

Article

Low-Cost Transmitarray Design with High Gain Bandwidth and Suppressed SLL

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Abstract

This study presents a transmitarray antenna design operating at a center frequency of 9 GHz, addressing the need for high-gain and broad bandwidth antennas in modern data communication. The proposed design is structured as a quad-layer configuration using FR-4 dielectric substrates. The transmitarray's phase profile is tailored to deliver a wideband flat response with low Side Lobe Level (SLL) and stable aperture efficiency across the operating band. It achieves a 1-dB gain bandwidth of 12.12% (from 8.56 GHz to 9.67 GHz) and a 3-dB gain bandwidth of 49.43% (from 8.45 GHz to 13.46 GHz) with an aperture efficiency of 21.3%. A prototype of the proposed design with 11×11 elements was fabricated and measured, and its measurement results closely aligned with simulation results, validating its performance. The proposed simple design realizes reduced complexity and fabrication costs while expanding operational gain bandwidth, thereby demonstrating substantial promise for next-generation X-band communication systems.

Keywords: antenna; aperture efficiency; bandwidth; low cost; SLL; transmitarray; wideband



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1. Introduction

Transmitarray antennas, with their low spatial profile, cost-efficient fabrication, conformal capabilities, and ability to generate high-gain beams [1], are ideally suited for various important applications, such as 5G communication [2,3], millimeter-wave applications [4], V-band applications [5], and tracking radar systems [6]. By combining the principles of lens and microstrip array technologies, transmitarray antennas offer several notable advantages, including high efficiency, high gain, compact size, and lightweight construction [7]. Transmitarray antennas demonstrate superiority over reflectarrays by achieving high radiation efficiency without the issue of feed blockage [8,9]. However, transmitarray antennas are limited by narrow bandwidth and lower efficiency, primarily due to reduced transmission magnitude and the inherent narrowband characteristics of their elements [10,11]. Consequently, the development of transmitarray antennas with enhanced efficiency and broader bandwidth is of critical importance to address these limitations and meet the demands of modern applications.

In transmitarray design, the primary focus lies in developing the transmitarray unit cells. These cells must achieve a broad transmission phase range, ideally spanning 360° or more, alongside a high transmission magnitude.

Multiple techniques are available to facilitate the design of these unit cells. One of them is Huygens' metasurface structures. Huygens' metasurface has the advantages of

simple fabrication with only two layers on a thin substrate [12]. Reference [13] presents a conformal transmitarray with high efficiency, employing an ultrathin dual-layer Huygens' element. They utilized a pair of metallic layers on a single substrate of thickness $\lambda_0/60$, and the antenna achieved a peak efficiency of 47%. As reported in [14], a novel transmitarray antenna based on Huygens' metasurfaces is presented. Using wire and loop unit cells on a low-profile $0.2\lambda_0$ aperture, it achieves a high aperture efficiency of 65% with a bandwidth of 14% and a Side Lobe Level (SLL) of -19 dB. In [15], a wideband E-band conformal transmitarray using dual-layer Huygens' elements with overlapped metallic strips is developed, achieving efficient phase control from 71 to 87 GHz. The prototype at 78 GHz reaches a 26.6 dB peak gain, 37.2% aperture efficiency, and 20.4% 3-dB gain bandwidth.

Another technique for the design of transmitarray unit cell is receiver–transmitter radiating elements. In [16], a double-folded transmitarray antenna exhibiting circular polarization is proposed, realized by combining receiver–transmitter metasurfaces with a polarization-rotating layer. The design reduces the antenna profile to $1/4$ of the focal length and achieves a peak gain of 21.8 dB at 9.8 GHz, with 40% aperture efficiency and a 6% bandwidth for a 1-dB gain. Ref. [17] introduces a reconfigurable Ku-band transmitarray with independent dual linear polarization control using a 1-bit receiver–transmitter element. Phase shift is achieved via two pin diodes. The prototype achieves an 18.3 dB gain at 12.2 GHz with 22.6% aperture efficiency and $\pm 50^\circ$ beam-scanning, showing a maximum scan loss of 2.9 and 3.5 dB in principal planes.

