

Multi-band MIMO Antenna with Square-Ring Slots for 5G Services

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Abstract— Mobile communications technology is evolving rapidly with the introduction of 5G networks, which offer high speeds, low latency, and greater network capacity. To support these services, antennas that can operate optimally in a wide frequency range are required. This research focuses on designing and analyzing a multi-band square-ring slot MIMO antenna for frequencies of 2.6 GHz, 3.6 GHz, and 5.25 GHz, using CST Studio Suite 2019. The simulation results are compared with measured outcomes after fabrication. The antenna structure utilizes a microstrip design with an FR-4 substrate, optimizing parameters such as slot dimensions, feed line positioning, and element spacing to achieve the desired performance. The results show that the designed antenna has a return loss of < -10 dB, VSWR values in the acceptable range ($1 \leq \text{VSWR} \leq 2$), mutual coupling isolation below -20 dB, and $\text{ECC} < 0.05$, indicating good MIMO performance. In addition, the antenna exhibits an omnidirectional radiation pattern, a gain of more than 4 dBi with a maximum of 5.25 dBi at 2.6 GHz, and a wide bandwidth suitable for 5G applications. Despite minor differences between simulated and measured results due to environmental factors and manufacturing tolerances, the antenna performance remains within acceptable limits. This research proves that the multi-band MIMO design with a square-ring slot can be an effective and practical solution to enhance 5G service quality, offering advantages for future wireless communication systems.

Keywords: MIMO antenna; square ring slot; 5G

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I. INTRODUCTION

The evolution of mobile communication technology from 2G, 3G, 4G, and now 5G have significantly improved in data transmission speed, network capacity, and latency. Fifth-generation (5G) technology is designed to provide ultra-fast connectivity, high reliability, and low latency to support a wide range of advanced applications.

According to 3GPP Rel-15, the 5G spectrum is divided into Frequency Range 1 (FR1), known as Sub-6 GHz (450 MHz–6000 MHz), and Frequency Range 2 (FR2), known as millimeter wave (24.25–52.6 GHz). In Indonesia, the Ministry of Communication and Information Technology (Kominfo) began implementing 5G services in 2021, utilizing frequencies such as 700 MHz, 2.6 GHz, 3.5 GHz, and 26–28 GHz bands.

To support the optimal performance of 5G services, the development of compact and efficient antennas is essential. One of the most suitable candidates for integration into 5G devices is the microstrip antenna, which is known for its compact size, light weight, and ease of fabrication. However, microstrip antennas have inherent limitations, such as low gain and narrow bandwidth. To overcome these limitations, Multiple Input Multiple Output (MIMO) technology has been widely adopted in 5G networks, offering improved service quality through increased capacity and reliability.

Recent studies have explored various MIMO antenna designs to improve antenna performance. Joe et al. (2023) investigated three 2×2 MIMO designs using different slot configurations and found that antennas with slots provided higher gain compared to those without. Another study by Dhanyswari et al. (2023) presented a dual-band microstrip MIMO antenna using U-shaped slots, achieving a gain of

15.70 dB at 3.5 GHz. Meanwhile, Parchin et al. (2019) designed a multiband MIMO antenna using double-element square-ring slots placed at different PCB corners, achieving isolation levels above -17 dB. Although promising, isolation above -20 dB is preferable for optimal 5G performance.

Building upon these findings, this research proposes a multi-band MIMO microstrip antenna with square-ring slots, optimized from Parchin’s reference design. The antenna is intended to operate in the frequency bands of 2.6 GHz, 3.6 GHz, and 5.25 GHz, which are relevant to 5G applications in Indonesia. The design is developed using CST Studio Suite 2019, with optimizations including the addition of square-ring elements from two to three in order to improve bandwidth, gain, and isolation between antenna elements.

II. MATERIALS AND METHODS

This research began by reviewing previous MIMO antenna designs with multiband performance suitable for 5G applications. The reference design was adapted from Parchin et al. (2019), which utilized a double-element square-ring slot configuration. To enhance isolation and gain, this research introduced a third square-ring slot element arranged in a symmetrical configuration. The proposed antenna is designed to operate at three target frequency bands: 2.6 GHz, 3.6 GHz, and 5.25 GHz.

The design process was carried out using CST Studio Suite 2019, a 3D electromagnetic simulation software. The antenna structure consisted of a rectangular microstrip patch with square-ring slots etched on the radiating element. The patch was mounted on an FR-4 substrate with a relative permittivity of 4.3 and a thickness of 1.6 mm. The antenna was fed using microstrip transmission lines and terminated with 50-ohm ports.

The geometry was optimized by varying the dimensions of the slots, feedline position, and element spacing. A parametric study was also performed to investigate the effect of substrate size and slot width on antenna performance. The design diagram is shown in Figure 1.

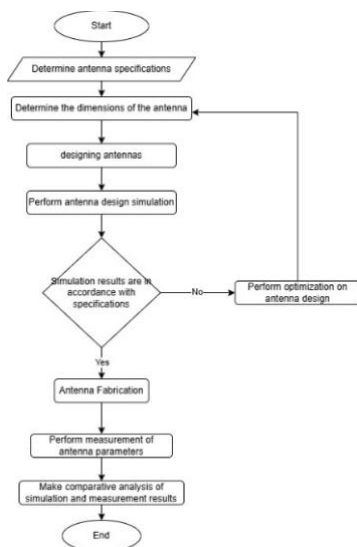


Fig. 1 Flowchart of the research

A. Antenna Design and Dimensions

The antenna is a 4x4 MIMO antenna with dimensions of 80 x 150 x 1.6 mm³ that has a Sub-6 GHz working frequency at 2.6 GHz, 3.6 GHz, and 5.25 GHz.

