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RESEARCH ARTICLE OPEN ACCESS

ENHANCED PERFORMANCE OF MICROSTRIP ANTENNA ARRAYS THROUGH CONCAVE MODIFICATIONS AND CUT-CORNER TECHNIQUES

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ABSTRACT

This paper presents the design and analysis of a high-performance 4×1 linear microstrip-fed antenna array optimized for wireless communication systems operating at 2.45 GHz. A novel concave-shaped modification is introduced on both the horizontal and vertical edges of the rectangular patch elements, significantly enhancing key performance metrics such as gain, impedance matching, and radiation efficiency. In addition, cut-corner techniques are applied to each patch element to minimize return loss and improve bandwidth, effectively addressing common limitations of traditional rectangular patch antennas, such as low gain and narrow bandwidth. Through rigorous simulations and physical prototyping, the proposed antenna array demonstrates a peak gain of 18 dB and a return loss of -33.82 dB at the target frequency. This makes it highly suitable for high-performance wireless applications, including WLAN, mobile communications, and smart transportation systems. The design not only improves antenna efficiency but is also cost-effective and simple to fabricate, making it ideal for mass production in modern communication systems.

I. INTRODUCTION

The manipulation of electromagnetic (EM) waves is critical for advancing modern technologies, such as sensing and biosensing devices [1], energy harvesting [2],[3], and communication systems. Simultaneously, the rapid growth of wireless communication technologies has heightened the demand for efficient, high-gain, and compact antenna systems, capable of supporting a wide range of applications [4],[5], from wireless local area networks (WLAN) to mobile and satellite communications. A key frequency band for these applications is 2.45 GHz, extensively used in Bluetooth, WLAN, and industrial, scientific, and medical (ISM) bands.

It is well-established that the use of substrate materials in radio frequency (RF) and microwave circuits, particularly printed circuit boards (PCBs), presents notable challenges [6]. Among various microstrip patch antenna (MPA) feeding techniques, the microstrip feed line is one of the most commonly employed [7]. The 2.45 GHz band is versatile, supporting applications such as

WLAN, multiple-input and multiple-output (MIMO) systems, Wi-Fi, Bluetooth, and ZigBee [8-10]. In this context, microstrip antennas have gained prominence due to their low profile, lightweight design, ease of fabrication, and compatibility with integrated circuit (IC) technologies. However, despite these advantages, conventional microstrip antennas face limitations, including low gain, narrow bandwidth, and surface wave excitation, which hinder their use in high-performance wireless communication systems.

To address these limitations, research has focused on optimizing microstrip antenna designs, particularly in array configurations, which offer enhanced directivity and gain. Array antennas are especially suitable for applications requiring precise radiation control. Although various geometries—such as circular, triangular, and elliptical-have been explored, the rectangular patch remains the most widely used due to its simplicity and ease of design [11]. Nevertheless, further performance enhancements are essential to meet the increasingly stringent demands of modern communication systems.

Several techniques have been developed to improve the performance of rectangular patch antennas, including careful substrate material selection, optimization of feed networks, and geometric modifications. Among these approaches, the introduction of concave-shaped forms and cut-corner techniques has shown significant promise in addressing the drawbacks of traditional designs. These modifications aim to enhance impedance matching, increase gain, and reduce return loss, ultimately boosting overall system efficiency [12-15].

In this work, we present a novel 4×1 linear microstrip-fed antenna array that incorporates concave-shaped forms on both the horizontal and vertical edges of the rectangular patch elements. This design is further refined by applying cut-corner techniques to the patch elements, which not only reduce return loss but also improve radiation performance. The primary objective of these modifications is to significantly enhance the antenna's gain and minimize return loss, making the array highly suitable for high-performance wireless applications.

The design process involved two key stages. First, the corporate feed network was optimized to ensure uniform power distribution across all patch elements. Then, concave-shaped forms and cut corners were applied to maximize the performance of each patch. Simulations were conducted using the High-Frequency Structure Simulator (HFSS), a widely used tool based on the finite element method (FEM) for antenna design and analysis. Following the simulations, a physical prototype was fabricated and tested in an anechoic chamber to validate the results.

The findings demonstrate that the proposed antenna array significantly outperforms conventional designs in both return loss and gain. The introduction of concave-shaped forms effectively reduced return loss, while the cut-corner technique further improved radiation efficiency and gain. The measured peak gain of 18 dB and return loss reduction to -33.82 dB validate the effectiveness of the proposed design for high-performance wireless systems operating at 2.45 GHz [16].