FSS structures and patch antennas are widely utilized as transmitarray elements due to their simplicity. However, this simplicity also significantly restricts the bandwidth achievable by the transmitarray antenna. Although multilayer FSS configurations [18–23] have been implemented to enhance bandwidth, their fabrication and assembly processes become highly complex, especially at higher operating frequencies.

Beyond efficiency and reconfigurability, Side Lobe Level (SLL) is a decisive metric for array performance. Achieving low SLL requires coordinated amplitude–phase control across the aperture [24]. Evidence across diverse array platforms shows this joint shaping can push SLL well below -20 dB: a 5.8 GHz CP ETC array optimized via weighted constrained method of the maximum power transmission efficiency (WCMMPTE) reports -30 dB SLL with preserved gain/beamwidth [25]; an extended method of maximum power transmission efficiency (EMMPTE)-based weighted design with particle swarm optimization (PSO) yields multi-beam synthesis with explicit SLL suppression and reduced search complexity [26]; and a compact cosecant-squared array meets coverage targets while maintaining $\text{SLL} < -20$ dB [27]. These results motivate SLL-aware synthesis as a first-class design objective in our work.

In the study [28], the folded configuration of a phase-gradient reflective surface, the space sandwiched by the transmitarray surface, is proposed. A 1-bit phase resolution, capable of supporting only two discrete phase states (0° and 180°), is employed. In the design, the feed pin operates in concert with the surrounding shorting vias to channel energy from the input port to the excitation region. The measured results demonstrate a 3-dB gain bandwidth of 26% for x-polarization and a peak aperture efficiency of 21%.

In this work, a simple unit cell structure, resembling the one presented in [28], is designed to achieve a full 360° phase range. Unlike the previous design, the proposed multilayer unit cell configuration does not employ additional components such as feeding pins or shorting vias. Using this simplified element, the resulting antenna array achieves 1-dB and 3-dB gain bandwidths of 12.12% and 49.43%, respectively, along with an aperture efficiency of 21.3%. Also, the proposed transmitarray has an SLL of -24.89 dB in the E-planes at 9 GHz. By adopting a multilayer FSS architecture on an FR-4 substrate, we obtained a wide gain bandwidth while keeping the design via-free and low-cost. Additionally,

the unit cell structures in the multilayer FSS were chosen to be simple, which streamlined the manufacturing process. Consequently, we achieved a total thickness of $0.37\lambda_0$, avoiding a bulky structure.

2. Unit Cell Design

Figure 1 illustrates the presented unit cell design, which consists of four dielectric layers and four metallic layers, including a plus-shaped patch at the center and squares located in the four segments of the plus shape. The horizontal and vertical lengths of the plus-shaped patch differ from each other, and the side lengths of the squares are related to the lengths of the plus-shaped patch. By changing the lengths, a phase range of 360° was achieved, thereby having a total transmission phase coverage of 360° to create a transmitarray with complete effective performance [29].

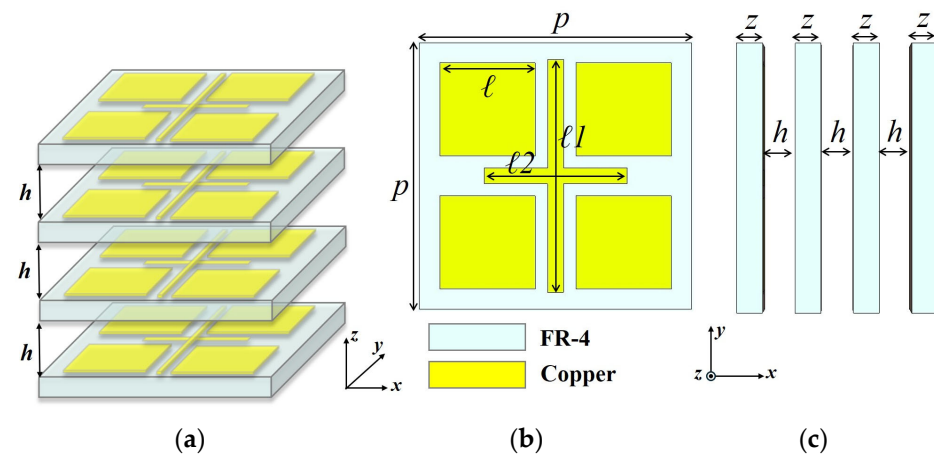


Figure 1. Unit cell structure: (a) Perspective view, (b) top view, (c) side view.

