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Design of Patch array antennas for 5G base station

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Abstract: - This work resulted with a design of single patch antenna to 1X2 and 2X2 array antenna for 5G applications. Comparison between simulated antenna parameters is presented here. This shows 2X2 array antenna performs well by giving high directivity. Simulations are carried out in CST microwave studio. These antennas are also fabricated and tested using Vector network analyzer. The simulated and fabricated antenna parameters are well matched. Throughout the process 2X2 array has outperformed other patch antenna giving high directivity and gain. By addressing challenges within the design and optimization process, particularly for mm-wave frequencies and massive MIMO configurations, this specific research aims to contribute greatly to the advancement of 5G technology.

Keywords: Antenna, 2X2 array, patch

I. INTRODUCTION

The world of communication is evolving rapidly, and one of the most exciting advancements is the development of 5th Generation (5G) technology. 5G promises to bring faster internet speeds, lower latency (meaning less delay), and better connectivity for all kinds of devices, from smartphones to smart homes [1]. To make 5G work effectively, we need antennas – these are the devices that send and receive signals. In 5G, there are different types of antennas used, but one popular choice is called a "microstrip patch antenna"[2]. These antennas are small, lightweight, and can be easily integrated into the design of modern communication devices. Now, let's talk about why these antennas are important and what makes them special for 5G. Firstly, microstrip patch antennas are great for 5G because they can handle the high frequencies that 5G uses. Some of the papers we've looked at focus on designing these antennas specifically for 5G applications. [3], [4], [5].

One advantage of microstrip patch antennas is that they can be made to work at different frequency bands, including the mm-wave bands used in 5G. For example, one paper discusses designing an antenna for the 28GHz frequency band, which is crucial for 5G communication [6]. Another benefit is that these antennas are quite versatile – they can be arranged in arrays (groups of antennas) to improve performance [7], [8]. Arrays can help with things like increasing signal strength or focusing the signal in a particular direction. However, it's also important to consider the challenges. One issue with microstrip patch antennas is that they can be affected by surrounding objects, like buildings or trees, which can weaken the signal. [9]. Plus, making sure the antennas work well across all the different frequencies used in 5G can be tricky [10]. A patch antenna of bandwidth of 3.5 GHz with dielectric constant of 4.4 is designed and tested in [11]. The antenna proposed in [12] operates in the 5th generation bandwidth of 3.4-3.6 GHz and results in 3.5 GHz of resonating frequency. An antenna operating at 4.5 GHz using HFSS tool is designed and analyzed in [13]. Antenna fine-tuned for 5G and satellite communication is presented in [14].

In summary, the literature explores the world of microstrip patch antennas for 5G. However most designed antennas are not fabricated and tested in real world scenario. By understanding more about these antennas, this work focuses on designing, testing of fabricated antennas.

II. PROBLEM STATEMENT

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The main objective of this work is to design an optimized patch array antenna for 5G applications. Selection of frequency band, gain maximization and directivity attainments are the challenges in this design. A strong signal strength and proper steering of radiation pattern towards a coverage area is required in 5G applications. To address these requirements a patch antenna is designed in this work. Further array antennas were built to understand the further progress. An efficient patch array antenna supports increased data rates and integration into developing eco system of 5G.

III. METHODOLOGY

The methodology for designing patch array antennas for 5G applications involves a systematic approach to meet specific design specifications and optimize antenna performance as depicted in flow diagram of Figure 1. Initially, the design specifications, including parameters like relative permittivity, substrate thickness (h), and loss tangent, are determined. These specifications influence the antenna's characteristics and resonance frequency. Subsequently, the antenna parameters such as length (L) and width (W) are calculated based on the design specifications to define the physical dimensions of the antenna.