This paper is organized as follows. Section 2 provides a detailed description of the proposed antenna array design, including feed network optimization and geometric modifications. Section 3 presents the results and findings and their discussion, along with a comprehensive analysis of the antenna’s performance in terms of return loss, gain, and radiation patterns. Finally, Section 4 concludes the paper with a summary of findings and future research directions.

II. MATERIALS AND METHODS

II.1 PROPOSED ANTENNA ARRAY DESIGN

This section provides a comprehensive overview of the design process for the proposed 4×1 linear microstrip-fed antenna array. The primary goal of this design was to create a compact yet high-performance antenna array, specifically tailored for wireless communication systems operating at the frequency of 2.45 GHz. To achieve this, the design focused on enhancing critical performance metrics such as gain and optimizing impedance matching. The approach employed several innovative modifications, including concave-shaped alterations to the edges of the rectangular patch elements and the implementation of cut-corner techniques. These modifications were strategically introduced to address the inherent drawbacks of conventional rectangular microstrip patch antennas, which often suffer from limited gain and bandwidth. By incorporating these geometric enhancements, the proposed design aims to improve overall efficiency and meet the demands of modern wireless systems.

II.2 SUBSTRATE AND PATCH DESIGN

The selection of an appropriate substrate is critical to determine the performance of the antenna array. The proposed antenna is designed on a Rogers R04350B substrate, which offers enhanced characteristics for high-frequency applications. This substrate has a relative dielectric constant (εr) of 3.48, a thickness of 1.52 mm, and a low loss tangent (δ = 0.004). These properties help to minimize dielectric losses, contributing to higher radiation efficiency and bandwidth performance [16],[17]. The substrate dimensions are 255mm × 123mm, as shown in Figure 1, which were carefully chosen to accommodate the array elements and provide sufficient surface area for the corporate feed network.

Each element of the array consists of a modified rectangular patch, designed to operate at the center frequency of 2.45 GHz. The dimensions of each patch are determined based on the resonant frequency, calculated using standard microstrip patch antenna design equations, as outlined in references [18-21]. The optimal geometrial design parameters for the antenna array are detailed in Table 1.

Table 1**:** Optimal dimensions of the proposed antenna array.

Parameters	**Values (mm)**	**Parameters**	**Values (mm)**
W	40.91	W_1	1.85
L	32.40	ΔW_0	3.8
g	1.72	ΔW_1	1.68
l	10.46	l_0	15.85
l_f	19.49	l_1	19
h	3.5	d	62
a	3	D	255
W_0	3,44	S	123

Source: Authors, (2025).

II.3 CORPORATE FEED NETWORK

The feed network is a crucial aspect of the antenna array design, as it ensures efficient power distribution among the array elements. The proposed array employs a corporate feed network, which provides equal phase and amplitude excitation to all four patch elements.This network is designed using T-junction power dividers and microstrip transmission lines, ensuring minimal power loss and high efficiency. The characteristic impedance of the main transmission line is Z0=50Ω, while the quarter-wave transformers, used to match the impedance between the transmission line and the patch elements, have an impedance of Z1=70.7Ω.The feed network utilizes three symmetric T-junction power dividers with triangular notches of dimension ΔW1 = 1.68 mm to reduce unwanted reflections at junctions, which helps maintain impedance matching across the entire structure [22], [23]. The design ensures minimal radiation loss at the right-angled bends by introducing chamfered bends with dimensions ΔW0 = 3.8 mm, which smooths the current flow and prevents sharp turns that could lead to performance degradation [24-28].The corporate feed network is optimized to minimize return loss and achieve high directivity by ensuring that the separation distance between each patch element is approximately λ/2, which corresponds to 62 mm at the operating frequency of 2.45 GHz. This spacing is essential to reduce mutual coupling between the elements and achieve the desired radiation characteristics.

II.3 CONCAVE-SHAPED PATCH MODIFICATION

The proposed patch antenna design introduces concave-shaped geometrical modifications on both the horizontal and vertical edges of each radiating element in the antenna array. These concave features are incorporated with a depth of 3.5 mm, which was determined through parametric studies and simulations. The key objective of these modifications is to enhance the antenna's radiation characteristics, specifically improving its gain and directivity.

The concave shapes, as seen in the image, are implemented on all four sides of each patch element. These structural modifications influence the distribution of surface currents, which is crucial for better impedance matching and reduced surface wave excitation. Additionally, the four corners of each patch are truncated by a distance of 3 mm (denoted as a), a strategic alteration that helps to minimize return loss, further improving the directivity and gain of the antenna (FIgure 1).