TABLE I
ANTENNA OPTIMIZATION PARAMETERS

Parameters	Value (mm)	Parameters	Value (mm)
W _{sub}	80	W	18.5691
W _s	29.999	W ₃	12.6
G	0.5499	D	6
W ₂	14.1650	W ₁	14.1650
W _B	11.1650	w _f	3
L _{sub}	150	L _{f2}	11.6505
L _f	11.65		

The design of the antenna is shown in Figure 2.

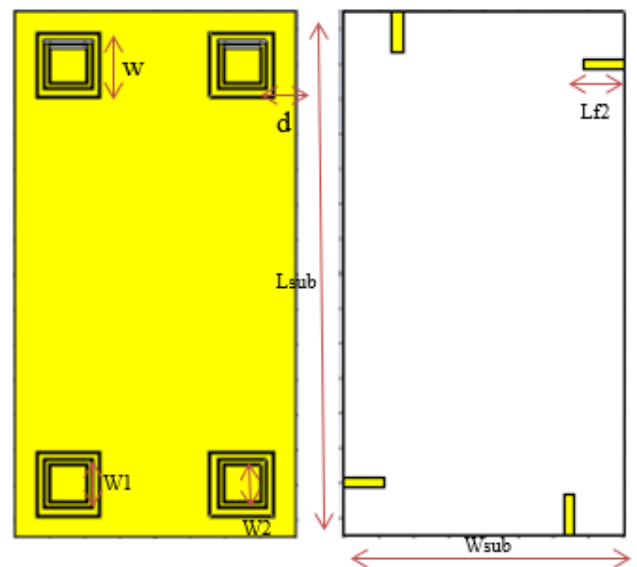


Fig. 2 Antenna Design

B. Antenna Design Steps

The steps in making Multiband MIMO antennas with Square-Ring slots for 5G services are as follows.

1) Microstrip Antenna without Slot

The first step in designing a MIMO antenna is to make a single antenna without a slot. Figure 3 shows the design of a slotless ground full microstrip antenna.

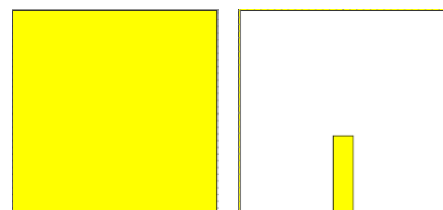


Fig. 3 Microstrip Antenna without Slot

The results of the antenna simulation can be seen in Figure 4, which shows that the antenna works at a higher frequency of

> 25 GHz. In the research, the frequency range used is the Sub-6 GHz frequency, so to overcome this, additional slots are added to the ground.

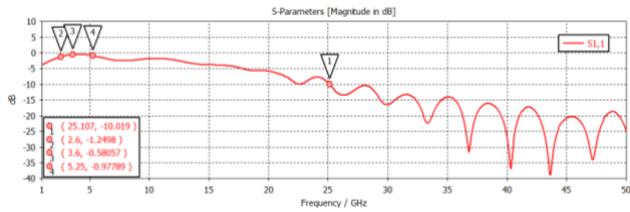


Fig. 4 S-Parameters of antenna without slot

2) *Antenna Design with One Square-Ring Slot Element*

Figure 5 shows a Ground Full microstrip antenna design with one square-ring slot element. By adding one square-ring slot element on the ground with a size of $W/2 + g$, the antenna produces a working frequency of 2.6 GHz.

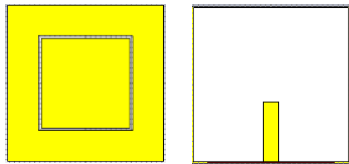


Fig. 5 Antenna design with one square-ring slot element

The results of the antenna simulation can be seen in Figure 6, the resonant frequency is obtained in the frequency range of 2.6 GHz with a value of -34.059 dB.

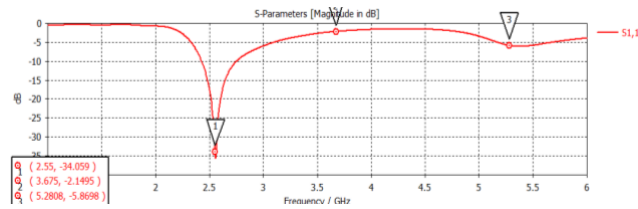


Fig. 6 S-Parameters of antenna with one square-ring slot element

3) *Antenna Design with Two Square-Ring Slot Elements*

Figure 7 is the design of the Ground Full microstrip antenna by adding two square-ring slot elements with a second slot size of $W/2 + g$.