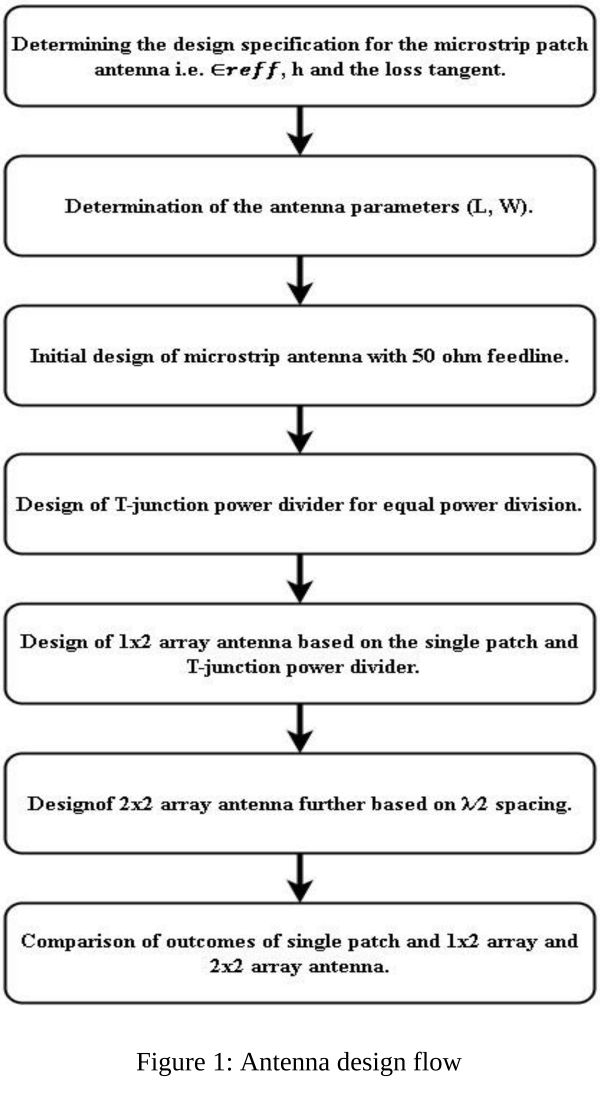


Figure 1: Antenna design flow

Following this, an initial design of the microstrip antenna is developed, incorporating a 50 ohm feedline to ensure efficient power transfer and impedance matching. Additionally, a T-junction power divider is designed to achieve equal power distribution among the antenna elements in the array, ensuring uniform performance. With the single patch design and the T-junction power divider as the foundation, 1x2 and 2x2 array antennas are then designed. The spacing between elements in the array, typically λ/2, is carefully determined to optimize performance and radiation characteristics. Finally, the outcomes of the single patch antenna and the array antennas are compared, evaluating parameters such as gain, directivity, radiation pattern, and impedance matching to assess the performance enhancements achieved with the array configurations. This systematic methodology ensures the design and optimization of patch array antennas that meet the requirements of 5G communication systems, providing enhanced performance and compatibility.

A. Design Equations for patch

$$W = \frac{c_0}{2f_r}\sqrt{\frac{2}{\in_r + 1}}$$

$$L = \frac{c_0}{2f_r\sqrt{\in_{reff}}} - 2\Delta L$$

$$\in_{reff} = \frac{\in_r+1}{2} + \frac{\in_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2}$$

$$\Delta L = 0.412h\frac{(\in_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\in_{reff} - 0.258)(\frac{W}{h} + 0.8)}$$

Dielectric Constant ($\in_r$) = 2.2
Dielectric Height (h) =1.56mm
Operating Frequency (f_r) = 2.45GHz

c_0 = 3*10^8 m/s
$W = \frac{3*10^\wedge 8}{2*2.45*10^\wedge 9}\sqrt{\frac{2}{2.2+1}}$ = 47.434 mm

$\in_{reff} = \frac{2.2+1}{2} + \frac{2.2-1}{2}\left[1 + 12\frac{1.58*10^\wedge -3}{47.434*10^\wedge -3}\right]^{-1/2}$ = 2.109

$L = \frac{3*10^\wedge 8}{2f_r\sqrt{\in_{reff}}} - 2\{0.412h\frac{(\in_{reff}+0.3)(\frac{W}{h}+0.264)}{(\in_{reff}-0.258)(\frac{W}{h}+0.8)}\}$ = 39.657 mm

The microstrip width and length are calculated to be approximately 48.37mm and 40.48 mm respectively. These values are based on the above equations. A dielectric constant of 2.2, dielectric height of 1.56 mm, and an operating frequency of 2.45GHz is selected. These dimensions are vital for designing microstrip transmission lines that effectively transmit electromagnetic waves at the specified frequency while ensuring impedance matching and minimal signal loss.

