

A Circularly Polarized 4×4 Microstrip Array Antenna Using Diagonal-Slot and Truncated-Patch Techniques for 2.4 Ghz WLAN Applications

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Received 31 December 2024; Received in revised form 16 December 2025

Accepted 13 January 2026; Available online 27 March 2026

ABSTRACT

The use of the latest wireless telecommunications technology emphasizes the importance of antennas in improving the performance of communication systems. One recommended option is a microstrip antenna because it is lightweight, easy to integrate with the circuit, and effective in receiving circular polarization signals. This study focuses on designing, simulating, and manufacturing microstrip antennas with diagonal slots and a truncated square patch array 4×4 at a frequency of 2.4 GHz. The goal is to create microstrip antennas that are optimal for signal reception. The antennas use arrays to increase gain, while diagonal slots and truncated patches achieve circular polarization. The single-enumeration technique was used with the feed line method and simulated with CST Microwave Studio Suite 2019. The simulation results show the characteristic parameters of the 4×4 array microstrip antenna, such as working frequency 2.4 GHz, return loss -27.90 dB, VSWR 1.0984, bandwidth 55.7 MHz, gain 6.93 dB, and axial ratio 2.5 dB.

Keywords: Arrays; Diagonal slot; Microstrip; Square patch; Truncated

1. Introduction

The development of wireless communication technology demands antennas with compact size, low cost, ease of integration, and reliable performance [1]. Mi-

crostrip antennas are a widely used solution due to their low profile, light weight, and ease of fabrication, as well as their ability to support various applications such as WLAN and IoT [2]. Furthermore, they are

increasingly important because they can reduce the effects of multipath and orientation mismatch between transmitting and receiving antennas.

In WLAN systems based on the IEEE 802.11b/g/n standard, antennas operating at 2.4 GHz are required to have low return loss, a VSWR of <2 , adequate bandwidth, and high gain to maintain communication quality in environments with high levels of interference. However, conventional microstrip antennas have limitations in terms of bandwidth, axial ratio, and gain, necessitating modifications to the patch structure to improve performance [2, 3].

Various techniques have been developed to produce circular polarization in microstrip antennas, including [3, 4], which produce two orthogonal modes with a 90° phase difference, and the addition of diagonal slots, which create current perturbations that generate additional orthogonal modes. Although both techniques have proven effective, their applications are generally separate and limited to small array configurations.

Several previous studies have shown promising results. Alam used the truncated corner technique on a 2×1 microstrip antenna array and achieved circular polarization at 3.5GHz [5]. Raharjo demonstrated increased gain in a 4×2 truncated array antenna for microwave communications [6]. Both studies confirmed that both diagonal slots and truncated corners have significant potential for improving microstrip antenna performance. Meanwhile, research by Amillia and Yadi proposed a combination of truncated corners and partial ground (defective ground) in a 1×2 array configuration to expand bandwidth and improve matching [7].

Therefore, this study proposes the design of a 4×4 microstrip antenna array

based on square patches, combining truncated corners and diagonal slots to achieve circular polarization and high gain at 2.4 GHz. This design is expected to improve antenna performance in terms of axial ratio, return loss, bandwidth, and gain, making it suitable for WLAN applications and modern wireless communication systems [8].

2. Materials and Methods

This paper discusses the design of a microstrip antenna with a diagonal slot and a 4×4 truncated square patch array operating at a frequency of 2.4 GHz.

2.1 Antenna material

The antenna designed in this study uses an FR4 epoxy substrate commonly used in mid-frequency applications due to its affordability and ease of fabrication. This substrate has a relative permittivity (ϵ_r) of 4.3 and a thickness of 1.6 mm, making it suitable for designing compact microstrip antennas at a frequency of 2.4 GHz [9]. The patch shape used is a rectangular patch modified with diagonal slots on its surface and arranged in a 4×4 array to increase gain. The addition of these slots functions as a current perturbation to help generate orthogonal modes required in the formation of circular polarization. In addition, a truncated corner is adopted which also supports the creation of a 90° phase difference so that circular polarization can be achieved more stably. The combination of these two techniques is designed to work synergistically in increasing the axial ratio and radiation quality of the antenna. The entire design and optimization process was carried out using CST Microwave Studio 2019 with the hope of being able to produce a high-performance antenna for WLAN applications and modern wireless communication systems.