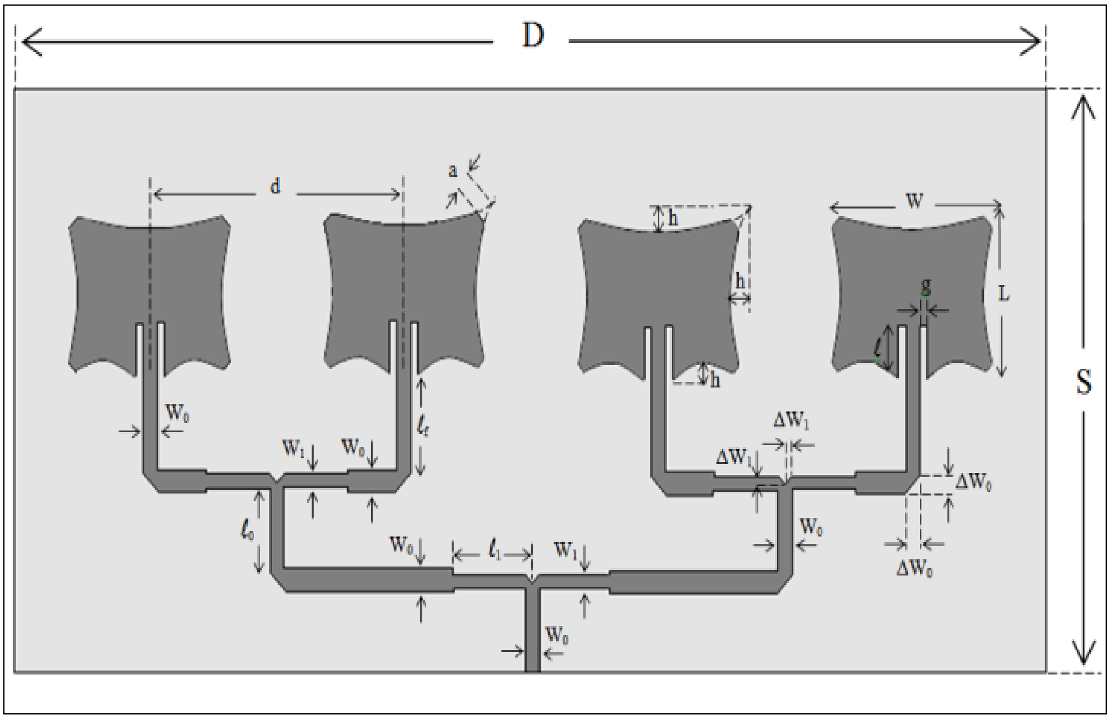

Figure 1: The geometry of the proposed linear microstrip-fed antenna array with four elements.
Source: Authors, (2025).

This concave shaping of the patch not only alters the current paths but also leads to a more focused radiation pattern. The result is a higher radiation efficiency by directing more of the radiated energy in the desired direction. The optimized depth of 3.5 mm was selected based on simulations using HFSS software, which demonstrated that this configuration provided the best balance between return loss and gain, ultimately yielding an antenna design with superior performance in terms of both impedance matching and radiation efficiency [15].

II.4 CUT-CORNER TECHNIQUE

In this configuration, each of the four corners of the rectangular patch elements is truncated by 3 mm. This alteration is aimed at improving impedance matching and reducing return loss, which in turn boosts the overall performance of the antenna.

The cut-corner technique plays a crucial role in increasing the bandwidth and minimizing the reflection coefficient (S11). By cutting the corners, the current distribution on the patch is more evenly spread, reducing unwanted resonances and reflections at the feed point. This leads to greater radiation efficiency and a broader operational bandwidth.

The effectiveness of the cut-corner technique was assessed by simulating three antenna configurations: a basic rectangular patch, a patch with concave-shaped modifications, and a patch incorporating both concave shapes and cut corners. Among these, the combination of concave shapes and cut corners produced the most notable improvement in return loss and impedance matching. Simulations showed a reduction in return loss to -29.90 dB at 2.62 GHz, while measured results indicated a further improved return loss of -33.82 dB at 2.65 GHz, confirming the design's effectiveness.

These dual modifications concave-shaped edges and cut corners work together to enhance impedance matching, increase bandwidth, and reduce the reflection coefficient. This combination results in more efficient radiation and overall better performance for the antenna array.