B. Calculations for substrate and ground

Let us consider
Dielectric constant ($\in_r$)=2.2, Substrate height = 5mm, operating frequency (f_r) = 2.45GHz
Substrate and Ground Width Calculation
c_0 = 3*10^8
$\lambda = \frac{c_0}{f_r}$
$h' = \frac{0.0606*\lambda}{\sqrt{\in_r}}$ = 5mm
$Wg = 6h' + W$ = 78mm
$Ws = 6h' + W$ = 78mm
Substrate and Ground Length Calculation
$Lg = 6h' + L$ = 70mm
$Ls = 6h' + L$ = 70mm

Feed Calculations

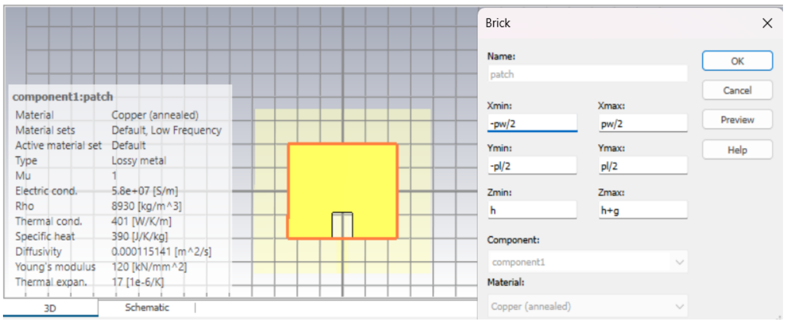
Feed Length

$$\lambda g = \frac{\lambda}{\epsilon_{reff}}$$

$$Lf = \frac{\lambda g}{4} = 21.07\text{mm}$$

$Wf < Lf/2$ on optimization 4.9mm

The patch is designed according to the calculated length and width. The Figure 2 represents the patch layout having length 40.48 mm and width 48.37 mm. The transmissive power of microstrip feed lines, notably efficient, gains visibility with superior compact signal transmitting capabilities. Calculated in equations with due consideration of dielectric properties plus frequency, optimizing dimensions result in superior signal propagation efficiently. Feed line is as shown in Figure 3.



component1:patch

Material	Copper (annealed)
Material sets	Default, Low Frequency
Active material set	Default
Type	Lossy metal
Mu	1
Electric cond.	5.8e+07 [S/m]
Rho	8930 [kg/m^3]
Thermal cond.	401 [W/K/m]
Specific heat	390 [J/K/kg]
Diffusivity	0.000115141 [m^2/s]
Young's modulus	120 [kN/mm^2]
Thermal expan.	17 [1e-6/K]

Brick

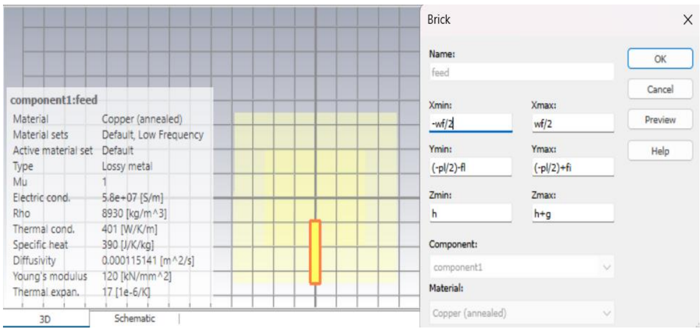
Name: patch

Xmin: -pw/2
Xmax: pw/2
Ymin: -pl/2
Ymax: pl/2
Zmin: h
Zmax: h+g

Component: component1

Material: Copper (annealed)