All results were obtained in CST Microwave Studio (Frequency-Domain Solver). For unit cell characterization, unit cell periodic boundaries were applied on $\pm x, \pm y$, while Floquet ports were assigned on $\pm z$ (with Open (add space) termination) to realize a top-down, normally incident plane wave.

The optimized parameters were obtained as follows: while the length ℓ_1 varies between 8 mm ($0.24\lambda_0$) and 15 mm ($0.45\lambda_0$) the parameters $z = 1.6$ mm ($0.048\lambda_0$), $p = 17$ mm ($0.51\lambda_0$), $\ell = \ell_1 \times 0.6$, $\ell_2 = \ell_1 \times 0.4$, and $h = 2$ mm ($0.06\lambda_0$) were used, where λ_0 denotes the wavelength in free space (at 9 GHz). Figure 2 illustrates the normalized transmission phase at the 9 GHz frequency. The results (Figure 2) confirm that the unit cell achieves a complete 360-degree phase coverage.

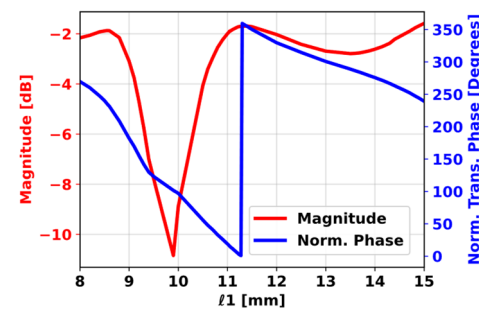


Figure 2. Normalized transmission coefficients in terms of ℓ_1 at 9 GHz (ℓ_1 is swept from 8 to 15 mm).

To substantiate the choice of the four-layer unit cell, Figure 3 compares the phase tuning at 9 GHz for two-, three-, and four-layer stacks. Only the four-layer configuration

achieves full 0–360° coverage without phase gaps and maintains a quasi-monotonic slope across the ℓ_1 sweep, which reduces quantization error in the aperture phase map. In contrast, the two-layer variant does not provide sufficient phase depth, and the three-layer version shows a phase singularity (jump) complicating phase assignment. Consequently, the four-layer via-free FR-4 stack was selected as it meets the phase-range requirement while keeping the fabrication flow compatible with standard PCB processes.

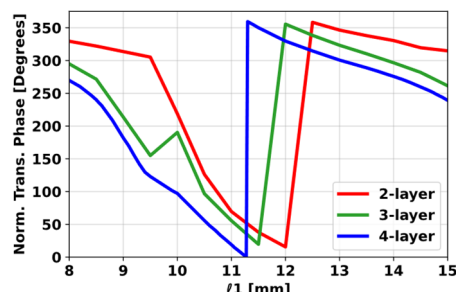


Figure 3. Comparison of transmission phase at 9 GHz vs. ℓ_1 (2/3/4-layer).

3. Design and Measurement of the Proposed Transmitarray with High Gain Bandwidth and Suppressed SLL

Following the completion of the design process of the presented transmitarray unit cell structure, the transmitarray antenna can be designed based on the phase compensation theory. During the synthesis of the transmitarray, the transmission phase for each element is typically derived to offset the phase lag introduced by the differing path lengths between the feed and every individual cell in the lattice. This phase distribution is necessary to focus the beam in a specific direction. Producing a high-gain beam requires the transmitarray to convert the spherical wave emerging from the feed into a planar wavefront; hence, the phase imparted by each unit cell is selected compensating for the spatial phase difference between the feed and the unit in question.

$$\psi_{ij} = k \left(R_{ij} - \vec{r}_{ij} \cdot \hat{r}_0 \right) + \psi_0 \quad (1)$$

In Equation (1), ψ_{ij} represents the transmission phase in degrees required for the ij -th unit cell, k denotes the propagation constant in free space, R_{ij} is the distance in meters from the feed antenna to the center of the ij -th element, $\vec{r}_{ij}$ is the position vector for the ij -th element, $\hat{r}_0$ is the unit vector of the main beam, and ψ_0 represents the phase offset in degrees. Using this equation, the phase distributions for the unit cell are calculated. The phase distribution diagram of the transmitarray illustrated in Figure 4, which is structured using this calculation.