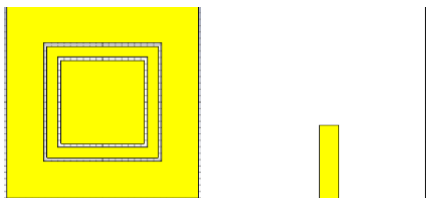


Fig. 7 Antenna design with two square-ring slot elements

From the S-Parameter simulation results shown in Figure 8, three resonant working frequencies are obtained, namely at a frequency of 2.6 GHz generated by the first slot, and a working frequency of 3.6 GHz generated due to the addition of the second slot, but at a frequency of 5.25 GHz which is the second harmonic of the second square ring slot, has a return

loss or s-parameter value that is still weak not reaching the value of -10 dB.

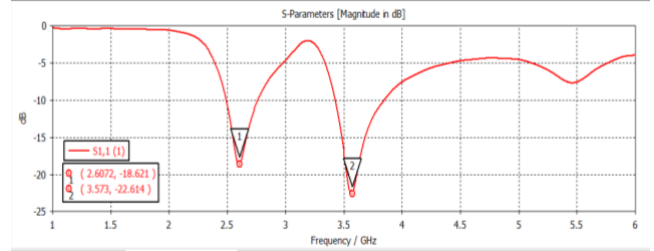


Fig. 8 S-Parameters of antenna with two square-ring slot elements

4) *Antenna Design with Three Square-Ring Slot Elements*

Figure 9 is a Ground Full microstrip antenna design with three square-ring slot elements. The addition of square-ring slots is done so that in the working frequency range of 5.25 GHz. Has a good return loss value and a larger bandwidth.

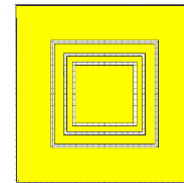


Fig. 9 Antenna design with three square-ring slot elements

From the simulation results shown in Figure 10, adding one square-ring slot increases the s-parameter value at 5.25 GHz and also increases the bandwidth.

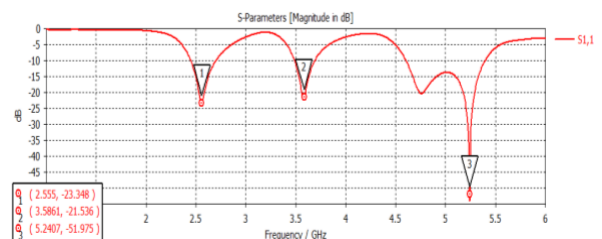


Fig. 10 S-Parameters of antenna with three square-ring slot elements

5) *MIMO Antenna with Three Element Square-Ring Slots*

The design of the MIMO antenna with three elements is shown in Figure 2, and the simulation results of the MIMO antenna are shown in Figure 11.

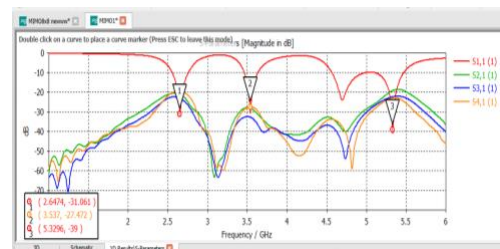


Fig. 11 S-Parameter of Antenna design with two square-ring slot elements

III. RESULTS AND DISCUSSION

A. *Parameter Study*

Parameter studies are used to obtain antenna simulation results that are as expected. This stage aims to see the effect

of changes in the microstrip antenna design from existing parameters. These changes can be seen from the simulation results. In addition, parametric studies are carried out by reducing or adding the size of the antenna design in order to get the desired value, but still maintain the previous parameters.

1) *Adding Rectangular-Ring Slot*

The MIMO antenna with three square-ring slot elements has a wider bandwidth and a better return loss value at a frequency of 5.25 GHz, and also the emergence of new resonant frequencies that are still in the 5.25 GHz range. This can be seen in Figure 12, which compares the return loss results of designs with two square-ring slot elements and three square-ring slot elements.

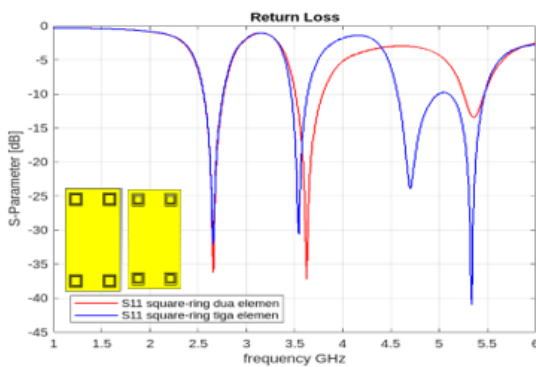


Fig. 12 Comparison of return loss of two-element and three-element square-ring slots

2) *Effect of Feed Line Position*

Antenna configurations with different feed line placements affect the mutual coupling and isolation values of the MIMO antenna. Figure 13 shows three antenna designs that have feed lines in different positions. Figure 13 (a) shows the feed line is on the long side of L_{sub} facing each other, Figure 13 (b) shows the feed line is on the W_{sub} side, and Figure 13 (c) is on different sides.

