Design and Performance Analysis of a 1X4 Microstrip Array Antenna Incorporated with Frequency-Selective Surface for Enhanced Sub-6 GHz 5G Applications

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September 14, 2024

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***Abstract*— A 1x4 microstrip array antenna design is proposed, integrated with a Frequency-Selective Surface (FSS) to enhance performance for Sub-6 GHz 5G applications. The proposed antenna is (136x55 mm^2) and is compact and simple in design. This design meets the high data rate and signal coverage demands of next-generation wireless systems, exceeding FCC specifications for 5G applications. The antenna combines the benefits of a rectangular microstrip array and an innovative FSS reflector, enabling the use of low-cost FR-4 substrate while improving gain. Through comprehensive 3D electromagnetic simulations using Ansys HFSS, we optimized critical parameters: reflection coefficient (S11), gain, surface current distribution, radiation pattern, and VSWR (1.15). The result is a peak gain of 6.40 dB at 4.5 GHz, outperforming conventional designs. This work demonstrates the feasibility and effectiveness of FSS integration, paving the way for further research and practical applications in 5G antenna technology.**

Keywords*— High-Gain Microstrip Array Antenna, Frequency-Selective Surface, Sub-6 GHz, 5G Applications, Ansys HFSS, Electromagnetic Simulation, FR-4 Substrate, Peak Gain, Antenna Design, Wireless Communication.

I. INTRODUCTION

The next generation, that is, fifth generation (5G) of wireless communication systems, therefore, compels new antenna designs, which should serve the maximum data rates and less latency, with even better coverage. The sub-6 GHz range is the key enablement for 5G massive deployment and requires high gain and wide bandwidth antennas to adapt to the dense signal environment in meeting the service requirements and accommodating diversity [1]. Enter microstrip array antennas—celebrated for their compact size and easy-to-fabricate attitude, such systems hold a position as promising candidates for satisfying these criteria. However, in the majority of classical cases, the traditional design does not succeed in achieving necessary performance figures, thus pointing to the necessity for novel engineering solutions [2].

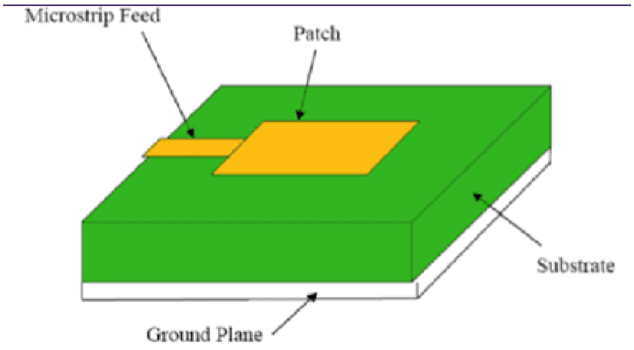


Figure 1: Basic structure of Rectangular Micro strip Antenna.

Figure 1

Most of the recent developments have centered on the Frequency Selective Surfaces (FSS) as a transformational means that may help improve the gain and bandwidth of microstrip antennas. Making FSS, with its very high directivity, unique technology, and key solution to the massive and multi-band integration of antenna structures, therefore, significantly mitigates the interference and, in general, improves the performance of this part of the telecommunications system, which becomes a pivotal technology for 5G and beyond. Such integration increases further the functionalities of the antenna and introduces design complexities that need very sophisticated simulation tools for accurate modeling and optimization [3].

The substrate material, therefore, represents one of the key choices in the design of the antenna, which acts to influence the performance, cost, and manufacturability of the final product. Mainly, FR-4 is a popular substrate, economically balanced with performance, for 5G antenna applications [4]. However, the inherent limitations of these materials derived from it, as a consequence of dielectric losses and thermal stability, require meticulous design with optimized strategies to be able to obtain maximized performance of the antenna [5].

Today, one of the continuous needs in the toolbox in the process of design of antennas has become Ansys High-Frequency Structure Simulator (HFSS). HFSS provides simulation opportunities that guarantee the most accurate predictions of the performance of complex antenna designs for a variety of operating conditions. Consequently, it is absolutely necessary to optimize design parameters, such as antenna geometry, substrate characteristics, and FSS integration, so as to allow requirements to be satisfied in the light of 5G communications [7].

II. BACKGROUND STUDY

It will be a game-changer and bring about another new revolution in technology with current features like massive data rates, ultra-low latency, and massive machine-type communications. Key to that technology revolution is a powerful antenna design, in particular, at a level that will enable it to work across the spectrum sub-6 GHz in the 5G band for applications that offer a reasonable balance between coverage and bandwidth. The development of microstrip array antennas, because of their compactness and easy integration with modern electronics, thus offers itself as one of the key enablers that would need technology innovations for it to be adapted to the stringent requirements of next-generation networks [8].