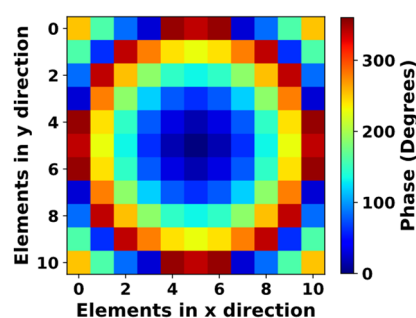


Figure 4. Transmission phase requirement for each cell based on its position within the antenna aperture.

Aperture efficiency is a crucial performance metric for transmitarray antennas. To enhance the aperture efficiency and minimize spillover loss, it is essential to select an optimal focal length to aperture dimension ratio (often denoted $\frac{f}{D}$) during the optimization stage of the design [30]. Each unit cell's phase is then precisely adjusted to ensure a consistent phase profile over the radiating aperture, thereby maximizing gain.

Figure 5 illustrates the simulation model of the transmitarray antenna, consisting of 11×11 unit cells and fed by a horn antenna, as analyzed in CST Microwave Studio. Figure 6 depicts the comprehensive layout of the proposed broadband transmitarray. The array consists of a multilayer structure, featuring a periodic lattice of unit cells arranged in four layers. The array has a square outline comprising 121 unit cells, giving it a total aperture of 187 mm. Its thickness amounts to $0.372\lambda_0$, where λ_0 denotes the wavelength in free space wavelength at 9 GHz, while the horn feed is set to 99 mm with respect to the array's center, resulting in an $\frac{f}{D}$ ratio of 0.53. A pyramidal horn antenna with a taper length of 120 mm and an aperture size of 61 mm $\times$ 45 mm was used as the feed. Proper focal distance placement generally enables wide beam steering ranges, enhancing spillover and illumination efficiency [31].

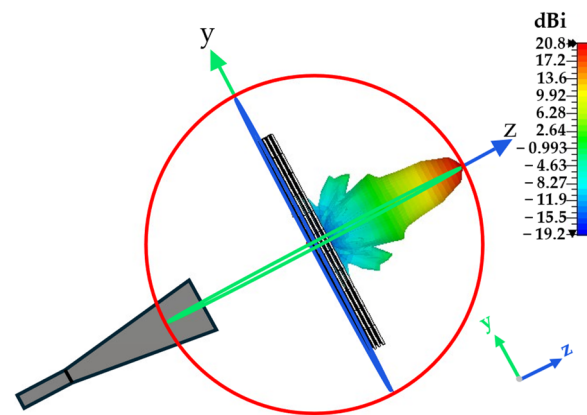


Figure 5. Simulated model of the 11×11 transmitarray with horn feed.

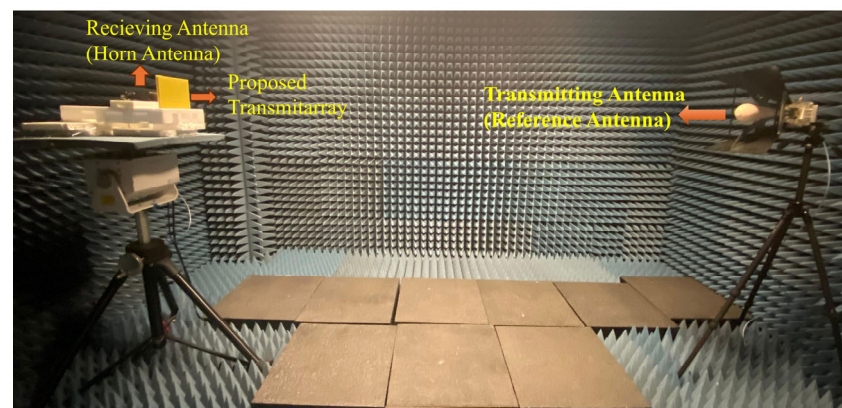


Figure 6. Anechoic chamber and the measurement setup.