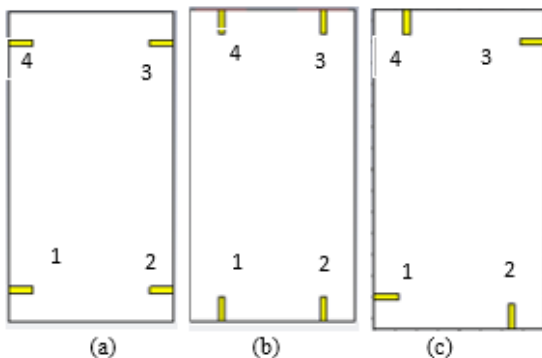


Fig. 13 Different Feed line positions (a) first, (b) second, (c) third

The simulation results for the S12 parameter of the three feed line positions above are shown in Figure 14. It can be seen that feed line position (a) has a small S12 value of -10 dB, and feed line (b) has a small S12 value of -15 dB, which indicates strong mutual coupling and low isolation. Meanwhile, feed line (c) has low mutual coupling and high

isolation, which is below -20 dB. The minimum mutual coupling value recommended for MIMO performance is below -20 dB.

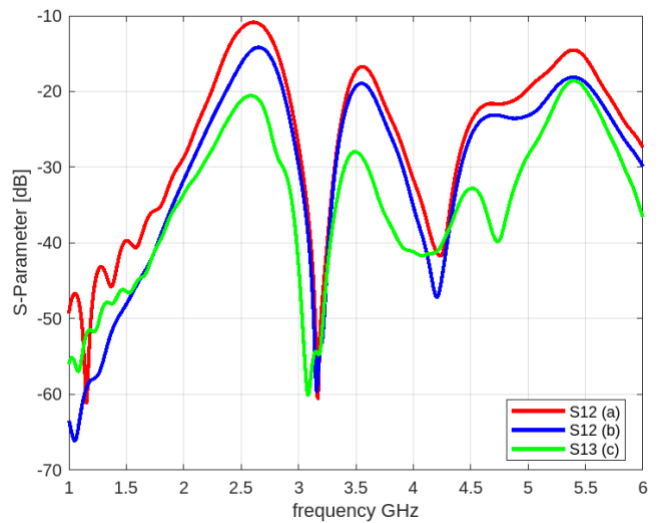


Fig. 14 Effect of feed line position on parameter S12

3) *Size Change of square-ring slot width (g), First Slot (W), and Second Slot (W1)*

Figure 15 displays the return loss value of simulation results by changing the value of parameter g or the square slot width. From the simulation results, it was known that changing the g parameter can easily adjust the working frequency band and affect the impedance match.

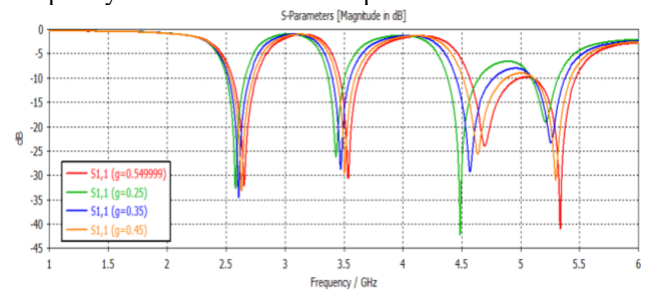


Fig. 15 Effect of Parameter (g) square slot size width

Furthermore, changing the value of parameter W is the size of the first square-ring slot. The simulation results of the parameter changes are shown in Figure 16. From the simulation results, it was known that changing the parameter value W has an impact on the first resonant frequency of 2.6 GHz and the third resonant frequency of 5.25 GHz, and does not affect the second resonant frequency of 3.6 GHz.

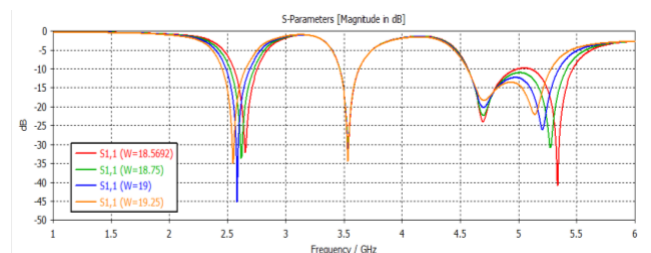


Fig. 16 Effect of Parameter W

From the simulation results, it was known that changing the W1 parameter has a major impact on the second resonant frequency of 3.6 GHz as well as on the new resonant frequency in the range of 5.25 GHz.

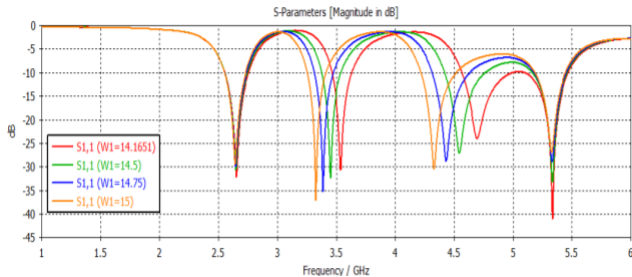


Fig. 17 Effect of Parameter W1

B. Antenna Fabrication

After designing, simulating, and optimizing the antenna design and getting the desired results, the next process is to carry out the fabrication process. The material used for fabrication is double layer FR-4. The results of the fabricated antenna are soldered to pair the port/connector. The connector used is the PCB port SMA female jack RF Adaptor. The fabrication results can be seen in Figure 18.

