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Compact Multi-Ring Reflectarray Antenna at Wi-Fi for Overcoming Signal Blockage in Dense Urban Areas

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ABSTRACT: The demand for reliable and high-speed wireless communication in urban environments such as offices and densely populated areas is often hindered by signal obstructions. Reflectarray antennas offering beam-steering capabilities through passive configurations have gained significant attention as a potential solution. However, existing designs at lower frequency bands struggle to achieve efficient phase variation within a single layer while maintaining high gain and consistent performance. In order to overcome these constraints, this work presents a reflectarray design that operates at 5 GHz. It utilizes a 15×15 multi-ring unit cell structure on a single-layer FR4 substrate to achieve a complete 360° phase variation. Two prototypes were fabricated to steer beams at 30° and 60°, demonstrating the design's flexibility and adaptability for various application-specific requirements. The proposed reflectarray realizes a peak gain of 21 dBi and operates over a wide frequency range of 4.5–5.5 GHz, as validated through simulated and experimental results. The design effectively enhances signal coverage and addresses blockage challenges in urban areas, providing a practical solution for passive reflectarrays in Wi-Fi and similar wireless communication applications.

1. INTRODUCTION

The demand for high-speed wireless communication has grown significantly in urban areas due to applications such as smart offices, the Internet of Things (IoT) systems, and industrial automation [1]. However, densely populated urban environments pose unique challenges, particularly signal blockages caused by large buildings, complex indoor layouts, and multipath propagation [2]. These issues degrade signal quality, limiting the performance of wireless communication systems, especially for Wi-Fi networks operating at 5 GHz [3]. To address these challenges, advanced beam-steering techniques are investigated to enable more efficient communication and minimize signal obstructions [4]. Beam steering is an essential approach for mitigating signal blockages in complex urban environments, as shown in Figure 1. It allows antennas to dynamically adjust the direction of transmitted or received signals to bypass obstacles and ensure reliable connectivity to the intended receiver [5]. Conventional beam-steering methods, including mechanical beam scanning [6], parabolic reflectors [7], and phased array antennas [8], have been widely used. However, each has drawbacks related to size, complexity, and efficiency [9]. Reflectarray antennas offer a promising alternative by combining the simplicity of parabolic reflectors with the usability of phased arrays, while maintaining a passive configuration [10, 11].

Reflectarrays consist of an array of unit cells capable of modifying the phase of incoming electromagnetic waves, enabling precise control over beam direction [12]. Unlike traditional phased arrays that rely on complex feeding networks, reflectarrays are more compact and lightweight, making them a better solution for overcoming signal blockages in urban environments [13]. Their ability to passively control phase at the unit cell level significantly reduces system complexity and power demand, making them an optimal solution for cutting-edge wireless communication systems. Various beam-steering techniques are used to steer the main beam and avoid blockages [14]. In the aperture phase-tuning approach, the phase of each element in the array is controlled individually. This can be done using a delay-line microwave network or by altering the physical parameters of scattering structures. The elements

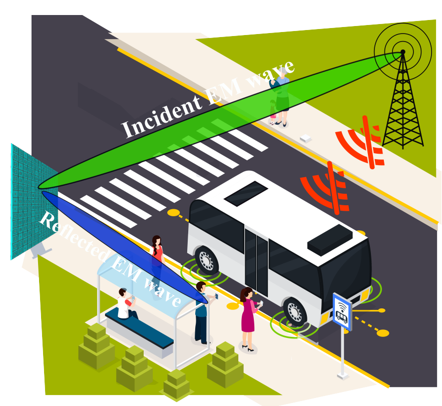

FIGURE 1. Application scenario of a reflectarray for overcoming signal blockage.

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can also be rotated on the aperture of the metasurface to change the phase, either electronically, mechanically, or passively [15]. This method provides a fine control over the beam direction and is highly effective for mitigating blockage issues caused by obstacles in urban areas. In the feed-tuning method, the beam is scanned by shifting the feed's phase center via translations [16]. This method allows the beam to be directed without physically altering the position of the antenna. In some designs, a tilt-table ground plane is used, particularly in reflectarray antennas, to achieve off-broadside beam steering. This technique is useful in applications where it is impractical to adjust the entire antenna assembly [17, 18].

