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Mutual Coupling Reduction of a Wideband Circularly Polarized Microstrip MIMO Antenna

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ABSTRACT Mutual coupling (MC) between elements in an antenna array could significantly affect antenna performance, but this effect has rarely been reported for circularly polarized (CP) antennas. Therefore, this paper investigates a wideband CP multiple-input-multiple-output (MIMO) antenna operating between 1.8 and 2.6 GHz. A line patch was introduced between closely placed radiating elements (0.3λ) to produce a high isolation between elements in the proposed antenna. The designed MIMO antenna has a wide impedance bandwidth, a wide axial ratio (AR) bandwidth, a very low MC ($S_{21} < -25$ dB), a low envelop correlation coefficient (ECC < 0.01), a high diversity gain (DG $\sim$ 10 dB), and a realized gain of above 2 dB over the entire frequencies. The prototype of the proposed antenna geometry was fabricated and measured. A good agreement between the simulated and measured results was observed.

INDEX TERMS Array antenna, circular polarized antenna, MIMO, mutual coupling.

I. INTRODUCTION

Mutual coupling (MC) is a phenomenon that distorts the behavior of radiating elements in an antenna array. Each element in an array affects every other element by radiating through air or by propagating surface currents through the ground plane. As a result, antenna gain, beam width, radiation characteristics, resonance frequency, and input impedance are also affected.

Surface current distribution is the main factor that influences the degree of mutual coupling between adjacent patches [1]. A practical design necessitates as compact an array antenna as possible; hence the patches are organized as close as possible while maintaining a certain antenna performance. Closely spaced antennas will introduce higher radiation interaction, which then results in higher mutual coupling. Various techniques have been developed to reduce this mutual coupling effect, such as employing EBG [2], [3], introducing a slot [4], [5], metal boundary [6], a defected ground plane structure (DGS) and notches on the ground plane that act as resonators [7].

A band-stop element was added to reduce the MC in an antenna array to less than −25 dB, as demonstrated in [8] and [9] with a closely distanced center-to-center patch of below 0.3λ. A small gap of 0.25λ was achieved in [9], however a micro-machined fabrication technique also had to be applied, which led to a more complex design as well as extra cost. An ultra-wide band MIMO antenna with a mutual coupling of less than −20 dB was presented in [10] in which an F-shaped stub was implemented in the ground plane. A five wideband MIMO antenna with maximum isolation improvement of 37 dB successfully presented in [11] by introducing EM-bandgap metamaterial fractal loading in between 1×2 array. But then, the fractal structure were complex and spacious, led to ∼0.65λ gap between patch elements.

A considerable amount of work has been published on the effect of mutual coupling in an array antenna. However, the effect of coupling on axial ratio performance has hardly been discussed. Using two similar CP microstrip antennas, a previous study [12] investigated the mutual coupling effect

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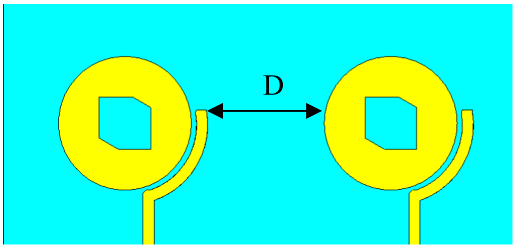


FIGURE 1. 1 × 2 circular polarized array antenna.

in a circularly polarized antenna by applying dyadic Green's function theory. In their analysis, the axial ratio was deduced by placing another antenna beside the antenna that became excited due to the coupling effect.

MIMO CP antenna with mutual coupling reduction of more than 10 dB were proposed in [13]–[15]. A hybrid technique combining DRA and parasitic patches and an axial ratio (AR) of 20.8% was proposed in the design of a MIMO antenna [13], while in [14], an FSS superstrate was used to suppress coupling, which resulted in a multi-layered complex design.

This paper investigates a broadband 2 × 1 CP array antenna with a very low mutual coupling of less than −25 dB and an edge-to-edge spacing of 0.3λ. The antenna also exhibits wide impedance of 36% and CP BWs of ∼23%. Along with this high diversity gain (DG), a low envelope correlation coefficient (ECC) was also observed. The proposed antenna operates over a wide frequency range of 1.84–2.57 GHz.