Figure 7 demonstrates the fabricated prototype of the presented transmitarray. Full-wave electromagnetic simulations were performed with CST, and experimental measurements were carried out inside an anechoic chamber to validate the design. Figure 8 presents a comparison of simulation and measurement results at intervals of 0.5 GHz, ranging from 8.5 GHz to 12 GHz with the SLLs.

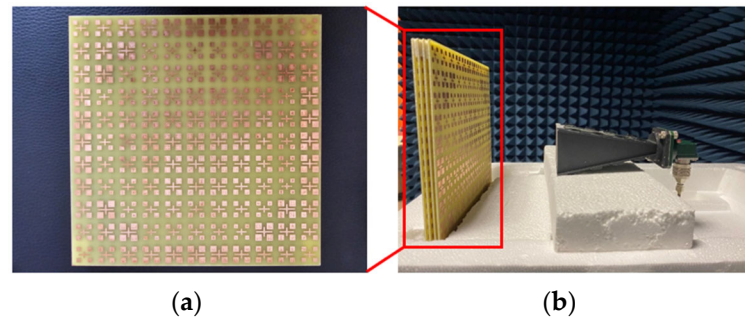


Figure 7. Fabricated prototype of the presented transmitarray (a) front view, and (b) perspective view with horn antenna.

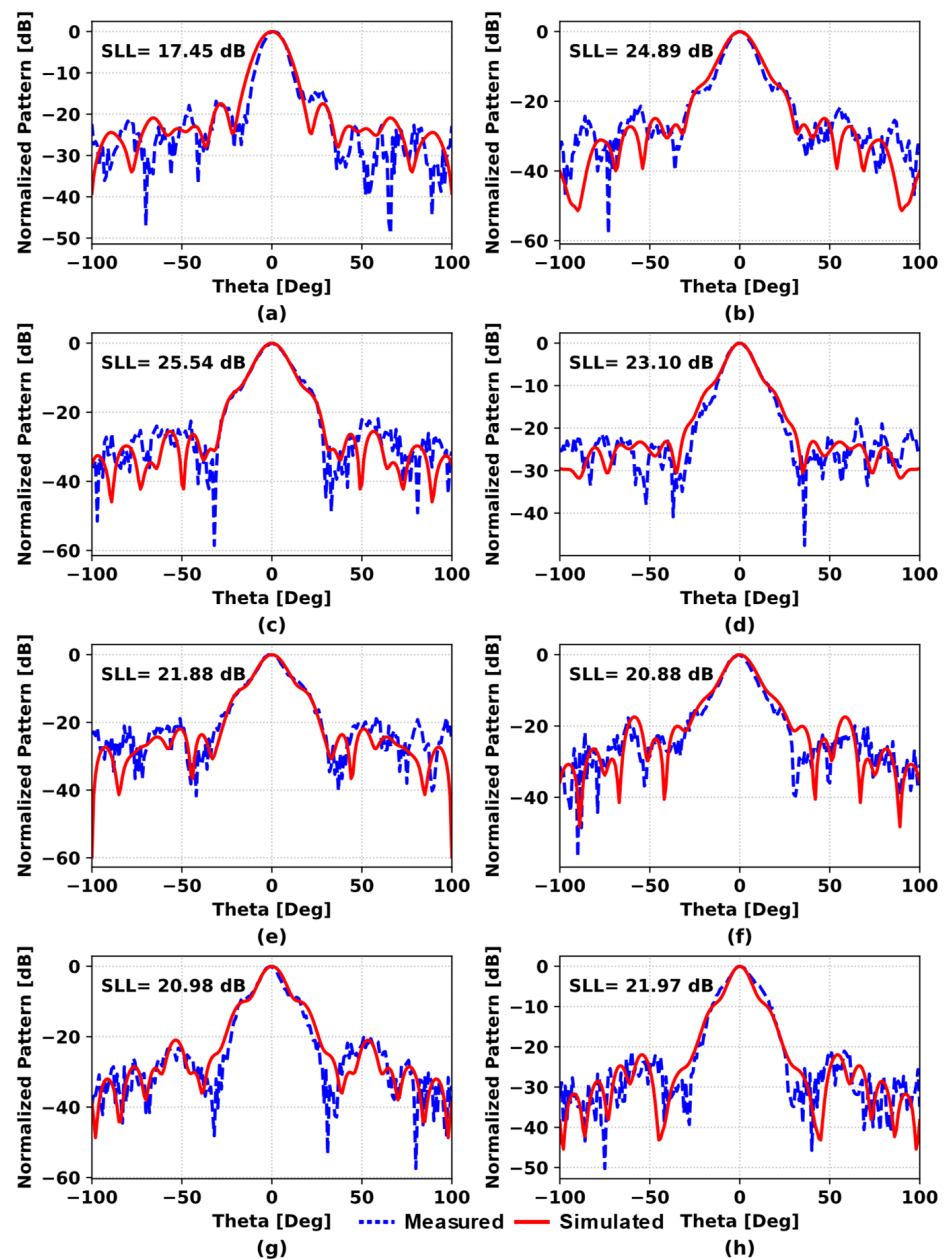


Figure 8. Simulated and measured radiation patterns in the xz-plane at (a) 8.5 GHz, (b) 9 GHz, (c) 9.5 GHz, (d) 10 GHz, (e) 10.5 GHz, (f) 11 GHz, (g) 11.5 GHz and (h) 12 GHz.

Another key measurement for the fabricated structure is the maximum gain values. The 1 dB gain bandwidth of the structure is 12.12%, spanning frequencies from 8.56 GHz to