Beam-steering reflectarray antenna systems utilizing feed-tuning techniques have been extensively investigated in [19] and [20]. These studies demonstrate that feed translation is effective for systems with a limited scanning range but suffers from significant gain reduction when steering the beam away from the broadside direction. Increasing the focal length-to-diameter (F/D) ratio can improve the antenna's performance by enhancing its focus and gain. However, it results in a costlier and bulkier antenna design, making it less practical and harder to integrate into space-constrained applications. To achieve wider beam-steering capabilities, hybrid approaches combining feed displacement and phase distribution methods have been explored. In [21], a scan range of $\pm 60°$ was achieved with a gain of 30 dBi, minimal scan loss, and low side-lobe levels by employing a bifocal aperture phase distribution technique. This approach outperformed the traditional parabolic phase method, with further optimization of the phase distribution enhancing both scanning range and gain performance [22]. Similarly, offset feed configurations have been introduced to reduce feed blockage, achieving a maximum gain of 36.4 dBi [23]. However, these techniques require mechanical rotation of the feed horn, which limits scanning speed and operational flexibility. Further advancements in beam-steering reflectarray designs include the combination of feed displacement and in-plane rotation of the reflectarray panel, allowing for a scan range of up to $\pm 70°$ [24]. However, this method supports only one-dimensional scanning and experiences scan losses of approximately 4.9 dB due to feed defocusing. Two-dimensional beam steering, achieved by tilting the panel to avoid feed blockage and rotating it along another plane for elevation control, demonstrated a $\pm 60°$ scan range with a gain of 26.47 dBi, but required substantial space for panel movement and had slower scanning speeds [25]. Mechanically rotating individual phase elements has also been investigated, where each unit cell acts as a localized phase shifter. Additionally, a broadband, wide-angle beam-steering reflectarray using rotatable elements was demonstrated, achieving a $\pm 60°$ scan range, a maximum gain of 25.6 dBi [26, 27]. Recent studies have explored multi-ring unit cell structures for achieving broader phase variation and improving bandwidth performance in reflectarrays. Ref. [28] employed concentric ring geometries to enhance angular stability, while [29] used nested resonators in a multi-layer design to achieve full phase control at X-band. However, these approaches often involve complex fabrication processes, multi-layer substrates, or operate at higher frequencies where phase manipulation is more straightforward.

Most reflectarray antenna designs target higher-frequency applications, where achieving a full 360° phase variation is relatively straightforward [30]. Such designs often rely on multi-layer architectures and complex unit cell structures to enable precise beam steering [31]. However, at lower microwave frequencies, particularly below 5 GHz, achieving full 360° phase variation within a single-layer configuration poses significant challenges [28]. These challenges are especially critical when developing compact and low-cost solutions for urban environments, where mobile and Wi-Fi networks predominantly operate below 5 GHz. In urban areas, where signal blockages caused by high-rise buildings and indoor structures are common, there is an increasing demand for efficient and cost-effective beam-steering solutions [29]. Metasurface-based reflectarray antennas present a promising alternative by offering precise phase control and beam steering capabilities in a compact and lightweight form factor. However, their practical deployment in dense urban settings requires careful optimization to ensure reliable performance across a wide range of beam-steering angles and operating frequencies. This study introduces a reflectarray antenna designed specifically to address signal blockage issues in urban environments. Operating at 5 GHz, the proposed design incorporates a 15×15 multi-ring unit cell structure on a single-layer FR4 substrate, achieving a full 360° phase variation. Two prototypes were fabricated to enable beam steering at 30° and 60°, demonstrating the design's flexibility and effectiveness in overcoming blockage-related challenges. Experimental results validate the proposed reflectarray's ability to achieve a measured gain of 21 dBi and deliver reliable signal coverage within the frequency range of 4.5–5.5 GHz, making it a practical solution for dense urban communication systems.

The primary contributions of this paper are as follows:

1. Development of a single-layer, multi-ring reflectarray antenna that achieves a full 360° phase variation by utilizing a multiple-resonance unit cell architecture, eliminating the need for a multi-layer structure. This design achieves 360° phase variation within a single layer using a low-cost FR4 substrate.

2. Experimental validation of flexible beam steering with 30° and 60° angles, demonstrating high-gain performance and adaptability for 5 GHz Wi-Fi networks, with a measured gain of 21 dBi, enhancing signal coverage in urban areas. Additionally, the proposed reflectarray operates effectively over a bandwidth range from 4.5 GHz to 5.5 GHz, ensuring consistent performance across a wide frequency range.

2. DESIGN METHODOLOGY

Figure 2 illustrates the proposed reflectarray configuration. The design process begins with the development of a unit cell, which serves as the fundamental building block of the array. The reflective surface is then constructed by systematically varying the geometric parameters of each unit cell to achieve the desired phase distribution for accurate beam steering.

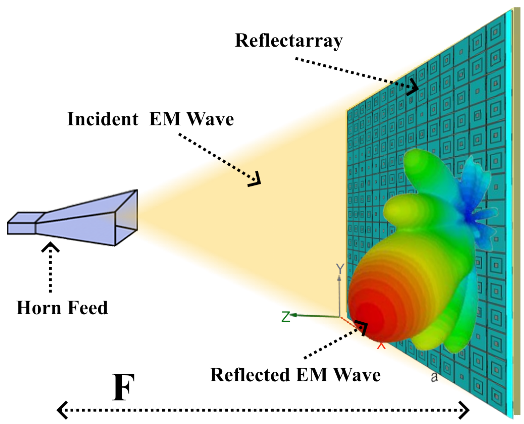

FIGURE 2. Schematic representation of the proposed reflectarray.