2.2 WLAN (Wireless Local Area Network)

A Wireless Local Area Network (WLAN) in the 2.4 GHz frequency band is one of the most widely used wireless communication technologies because it has a relatively wide range and high compatibility with various devices. This band is included in the Industrial, Scientific, and Medical (ISM) band, so it can be used without a license and supports the IEEE 802.11b/g/n standard [10]. Despite its advantages in terms of signal penetration and area coverage, 2.4 GHz WLAN often experiences interference due to the dense use by various other wireless devices. Therefore, WLAN systems at this frequency require antennas with good performance, including optimal impedance matching, adequate bandwidth, high enough gain, and stable polarization characteristics to maintain communication quality and reliability.

2.3 Circular polarization in microstrip antennas

Circular polarization is used because it does not depend on antenna alignment, thus reducing power loss due to polarization mismatch. Furthermore, this polarization is more resistant to multipath and reflection effects, which are common in wireless communication environments such as WLANs. Thus, circular polarization can improve communication stability and reliability, especially for devices that frequently change position [11].

Circular and elliptical polarization can be achieved using various feed arrangements or slight modifications to the patch elements. Practical methods for achieving near-circular polarization exist. For rectangular patches, circular polarization can be achieved by inserting very thin slots, as shown in Fig. 1(a). In addition to inserting

slots, the patch can also be truncated at the corners, as shown in Fig. 1(b) [12].

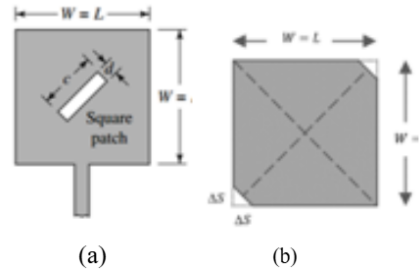


Fig. 1. Circular polarization for square patch with slot and truncation on patch.

2.4 Array Techniques in microstrip antennas

An array antenna is an arrangement of multiple identical antennas. In a microstrip patch antenna, the patch portion is the array. The total field of an array antenna is determined by the vector sum of the fields radiated by the individual elements. To form a pattern with a specific direction, the fields from each array element must interfere constructively in the desired direction and destructively in the other directions.

One technique that can support impedance matching in transmission lines, particularly for microstrip array antennas, is a power divider. In this case, the Wilkinson method is a commonly used technique. Fig. 2 shows the Wilkinson method power divider [13]. In the Wilkinson method,

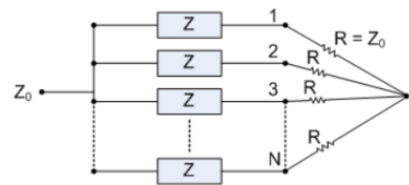


Fig. 2. N-Ways Wilkinson combiner.

the impedance value Z is given by the

following equation:

$$Z = Z_0 \sqrt{N}, \quad (2.1)$$

where N is the number of branching points and Z_0 is the initial input impedance. T-Junction is a power divider technique commonly used in antenna array configurations [4]. There are 2 types of 50Ω T-Junctions that can be used as power dividers as shown in Fig. 3.

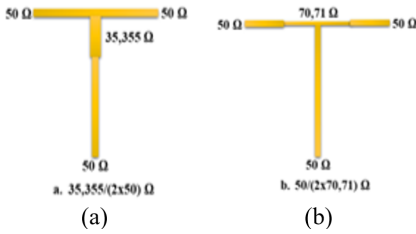


Fig. 3. T-Junction 50Ω .