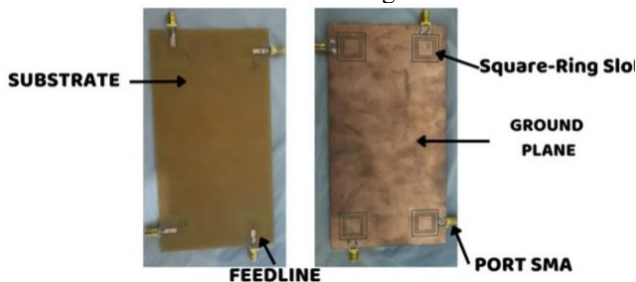


Fig. 18 Antenna Fabrication

C. Antenna Parameter Simulation and Measurement Result

The fabricated antenna is then measured with a Vector Network Analyzer and compared with the simulation results of the antenna that has been designed before.

1) Return Loss

The return loss value obtained meets the maximum limit of -10 dB. The smallest return loss value at each working frequency is -18.6901 dB at 2.825 GHz, -14.9869 dB at working frequency 3.85 GHz, and -15.2913 dB at working frequency 4.85 GHz. Figure 19 shows the return loss of the simulated and fabricated antennas. From the figure, the antenna shows better simulation results than measurements. The measurement results also show good performance, but there is a deviation at the working frequency.

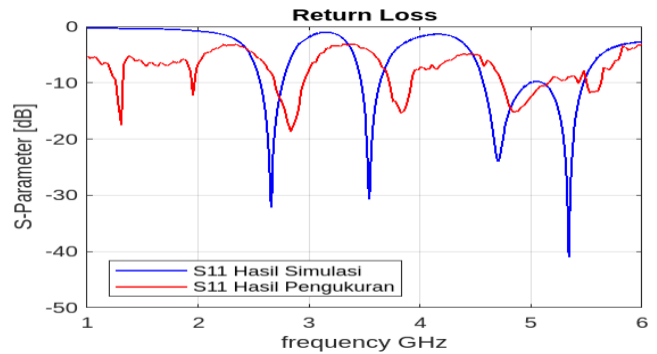


Fig. 19 Comparison of Simulation and Measurement Return Loss

2) Mutual Coupling

In Figure 20, shows a comparison of the S12 values on the simulated and measured antennas. The figure shows that the isolation value of the simulated and fabricated antennas is good. The simulated S12 parameter results are better than the measurement results. At around 3 GHz, the isolation reaches -60 dB in the simulation, but the measurement results show a worse isolation of around -38 dB. However, at a frequency of 5.25 GHz, the measured isolation value is better than the simulated one.

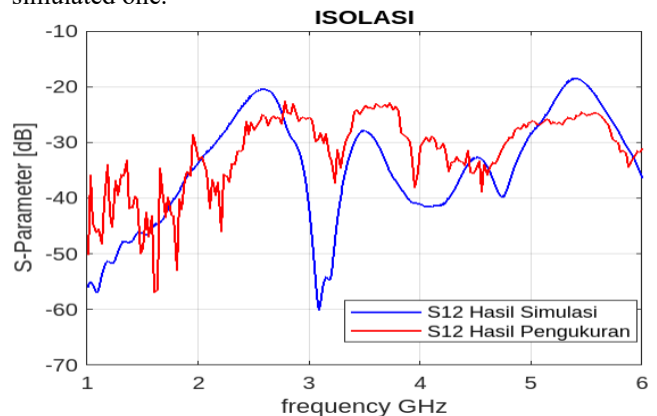


Fig. 20 Measurement and Simulation Results of Parameter S12

3) Current Distribution

Current distribution is also one of the parameters that can be used to look at isolation to reduce mutual coupling. Figure 21 shows the current distribution on the modified antenna at frequencies of 2.6 GHz, 3.6 GHz, and 5.25 GHz. From Figure 21 (a), the current distribution at a frequency of 2.6 GHz high current concentration at the bottom of the antenna near the port, and is contracted in certain directions, so the isolation is better because the electromagnetic waves do not spread too much to other elements. In Figure 21 (b) current distribution at a frequency of 3.6 GHz the current is more evenly distributed along the antenna surface, the current pattern that spreads at some points indicates coupling between elements so that the isolation decreases slightly, and in Figure 21 (c) current distribution at a frequency of 5.25 GHz the current pattern is more concentrated around the feed line which can reduce mutual coupling, but there is the potential for high mutual coupling if the current distribution from one element disturbs other elements.

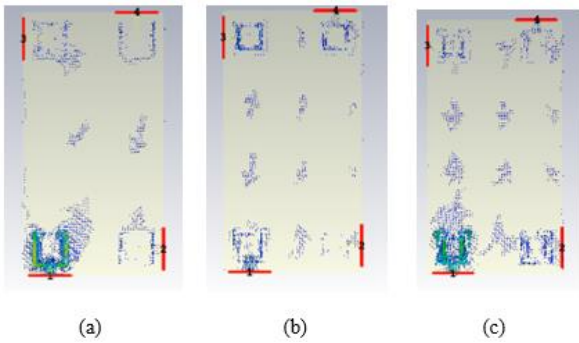


Fig. 21 Current Distribution (a) 2.6 GHz (b) 3.6 GHz (c) 5.25 GHz

4) **Bandwidth**

Bandwidth is a frequency range or commonly called a frequency band, where the antenna can operate properly. The bandwidth value is obtained from looking at the highest frequency and the lowest frequency that has a return loss ≤ -10 dB. In Figure 22, we can see the bandwidth at frequencies of 2.6 GHz, 3.6 GHz, and 5.25 GHz. Where at frequency 2.6 GHz has an upper frequency of 2.7547 GHz and a lower frequency of 2.5557 GHz, for working frequency 3.6 GHz has an upper frequency of 3.6317 and a lower frequency of 3.4624 GHz, and for working frequency 5.25 GHz has an upper frequency of 5.4621 GHz and a lower frequency of 4.5688 GHz. The following is the calculation of bandwidth values at each antenna working frequency, calculated based on the bandwidth calculation formula.