This paper is organized as follows: Section II outlines the antenna characterization element, after which a study on the mutual coupling effect in the CP antenna is presented. The section is divided into three parts, which are distance analysis, mutual coupling reduction technique and gain, and radiation via the envelope correlation coefficient analysis. The measurement results of the prototype are discussed in Section IV. The conclusions are drawn in Section V.

II. ANTENNA CHARACTERIZATION

A CP antenna with a simple two-element structure was chosen to demonstrate the mutual coupling reduction technique in this study. The electromagnetically fed circularly polarized antenna is a broadband antenna that resonates at 2.08 GHz. The single-element antenna was designed using a FR4 substrate with a square substrate measuring 66 × 66 mm^2. The antenna has a return loss of below −10 dB from 1.73 GHz to 2.59 GHz, which yields a bandwidth of 39.56% and an axial ratio (AR) bandwidth of 22% centered at 2.08 GHz. As shown in Figure 1 the array is composed of two CP antennas with a distance D from antenna edge A to antenna edge B. A CST Microwave Studio simulation tool was used for the design and simulation phase in this study.

III. MUTUAL COUPLING STUDY OF THE CP ANTENNA

The performance of an antenna in an antenna array, particularly a CP antenna, could change. By creating an array, the gain of a single antenna can be enhanced; however, this will negatively change the CP characteristic of the antenna. The present study aims to assess the effect of mutual coupling on the performance of an antenna array. Mutual coupling exists due to the electromagnetic interaction between elements in an antenna array. This issue becomes more significant with a small spacing between patches.

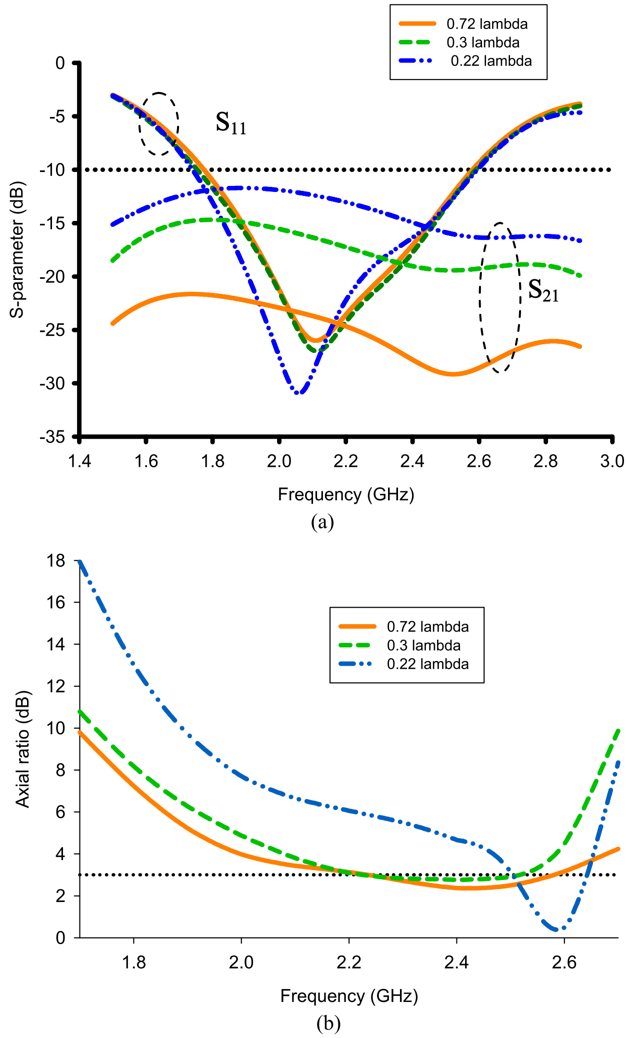


FIGURE 2. Simulated result of antenna array with different distance: (a) S_{11} and S_{21}, and (b) AR.

A. DISTANCE ANALYSIS

The mutual coupling of an array antenna is highly dependent on the distance between antenna patches. The relationship between distance and antenna performance such as the reflection coefficient (S_{11}), isolation (S_{21}), and the axial ratio are explained by the simulated result in Figure 2. Varying the distance between two radiating patches did not significantly change the operating bandwidth of the antenna array. However, as shown in Figure 2(a), the S_{21} values increased with decreasing distance, which indicates stronger coupling between the patches.