Fig. 3 shows a T-junction configuration in the antenna array feed network that functions to distribute power evenly with proper impedance matching. In configuration (a), two 50Ω channels are transformed into one 35.355Ω channel, while in configuration (b) one 50Ω channel is divided into two 70.71Ω branches to maintain the equivalent impedance match. This principle is important in designing the 4×4 antenna array feed network to ensure even power distribution, minimal power reflection, and optimal radiation performance and gain [14, 15].

2.5 Design of microstrip antenna patch

2.5.1 Microstrip patch antenna dimensions

The first step is to determine the length of the antenna patch sides, which begins with determining the wavelength of the patch, using the following equations:

$$F = \frac{8.791 \cdot 10^9}{f_r \sqrt{\epsilon_r}}, \quad (2.2)$$

where, F is patch wavelength, f_r is working frequency (Hz) and ϵ_r is the relative dielectric constant [16].

From the formula above, the patch wavelength (F) is 1.7664. Once F is found, you can find the side length of the patch using the following equation:

$$L_p = \frac{F}{\sqrt{\left\{1 + \frac{2h}{\pi \cdot \epsilon_r \cdot F} [\ln(\frac{\pi \cdot F}{2 \cdot h} + 1.7726)]\right\}}} \times 2, \quad (2.3)$$

where L_p is patch side length (cm) and h is substrate thickness (cm). So the calculation obtained for the length of the patch side is 3.46493 cm.

Determine the dimensions of the slot inserted in the patch using the following equation:

$$p = \frac{L_p}{2.72}, \quad (2.4)$$

$$l = \frac{L_p}{27.2} = \frac{p}{10}, \quad (2.5)$$

where p is slot length (cm) and l is slot width (cm). So the length and width of the slot are 1.2739 cm and 0.12739 cm.

Determine the length of the corner of the cut patch using the following equation:

$$\Delta s = \frac{L_p}{8}, \quad (2.6)$$

$$s = \Delta s \sqrt{2}, \quad (2.7)$$

where Δs is the length of the cut patch side (cm), s is the length of the corner of cut patch (cm) Eq (2.6). So, the length of the corner of the cut patch is 0.613 cm.

2.5.2 Design of substrate and ground plane dimensions for microstrip antennas

In designing the dimensions of the microstrip antenna substrate with diagonal

slots and a truncated square, use the following equation [17, 18]:

$$L_g = (6 \cdot h) + L_p, \quad (2.8)$$

where L_g is substrate side length (cm). So the length of the substrate side is 4.42493 cm.

2.5.3 Microstrip antenna feeder design

The feeder on the microstrip antenna with diagonal slots and a truncated square patch array 4×4 works at a frequency of 2.4 GHz, so it is done in 3 steps [19].

The first is to determine the width of each feeder. The required feeder impedance is $Z_{0a} = 50 \Omega$, $Z_{0b} = 35.355 \Omega$, and $Z_{0c} = 70.71 \Omega$. This step begins by finding the value of A , which is the rank that determines the width of the feeder with following equation:

$$A = \frac{Z_0}{60} \cdot \sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1} \left(0.23 + \frac{0.11}{\epsilon_r} \right), \quad (2.9)$$

where A is the power of determining feeder width, Z_0 is feeder impedance (Ω). The value of A for $Z_{0a} = 50 \Omega$ is 1.5157, $Z_{0b} = 35.355 \Omega$ is 1.11837, and $Z_{0c} = 70.71 \Omega$ is 2.07759.

After obtaining the value of A , you can find the width of the feeder using the following:

$$W = \frac{8e^A}{e^{2A} - 2} \cdot h, \quad (2.10)$$

where, W is feeder width (cm). So the feeder width for $Z_{0a} = 50 \Omega$ is 0.311186 cm and $Z_{0b} = 35.355 \Omega$ is 0.53195 cm, and $Z_{0c} = 70.71 \Omega$ is 0.16549 cm.

