpha_i)\frac{R_0 - z_a + tan(\alpha_i x_a)}{2} \tag{3}$$

$$y_{wi} = y_a \tag{4}$$

$$z_{wi} = R_0 - cos^2[\alpha_i(R_0 - z_a + tan(\alpha_i x_a))] \tag{5}$$

Applying (1) to each focal point and wavefront, two different unifocal phase corrections are obtained. Now, a pseudo-bifocal phase correction can be computed as a combination of both unifocal cases. The bifocal phase correction can be expressed as

$$\phi^b(x_a, y_a, z_a) = \frac{\sum_i A_i \cdot \phi_i^u(x_a, y_a, z_a)}{\sum_i A_i} \tag{6}$$

where A_i is related to the incident field and it behaves as a weighting function.

The bifocal phase correction mainly ensures a smooth transition in the phase correction through the entire aperture, thus as the feeder moves from f_1 and f_2.

III. Scanning Performance using Curved Surfaces

The use of curved surfaces enables a new degree of freedom in the design of beam steering antennas, improving scanning performance over planar apertures. This section introduces a detailed comparison of the scanning performance of a planar transmitarray (PTA) against its curved shape (CTA). The PTA presents an aperture of $21.5\lambda_0 \times 14.2\lambda_0$ at 30 GHz $(215 \times 142\ mm^2)$ with a total number of 4902 elements. These elements are distributed in a regular grid of periodicity $0.25\lambda_0 \times 0.25\lambda_0$ $(2.5 \times 2.5\ mm^2)$ in the x- and y-direction. The curvature of the CTA is given by a cylinder of radius $R_0 = 400$ mm and centre $(x_c, y_c, z_c) = (62.50, 0, R_0)$ mm, resulting in a new distribution of the elements according to (2).

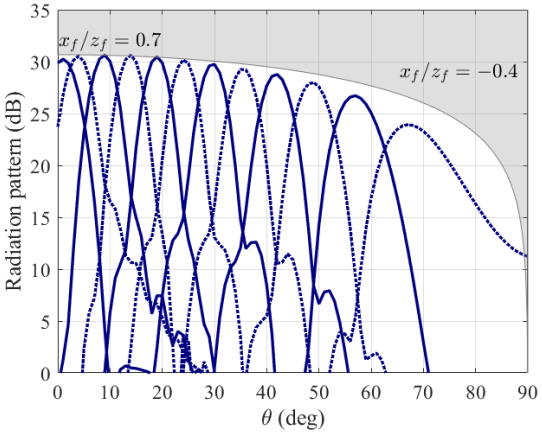


Fig. 3. Beam steering pattern of the PTA moving the feeder from x_f∈[-40,70] mm at 30 GHz..

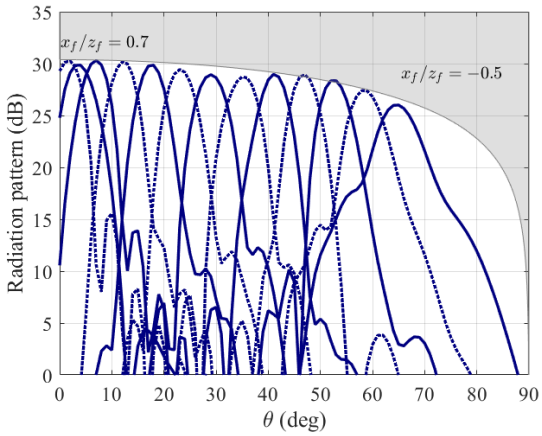


Fig. 2. Beam steering pattern of the CTA moving the feeder from x_f∈[-40,70]mm at 30 GHz..

Locating the feeders at $f_1 = (-20,0,-100)$ mm and $f_2 = (30,0,-100)$ mm, and defining the propagation direction of W_1 and W_2 in the angles $\alpha_1 = 50°$ and $\alpha_2 = 20°$, respectively, a bifocal phase correction is used for both PTA and CTA. The feeder is modelled using a Gaussian beam providing an illumination taper of -14 dB at the edge of the transmitarray. This illumination is also used as the weighting function in (6). For these two antenna geometries, the radiation pattern is computed through an in-hose EM software, which allows for computing the radiated pattern of arbitrary apertures solving the Straton-Chu formulation based on Physical Optics.

In the PTA the feeder is displaced within the range $x_f \in [-40,70]\ mm$, resulting in the radiation pattern shown in Fig. 2. The maximum directivity is obtained for the beam pointing to $\alpha_f = 10°$ associated to the position $x_f = 50$ mm. The scanning performance presents successful performance up to $30°$, obtaining the scan loss predicted by the cosine law for each position. Beyond this range, the scan loss progressively increases until notably degrading the beam. For the extreme position at $x_f = -40$ mm the scanning range is about $68°$ with scan losses of 6.71 dB, which are 2.5 dB from the expected cosine law. If the previous beam is considered, thus $x_f = -30$ mm, the scan performance is significantly improved with 3.90 dB of scan losses within 57°-scan range, which is 1.30 dB more than the cosine law. Moreover, the SLL are below -10 dB, which is the threshold for this figure of merit. The bifocal phase correction in the PTA provides very good results for a range of $50°$, whereas beyond this range, the scan losses increase due to phase aberrations.