2.1. Unit Cell Design

The designed unit cell depicted in Figure 3, features a multi-ring structure with an outer square ring. The structure is fabricated on a 4.6 mm thick FR4 epoxy with $\epsilon_r = 4.3$. The unit cell has dimensions of 20 mm × 20 mm. The other geometrical parameter are '$V' = 20$ mm. The equivalent circuit model of the proposed unit cell, shown in Figure 3(c), provides a simplified representation of the unit cell's electromagnetic behavior. The model comprises a combination of inductors and capacitors that emulate the resonant characteristics of the multi-ring structure. Each ring introduces an inductive effect due to the looped surface current paths, while the gaps between rings and the substrate layers contribute to the capacitive coupling. This LC network forms a multi-resonant structure, allowing broadband response and continuous phase variation. The series and parallel branches of the circuit model capture the coupling between adjacent rings as well as the interaction with the substrate (FR4). The characteristic impedance of the substrate and surrounding media is represented using lumped impedances, while the reflection behavior is modeled through the impedance mismatch with the terminating load. This model offers intuitive insight into how geometric parameters influence the reflection phase and supports the design strategy for achieving full 360° phase coverage across the operating band. Figure 4 presents the variation in reflection phase response of the unit cell with respect to 'V', showing a phase variation of up to 360°. As illustrated in Figure 5, the reflection phase remains unaffected by variations in the Incident ray angle and polarization. The bandwidth (BW) of the unit cell is calculated using the formula [32]:

$$\text{BW} = \frac{2(f_u - f_l)}{f_u + f_l} \tag{1}$$

where f_l and f_u are the lower and upper frequencies corresponding to a 45° phase shift from the center frequency. The simulated reflection phase response across various frequencies is shown in Figure 4, demonstrating an operating range from 4.5 GHz to 5.5 GHz. The use of a single-layer architecture leads to a significant enhancement in the linear phase BW. Additionally, the unit cell maintains consistent performance when subjected to variations in incident angle and polarization, evaluated within a 30° range, confirming its reliability and suitability for practical applications in dynamic environments.

2.2. Reflectarray Design

The antenna comprises an array of $M \times N$ unit elements, where M and N indicate the number of elements arranged along the horizontal and vertical axes, respectively. The array is illuminated by a focused horn antenna, ensuring consistent excitation across the reflective surface. The required phase shift for each unit element at coordinates (m, n) is determined using the following equation:

$$\phi_i = \frac{2\pi}{\lambda} \left(\Delta x_i \sin\theta \cos\phi + \Delta y_i \sin\theta \sin\phi\right) \tag{2}$$

In this expression, λ represents the wavelength in free space, and (x, y) are the positional coordinates of the unit element with respect to the center of the array.

A standard horn antenna, providing a directive gain of 13 dBi, is used as the feed. The spacing F plays a significant role in balancing aperture efficiency and minimizing spillover loss. Reducing F lowers spillover; however, it can adversely impact the uniformity of illumination. For this design, F is optimized to 300 mm to ensure improved gain and effective operation. The reflective surface is constructed with 15×15 unit cells, covering a total area of 300 mm × 300 mm. Figures 6(a), 6(b), and 6(c) display the phase distributions required on the reflective surface to steer the beam at angles of 30° and 60°, respectively. To achieve a beam steering angle of 30°, the unit cells are systematically arranged on the reflective surface by varying their geometric parameters in accordance with the calculated phase requirements(Figure 7). Similarly, for beam steering at 60°, the arrangement of unit cells is modified to satisfy the phase relation dictated by Equation (2). Using this phase relation, the designed unit cells can be configured on the reflective surface to steer the beam in any desired direction, providing a versatile and adaptable solution for beam steering applications. The simulations were conducted using CST Microwave Studio.

The resulting 3-D far-field radiation patterns are displayed in Figure 8. Figures 8(a), 8(b), and 8(c) depict the radiation patterns at lower (4.5 GHz), resonant (5 GHz), and higher (5.5 GHz) frequencies for 30° beam steering, respectively. Figures 8(d), 8(e), and 8(f) show the corresponding radiation patterns at the same frequencies for 60° beam steering. The simulation results, together with the unit cell's reflection phase and geometrical phase data, confirm that both the unit cell and the overall system operate effectively within the frequency range of 4.5–5.5 GHz. The simulated 2-D radiation patterns are compared with the measured results in Figures 10 and 11.

3. ANTENNA PROTOTYPE

Separate prototypes were fabricated to validate the beam steering performance at 30° and 60°, respectively. Figure 9 shows photographs of the fabricated reflectarray antennas. A standard horn antenna (BBHA9120D) was utilized as the feed source for the reflectarray system. The prototypes were evaluated for

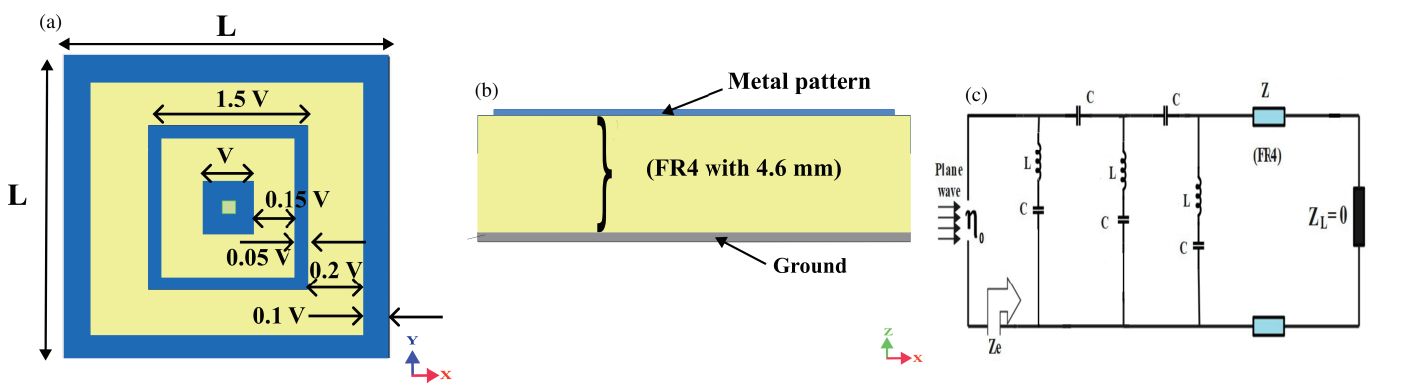

FIGURE 3. Unit cell. (a) Top view. (b) Side view. (c) Equivalent circuit model.