III. RESULTS AND DISCUSSIONS

III.1 SIMULATED AND MEASURED PERFORMANCE

The performance of the proposed antenna array was first analyzed through comprehensive simulations using Ansoft HFSS, a software based on the finite element method (FEM) as shown in Figure 2. These simulations evaluated critical parameters such as return loss, gain, and the radiation pattern, providing an in-depth understanding of the antenna's behavior and forming the basis for experimental validation.

Following the design optimization, a prototype of the antenna array was fabricated using standard PCB manufacturing techniques. The patch elements and feed network were etched onto a Rogers R04350B substrate, chosen for its superior dielectric properties, ideal for high-frequency applications. To ensure reliable signal transmission, a 50 Ω Sub Miniature version A (SMA) connector was integrated into the design.

The prototype was rigorously tested in an anechoic chamber as shown in Figure 3, which minimizes external interference and reflections. Key performance metrics, including return loss, gain, and radiation pattern, were measured to validate the antenna's real-world performance. Testing was conducted using an Agilent 8722ES vector network analyzer (VNA) to assess the S11 parameter, and the radiation pattern was mapped in the chamber.

The measured results closely aligned with the simulations, confirming the accuracy of the design. The antenna achieved a peak gain of 18 dB and a return loss of -33.82 dB at its operating frequency of 2.45 GHz. Additionally, the radiation pattern exhibited a well-defined main lobe with minimal side lobes, indicating strong directivity and low interference.

These findings demonstrate the effectiveness of the design enhancements, particularly the concave-shaped edges and cut-corner modifications, which significantly improved the antenna's gain, impedance matching, and overall radiation efficiency. The strong correlation between simulated and experimental results highlights the reliability of the design process and its practical applicability.

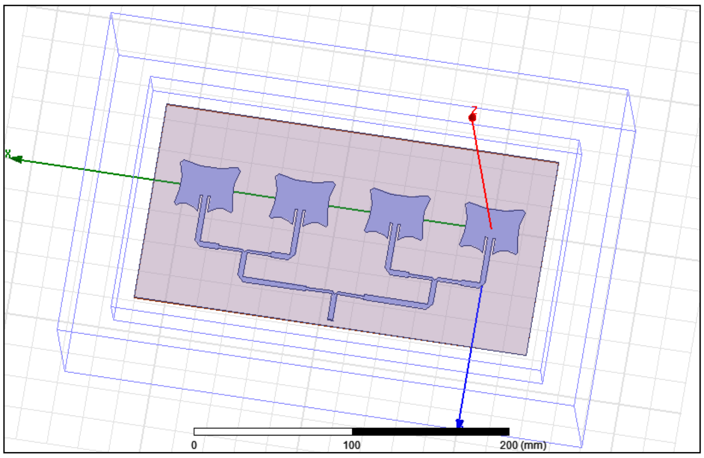

Figure 2: The layout of the proposed (4×1) linear microstrip patch antenna array in HFSS.
Source: Authors, (2025).

The investigated (4×1) linear microstrip patch antenna array was fabricated on thick Rogers R04350B of 1.52mm and permittivity of $\varepsilon r=3.48$, with tangent loss of substrate $\tan\delta=0.004$. The substrate size is of (255mm×123mm). The return loss characteristic of the manufactured antenna array is measured with an Agilent 8722ES vectorial network analyzer (VNA) as shown in Figure 3a. The radiation pattern of the proposed antenna at the resonant frequency is measured in an anechoic chamber as shown in Figure 3b.