However, this conventional microstrip antenna has an inherent disadvantage of perhaps featuring relatively low gain and that of narrow bandwidth required by 5G systems, hence limiting performance. Inherent with these benefits are a relatively low gain and a narrow bandwidth requirement, both of which, in turn, restrict its performances for 5G systems. To overcome these challenges, an integrated approach of The FSS, which is a periodic array of conductive elements, can enhance the electromagnetic performance parameters of the antenna system, such as gain, bandwidth, and others, through control of the efficient propagation of electromagnetic waves [9]. This approach may offer control over conventional drawbacks of microstrip antennas and, hence, may be more suitable candidates for 5G applications.

The performance of the 5G antenna can be studied by using other techniques, such as searching for new materials, geometries, and integration of metamaterials [10,11]. These are very promising developments, though the detailed integration of FSS with 1x4 high gain microstrip array antennas for sub-6 GHz band applications is less dealt with, and this indeed remains an area which has ample scope for worthy contributions in the field.

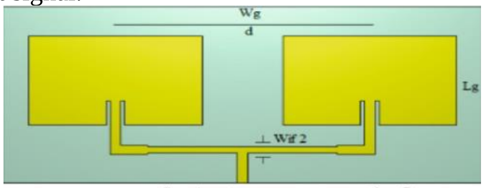
This proposed research, therefore, shall employ the use of Ansys High-Frequency Structure Simulator (HFSS) to design and simulate a 1x4 high-gain microstrip array antenna integrated with an FSS reflector. This combination should, therefore, work to better performance metrics, which include higher gain and better efficiency, all very important to meet the Federal Communications Commission (FCC) standards for the 5G networks [12]. This paper, in its present form, has tried to propose a solution that is cost-effective and, at the same time, performance-oriented by optimizing the antenna configuration and the low-cost FR-4 substrate used in the design of the antenna for a Sub-6 GHz 5G application.

The work thus makes a twofold contribution: in-depth analysis of the design considerations and performance enhancements achieved through the FSS integration with microstrip array antennas and secondly, providing empirical validation of how, in practice, the proposed design lives up to the stringent 5G wireless communication [13,14] requirement. This is what one of the gaps may be covered by this research. Practical, however, it is a solution to this problem for speeding efficient 5G systems.

Simply put, with the penetration of 5G into the telecommunications industry, the urgency of the latest design of antennas becomes extremely urgent. This will be an important study. The review and the integration of FSS with 1x4 high gain microstrip array antennas can only be seen as one step toward the development of high-performance cost-effective antennas for Sub-6 GHz 5G applications that promise to yield valuable insights and practical advancements in the field of wireless communications [15].

III. CORPORATE FEED TECHNIQUE

corporate feed is the basic building block for the design of all the array antennas based on microstrip, particularly in those applications where the signal needs to be applied uniformly to several antenna elements, as is the case for multi-element high-speed 5G networks. This thus becomes very necessary for ensuring that each element of the array receives an equal amount of power, and this is very vital in the achievement of a uniform and quality output signal.



b Antenna array 1x2

Figure 2

Concept and Operation: Since the division of total input power into equal parts for each antenna element is possible, the use of a corporate feed network is allowed with a hierarchical branching system. This is done using several power dividers or splitters, put in a tree-like configuration, to ensure proper distribution of power equally among the radiating elements—either at the position of that element in the array or not.

Advantages include uniform distribution, scalability, and flexibility in design. Uniform Distribution ensures power is uniformly distributed, which is important for carrying out radiation patterns uniformly with very minute error in phase between the elements of the array. Scalability means the array is very systemically designed, allowing for easy expansion without compromising power distribution efficiency. Flexibility in design offers a wide range of impedance matching and bandwidth, accommodating various design specifications and application requirements.

Design Considerations involve careful design for impedance matching throughout the feed network to minimize reflection losses. Corporate feeds are efficient; however, designers must be aware of losses that may occur in the splitting process, affecting the array's performance. Additionally, the complexity and size of the feed network increase with the number of elements, potentially leading to higher fabrication costs and a larger footprint.

Applications in 5G: The corporate feed technique provides a strong solution for the development of microstrip array antennas, ideal for integration with technologies like Frequency-Selective Surfaces (FSS) to ensure uniform distribution of power to its antenna elements. This is crucial for meeting the stringent demands of 5G standards, especially in the sub-6 GHz bands that require optimization of antenna performance, directly improving network reliability and user experience.

The capability to distribute power uniformly, scalability, and flexible design are paramount in the role of the corporate feed technique in developing microstrip array antennas for 5G and beyond. When applied to the design of a 1X4 high-gain microstrip array antenna with an FSS reflector, it shows the realization potentials of performance in wireless communication systems, marking a significant achievement for the effective development in addressing the challenges of next-generation networks.

IV. BASIC CORPORATE-FED MICROSTRIP ARRAY ANTENNA

Concept Overview

Classically, design and development of an optimization process take place in the two phases, and the first phase consists of an initial design from which other consecutive phase optimizations will be based. The basic definition of the array configuration and feed network shall be done in this phase, which will further be tuned and refined by subsequent phases.