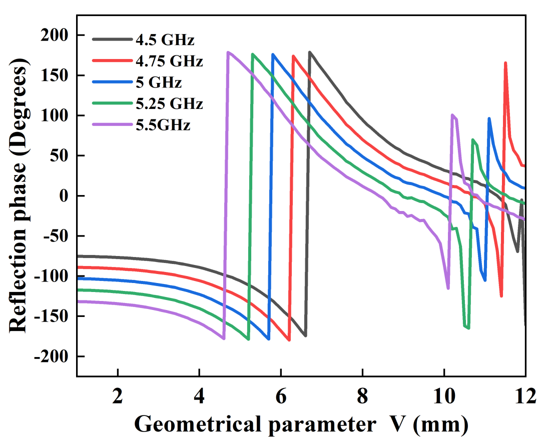

FIGURE 4. Reflection phase versus geometrical parameter V at different frequencies.

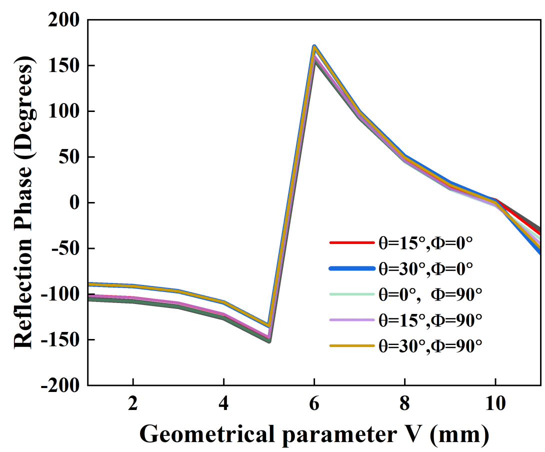

FIGURE 5. Reflection phase versus geometrical parameter V at different incident angles.

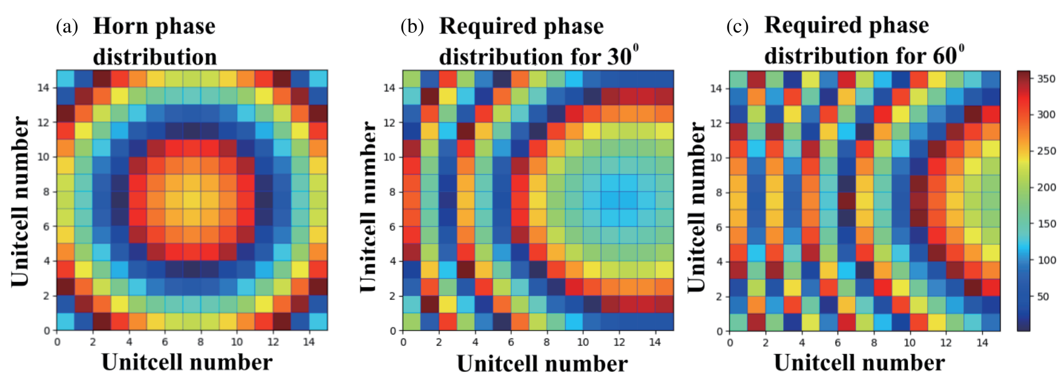

FIGURE 6. (a) Phase of the horn antenna, required phase distribution of the reflective surface (b) for 30°, and (c) for 60°.

TABLE 1. Comparative analysis of reflectarray antenna designs.

Ref.	Freq. (GHz)	BW (GHz)	Gain (dBi)	Steering	Layers	Tuning Method	Remarks
[19]	10.5	1.5	24.5	±30°	Multi (Rogers)	Feed displacement	Narrowband
[23]	12.0	2.0	36.4	±60°	Multi (Duroid)	Rotating feed	High complexity
[24]	5.5	1.0	18.6	±70°	Single-layer	Mechanical rotation	Large structure
[27]	8.0	2.0	25.6	±60°	Multi-layer	Rotatable cells	Broadband
This Work	5.0	1.0 (4.5–-5.5)	21.0	30°, 60°	Single (FR4)	Passive tuning	Compact, low-cost

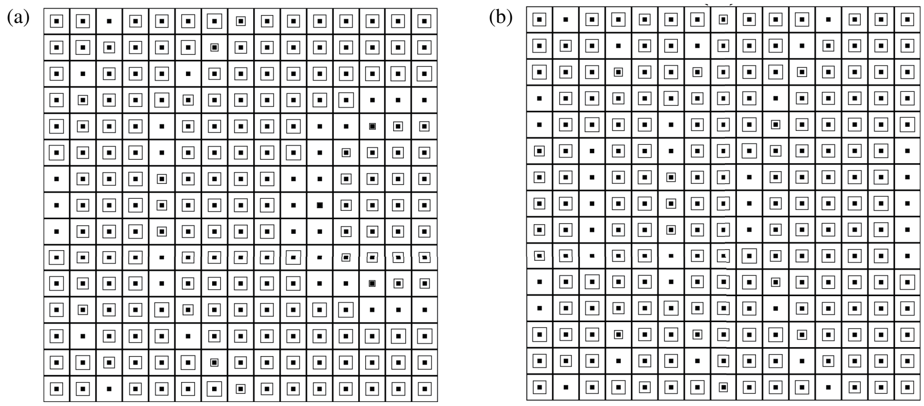

FIGURE 7. Physical configuration of the reflective surface with varying parameter 'L' of the unit cells for (a) 30° and (b) 60°.