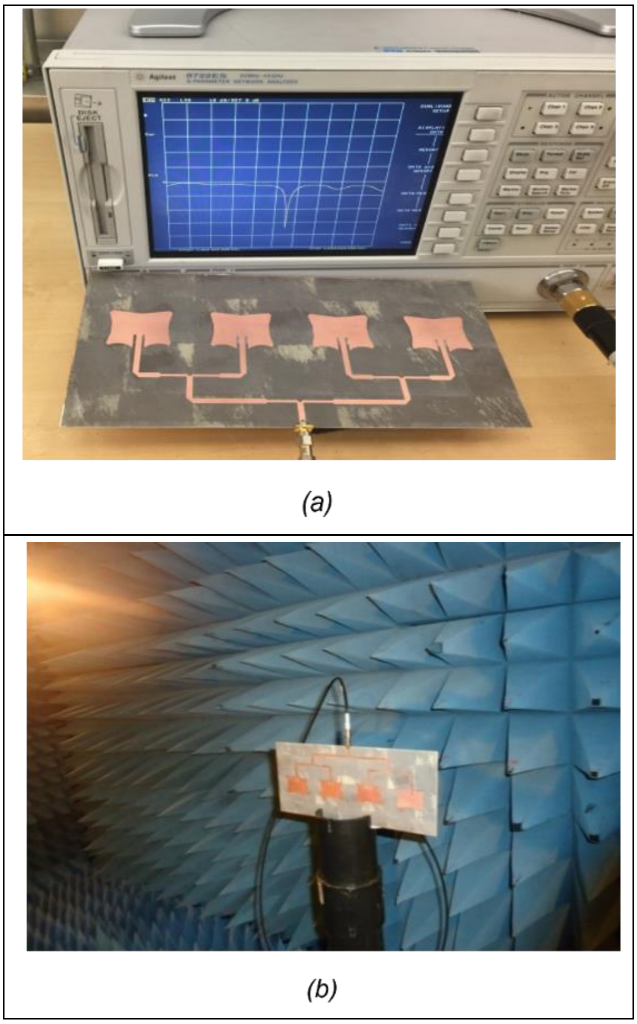

Figure 3: Photograph of the fabricated (4×1) array antenna prototype. (a) S11 parameter measurement protocol with the VNA. (b) Radiation pattern measurement in the anechoic chamber.
Source: Authors, (2025).

Figure 4 presents a comparative study of three different models of a linear (4×1) microstrip patch antenna array. All models are designed using a Rogers R04350B substrate and operate at a frequency of 2.45 GHz. These models explore the effects of geometric modifications on the antenna's performance, specifically return loss, gain, and radiation characteristics.

The first model, shown in Figure 4(a), features the basic structure of the antenna array with standard rectangular patch elements. This configuration serves as the foundational design for subsequent modifications. In Figure 4(b), the second model introduces a concave-shaped form on the patches. This modification, characterized by a depth hhh, is intended to improve the radiation characteristics of the array by altering the current distribution across the patch surface.

Finally, Figure 4(c) depicts the third model, which combines the concave-shaped form with cut corners, where each patch's four corners are truncated by 3 mm. This additional alteration is designed to enhance impedance matching, reduce return loss, and further increase the antenna's gain and directivity.

Each of these models demonstrates the progressive refinement of the antenna design, highlighting the impact of specific geometrical changes on the overall performance.

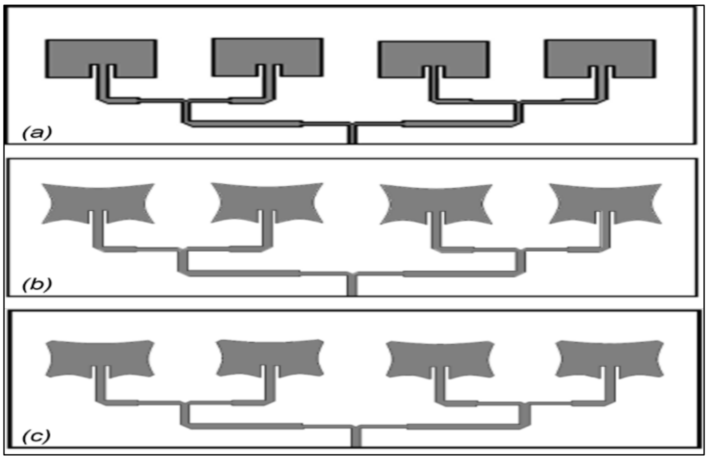

Figure 4: Linear (4×1) microstrip patch antenna array. (a) Basic structure. (b) Basic structure with concave-shaped form. (c) Basic structure with concave-shaped form and cut corners.
Source: Authors, (2025).

Figure 5 illustrates the return loss (S11) for three different microstrip patch antenna array structures presented earlier in Figure 4. The basic model (a) exhibits a simulated return loss of -22.43 dB at the operating frequency of 2.45 GHz. When a concave-shaped form with a depth of h = 3.5 mm is introduced in model (b), the return loss improves, reaching -26.42 dB at 2.56 GHz, reflecting a notable improvement of approximately 2.6 dB compared to the basic structure. Furthermore, the proposed model (c), which incorporates both the concave shape and additional modifications by cutting each corner by a distance of a = 3 mm, results in a significant enhancement of the return loss. The simulated S11 for model (c) achieves -29.90 dB at a frequency of 2.62 GHz.