$$\begin{aligned} \text{Frequency Bandwidth 2.6 GHz} &= f_{\text{upper}} - f_{\text{lower}} \\ &= (2.7547 - 2.5557) \text{ GHz} \\ &= 0.1977 \text{ GHz} \\ &= 197.7 \text{ MHz} \end{aligned}$$

$$\begin{aligned} \text{Frequency Bandwidth 3.6 GHz} &= f_{\text{upper}} - f_{\text{lower}} \\ &= (3.6317 - 3.4624) \text{ GHz} \\ &= 0.1693 \text{ GHz} \\ &= 169.3 \text{ MHz} \end{aligned}$$

$$\begin{aligned} \text{Frequency Bandwidth 5.25 GHz} &= f_{\text{upper}} - f_{\text{lower}} \\ &= (5.4621 - 4.5688) \text{ GHz} \\ &= 0.8933 \text{ GHz} \\ &= 893.3 \text{ MHz} \end{aligned}$$

From the results obtained, it is known that the bandwidth of the antenna design has a large bandwidth value of 150 MHz, which can be used for 5G antennas.

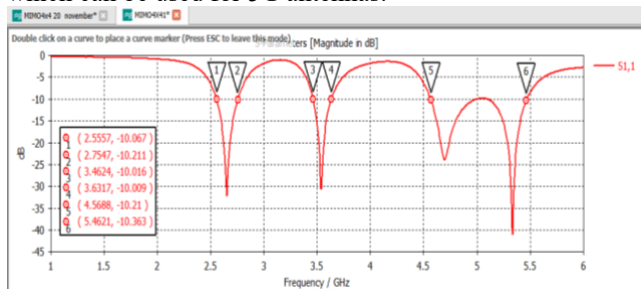


Fig. 22 Antenna Bandwidth

5) **Gain**

The results of the antenna gain parameters are shown in Figure 23. From the simulation results, it can be seen that at the working frequency, the antenna has a gain value above 4 dBi, with a maximum gain of 5.25 dBi at a frequency of 2.6 GHz.

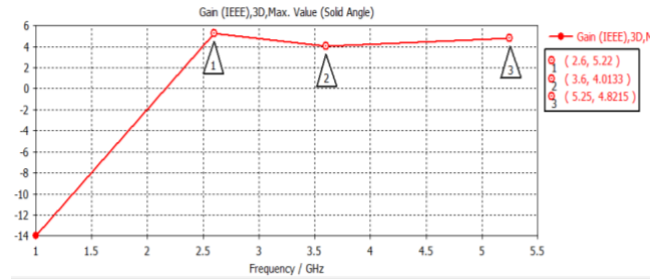


Fig. 23 Antenna Gain

6) **Radiation Pattern of Antenna**

Figure 24 and Figure 25 are antenna radiation patterns on antennas 1 and 2 of the MIMO antenna. From the Figure 24 and Figure 25 (a) displays the radiation pattern of antenna 1 and antenna 2 in the horizontal direction or antenna E field with $\phi = 0$ degrees, and for image (b) displays the radiation pattern of the antenna in the vertical direction or antenna H field with $\phi = 90$ degrees. From the figure, it can be seen that the radiation pattern produced is omnidirectional in both the vertical and horizontal directions. Symmetrical radiation patterns in both directions indicate optimal performance for 5G network MIMO applications. Figure 26. shows the 3D shape of the radiation polar at each working frequency of antenna 1.

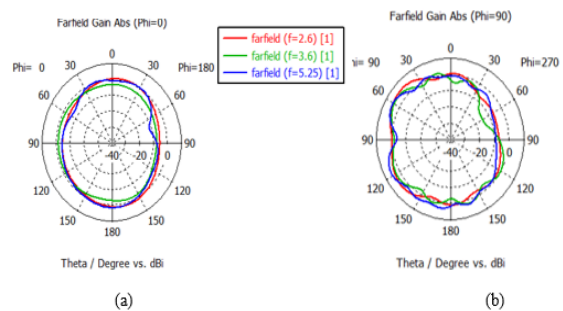


Fig. 24 Radiation Pattern of Antenna 1 (a) Vertical (b) Horizontal

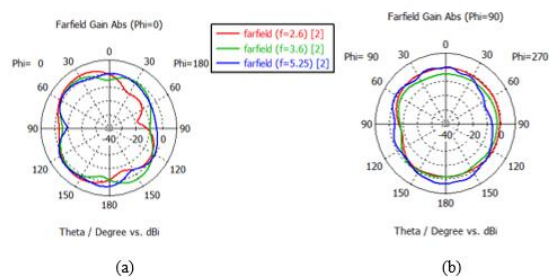


Fig. 25 Radiation Pattern of Antenna 2 (a) Vertical (b) Horizontal

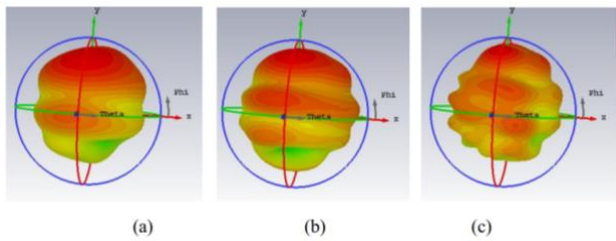


Fig. 26 3D Radiation Pattern of Antenna (a) 2.6 GHz (b) 3.6 GHz (c) 5.25 GHz

7) Voltage Standing Wave Ratio (VSWR)