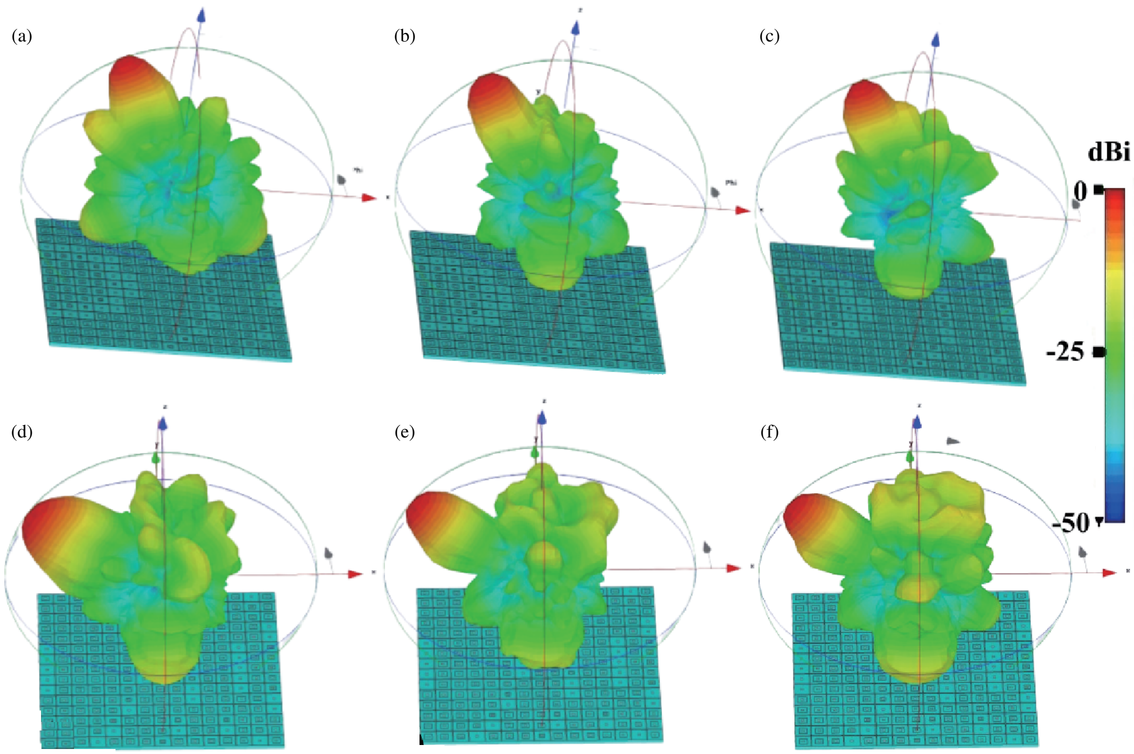

FIGURE 8. Simulated 3-D patterns for beam steering: (a)–(c) for 30° steering. (a) at 4.5 GHz, (b) at 5 GHz, (c) at 5.5 GHz; and (d)–(f) for 60° steering, (d) at 4.5 GHz, (e) at 5 GHz, (f) at 5.5 GHz.

their radiation characteristics in an anechoic chamber, as depicted in Figure 10. Figure 11 compares the measured and simulated 2-D radiation patterns for the 30° and 60° beam steering cases across the lower (4.5 GHz) and higher (5.5 GHz) ends of the operating frequency range. The comparison shows close agreement between the simulated and measured results, confirming the design's accuracy. Minor discrepancies observed are likely due to feed misalignment or reflections caused by the supporting structures. The gain vs. frequency plot for the 30° prototype is presented in Figure 12. The antenna demonstrates a peak gain of 21 dBi at the resonant frequency of 5 GHz, with a variation of approximately 1 dB across the entire operating bandwidth, from 4.5 GHz to 5.5 GHz. Table 1 presents a comparison between the proposed reflectarray and representative designs from the literature. While some earlier works demonstrate higher gain or wider beam steering, they often require multi-layer substrates or complex tuning mechanisms. In contrast, the proposed design achieves a gain of 21 dBi, wide bandwidth (4.5–5.5 GHz), and beam steering at 30° and 60° using a compact, single-layer passive structure. These features make it a promising solution for low-cost, high-efficiency urban wireless applications. While the beam steering is not dynamically reconfigurable in this implementation, different reflectarray configurations can be fabricated for specific coverage needs. This method is particularly suitable for cost-sensitive deployments where beam direction can be fixed after planning,