The second step is to determine the length of each feeder. The required feeder impedance is $Z_{0a} = 50 \Omega$, $Z_{0b} = 35.355 \Omega$,

and $Z_{0c} = 70.71 \Omega$. This step begins by finding the value of $\frac{W}{h} > 1$ or $\frac{W}{h} < 1$ which is then used to calculate ϵ_{eff} , where for this condition $\frac{W}{h} > 1$, to calculate ϵ_{eff} is to use the following equation:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + \frac{12h}{W}}} \right]. \quad (2.11)$$

Meanwhile, when the value of $\frac{W}{h} < 1$ then, to calculate ϵ_{eff} is using the following equation:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + \frac{12h}{W}}} + 0.04 \sqrt{1 - \frac{W}{h}} \right], \quad (2.12)$$

where ϵ_{eff} is the effective dielectric constant. So that the value of ϵ_{eff} for $Z_{0a} = 50 \Omega$ is 3.2662, $Z_{0b} = 35.355 \Omega$ is 3.4185, and $Z_{0c} = 70.71 \Omega$ is 3.1148.

Then the value of the feeder length can be determined based on the following equation:

$$L = \frac{\lambda_g}{4} = \frac{\lambda_0}{4 \cdot \sqrt{\epsilon_{eff}}} = \frac{c}{4 \cdot f_r \cdot \sqrt{\epsilon_{eff}}} \quad (2.13)$$

where, L is feeder length (cm) And we can find the value of the feeder length (L) for $Z_{0a} = 50 \Omega$ is 1.73 cm, $Z_{0b} = 35.355 \Omega$ is 1.69 cm, and $Z_{0c} = 70.71 \Omega$ is 1.77 cm

Then the third is to determine the distance between patches to create an array on the antenna with Eq. (2.14).

$$d = \frac{\lambda_0}{2} = \frac{c}{2 \cdot f_r}, \quad (2.14)$$

where, d is distance between patches (m), c is speed of light (m/s) f_r is working frequency (Hz), So the value of d is 6.25 cm.

Table 1. Calculation result of dimension microstrip antenna.

Parameter	Symbol	Dimension (cm)
Patch side length	L_p	3.46493
Slot Length	p	1.2739
Slot width	l	0.12739
Truncated side length	s	0.613
Ground plane	L_s	4.42493
Feeder length 50 Ω	L_a	1.73
Feeder length 35.355 Ω	L_b	1.69
Feeder length 70.71 Ω	L_c	1.77
Feeder width 50 Ω	W_a	0.311186
Feeder width 35.355 Ω	W_b	0.53149
Feeder width 70.71 Ω	W_c	1.6549
Spacing patches	d	6.25
Substrate thickness	H	0.16
Conductor thickness	h_p	0.0035

2.6 Antenna design stages

The antenna fabrication process begins with the design of a single 2.4 GHz microstrip antenna, as shown in Fig.4 (a), with a modified rectangular patch using diagonal slots and truncated corners. The single antenna is simulated to ensure its return loss and VSWR characteristics meet specifications before being developed into an array configuration. Next, the single antennas are arranged in 1×4 and 2×4 arrays, as shown in Fig.4(b) and Fig.4(c) with the addition of a T-junction-based feed network for even power distribution. In the final stage of designing a 4×4 array, Fig.4(d) shows an antenna using a corporate feed network that is optimized to increase gain and polarization stability, then realized and tested to validate the simulation results.

From the design drawing above, we will make an array antenna 4×4 ; the design drawing is shown in Figs. 5-6 is the fabricated antenna.

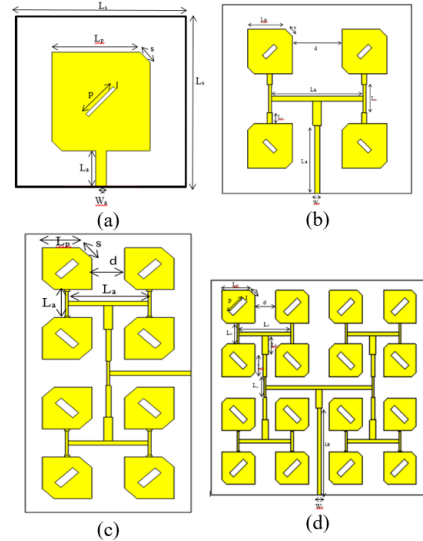


Fig. 4. Stages in designing a microstrip antenna.