From the measurement results, it was observed that the VSWR value at the working frequency is still in the 1-2 value range. The VSWR value at the working frequency of 2.6 GHz is 1.72 and the best VSWR value is at a frequency of 2.75 GHz with a value of 1.10, while for the frequency range of 3.6 GHz and 5.25 GHz the VSWR value is at a value of 2. It is known that the simulated VSWR value is better than the measurement, because in the desired working frequency range, the VSWR value is less than 2

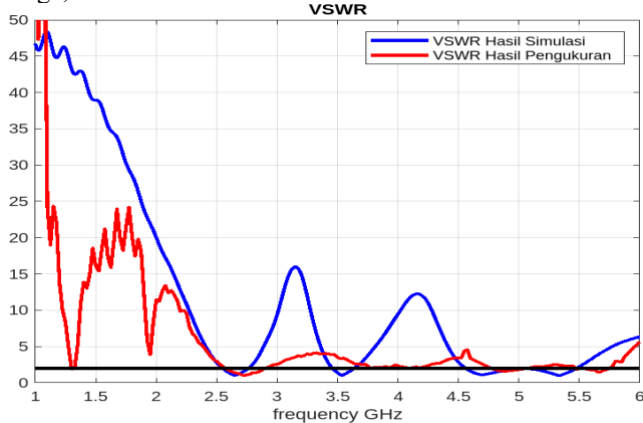


Fig. 27 VSWR

8) Envelope Correlation Coefficient (ECC)

The fabricated antenna has a better ECC value compared to the simulation results. The ECC value of the fabricated antenna at the working frequency has an ECC value of less than 0.0031, while the simulated antenna ECC value at the working frequency is less than 0.0033. The ECC value obtained from simulation and measurement results is almost close to the value of 0, the closer to 0 the ECC value, the antenna is not correlated, which means that the power received or emitted by the antenna elements does not interfere with each other and interference, thereby increasing the efficiency and performance of the MIMO system.

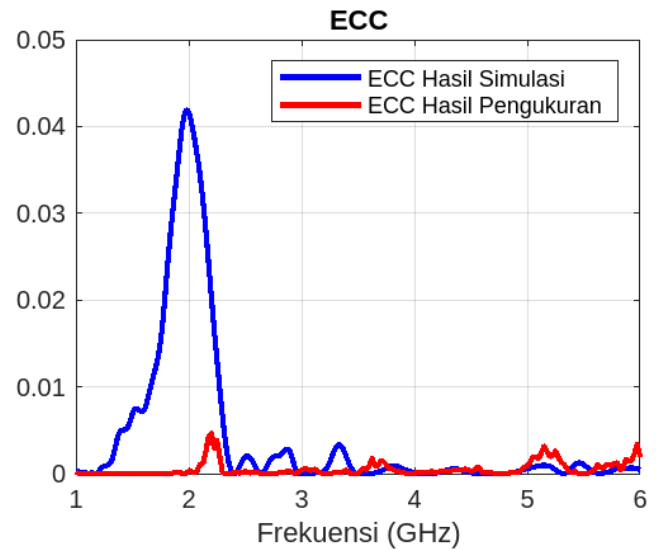


Fig. 28 Comparison of ECC Simulation and Measurement Results

9) Diversity Gain (DG)

The Diversity Gain values obtained from the measurement and simulation results show that at the working frequency, the diversity gain value of the antenna is around 9.98-10 dB. This shows that the MIMO antenna has good performance and almost no loss of signal efficiency, even though there are many reflections and disturbances in the communication channel. A comparison of the simulated and fabricated antenna diversity gain values can be seen in Figure 29 below.

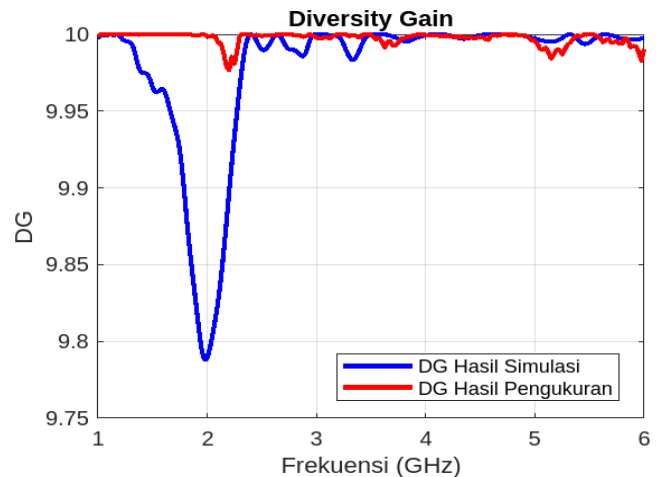


Fig. 29 Comparison of DG Simulation and Measurement Results

10) Total Active Reflection Coefficient (TARC)

The measurement results show that the TARC value in the working frequency range is below -10 dB. The lowest TARC value on the measurement antenna is -57.4552 dB at a frequency of 2.725 GHz.