Figure 2: Patch antenna



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Material	Copper (annealed)
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Thermal expan.	17 [1e-6/K]

Brick

Name: feed

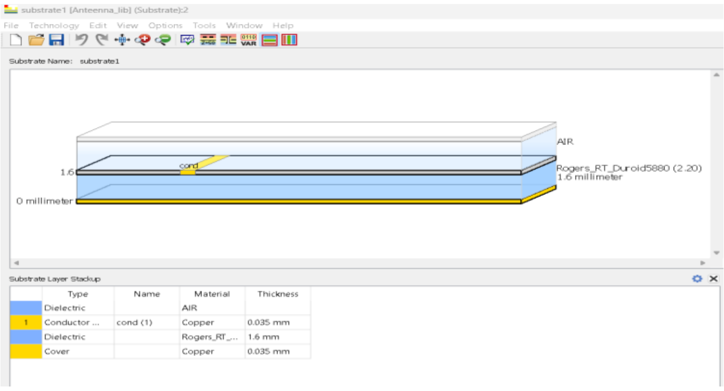
Xmin: -wf/2
Xmax: wf/2
Ymin: (-pl/2)-fl
Ymax: (-pl/2)+fi
Zmin: h
Zmax: h+g

Component: component1

Material: Copper (annealed)

Figure 3: Feed line

The Figure 4 shows a microstrip substrate used in antenna design, specifically Rogers RT/Duroid 5880. With a low dielectric constant of approximately 2.2 to 2.3 and a minimal loss tangent ranging from 0.0009 to 0.0013, it ensures efficient signal transmission with minimal loss and distortion. Its dimensions of 70.48 units in length and 78.37 units in width provide ample space for designing intricate antenna structures. It features two copper conductor layers, each 0.035 millimeters thick.



substrate1 [Anteenna_lib] (Substrate):2

Substrate Name: substrate1

Substrate Layer Stackup

	Type	Name	Material	Thickness
	Dielectric		AIR	
1	Conductor ...	cond (1)	Copper	0.035 mm
	Dielectric		Rogers_RT_...	1.6 mm
	Cover		Copper	0.035 mm

Figure 4: Substrate

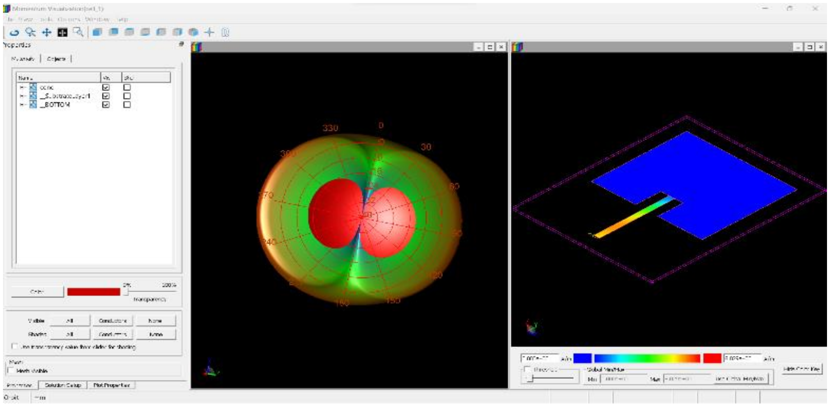


Figure 5: Antenna Visualization

Figure 5 appears to show a 3D model of a microstrip patch antenna on a dielectric substrate. The antenna is a square patch of metal placed on a rectangular substrate.

The 1x2 array antenna configuration involves the arrangement of two patch antennas in a linear array, typically spaced apart at a certain distance is shown in Figure 6. This arrangement of array antenna functions at 2.45 GHz, consists of two rectangular patch elements organized in a 1x2 grid. Each patch element is engineered precisely to resonate at the 2.45 GHz frequency, aligning with the 5G spectrum. With multiple antennas operating in parallel, the system can maintain connectivity even if one of the antennas fails or experiences signal degradation due to obstructions or interference. This redundancy enhances the reliability and robustness of the antenna system, ensuring uninterrupted communication in challenging environments.