Although the distance between patches in an array did not much affect S_{11}, the CP characteristic of the antenna was

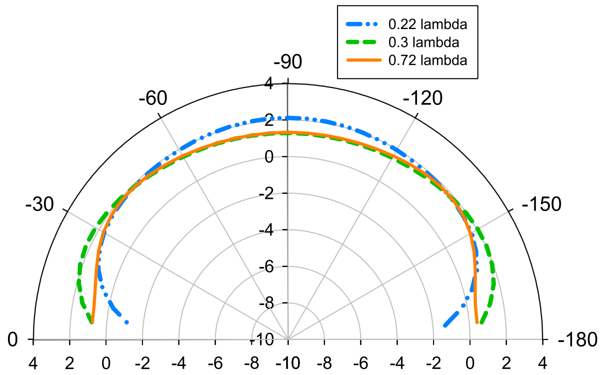
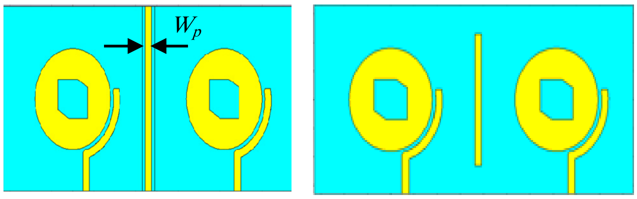


FIGURE 3. Radiation pattern of 2 × 1 array antenna with varying distance at 2.08 GHz.



(a) (b)

FIGURE 4. Adding elements between patches: (a) Line patch and (b) Line patch center (***Wpc***).

still altered, as can be seen in Figure 2(b). The AR of the antenna clearly changed with a different patch distance.

When the distance decreased, the AR center shifted to a higher frequency and the percentage of AR bandwidth reduced. Simulating a distance of 0.72λ (104.23 mm), the AR was observed to fall to 2.4 GHz with an AR bandwidth of 14.8%. When the distance was reduced to 0.22λ (31.35 mm), the AR shifted to 2.6 GHz with a 4.9% AR bandwidth. In addition, it was noted that the AR shifted to a higher frequency when the distance was reduced. Meanwhile, as shown in Figure 3, the radiation pattern of the antenna did not change significantly, but it became broader when the coupling was reduced.

B. MUTUAL COUPLING REDUCTION

In this part, a patch gap of 0.22λ was chosen as the control element for the analysis, such that the AR bandwidth is 4.9% and an S_{11} bandwidth of 42%. A line patch was introduced between the antenna elements to reduce the mutual coupling effect and to increase the AR bandwidth of the proposed antenna, as illustrated in Figure 4. The results obtained from this work are compared in Table 1.

In general, for different *Wp* applied, no obvious changes in S_{11} were observed. Introducing the line patch with continuous ground plane (*Wp-CG*) structure into the array, shrinking the impedance bandwidth of the antenna from 42% to 36% caused the AR to vanish with a reduced gain to 2.2dB. While, reducing the line patch length (*Wpc*), the isolation increased to −35 dB, but the impedance BW and AR BW of the antenna decreased to 26% and 7.4% respectively. On the other hand, introducing a full line patch (*Wp*) improved the CP performance of the antenna with isolation value of −20dB. Although the impedance bandwidth percentage reduced to 29%, the AR bandwidth increased to 8.1% for a line patch of 0.007λ. Hence, further analysis on the line patch with discontinuous ground was performed, and the results discussed in more detail in the next paragraph.

TABLE 1. Array antenna performance for different mutual coupling techniques applied.

Parameter	0.007λ *Wp*	0.007λ *Wpc*	0.007λ *Wp-CG*
S_{11} (GHz), f_{min}	1.84	1.97	1.75
S_{11} (GHz), f_{max}	2.54	2.56	2.53
% BW	29	26	36
Isolation (dB)	-17	-35	-18
AR (GHz), f_{min}	2.49	2.45	>5 dB
AR (GHz), f_{max}	2.7	2.64	>5 dB
% AR BW	8.1	7.4	-
Realized Gain (dB	2.6	2.4	2.2

* *Wp* – Width of the line patch, *CG* – Continuous ground

Figure 5 compares the reflection coefficient (S_{11}) and isolation of the antenna with different sizes of line patches present in the center between the array elements. Adding a line patch in between the array improved the antenna performance in terms of isolation and CP of the antenna. From the graph of Figure 5(a), it can be observed that the reflection coefficient (S_{11}) and the impedance bandwidth of the antenna were reduced when the line patch was introduced. Increasing the line patch size resulted in better isolation; however, S_{11} and the impedance bandwidth of the antenna were reduced.