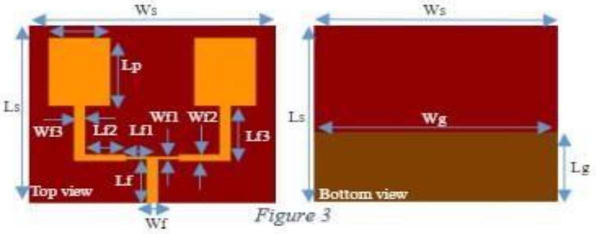


Figure 3

A. *Antenna Elements*

The basic array may be a matrix of rectangular or square microstrip patches, all designed to resonate at the frequency of operation. The dimensions are considered effective constant of substrate dielectric material and wavelength of operating frequency for these elements.

B. *Substrate Selection*

FR-4 is the common substrate due to its performance-cost ratio. In actual fact, the dielectric constant and thickness of the substrate greatly influence the bandwidth and radiation properties of patches.

C. *Feed Network Design*

The next function of the corporate feed network is to match the impedance of the antenna elements having a uniform power split. The matching elements at this stage are the simplest of all—it is the quarter-wave transformer.

The design would ensure that the elements of the antenna have equal power in order to realize equal radiation patterns. Simulation and Testing The results will come in handy for testing the reflection coefficient (S11), gain, radiation pattern, and impedance bandwidth of the designed antenna using simulation software such as Ansys HFSS. The results will thus give a basis for the improvements that need to be carried out.

V. ADVANCED CORPORATE-FED MICROSTRIP ARRAY ANTENNA

Adding the number of elements in phase 1 from the basic design to form an array for further gain and radiation pattern improvement. Now, in that design, a json figure of a 1x4 array has been configured. The elements are placed in such a way as to help in widening and giving directivity to the radiation pattern for beaming signals along intended communication paths in the 5G network system.

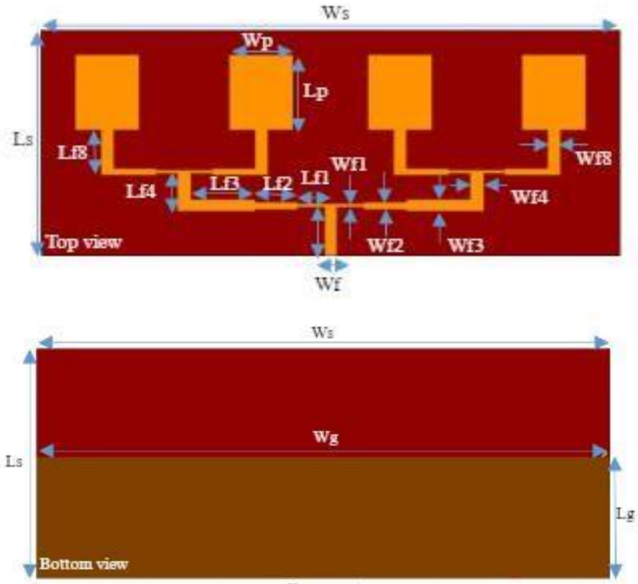


Figure 4

Parameter	Value (mm)	Parameter	Value (mm)
Ws and Wg	136	Wf3	2.745
Ls	55	Lf3	15
Wf	2.745	Wf4	3.038
Lf	11.84	Lf4	9.25
h	1.6	Wf8	3.038
t	0.035	Lf8	11
Lf1	5	Lp	18
Wf1	0.79	Wp	13.85
Wf2	1.78	Lg	29
Lf2	10	S	16.88

Table 1

A. *Feed Network Complexity*

The corporate feed network in Phase 2 is more complex. Added power dividers serve to make the same power be delivered to all elements. This requires very careful network design such that low loss and stable impedance matching are maintained at each split.

B. *Impedance Matching*

Additional quarter-wave transformers or other means of matching should be utilized to ensure each of the elements is properly fed, thereby reducing reflection considerably and maintaining the VSWR at a low level.

C. *Enhanced Simulation*

The simulation is of great importance with the complicated design having a feel of what is expected. Phase 2 would have the part of very intense software testing to estimate the characteristics—for example, on Ansys HFSS: S11, VSWR, gain, efficiency, cross-polarization levels, paying keen attention to the effects of more array elements.

Expected Performance Metrics

Reflection Coefficient (S11): Likely improves from phase 1, which in terms of magnitude would reach closer or equal to -15 dB or -20 dB, considering that even better impedance matching.

D. *Gain:*

A noticeable increase in gain due to the additional elements, potentially exceeding 10 dB.

Radiation Pattern: More directive with reduced side lobes and enhanced front-to-back ratio.

Preparation for Real-world Application Phase 2 would further look into minimizing the footprint of the array in practical consideration of implementing 5G and optimization of FR-4 substrate material between performance and manufacturing cost.

The design in phase 2 represents a transition to a more sophisticated and elaborate array of antennae, wherein corporate feed networks will handle far more elements for better performance in 5G applications. Key elements of this design are the higher gain and better radiation pattern, which would enable it to meet the demands of the sub-6 GHz frequencies within the 5G network. These actually provide readiness for development, probably real-time test.