Fig. 5. Fabricated microstrip antenna.

3. Results and Discussion

In addition to analyzing the simulation results of the antenna design, analysis was carried out on the measurement results of the manufactured antenna. Therefore, the results obtained when measuring the antenna characteristics can be compared with the results obtained in the simulation. However, the results being compared are the final results of the antenna array 4×4 in the simulation and the antenna-fabricated results.

Based on the simulation results using

CST Microwave Studio, the designed microstrip antenna has a compact overall dimension and is suitable for 2.4 GHz WLAN applications. The size of each rectangular patch element is determined based on theoretical calculations and simulation optimization processes, taking into account the characteristics of the FR4 substrate.

Table 2. Dimension microstrip antenna after optimization.

Parameter	Symbol	Dimension (cm)
Ground Plane	L_s	18,8
Side Patch Length	L_p	2,85
Slots Length	p	1,7
Slots Width	l	0,5
Truncated Side Length	s	0,557
Spacing Patch	d	4,7

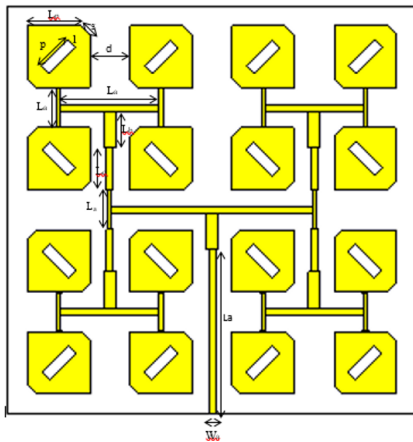


Fig. 6. Dimension of design microstrip antenna.

3.1 Measurement of return loss and VSWR

The results of measuring the working frequency, return loss and bandwidth of a microstrip antenna with a diagonal slot and a truncated square patch array 4×4 are shown in Fig. 7.

Based on the capture results on the Network Analyzer, the working frequency is 2.4 GHz with a return loss of -28.304 dB marked in B; there is also a lower frequency value of 2.3 GHz marked in A and

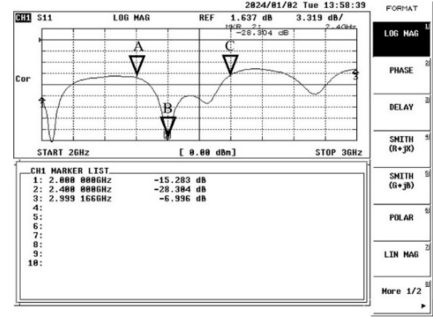


Fig. 7. Measurement results of the S11 parameter on the fabricated antenna.

an upper frequency of 2.6 GHz marked in C, where the lower frequency and upper frequency are stated when the return loss is -10 dB. Then for the bandwidth value of 300 MHz. While in the simulation, the return loss value is -27.95 dB with a bandwidth of 55.7 MHz. for comparison of the S11 parameter values can be seen in the image below.

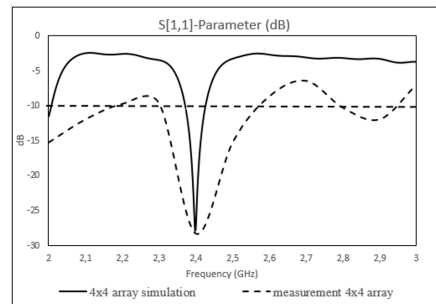


Fig. 8. Comparison chart of S11 parameters between the simulated antenna and the fabricated antenna.

Fig. 8 shows the return loss characteristics of the simulated antenna in the frequency range of 2–3 GHz. The antenna experiences a main resonance at a frequency of around 2.4 GHz with a minimum return loss value of -27.13 dB, indicating excellent impedance matching. The bandwidth range is determined based on the S11 < -10 dB criterion, which is between 2.3707

GHz and 2.4263 GHz, resulting in a bandwidth of around 55.6 MHz. These results indicate that the antenna has met the working specifications in the 2.4 GHz WLAN band with optimal impedance matching performance. The return loss results obtained tend to be better when tested in real conditions, namely producing a value of -28.304 dB compared to when tested in ideal conditions or when simulating, which produces a return loss of -27.895 dB.