9.67 GHz. The aperture efficiency of the proposed transmitarray was evaluated for both measured and simulated data by applying the formulation in Equation (2); the resulting efficiency curves, together with the corresponding gain responses, are depicted in Figure 9.

$$n_{ap} = \frac{G}{D_{max}} \quad D_{max} = \frac{4\pi A}{\lambda_0^2} \quad (2)$$

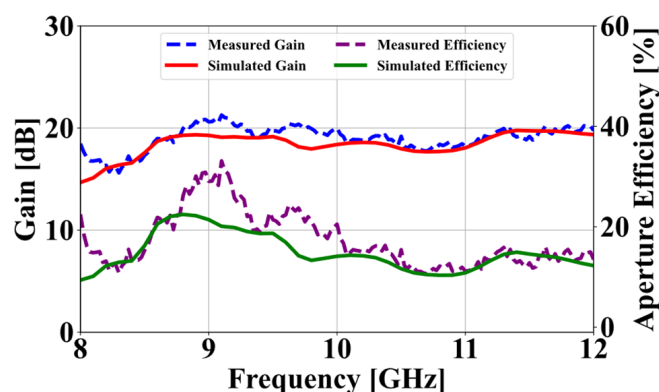


Figure 9. Measured and simulated results of gain and aperture efficiency for the proposed transmitarray.

Here, G signifies the antenna gain, D_{max} indicates the peak directivity, A corresponds to the physical aperture area and λ_0 denotes the wavelength in free space.

In examining Equation (2), even small differences in gain values between measurement and simulation results significantly impact aperture efficiency due to the influence of gain in the efficiency calculation. This effect is the primary reason for the discrepancies observed in Figure 9. Table 1 presents a performance comparison of this study with other studies in the literature based on various attributes.

Table 1. Comparison between the proposed and previously reported wideband transmitarray antennas.