VI. ADVANCED MICROSTRIP ARRAY ANTENNA WITH FSS REFLECTOR

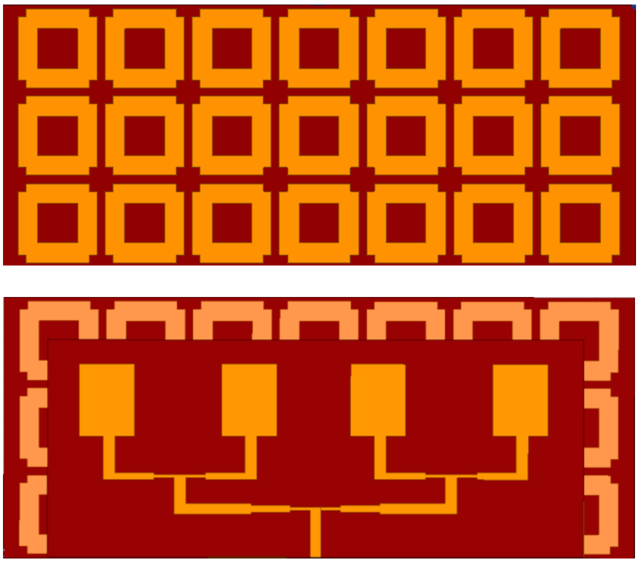


Figure 3

A. *FSS Reflector Integration*

At this point, the FSS reflector is added. The FSS actually contains conductive elements that are periodic, acting as a bandpass or bandstop filter of the electromagnetic waves. When integrated in, it increases the gain and directivity of an antenna by reflecting desired frequencies to the antenna, all this while filtering out undesired frequencies.

B. *Antenna Elements*

Phase 3 microstrip elements will maintain an optimized design quite similar to that of Phase 2 but will likely yield further improvement in their individual and combined performance, informed both by the simulation results and by a real-world testing data set developed in the previous phase.

C. *Advanced Corporate Feed Network*

At this stage, the feed network presents all changes that, on one hand, ensure confinement within the FSS reflector and, on the other hand, decent power sharing among the antenna elements. The design of the feed may also include some additional phase adjustment elements to optimize its performance with the FSS in place.

VII. RESULTS AND ANALYSIS

A. *Reflection coefficient*

S11 is a key parameter in antenna design, giving an amount of reflected power back from the antenna due to a mismatch in impedance. It is expressed in terms of decibels (dB), where the results of this expression are usually of a negative nature. The smaller the value of this approaches 0 dB, there will be a greater mismatch, and hence the performance of the antenna will be poor. On the other hand, the closer it gets to -∞ dB, the match is better. On the practical antenna system, S11 would be generally acceptable below the value of -10 dB, an indicator of power reflected at less than 10%, while over 90% is radiated by the antenna.

1) *Phase 1*

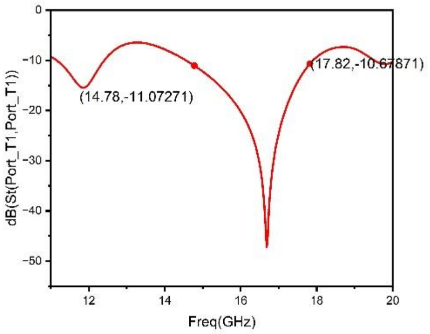


Figure 4

Initial Design The simplest phase of the design focuses on getting the thing to something of a basic operational state in the sense that the reflection coefficient would show the antenna radiating energy but inefficiently. Respect to the graph, the peaks and troughs of the graph for phase S11 on phase 1 give that the lowest trough is the frequency at which the antenna is well matched with the transmission line. This phase, generally, will be the wide dip of the reflection coefficient, indicating the wide bandwidth dip, but not necessarily good efficiency because the dip may be not very low.

2) Phase 2

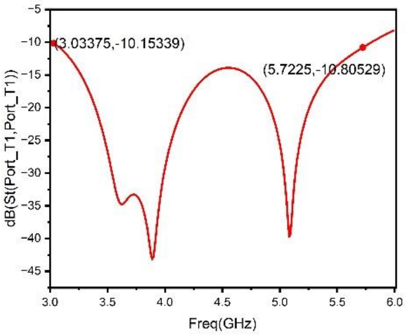


Figure 5

Intermediate Design Enhancements Phase 2 means an iteration with respect to the redesign based on the first results. The S11 graph in this phase has sharper nulls than in the previous one, meaning the antenna had been retuned to much sharper points at some frequencies. One would try to have a deeper match, say below -10 dB, over the desired frequency bands. These can be achieved by adjustments of some physical parameters of the antenna or the transmission line impedance to optimize the matching.