The AR of the antenna determines the antenna polarization—whether linear or circularly polarized. The initial AR value of the array without the line patch applied ranged from 2.505 GHz to 2.63 GHz, with a 4.9% bandwidth. When the line patch was added to the array, the AR bandwidth increased to up to 8.9% for a 1 mm width patch (*Wp*), giving the best AR at 0.3 dB. With increased *Wp*, the AR slowly decreased, but AR became higher than 3 dB when *Wp* = 7 mm. However, this was not the best distance for the antenna design, as the CP characteristic could only be obtained at 2.45 GHz and above. Hence, the study further examined the effect of increasing the distance of the array elements to 0.3λ with the line patch in between.

The reflection coefficient (S_{11}) and isolation of the antenna are compared in Figure 6. In this work, the line patch

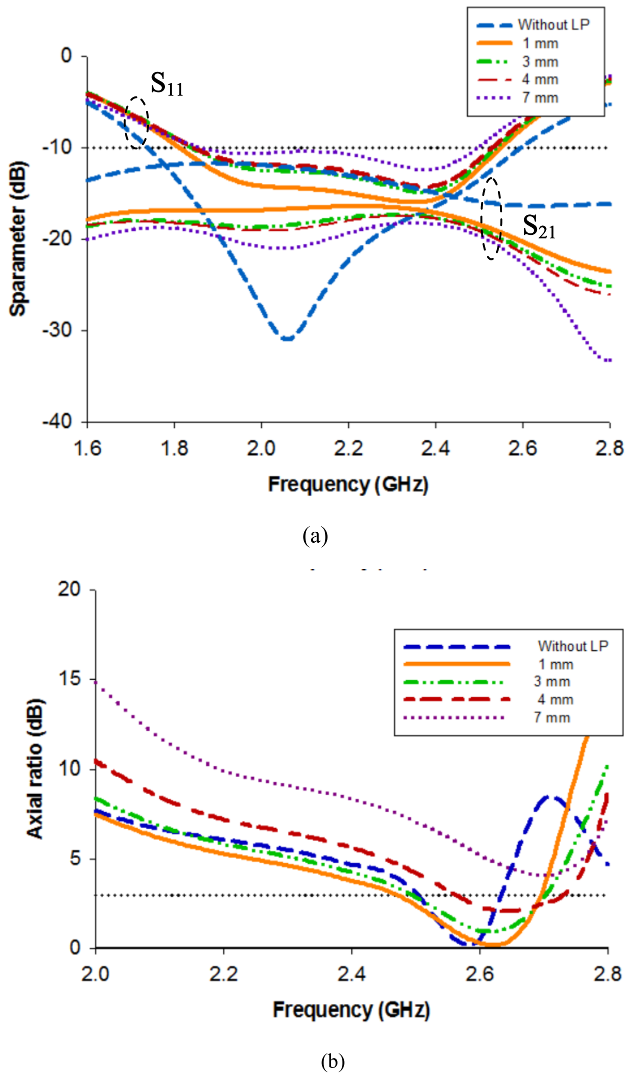


FIGURE 5. Simulated result of antenna array with different size of line patch at 0.22λ: (a) S_{11} and S_{21}. (b) AR.