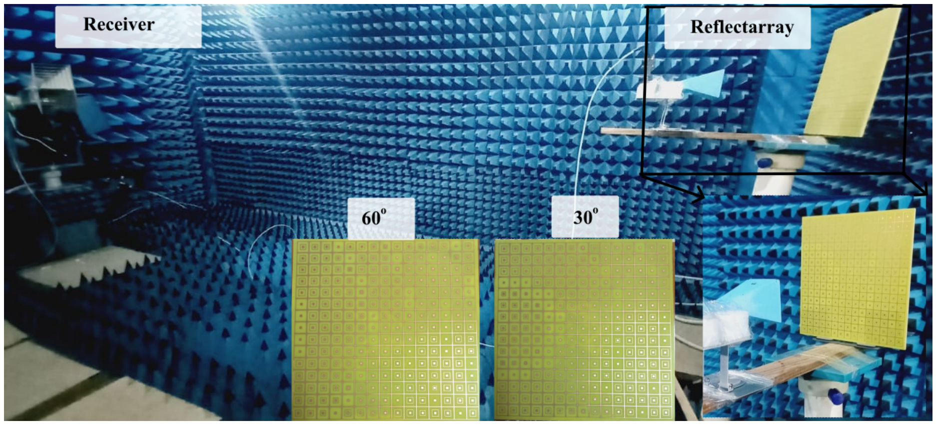

FIGURE 9. Experimental setup of the proposed reflectarray with a horn feed.

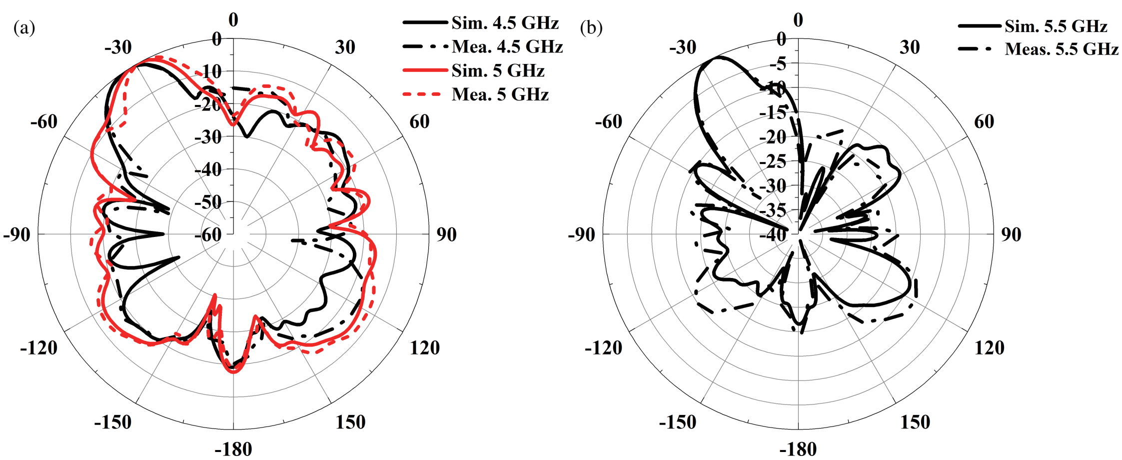

FIGURE 10. Radiation patterns for 30°: (a) at 4.5 GHz and 5 GHz, (b) at 5.5 GHz.

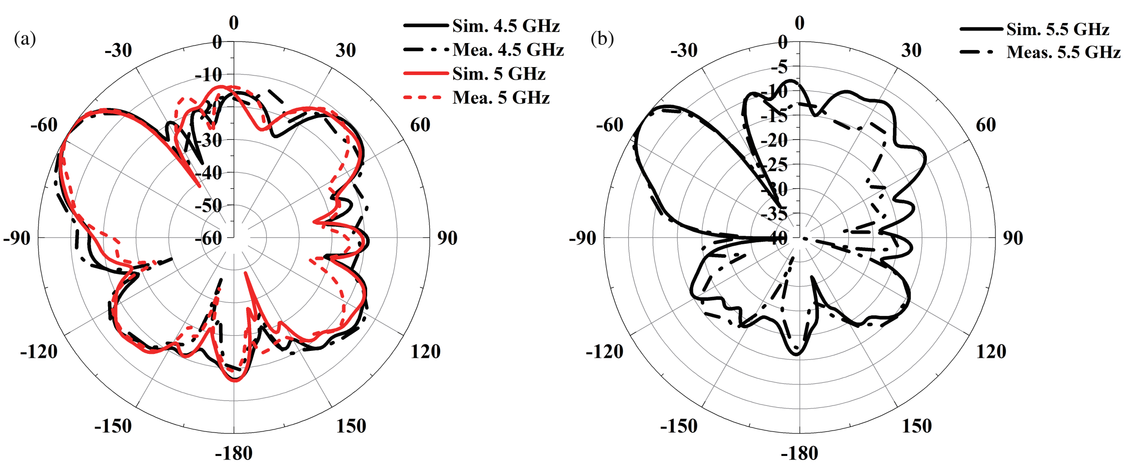

FIGURE 11. Radiation patterns for 60°: (a) at 4.5 GHz and 5 GHz, (b) at 5.5 GHz.

such as outdoor smart city nodes or building-to-building wireless links.