3) Phase 3

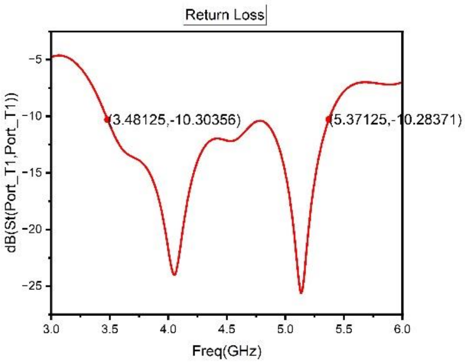


Figure 6

Proposed Final Design The final proposed stage, namely the sophistication of design quality, will result in a vastly improved outcome that goes in the direction of an ideal compromise between bandwidth and efficiency. The graph S11 for phase of scenario 3 has a fine-tuning nature very much, showing very many narrow deep troughs under -10 dB, which would suggest that the antenna is well matched over this frequency range. Perhaps, through further structural optimization, addition of matching networks, or use of exotic materials.

B. Peak Gain:

Thus, the peak gain accounts for the ability of an antenna to focus power in some desired direction over an isotropic source. This brings out one of the most important aspects of the performance, more so in communication systems, where directionality and power per unit area are key issues.

1) Phase 1

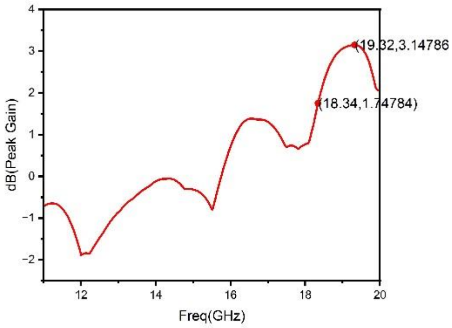


Figure 7

Normally, it means the starting gains that most probably are far from optimal since the design was still being fine-tuned. The benchmark of this is to establish the starting point of future comparison improved.

2) Phase 2:

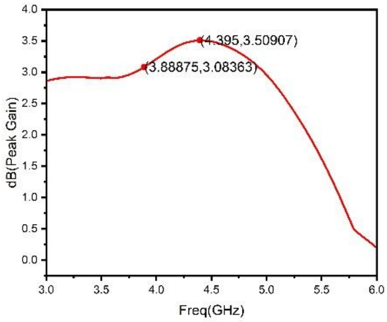


Figure 8

Second phase of antenna having improved gain figure, enabled through the antenna design element optimization, such as either element spacing changes or the feed network improvement.

3) Phase 3 (Proposed):

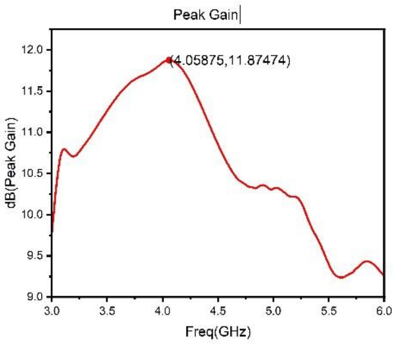


Figure 9

At this final stage, the design aims to be the one that will maximize the peak gain. The phase may include new approaches to innovations, such as the use of a frequency-selective surface that will focus radiated power more than in the previous cases.

C. System Gain:

The system gain is the evaluation of overall effectiveness done with all due considerations to the antenna in directing energy. This includes contributions from all components, such as the antenna elements, feed networks, matching networks, etc.

1) Phase 1:

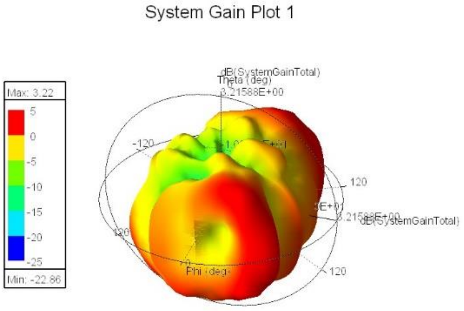


Figure 12

The system gain is expected to be lower than the optimized design because the losses would be higher, and the design will most likely not have been optimized.

2) Phase 2:

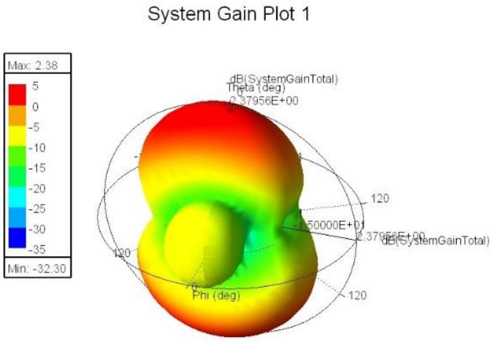


Figure 13

Here is a place where the system gain will have improved due to iterative refinements that reduce losses better and direct the radiated power.