Ref.	Freq. (GHz)	Number of Metallic Layers	F/D	Unit Cell Dimension (λ_0)	Aperture Size (λ_0)	Phase Range ($^\circ$)	Via	1-dB/3-dB Gain BW (%)	Aperture Efficiency (%)	SLL (dB)
[28]	26	2	0.4	0.56	9.02	1-Bit	Yes	12 (1-dB) 26 (3-dB)	20	Not Specific
[32]	10	3	0.25	0.47	10.7	360	No	24.5 (3-dB)	40	<25
[33]	10	2	1.27	0.32	6.08	360	No	7.5 (1-dB)	58.5	Not Specific
[34]	10	2	0.64	0.067	9.5	360	No	7 (1-dB)	42	20.5
[35]	9	3	0.56	0.54	12.96	2-Bit	No	8.1 (1-dB)	45	<15
[36]	8	2	1.5	0.21	Not Specific	1-Bit	Yes	16.5 (3-dB)	30.4	<15.3
[37]	12	2	1.4	0.52	5.72	360	No	5.4 (1-dB)	44	13.4
This Work	9	4	0.53	0.51	5.61	360	No	12.12 (1-dB) 49.43 (3-dB)	21.3	24.89

Upon reviewing Table 1, it becomes evident that the presented transmitarray antenna design has advantages over previous studies, including a broader 1-dB and 3-dB bandwidth, a more compact aperture size, and cost-effectiveness, although it is disadvantaged in terms of aperture efficiency. This drawback primarily arises from the use of FR-4 as the dielectric layer, which exhibits losses at the relevant frequencies. Additionally, using FR-4 as the dielectric and manufacturing the prototype with standard production dimensions significantly reduces the overall cost of the study. Also, proposed transmitarray has an SLL of 24.89 dB in the E-planes at 9 GHz.

A folded transmitarray is realized by inserting a phase-gradient reflective surface to generate a virtual focus and shrink the Height to Focal length (H/F) ratio; a center-fed

magnetoelectric-dipole element affords independent 1-bit control for dual linear polarizations [28]. A broadband filtering circularly polarized folded transmitarray is implemented in which the top metasurface performs LP to CP conversion, phase compensation and out-of-band spatial filtering to maintain a low profile [32]. A high-efficiency transmitarray uses a two-layer element etched on a compound substrate with horizontally arranged dielectrics; a metal square loop and a patch on opposite faces provide full 360° transmission phase with low loss [33]. An ultrathin metal-only transmitarray is devised using a two-metal-layer polarization-rotation unit cell with perpendicular fan-shaped slits, enabling cross-polar transmission phase tuning at $\sim 0.067\lambda_0$ thickness [34]. A dual-band shared-aperture solution co-integrates a Fabry–Perot cavity (X-band) and a folded transmitarray (Ka-band); the aperture acts as PRS at X and polarization grating at Ka, while the ground serves as reflector and reflecting polarizer [35]. A low-profile dual-LP 1-bit transmitarray is obtained via azimuth-insensitive polarization-rotator unit cells, achieving $0.08\lambda_0$ thickness with only two metallic layers [36]. A distinct two-layer element on a specially designed substrate with double square loops delivers 360° phase coverage with <3.8 dB amplitude loss and $\sim 44\%$ aperture efficiency near 12 GHz [37].

4. Conclusions

The quad-layer transmitarray using wideband elements is presented for X-band applications. The proposed transmitarray, characterized by low fabrication costs and a simple design, features high gain bandwidth and low SLLs and is realized based on these attributes. It achieves 1 dB and 3 dB gain bandwidths of 12.12% and 49.43%, respectively, with an aperture efficiency of 21.3%. Given these priorities, the modest aperture efficiency is an expected outcome of balancing peak efficiency against wide gain bandwidth and reduced fabrication cost. The measured results are in reasonable agreement with the simulated results. At 9 GHz, simulations indicate a peak gain of 19.28 dB and an E-plane SLL of 24.89 dB. The good agreement between these experimental results and the simulated data confirms the validity of the proposed design. These appealing performances make the proposed design suitable for a wide range of high-gain X-band applications. Future research may focus on improving aperture efficiency by employing low-loss dielectric materials, optimizing the multilayer configuration, or reducing the number of layers, while maintaining the wide bandwidth, low SLL, low cost, and manufacturability demonstrated in this work.

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Abbreviations

The following abbreviations are used in this manuscript:

SLL	Side Lobe Level
PRS	Partially Reflecting Surface
LP	Linear Polarization
CP	Circular Polarization

EMMPTE	Extended Method of Maximum Power Transmission Efficiency
WCMPTE	Weighted Constrained Method of the Maximum Power Transmission Efficiency
PSO	Particle Swarm Optimization

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