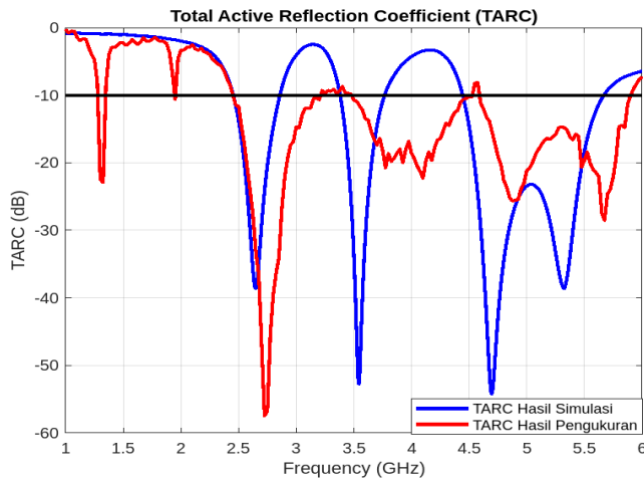


Fig. 30 Comparison of TARC Simulation and Measurement Results

11) Channel Capacity Loss (CCL)

From the measurement results, it was observed that the CCL value at a frequency of 2.6 GHz has a small value of 0.4 bit/s/Hz, but for frequencies of 3.6 GHz and 5.25 GHz, it has a large value of 0.4 bit/s/Hz. A comparison of the CCL values of the measurement and simulation results is shown in Figure 31. From the figure, it was observed that the CCL value during simulation is better than the fabricated antenna because it has a CCL value that is smaller than 0.4 bit/s/Hz at all three working frequencies.

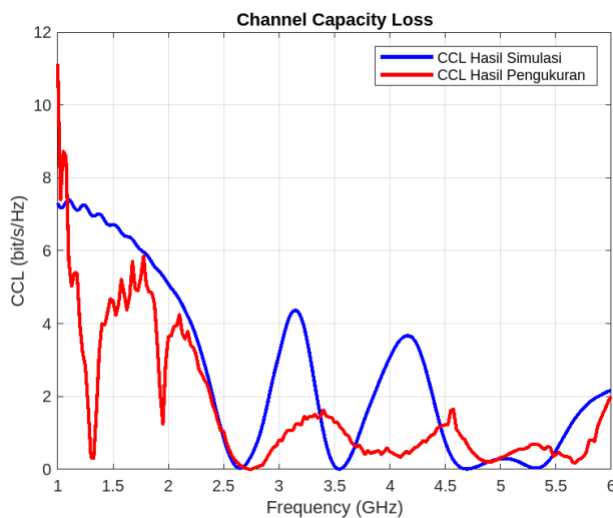


Fig. 31 Comparison of CCL Simulation and Measurement Results

Table 1 shows a comparison of the simulated, fabricated, and reference antennas. From the table, it was known that the measurement parameter values obtained are slightly different from the measurement results of the simulated and reference antennas, but show competitive and superior performance in several parameters shown in the isolation and ECC parameters.

TABLE I
COMPARISON OF SIMULATED, FABRICATED, AND REFERENCE ANTENNA
PARAMETER RESULTS

NO	Parameters	Result
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		Simulation	Measurement	References [4]
1	Frequency Range (GHz)	2.55-2.75 3.46-3.63 4.56-5.46	2.70-2.93 3.73-3.90 4.75-5.13, 5.43-5.63	2.5-2.7 3.45-3.8 5-5.45
2	Return Loss	< -10 dB	< -10 dB	< -10 dB
3	VSWR _{min}	1.3	1.10	-
4	Isolation	< -20 dB	< -22 dB	< -17 dB
5	ECC	< 0.05	< 0.005	< 0.05
6	Gain	4 – 6 dBi	4 – 6 dBi	5 – 6 dBi
7	TARC	< -10 dB	< -10 dB	< -10 dB

IV. CONCLUSION

After conducting a simulation, fabrication, and data analysis, this final project concluded that a MIMO antenna with three square-ring slot elements has been designed and simulated using CST Studio Suite 2019 to work at frequencies of 2.6 GHz, 3.6 GHz, and 5.25 GHz. The antenna has a size of 80 x 150 x 1.6 mm³. The addition of a square-ring slot element increases the bandwidth and return loss, especially at 5.25 GHz. Optimization of the 4x4 MIMO antenna is carried out by sweeping parameters at the feed line position, square-ring slot width (g), first square-ring slot size (w), second square-ring slot size (w1), and the addition of square-ring slots that can produce a wide bandwidth and improve isolation. Measurements of the antenna parameters indicate that the fabricated antenna achieves performance close to the simulated results. Small differences in the Channel Capacity Loss (CCL) and VSWR values at higher frequencies (3.6 GHz and 5.25 GHz) are attributed to fabrication tolerances, measurement calibration, and environmental conditions during testing. Comparison between the proposed antenna and a reference design demonstrates competitive performance in terms of return loss, isolation, and ECC.

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