Notably, the measured return loss for model (c), obtained using an Agilent network analyzer, aligns closely with the simulated results, achieving -33.82 dB at 2.65 GHz. The close agreement between the simulated and measured results for model (c) demonstrates the effectiveness of the concave design combined with corner cuts in further optimizing the antenna's performance. This enhanced return loss in both the simulation and measurement highlights the robustness of the proposed design for practical applications.

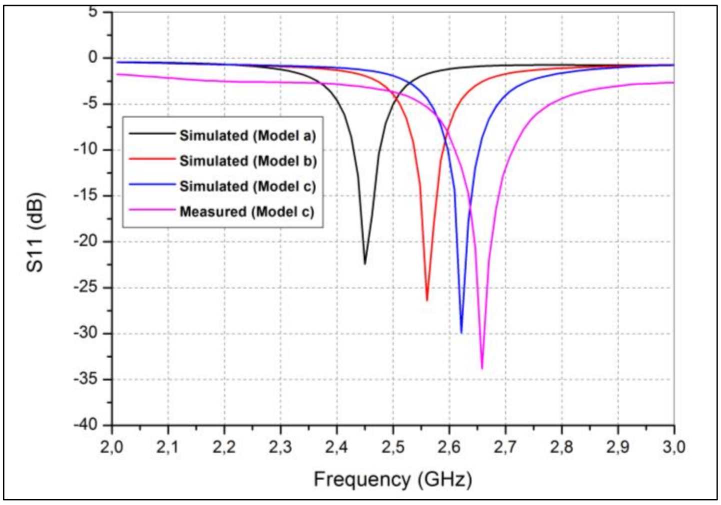

Figure 5: Return loss (S11) for the linear (4×1) microstrip patch antenna array structures. (a) Basic structure. (b) Basic structure with concave-shaped form. (c) Basic structure with concave-shaped form and cut corners.
Source: Authors, (2025).

To geometrically assess the impact of the concave-shaped form's depth (h) on the return loss and radiation pattern, Figure 6 presents the simulated S11 parameters for various values of h, ranging from 0 mm to 3.5 mm. The graph shows how increasing the concave depth progressively improves the antenna's return loss. Initially, with h = 0 mm (black curve), the return loss is -22.43 dB at the operating frequency of 2.45 GHz.

When the depth increases to h = 2.5 mm (red curve), the return loss improves to -23.84 dB. Further enhancements are observed at h = 3 mm (blue curve), where the return loss reaches -25.90 dB at 2.55 GHz. The most significant improvement occurs at h = 3.5 mm (purple curve), achieving a return loss of -26.42 dB at 2.56 GHz. This trend demonstrates that increasing the concave depth leads to a progressive reduction in return loss, improving the impedance matching at the target frequency.

These results emphasize the geometric influence of the concave depth on the antenna's performance, showing that deeper concave shapes lead to better return loss characteristics, which is crucial for optimal radiation pattern and overall antenna efficiency.

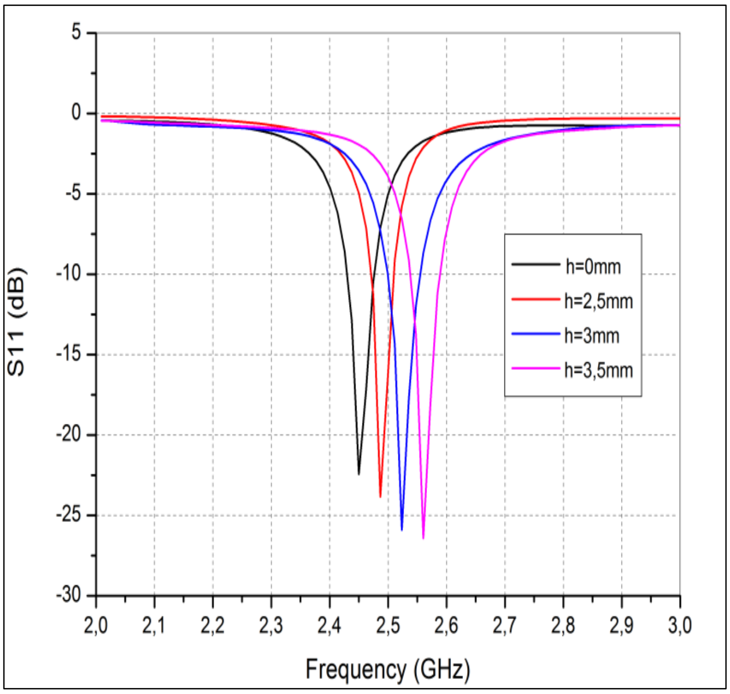

Figure 6: Effect of the concave-shaped form depth on the return loss.
Source: Authors, (2025).