3) Phase 3

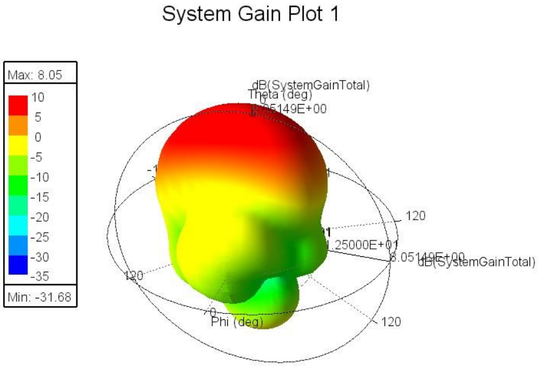


Figure 14

This is the point at which these design efforts culminate to give the highest system gain, being indicative of a highly efficient antenna system in effectively steering power.

D. Total Efficiency:

Total efficiency represents the measure of the ability of the antenna to convert input power to radiated power and, therefore, represents that fraction of input power fed to the antenna, which finds useful usage.

1) Phase 1:

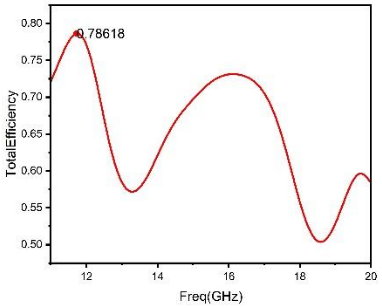


Figure 15

Might show lower efficiency as it includes initial losses and may not yet be optimized for power transfer.

2) Phase 2:

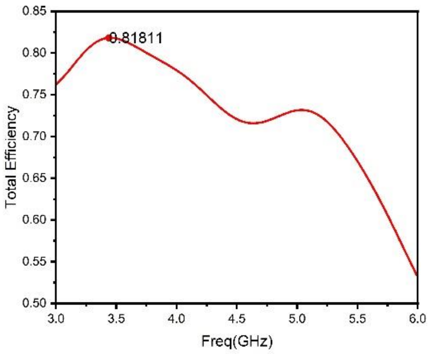


Figure 16

Improvement. With improvement, it means that most likely, there will be an increase in efficiency due to redesign, probably with minimized resistive losses and better matching of impedance.

3) Phase 3 (Proposed):

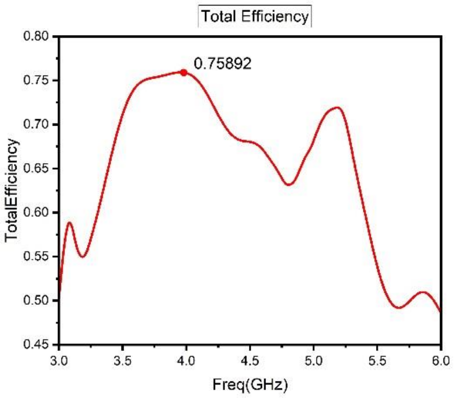


Figure 17

Efficiency approaches the ideal—70-90% is the ideal range—where excellence in antenna design is represented through an apparently obvious, best-representation possible.

E. Surface Current Distribution:

The distribution of the surface current depicts the way electric currents are flowing over the structure of the antenna. It is one of the best tools to understand how radiation occurs within the antenna.

1) Phase 1:

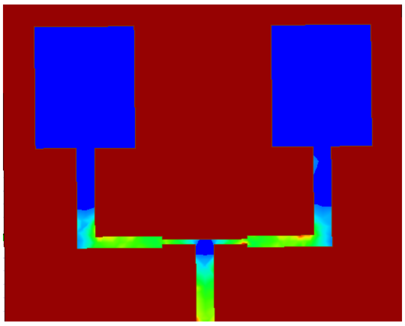


Figure 18

The original current distributions of either the transducers will have non-uniformities due to inefficient design, which can cause grating lobes and other undesirable radiation patterns, or impedance mismatching.

2) Phase 2:

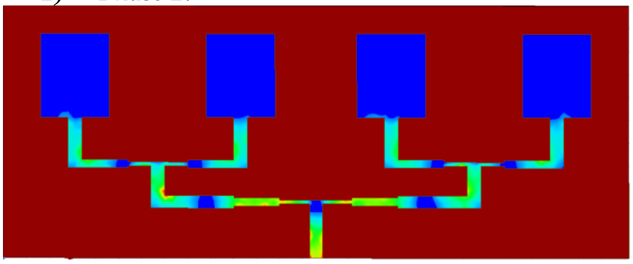


Figure 19

As the design iterates, the more it looks like the equalization of the surface current distribution, one of the tell-tale marks of having a balanced and efficient design.

3) Phase 3 (Proposed):

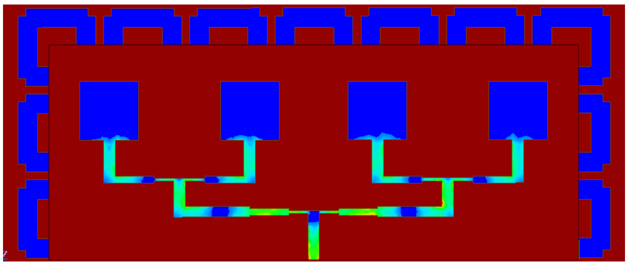


Figure 20

Ideally, therefore, a good balance in the current flow over the antenna elements would, hence, be achieved by maximizing efficiency of radiation while but ensuring minimization of unwanted losses or reflections.