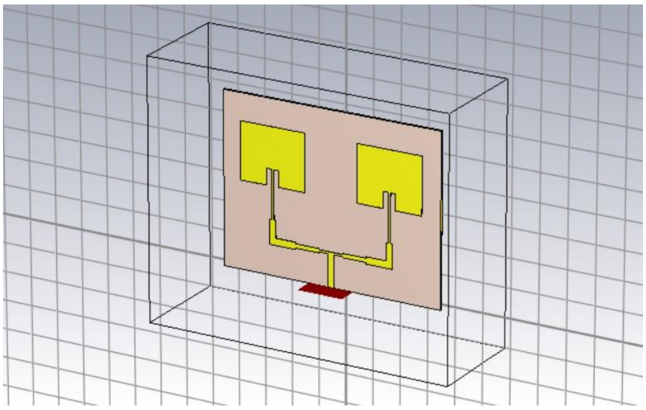


Figure 6: 1x2 Patch array antenna system

The T-junction power divider with impedances of 50 ohms, efficiently splits incoming signal power equally between two output ports is shown in Figure 7. This ensures each patch element in the antenna array receives balanced power, promoting consistent performance. The T-junction power divider boasts simplicity, low insertion loss, and wide bandwidth, making it a favored choice in antenna arrays like the 1x2 array antenna.

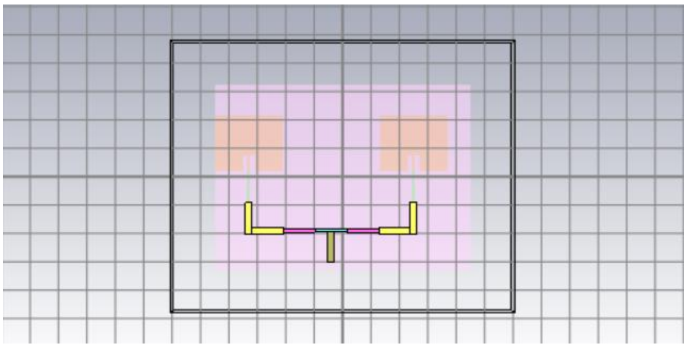


Figure 7: T-junction power divider

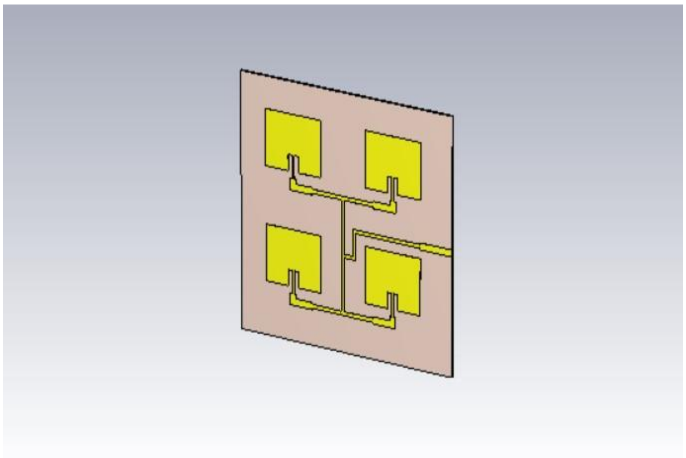


Figure 8: 2x2 Patch array antenna system

A 2x2 array antenna is a configuration consisting of two rows and two columns of antenna elements, typically spaced λ/2 apart on both sides is shown in Figure 8. Firstly, the 2x2 array antenna provides increased gain and directivity compared to single-element antennas. By combining the radiation patterns of multiple antenna elements, the array can focus radiation in desired directions, resulting in higher signal strength and improved coverage.