Figure 7 presents the simulation results for the antenna's gain as a function of the angle θ (theta), for various concave-shaped form depths h, specifically 2.5 mm, 3 mm, and 3.5 mm. The plot illustrates a significant improvement in the antenna gain as the concave depth increases.

For a depth of h = 2.5 mm (black curve), the peak gain reaches 11.20 dB. Increasing the depth to h = 3 mm (red curve) enhances the gain to 14.97 dB, while a further increase to h = 3.5 mm (blue curve) results in a peak gain of 16.49 dB.

This trend demonstrates a clear improvement in gain as the concave depth increases, with the deepest concave shape providing the best performance. The graph also shows that the gain pattern becomes more uniform with increasing h, with reduced fluctuations, particularly around 0° and ±90°, leading to better directivity and overall antenna efficiency. These results confirm that optimizing the concave depth not only enhances return loss but also significantly improves the antenna's gain.

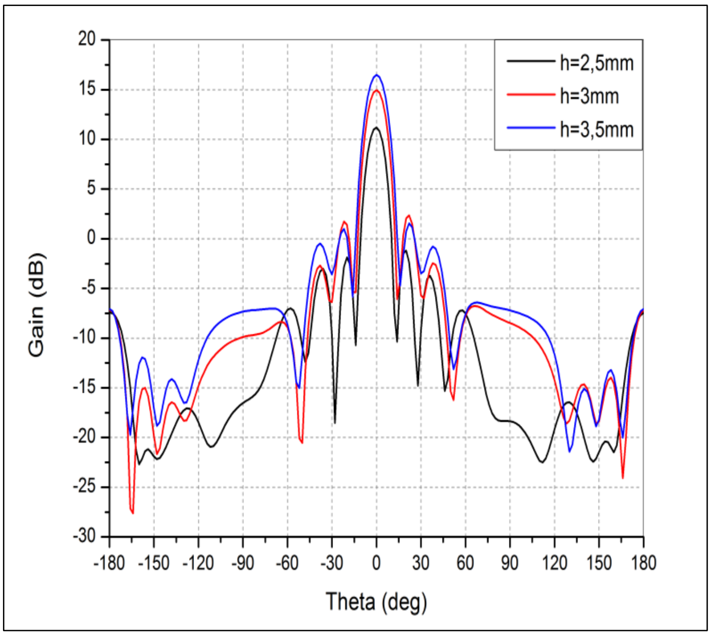

Figure 7: Influence of the concave-shaped form depth on the antenna array gain
Source: Authors, (2025).

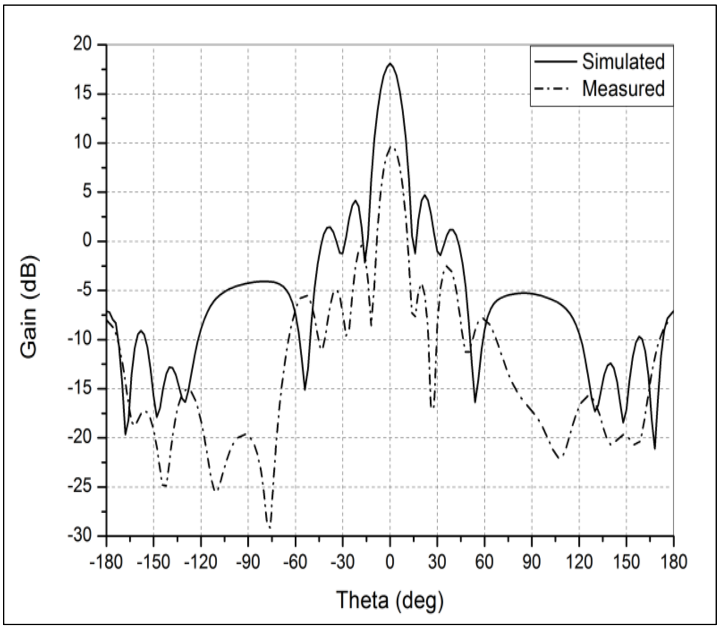

Figure 8: Simulated and measured E-plan gain of the proposed antenna array.
Source: Authors, (2025).

Measured and simulated E-plan gain of the manufactured final structure with the concave-shaped form of a depth h= 3.5mm and cut corners at 2.45 GHz are plotted in Figure 8. It can be noted that the measured gain is lower than that of the simulated model who achieves the best value of gain which is of 18.11dB, whereas for the measured result the E-plan gain is about 9.58dB.