The bandwidth from measurements of the manufactured antenna in real conditions obtained a very large value when compared with the test results in the simulation.

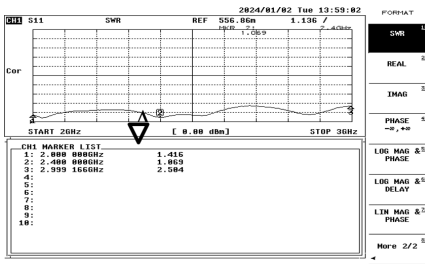


Fig. 9. VSWR measurement results of the fabricated antenna.

The results of the VSWR test of the fabricated antenna under real conditions obtained a smaller VSWR value compared to the VSWR value obtained based on the simulation as in Fig. 9. For a comparison of the VSWR values, see Fig. 10.

The results of measuring the VSWR of the manufactured antenna in real conditions (Fig. 10) show that the VSWR value was smaller than the VSWR value obtained based on the simulation, as shown in the figure, namely, when simulating, the value was 1.0921, and when testing in real conditions, the value was 1.069.

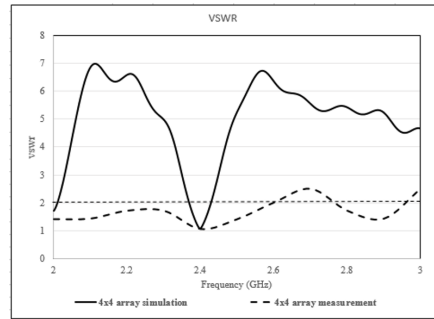


Fig. 10. Comparison graph of VSWR values between simulated antennas and fabricated antennas.

3.2 Antenna radiation pattern measurement

The results of the comparison of the vertical plane radiation pattern of the manufactured antenna and the simulation can be seen in the graphic comparison in Fig. 11, while the comparison of the horizontal plane radiation pattern can be seen in the graphic comparison as in Fig. 12.

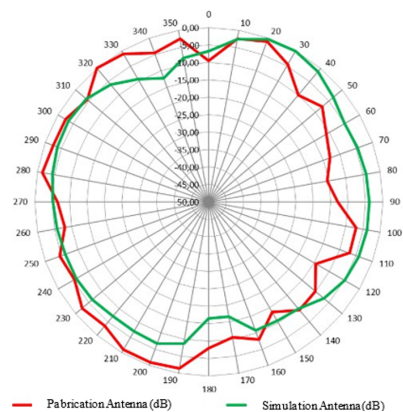


Fig. 11. Comparison graph of antenna vertical field radiation patterns.

The radiation pattern graph shows a comparison of the simulated antenna radiation pattern and the normalized measured results. The simulated antenna radiation pattern shows a relatively symmetrical and even radiation pattern across all angles, in-

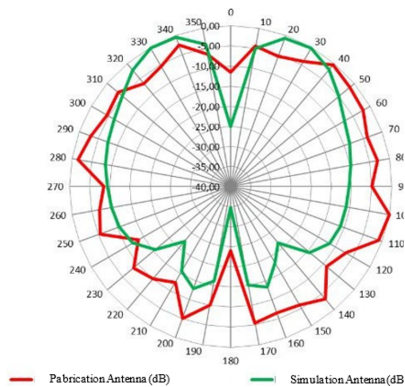


Fig. 12. Comparison graph of horizontal plane radiation patterns of fabricated and simulated antennas.

dicating good radiation performance for the 4×4 array antenna. Meanwhile, the measured antenna has a shape that still follows the simulated pattern, although there are some deviations at certain angles due to environmental factors, fabrication tolerances, and the imperfections of the measuring instrument. Overall, the measured radiation pattern still shows good agreement with the simulated results, indicating that the realized antenna is capable of producing a radiation pattern close to the design.