IV. RESULTS AND DISCUSSION

The analysis of antenna with simulation parameters are carried out using CST microwave studio for. Our investigation primarily focuses on crucial metrics, including but not limited to, S-Parameter performance, radiated power characteristics, gain attributes, and directivity behaviors. The design frequency of antenna is 2.45 GHz. The outputs of antenna like radiation pattern, gain offers uniquely insights into the antenna's behavior. The S-parameter, specifically S11, at a frequency of 2.45 GHz, is depicted in the Figure 9 represents the reflection coefficient of the antenna. the return loss is around -25dB is observed from result. It can be observed that the directivity is 7.250 dBi at 2.45GHz for a single patch antenna. Radiation pattern of the directivity as shown in the Figure 10.

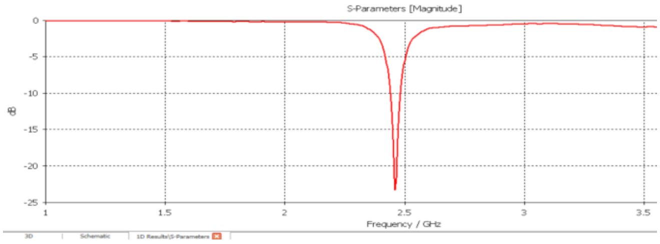
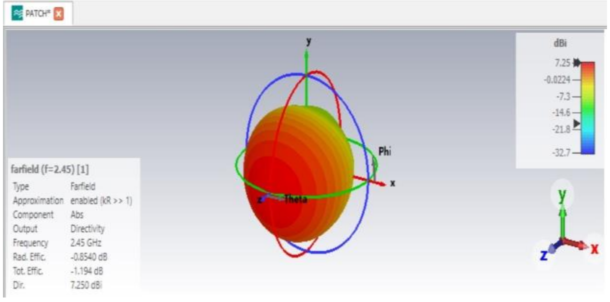


Figure 9: S-Parameter of single patch antenna



farfield (f=2.45) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	2.45 GHz
Rad. Effic.	-0.8540 dB
Tot. Effic.	-1.194 dB
Dir.	7.250 dBi

Figure 10: Directivity of Single Patch

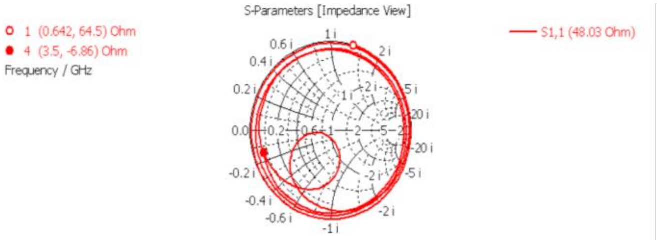


Figure 11: Smith Chat

The Smith chart displays impedance characteristics at 2.45GHz within a frequency range of 1GHz to 4GHz is shown in figure 11. It delineates various combinations of resistance (R) and reactance (X) through concentric circles and radial lines. Engineers can interpret this chart to understand impedance matching and circuit design specifically at the frequency of 2.45GHz, optimizing performance within this targeted frequency range. Figure 12 shows the return loss of the single patch antenna measured using a network analyzer. We observed that the return loss is -19.07dB at 2.49 GHz.