Finally, the overall performance of the prototypes confirms that the proposed reflectarray design not only is capable of achieving accurate beam steering but also maintains high gain and wideband characteristics. This demonstrates its potential for practical deployment in beam steering applications for Wi-Fi and similar communication systems. In most scenarios, signal blockage occurs at fixed locations, making low-cost passive reflectarrays a more suitable option compared to complex

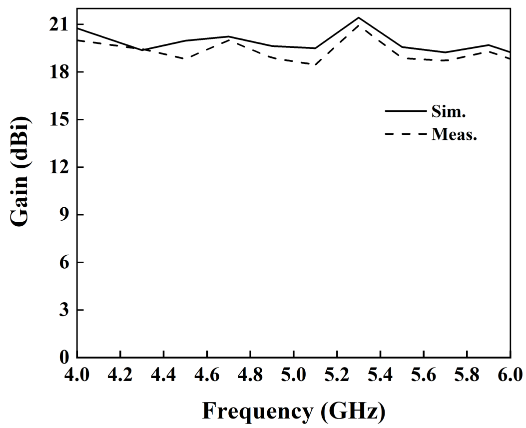

FIGURE 12. Comparison between simulated and measured gains.

reconfigurable designs. In this context, the implementation aspects of the beam-steerable reflectarray with a planar feed source will be addressed as part of our ongoing research activities and covered in future work.

4. CONCLUSION

This paper presented the design, development, and experimental validation of a single-layer multi-ring reflectarray antenna that operated at 5 GHz to address signal blockage challenges in urban areas. The proposed 15×15 multi-ring reflectarray, fabricated on a low-cost FR4 epoxy substrate, utilized a multiple-resonance unit cell architecture to achieve a complete 360° phase variation. Prototypes were fabricated to demonstrate beam steering at 30° and 60°, highlighting the design's adaptability to various application-specific requirements. Measured results closely aligned with simulations and confirmed consistent gain and efficient beam steering across a wide frequency range of 4.5–5.5 GHz. The antenna achieved a peak gain of 21 dBi at 5 GHz with minimal variation across the operating bandwidth. These findings validated the reflectarray's suitability for deployment in Wi-Fi and other wireless communication systems, particularly in urban environments where signal blockage was prevalent.

REFERENCES

[1] Osterrieder, P., L. Budde, and T. Friedli, "The smart factory as a key construct of industry 4.0: A systematic literature review," *International Journal of Production Economics*, Vol. 221, 107476, 2020.

[2] Zhang, Y., S. R. Khosravirad, X. Chu, and M. A. Uusitalo, "On the IRS deployment in smart factories considering blockage effects: Collocated or distributed?" *IEEE Transactions on Wireless Communications*, Vol. 23, No. 9, 12 084–12 098, 2024.

[3] Callaghan, P. and P. R. Young, "Beam-and band-width broadening of intelligent reflecting surfaces using elliptical phase distribution," *IEEE Transactions on Antennas and Propagation*, Vol. 70, No. 10, 8825–8832, 2022.

[4] Quevedo-Teruel, O., H. Chen, A. Díaz-Rubio, G. Gok, A. Grbic, G. Minatti, E. Martini, S. Maci, G. V. Eleftheriades, M. Chen, *et al.*, "Roadmap on metasurfaces," *Journal of Optics*, Vol. 21, No. 7, 073002, 2019.

[5] Xu, L., C. Yuan, Q. Zhang, J. Liu, Q. Zhang, and Y. Sun, "Design and experiments of a beam-steerable wideband reflectarray antenna for high-power microwave applications," *IEEE Transactions on Antennas and Propagation*, Vol. 71, No. 2, 1955–1959, 2023.

[6] Chen, R., Z. Tian, W.-X. Long, X. Wang, and W. Zhang, "Hybrid mechanical and electronic beam steering for maximizing OAM channel capacity," *IEEE Transactions on Wireless Communications*, Vol. 22, No. 1, 534–549, 2023.

[7] Zhang, S. and B. Duan, "Random error characterization of nonsmooth parabolic reflector antennas with gore-faceted or discontinuous surface," *IEEE Transactions on Antennas and Propagation*, Vol. 69, No. 4, 1922–1930, 2021.

[8] Cho, H., H.-W. Jo, J.-W. Kim, K.-S. Kim, J.-I. Oh, and J.-W. Yu, "Shorted trapezoidal SIW antenna with quasi-hemispherical pattern for 2D wide scanning planar phased array antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 70, No. 8, 7211–7216, 2022.

[9] Liu, F., D.-H. Kwon, and S. Tretyakov, "Reflectarrays and metasurface reflectors as diffraction gratings: A tutorial," *IEEE Antennas and Propagation Magazine*, Vol. 65, No. 3, 21–32, 2023.

[10] Mei, W., B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless networks: From single-reflection to multireflection design and optimization," *Proceedings of the IEEE*, Vol. 110, No. 9, 1380–1400, 2022.

[11] Basharat, S., M. Khan, M. Iqbal, U. S. Hashmi, S. A. R. Zaidi, and I. Robertson, "Exploring reconfigurable intelligent surfaces for 6G: State-of-the-art and the road ahead," *IET Communications*, Vol. 16, No. 13, 1458–1474, 2022.

[12] Rao, M. V., J. Malik, S. Yuvaraj, and M. V. Kartikeyan, "Polarization insensitive reflectarray for OAM beam generation over octave bandwidth for 5G applications," *AEU — International Journal of Electronics and Communications*, Vol. 170, 154775, 2023.