3.3 Antenna gain measurement

Gain value at each signal strength measurement distance, which, if averaged, is found to be 6.93 dB.

The gain value in the simulation is 7.426 dB; in other words, the fabricated microstrip array antenna 4×4 experienced a decrease in the gain value compared to the simulation of 0.497 dB.

4. Conclusion

The simulation results of a microstrip array antenna 4×4 show the following parameters: working frequency 2.4 GHz, return loss -27.90 dB, VSWR 1.0984, bandwidth 55.7 MHz, gain 7.426 dB, and ax-

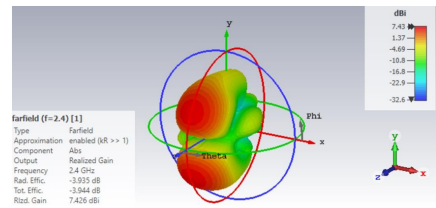


Fig. 13. Gain characteristics of array antenna 4×4 in simulation.

ial ratio 1.752 dB. Meanwhile, the pabrocatng test results have the same working frequency but a return loss of -28.304 dB, VSWR 1.069, a bandwidth of 300 MHz, an average gain of 6.93 dB, and an axial ratio of 2.5 dB. Comparison between simulation results and measurements produces error values of 1.47% for return loss and 2.68% for VSWR. The use of a patch array increases the gain, as seen in the simulation results (7.426 dB) and manufacturing results (6.93 dB), compared to a single antenna (3.296 dB). Providing diagonal and truncated slots reduces the axial ratio, creating circular polarization, which is proven in simulations and manufacturing measurement results with an axial ratio of 2.50 dB.

Acknowledgements

The authors would like to thank the Telecommunication Equipment Testing Center (BBPPT) for the antenna testing facilities we built.

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Table 3. Comparison of the signal strength of the reference antenna (TP-Link) and the microstrip array antenna 4×4.

Distance (meter)	TP Link Antenna			Microstrip Antenna			
	Strength (dBm)		Average (dBm)	Strength (dBm)		Average (dBm)	Gain (dB)
	Data 1	Data 2		Data 1	Data 2		
0	-29,00	-31,00	-30,00	-23,00	-29,00	-26,00	8,00
5	-40,00	-44,00	-42,00	-41,00	-39,00	-40,00	6,00
10	-44,00	-45,00	-44,50	-41,00	-45,00	-43,00	5,50
15	-47,00	-44,00	-45,50	-43,00	-48,00	-45,50	4,00
20	-55,00	-58,00	-56,50	-51,00	-53,00	-52,00	8,50
25	-61,00	-57,00	-59,00	-55,00	-57,00	-56,00	7,00
30	-75,00	-71,00	-73,00	-67,00	-68,00	-67,50	9,50

Table 4. Comparison of the proposed antenna with reported antennas.

Ref.	Patch Size (mm ³)	Frequency/Band (GHz)	Substrate	Feed Technique	Technique	Gain (dB)
[20]	120 × 42,5 × 1,6	5,2 GHz, 5,8 GHz	FR4	microstrip line feed and CPW-to-Slot line feed.	circular ring slots	4dBi
[17]	38.036 × 29,443 × 1,6	2,4GHz	FR4	Inset feed line	Different ground plane	3,05DB
[7]	54,50 × 45,0×1,6	2,4GHz	FR4	Feed line	Truncated Corner and Partial Ground	6.05 dBi
[21]	90 × 45 × 1,6	2,3GHz	FR4	inset feed line	2×1 Truncated Corner Microstrip Edge-Fed Square	3.963 dB
[22]	17,61 × 10,22×1,6	5.8 GHz and 9.2 GHz	FR4	feedline	Patch Antenna using Truncated Technique	5,5dB
This works	18,8×18,8×1,6	2,5GHz	FR4	Feed line	Diagonal-Slot and Truncated-Patch	6,93dB

cated microstrip antenna with array 4×2 for microwave radio communication.

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