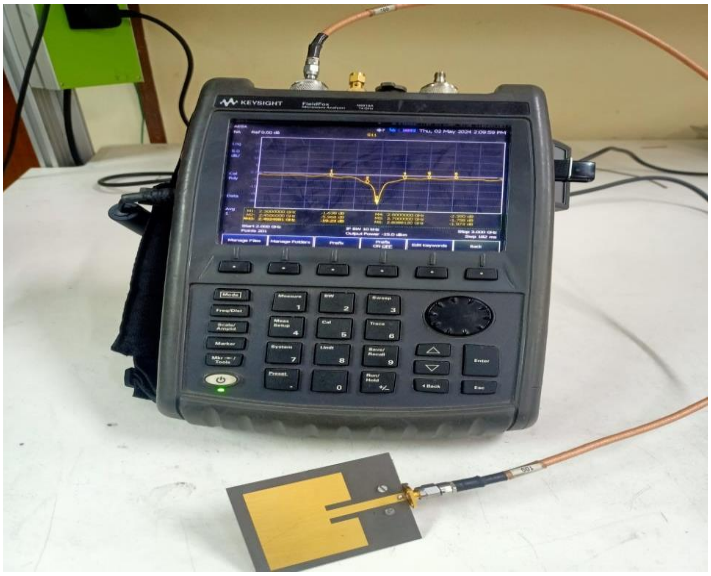


Figure 12: Measuring Return Loss of Single Patch Antenna

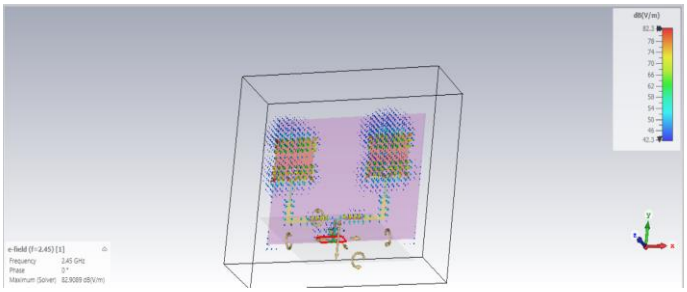


Figure 13 E-Field at 2.45 GHz in array antenna

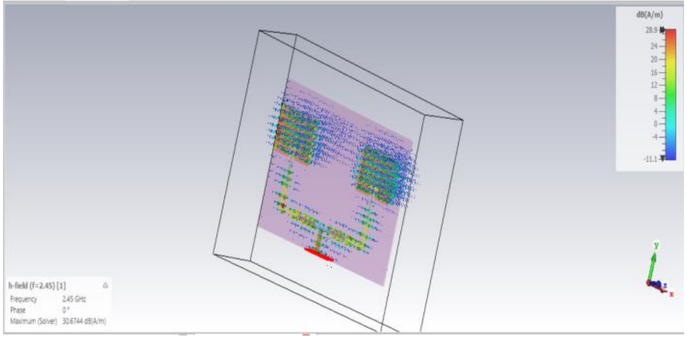


Figure 14: H-Field at 2.45GHz in array antenna

The 1x2 patch array antenna operates at 2.45 GHz and exhibits significant electromagnetic performance. The E-field, representing electric field strength, peaks at 82.9 dB(V/m) with a phase of 0 degrees, while the H-field, representing magnetic field strength, reaches 30.67 dB(A/m) under the same conditions. These measurements highlight the antenna's effectiveness in generating and propagating electromagnetic waves for communication purposes, making it a valuable asset in diverse applications.