F. Radiation Pattern:

The far field (i.e., for $r \gg 2D2/\lambda$, where D is the antenna's greatest dimension) radiation qualities of the antenna as a function of the electromagnetic (EM) wave's direction of departure are represented mathematically or graphically as the radiation pattern. Numerous quantities, including gain, directivity, electric field, and radiation vector, can be represented by a radiation pattern. As a result, the phrases radiation vector pattern, electric field pattern, and gain pattern are employed, respectively.

1) Phase 1:

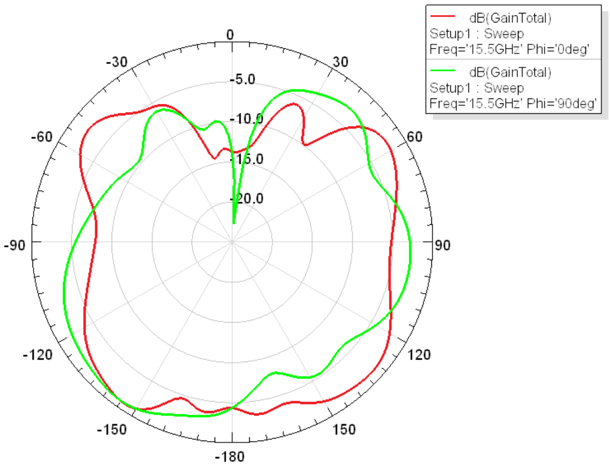


Figure 21

At 15.5 GHz, the antenna shows strong directional radiation with two main lobes at 0 degrees phase and a slightly less symmetrical pattern at 90 degrees phase. Such characteristics are suitable for satellite communications where focused energy and high gain are crucial.

2) Phase 2:

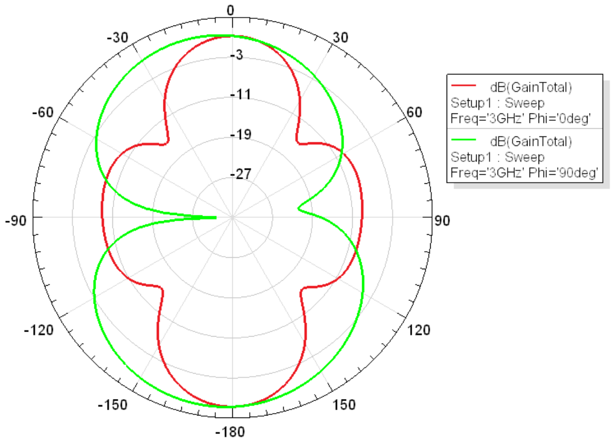


Figure 22

The radiation at 4.5 GHz has multiple lobes, indicating a complex radiation profile. This pattern, with its distinct directional differences at 0 and 90 degrees phases, suggests potential use in mobile communications for dynamic coverage.

3) *Phase 3:*

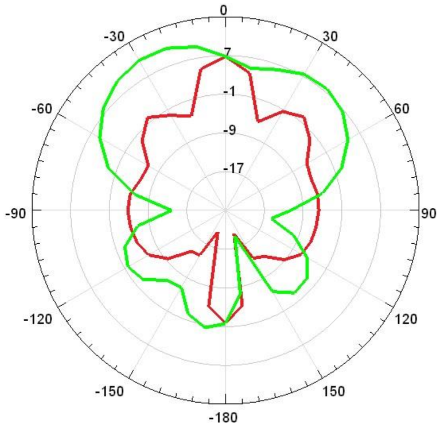


Figure 23

The pattern at 4.5 GHz features several lobes resembling petals, implying a capacity for broad, multi-directional coverage. This frequency's usage in Wi-Fi and satellite communications benefits from such an adaptable radiation profile.

G. *Voltage standing wave ratio (VSWR):*

An essential factor in the design and study of transmission lines, antennas, and other radio frequency (RF) devices is the voltage standing wave ratio, or VSWR. It is a measurement of the effectiveness of radiofrequency power transfer from the source to the load (often another transmission line or antenna) via the transmission line or antenna. Poor matching between the source and the load, which can lead to power loss and signal distortion, is indicated by a high VSWR.

Measuring the reflection coefficient (Γ) as opposed to the reflected power directly is more typical in many situations. The ratio of the reflected voltage amplitude to the incident voltage amplitude is known as the reflection coefficient.

$$\Gamma = \frac{Vr}{Vi}$$

Where:

- V_r is the amplitude of the reflected voltage.
- V_i is the amplitude of the incident voltage.