[13] Imaz-Lueje, B., D. R. Prado, M. Arrebola, and M. R. Pino, "Reflectarray antennas: A smart solution for new generation satellite mega-constellations in space communications," *Scientific Reports*, Vol. 10, No. 1, 21554, 2020.

[14] Wu, M., W. Rao, and L. Guo, "A broadband and high-efficiency folded transmitarray antenna," *Microwave and Optical Technology Letters*, Vol. 66, No. 10, e70006, 2024.

[15] Shojaeifard, A., K.-K. Wong, K.-F. Tong, Z. Chu, A. Mourad, A. Haghighat, I. Hemadeh, N. T. Nguyen, V. Tapio, and M. Juntti, "MIMO evolution beyond 5G through reconfigurable intelligent surfaces and fluid antenna systems," *Proceedings of the IEEE*, Vol. 110, No. 9, 1244–1265, 2022.

[16] Kim, H., J. Kim, and J. Oh, "Communication a novel systematic design of high-aperture-efficiency 2D beam-scanning liquid-crystal embedded reflectarray antenna for 6G FR3 and radar applications," *IEEE Transactions on Antennas and Propagation*, Vol. 70, No. 11, 11 194–11 198, 2022.

[17] Cano, H. P. Z., Z. D. Zaharis, T. V. Yioultsis, N. V. Kantartzis, and P. I. Lazaridis, "Pattern reconfigurable antennas at millimeter-wave frequencies: A comprehensive survey," *IEEE Access*, Vol. 10, 83 029–83 042, 2022.

[18] Luk, K.-M. and B. Xiang, "Transmitarray and reflectarray antennas based on a magnetoelectric dipole antenna," *Electromagnetic Science*, Vol. 1, No. 1, 1–14, 2023.

[19] Al-Nuaimi, M. K. T., A. Mahmoud, W. Hong, and Y. He, "Design of single-layer circularly polarized reflectarray with efficient beam scanning," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 6, 1002–1006, 2020.

[20] Ali, Q., W. Shahzad, I. Ahmad, S. Safiq, X. Bin, S. M. Abbas, and H. Sun, "Recent developments and challenges on beam steering characteristics of reconfigurable transmitarray antennas," *Electronics*, Vol. 11, No. 4, 587, 2022.

[21] Nayeri, P., F. Yang, and A. Z. Elsherbeni, "Bifocal design and aperture phase optimizations of reflectarray antennas for wide-angle beam scanning performance," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 9, 4588–4597, 2013.

[22] Li, H., C. Ma, T. Zhou, J. Wang, D. Ye, Y. Sun, W. Zhu, T. A. Denidni, and L. Ran, "Reconfigurable Fresnel lens based on an active second-order bandpass frequency-selective surface," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 5, 4054–4059, 2020.

[23] Gao, L., F. Yang, S. Xu, M. Li, and X. Liu, "Design of a beam-scanning reflectarray antenna with an offset mechanically rotational horn," in *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2281–2282, Vancouver, BC, Canada, 2015.

[24] Wu, G.-B., S.-W. Qu, S. Yang, and C. H. Chan, "Low-cost 1-D beam-steering reflectarray with ±70° scan coverage," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 6, 5009–5014, 2020.

[25] Abbasi, M. I., M. H. Dahri, M. H. Jamaluddin, N. Seman, M. R. Kamarudin, and N. H. Sulaiman, "Millimeter wave beam steering reflectarray antenna based on mechanical rotation of array," *IEEE Access*, Vol. 7, 145 685–145 691, 2019.

[26] Yang, X., S. Xu, F. Yang, M. Li, H. Fang, and Y. Hou, "Design of a circularly polarized reconfigurable reflectarray using micro-motors," in *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2155–2156, Vancouver, BC, Canada, 2015.

[27] Yang, X., S. Xu, F. Yang, M. Li, Y. Hou, S. Jiang, and L. Liu, "A broadband high-efficiency reconfigurable reflectarray antenna using mechanically rotational elements," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 8, 3959–3966, 2017.

[28] Tahseen, M. M. and A. A. Kishk, "Circularly Polarized Stepped Reflectarray: A new design approach for bandwidth enhancement," *IEEE Antennas and Propagation Magazine*, Vol. 66, No. 2, 43–54, 2024.

[29] Baki, A. K. M., A. R. Chowdhury, and M. S. Hasan, "Towards the realization of an intelligent reflecting surface with full 360° phase variation for beam steering applications at C and X bands," *IEEE Access*, Vol. 12, 113 178–113 192, 2024.

[30] Dahri, M. H., M. I. Abbasi, M. H. Jamaluddin, and M. R. Kamarudin, "A review of high gain and high efficiency reflectarrays for 5G communications," *IEEE Access*, Vol. 6, 5973–5985, 2018.

[31] Rao, M. V., J. Malik, S. Yuvaraj, and M. V. Kartikeyan, "A novel approach for the generation of OAM beam with high mode purity using the reflectarray," *Optik*, Vol. 296, 171557, 2024.

[32] Nayeri, P., F. Yang, and A. Z. Elsherbeni, "Introduction to reflectarray antennas," in *Reflectarray Antennas: Theory, Designs, and Applications*, 1–8, Wiley, 2018.