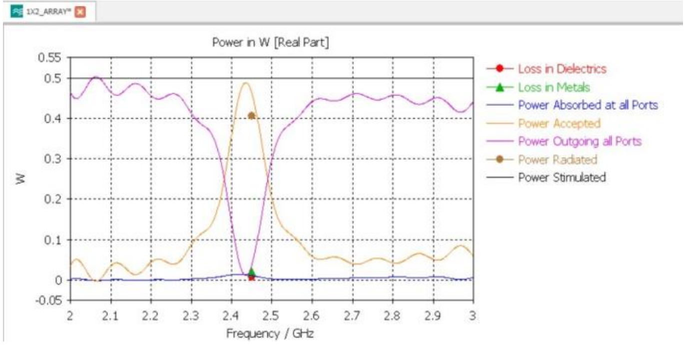


Figure 15: Power in Watts of 1x2 Array

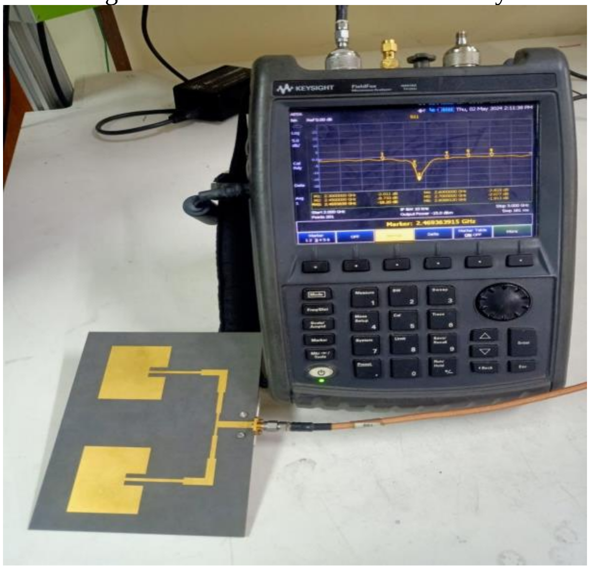


Figure 16: Measuring Return Loss of 1x2 Patch Array Antenna

Figure 17: Power in Watts of 2x2 Array

The figure 15 represents the accepted power and radiated power through 1x2 Array Antenna at 2.45 GHz. Figure 16 shows the return loss of the 1x2 patch array antenna measured using a network analyzer. We observed that the return loss is -19.28dB at 2.469GHz. The Figure 17 represents the accepted power and radiated power through 2x2 Array Antenna at 2.45GHz. Figure 18 shows the return loss of the 2x2 patch array antenna measured using a network analyzer. We observed that the return loss is -23.31dB at 2.496GHz. The gain of 2x2 array antenna at 2.45 GHz. We can observe that the gain is 13.55 dBi.

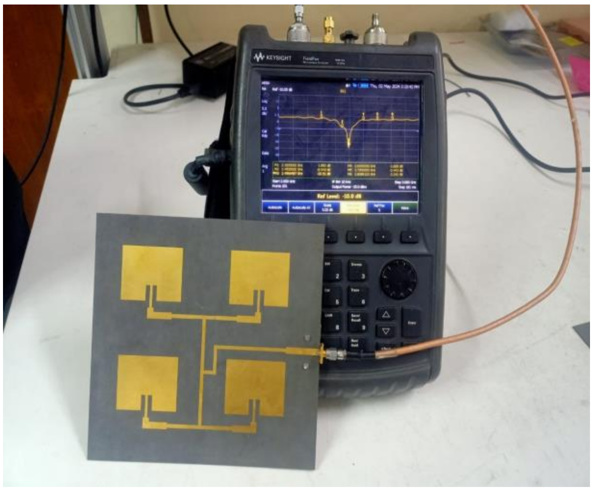


Figure 18: Measuring Return Loss of 2x2 Patch Array Antenna

Table 5.1: Comparison between single element, 1x2 array and 2x2 array antenna in terms of gain and directivity

In the context of 5G applications, the transition from a single patch to a 2x2 array antenna configuration signifies a significant advancement is depicted in Table 1. Specifically, in terms of gain and directivity, the improvement is notable. The gain of 2x2 Array has increased as compared to the single patch and 1x2 Array from 6.396dBi and 9.582dBi to13.55dBi.

Antenna Type	Gain in dB	Directivity in dB	Simulated Frequency in GHz	Practical Frequency in GHz
Patch	6.396	7.250	2.45	2.49
1x2	9.582	10.17	2.45	2.46
2x2	13.55	13.85	2.45	2.49

while directivity rises from 7.567 of single patch to 10.28 in 1X2 array antenna to 13.85 in 2X2 array antenna. These enhancements are crucial for 5G applications, where efficient signal propagation and reception are paramount. The 2x2 patch antenna exhibits the highest gain and directivity among the configurations considered, indicating superior performance in signal transmission and reception.

V. CONCLUSION

This work focused on the design and optimization of an antenna tailored specifically for 5G applications. With a dielectric constant of 2.2 and a dielectric height of 1.56 mm, antenna operates at the critical frequency of 2.45 GHz. Incorporating calculated dimensions of 48.37 mm width and 40.48 mm length, we ensured precise antenna geometry for optimal performance. Analysis of the radiation pattern simulation, power radiation plot, and Smith chart provided valuable insights into the antenna's behavior, guiding our optimization efforts. By considering these parameters and performance evaluations, our antenna demonstrates promising potential for enhancing wireless communication in 5G networks. Moreover, progressing from a 1x2 array configuration to a more advanced 2x2 array configuration mark a significant stride forward. This advancement further amplifies the gain, directivity, signal propagation capabilities.

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