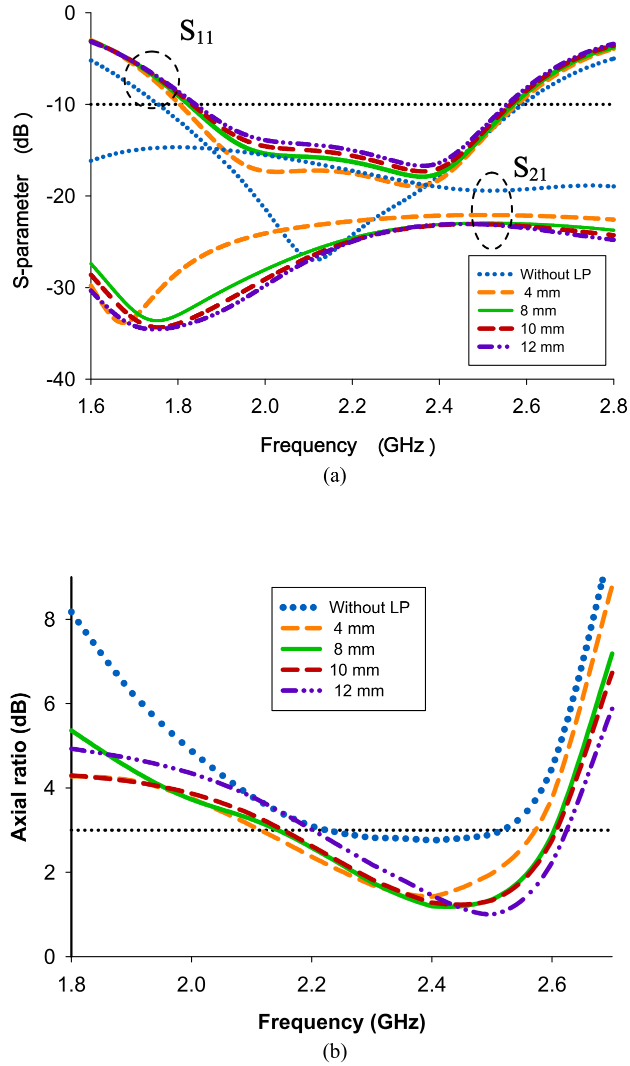


FIGURE 6. Simulated result of antenna array with different size of line patch at 0.3λ: (a) S_{11} and S_{21} and (b) AR.

width (*Wp*) was varied from 4 mm to 12 mm. The same trend in the distance of 0.22 λ could be seen, where the S_{11} performance decreased with increased *Wp*. However, the isolation showed a better value, as low as −34 dB, when the *Wp* was increased. In terms of the AR of the antenna, an enhancement of 8% was observed after the line patch was introduced into the array. Initially, the AR bandwidth was 11%, covering 2.23 GHz to 2.5 GHz at the lowest value of 2.75 dB. Prominent results were observed when a line patch width of 8 mm and 10 mm were simulated, which resulted in the AR being centered at 2.4 GHz and resulting in an improved bandwidth of up to 19% from 2.15 to 2.6 GHz. This result is favorable since the antenna manages to cover a wider frequency. It is also found to have good consistency with the impedance bandwidth of the antenna.

For this array configuration, the 0.3λ distance provided better performance in terms of the circular polarization characteristic. Moreover, the impedance bandwidth and AR bandwidth were matched, covering a range from 1.8 GHz up to 2.6 GHz. AR proved very sensitive although the electromagnetic circumstance of the antenna changed slightly [12]

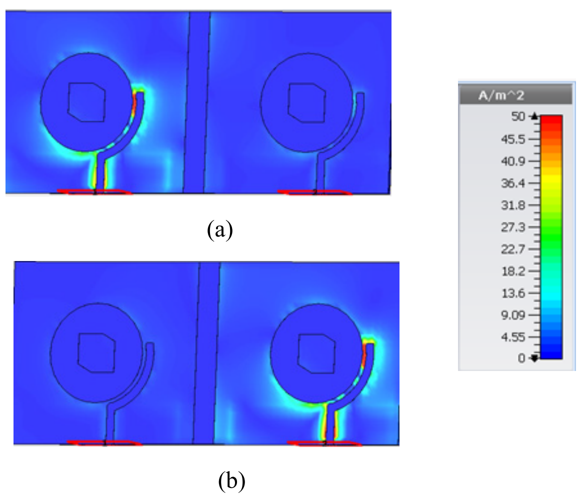
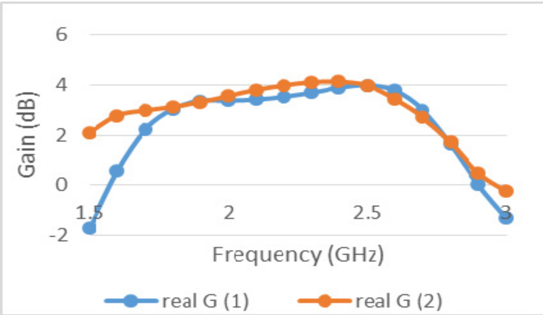
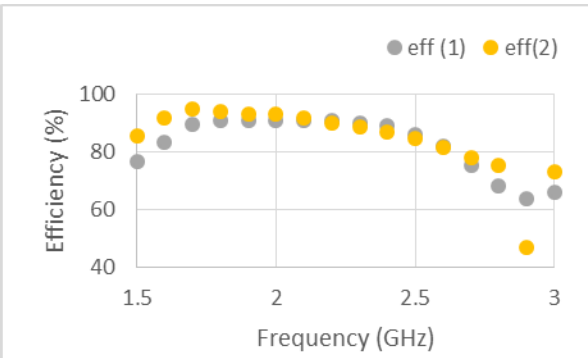