Fig. 3 shows the scanning performance of the CTA, moving the feeder in the range $x_f \in [-50,70]$ mm. Again, the maximum directivity is obtained for the beam at $\alpha_f = 10°$, slightly increasing the maximum value reached by the PTA. Within a $65°$-range the beams follow the cosine law almost perfectly, having 0.65 dB of additional losses in the central beam at $\alpha_i = 35°$. For the extreme feed at $x_f = -50$ mm, the beam points at $65°$ with only 4.30 dB, which is 0.60 dB worse than the expected cosine law. Furthermore, the beams are well collimated with SLL below -10 dB. These results significantly improve the obtained by the PTA. Considering that both designs are based on a bifocal phase correction, the enhancement on the scanning performance are due to the use of a convex surface instead of a planar one.

To further understand the improvement of curving a surface, it is necessary to study the influence of the vector normal $\hat{n}_a$ of the a-th element and the pointing direction $\hat{\alpha}_f$ of the outgoing beams. The PTA surface is totally flat, so the vector $\hat{n}_a$ is common for all elements, and it is defined parallel to the z-axis. However, in the CTA the vector $\hat{n}_a$ is defined by the unit vector defined in the direction from the centre of the a-th element to the centre of the cylinder that defines the curvature of the surface and (x_c, y_c, z_c).

The directivity of a planar aperture can be computed employing Franz's formulas as

$$D_{max} \approx \eta \left(\frac{4\pi\sigma}{\lambda}\right)^2 \tanh\left[\left(\frac{D}{4\sigma}\right)^2\right] \cos\alpha_i \qquad (8)$$

where η is the aperture efficiency accounting for the losses such as insertion losses, spill-over, phase aberrations, etc.; while the $\cos\alpha_i$ accounts for the aperture projected area (this is the term that defines the cosine law).

Since α_i is the angle formed by $\hat{n}_a$ and $\hat{\alpha}_f$, it can be easily concluded that the smaller the angle, the greater directivity. Therefore, the dot product $\chi = \hat{n}_a \cdot \hat{\alpha}_f$ can be used as figure of merit to intercompare the planar and curved surface. When the aperture is totally planar (PTA), thus $\hat{n}_a$ is $\hat{z}$ for all the elements, χ is constant within the aperture associated. However, when the aperture is curved χ is no longer constant within this range due to $\hat{n}_a$ changes from element to element. Furthermore, the dot product for each x_f is higher in the CTA than in the PTA (smaller α_i) if the largest angles are associated

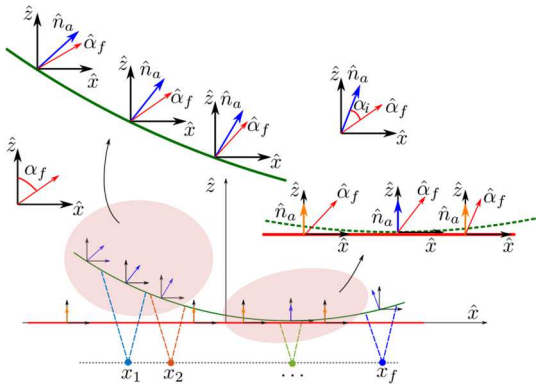


Fig. 4. Representation of the curved and planar surface and the unit vectors used as figure of merit.

to the higher curvature, see Fig. 4. As a result of this, $\cos \alpha_i$ is reduced, the directivity is increased and the scan loss reduced.

In the flattest area of the CTA, α_i is very small because α_f is also small and $\hat{n}_a$ is very close to $\hat{z}$, resulting in similar outcome in both cases. Therefore, the curvature of the surface significantly reduces the effect of the aperture projected area at higher angles, inherently increasing the gain in those beams while minimizing the scan losses of the entire scan range.

IV. Conclusions

This work introduces a novel method to improve the scanning performance of mechanical beam steering transmitarray antennas using a convex curved surface. This design enables scanning angles of up to 80° by enhancing the scan range and minimizing scan loss through a curved surface. The convex transmitarray integrates a generalized bifocal phase correction based on the element positions on the curve. Compared to conventional planar structures, the convex design achieves a scan range of 70° following the cosine law, with a prototype demonstrating an 80° scan range and 4.6 dB scan loss. This performance surpasses previous methods, including bifocal phase correction on planar surfaces. The concept also allows for dual-band operation by selecting appropriate unit cells and can be combined with multifocal techniques for a more compact design.

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