The radiation patterns in E-plane and H-plane at 2.45 GHz of the proposed (4×1) linear patch antenna array for h= 2.5mm, h=3mm and h=3.5mm with cut corners are exhibited in Figure 9. It is observed that good radiation performances are achieved by increasing h from 2.5mm to 3.5mm and it can be noted that the cut of the four corners of each patch can indeed provide an increased gain and give advantages in term of side lobes level and main beam width.

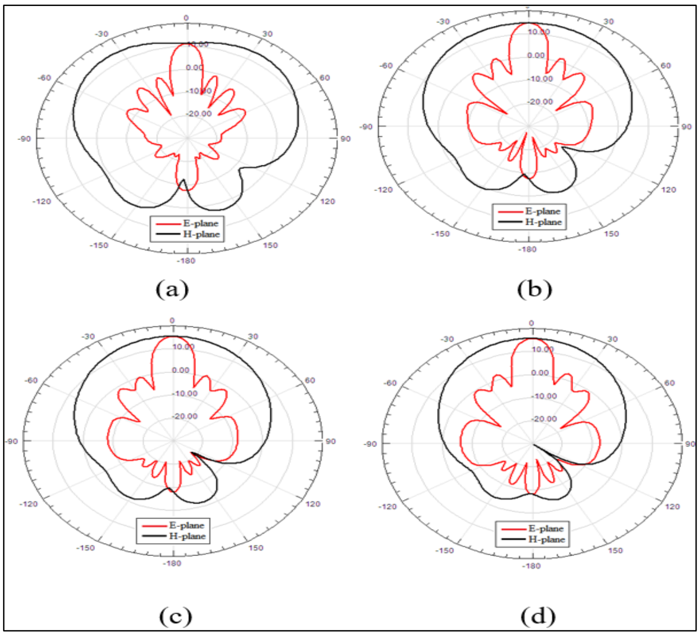

Figure 9: Radiation patterns at 2.45 GHz for the proposed linear patch antenna array. (a) h=2.5mm. (b) h=3mm. (c) h=3.5mm. (d) h=3.5mm and cut corners.
Source: Authors, (2025).

IV. CONCLUSIONS

In this paper, we introduced a novel microstrip-fed linear antenna array design, incorporating concave-shaped forms and cut corners to significantly improve its performance. The proposed design demonstrated substantial enhancements in key antenna characteristics, including return loss, gain, and radiation efficiency. Our approach, leveraging geometric modifications, provides a flexible and highly adaptable solution for optimizing antenna performance at 2.45 GHz, a crucial frequency for wireless communication systems. Both simulated and measured results confirm the effectiveness of the design modifications. The antenna array achieved a peak gain of 18 dB and a return loss of -33.82 dB, outperforming conventional rectangular patch antennas. The concave-shaped forms, in particular, proved effective in optimizing the current distribution, leading to improved gain and impedance matching. Meanwhile, the cut corners contributed to reducing return loss and improving bandwidth, addressing common limitations seen in traditional patch antennas. These design enhancements offer practical benefits for modern communication systems, including WLAN and mobile networks, where high gain and efficient radiation patterns are critical. Moreover, the progressive refinement of the design through simulations, followed by experimental validation, demonstrates the robustness of our methodology. The measured results closely aligned with simulations, showcasing the reliability of the proposed design process. This alignment between theoretical and practical performance reinforces the viability of the antenna for real-world applications.

In conclusion, the proposed microstrip antenna array with concave-shaped forms and cut corners provides a cost-effective, high-performance solution suitable for mass production. The design is simple to fabricate while achieving enhanced antenna characteristics that are crucial for a wide range of wireless applications, including smart transportation systems and mobile communications. Future work can explore further optimizations to extend the bandwidth and apply the design to other frequency ranges, ensuring.

V. AUTHOR'S CONTRIBUTION

Conceptualization: S. B, E.M, A.B, O.B
Methodology: E.M, A.B, O.B, A.R, M.G. A.D, I.T.
Investigation: E.M, A.B, O.B, A.R, M.G. A.D, I.T.
Discussion of results: S. B, E.M, A.B, O.B, A.R, M.G. A.D, I.T
Writing – Original Draft: S. B.
Writing – Review and Editing: E.M, A.B, O.B, A.R, A.D, I.T.
Resources: S. B.
Supervision: S. B, E.M.
Approval of the final text: S. B, E.M, A.B, O.B, A.R.

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