FIGURE 7. Current distribution at 2.4 GHz from: (a) port 1 and (b) port 2.



(a)



(b)

FIGURE 8. Antenna performance from both port 1 and port 2: (a) realized gain and (b) radiation efficiency.

with the introduction of a line patch between the arrays. Based on this result also, it can be concluded that AR and isolation are correlated i.e. better antenna isolation contributed to a greater AR bandwidth. To further illustrate the capacity of the proposed antenna, its current distribution by minimum value of AR at 2.4 GHz is shown in Figure 7. It is obvious that the introduction of the patch line in between the arrays blocked the current from flowing to the other side, which reduced coupling between the array elements.

C. GAIN, RADIATION EFFICIENCY AND CORRELATION ANALYSIS

The gain of the proposed antenna as a function of the frequency of port 1 and port 2 is depicted in Figure 8(a). From the result obtained, the gain of the antenna is observed to be above 3 dB for all resonant frequencies. One of the adverse effects of mutual coupling is the low efficiency of the antennas [16]. Figure 8(b) presents the radiation efficiency of the antenna where it can be seen that both ports 1 and 2 have a more than 85% efficiency, which is a reasonable value for array antennas.

The correlation between antenna elements can be described by the envelope correlation coefficient (ρ) and the diversity gain, which can be used to evaluate the diversity characteristic of the array antenna. The ECC (ρ) of the two

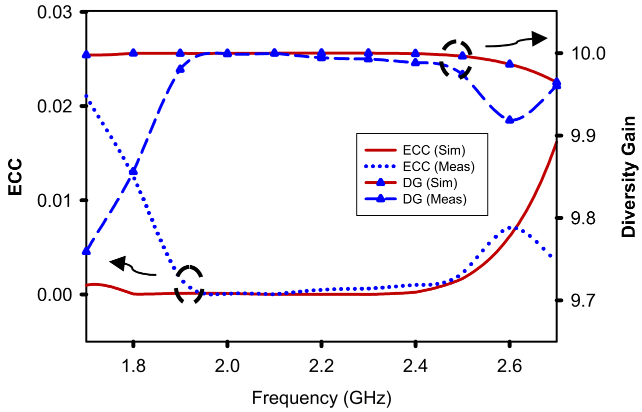


FIGURE 9. Diversity and envelope correlation coefficient (ECC) versus frequency plot.

(a) Front view

(b) Back view

FIGURE 10. Photograph of fabricated antenna: (a) front view and (b) back view.

antennas can be calculated using Equation (1) as in [10]:

$$\rho = \frac{\left|S_{11}^{*}S_{12} + S_{22}^{*}S_{21}\right|^{2}}{\left(1 - |S_{11}|^{2} - |S_{21}|^{2}\right)\left(1 - |S_{22}|^{2} - |S_{12}|^{2}\right)} \tag{1}$$

Meanwhile, diversity gain (G) can be derived from ECC (ρ) using Equation (2):

$$DG = 10\sqrt{1 - (\rho)^{2}} \tag{2}$$

The simulated and measured ECC and diversity gain versus frequency is plotted in Figure 9. As can be seen in Figure 9, ECC is below 0.01, which satisfies the desired diversity criteria, which should be less than 0.5 [14] and [15]. A low ECC will contribute to a high diversity gain, demonstrated by the

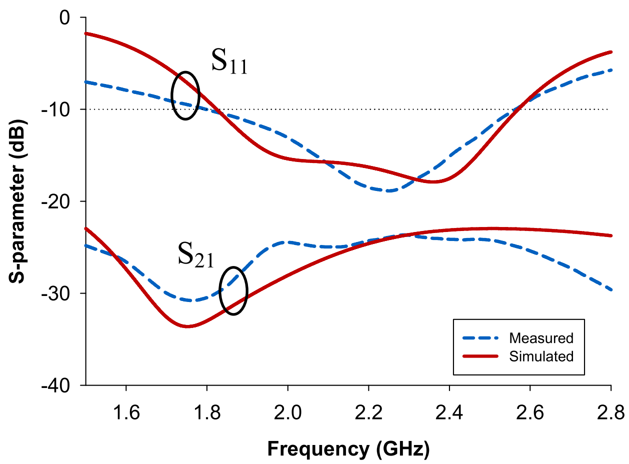


FIGURE 11. S-parameter simulation and measurement versus frequency.

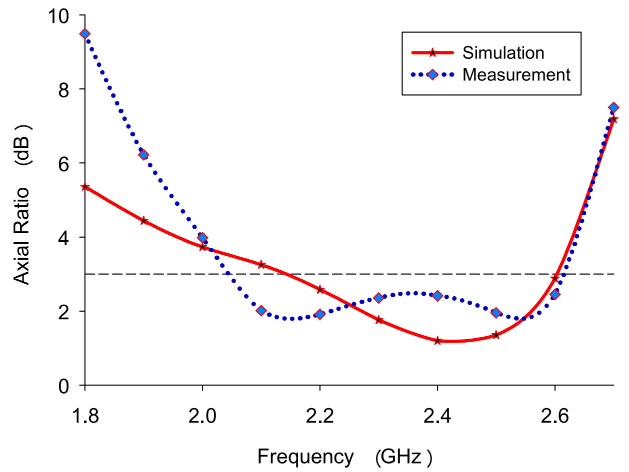


FIGURE 12. Simulated and measured axial ratio of the fabricated antenna.

diversity plot in Figure 9. For an ECC value of less than 0.1, the diversity gain is almost 10 dB.

IV. SIMULATION AND MEASUREMENT RESULTS

The proposed 1 × 2 array of circularly polarized antenna is shown in Figure 10. The S-parameter simulation and measurement results for the proposed antenna were found consistent, as illustrated in Figure 11. It can be observed that the reflection coefficients were below −10 dB for the range 1.82 GHz to 2.57 GHz, with ∼1% variation from simulation results. It can be noted also that the isolation between the two ports at 2.2 GHz was −24 dB for both the simulated and measured results. The variation of the axial ratio (AR) versus frequency is shown in Figure 12. The measured values were generally in agreement with the simulation results, which produced about a 0.1 GHz difference in bandwidth.

Additionally, Table 2 compares the performance of the proposed antenna against that of previous works on the basis of spacing, isolation technique, MC, and AR (BW%). It is apparent that the proposed work outperformed others in terms of AR bandwidth with a slightly greater spacing than [19] .

TABLE 2. Performance comparison between this work and previous works on the CP MIMO antenna.

Ref	Edge to edge spacing	Isolation Technique	S_{21} (dB)	AR (BW%)
[13]	0.5λ	Hybrid Parasitic patch +DRA	<-30	20.8 %
[14]	~0.2λ	FSS superstrate	<-25	~3.3 %
[15]	NA	Rotational structure	<-25	3.33 %
[19]	~0.28λ	Partial substrate	>-20	11 %
This work	0.3λ	Line patch	<-25	23 %

V. CONCLUSION

Reduced antenna performance (in terms of gain and efficiency) was observed when a single element was arranged into the array due to mutual coupling. Thus, to enhance the isolation between the radiating elements, a parasitic line patch was introduced into the array. Inserting the line in between patch elements suppress the reflections occurred between each patches. AR BW is broadened by increasing the line patch width (*Wp*). However, this will also shifted the AR to higher frequency. As a result, 8mm *Wp* was chosen where the isolation was increased by more than 10 dB and the AR bandwidth improved to 23%, which matched well with the impedance bandwidth of the antenna array.

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