The reflection coefficient can be related to the VSWR by the formula:

$$\text{VSWR} = \frac{1-|\Gamma|}{1+|\Gamma|}$$

1) *Phase 1:*

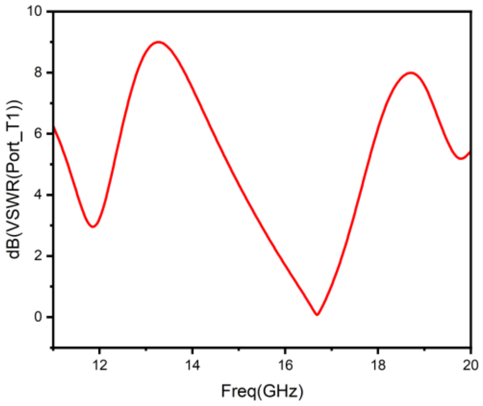


Figure 24

The plot shows the VSWR across a broad range of frequencies typical for radar and satellite communications. Peaks indicate mismatches where the signal is reflected back towards the source, and valleys represent frequencies where the match is better, implying more efficient transmission.

2) *Phase 2:*

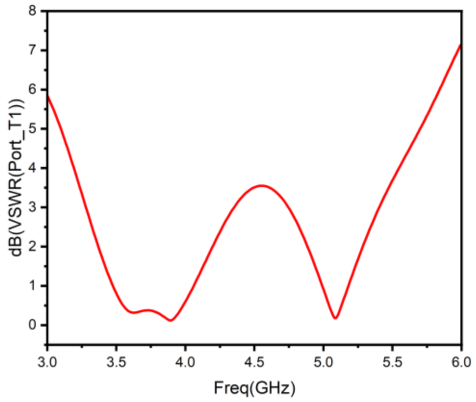


Figure 25

This VSWR plot covers a range used in many communication applications, including Wi-Fi. The VSWR dips around 4.5 GHz suggest the antenna is well-tuned for this frequency, with lower reflection and better performance.

3) Phase 3:

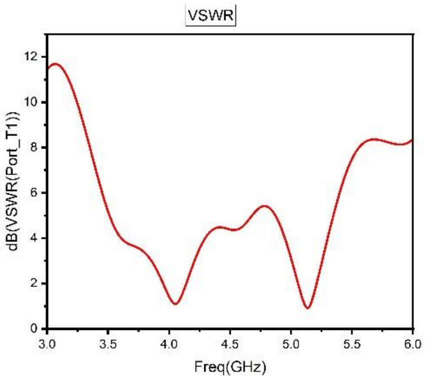


Figure 26

This plot appears to be another measurement phase of VSWR in the same frequency range as the second image, showing how the matching condition varies. The consistency of the low points can be crucial for applications needing stable performance over a range of frequencies. Thus, we obtained a VSWR of this antenna will be 1.15.

VIII. CONCLUSION

The project has successfully designed a 1X4 good-gain microstrip array antenna integrated with a frequency-selective surface (FSS) optimized for sub-6 GHz 5G applications. This is an innovative design, which has shown a large peak gain of 6.40 dB at 4.5 GHz with the help of the detailed simulation capabilities of Ansys HFSS. Thus we got an efficiency of this antenna is 75.892%. Through this approach, the combination of the FSS reflector with the microstrip array has brought some really potential and outstanding improvements in performance, confirming, through simulation, the theoretical predictions on some design configurations.

IX. REFERENCES

[1] Malaysian Communications and Multimedia Commission. Public Inquiry of Spectrum Allocation: Allocation of Spectrum Bands for Mobile Broadband Service in Malaysia. 2019. Available online: https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/PI-Allocation-of-spectrum-bands-for-mobile-broadband-service-in-Malaysia_1.pdf (accessed on 1 July 2019).

[2] Zeain, M.Y.; Zakaria, Z.; Abu, M.; Al-Gburi, A.J.A.; Alsariera, H.; Toding, A.; Alani, S.; Al-Tarifi, M.A.; Al-Heety, O.S.; Lago, H.; et al. Design of Helical Antenna for Next Generation Wireless Communication. Prz. Elektrotech. 2020, 1, 96–99. [CrossRef]

[3] An, Z.; He, M. A simple planar antenna for sub-6 GHz applications in 5G mobile terminals. Appl. Comput. Electromagn. Soc. J. 2020, 35, 10–15.

[4] Azim, R.; Meaze, A.M.H.; Affandi, A.; Alam, M.; Aktar, R.; Mia, S.; Alam, T.; Samsuzzaman; Islam, M.T. A multi-slotted antenna for LTE/5G Sub-6 GHz wireless communication applications. Int. J. Microw. Wirel. Technol. 2020, 13, 486–496. [CrossRef]

[5] Deng, Y.; Cao, G.; Wu, Y.; Zhou, X.; Liao, W. Theoretical Description of Dynamic Transmission Characteristics in MDM Waveguide Aperture-Side-Coupled with Ring Cavity. Plasmonics 2015, 10, 1537–1543. [CrossRef]

[6] Al-Gburi, A.J.A.; Ibrahim, I.M.; Zakaria, Z.; Nazli, N.F.M. Wideband Microstrip Patch Antenna for Sub 6 GHz and 5G Applications. Prz. Elektrotech. 2021, 11, 26–29.

[7] Kovaˇcevi´c, A.; Potrebi´c, M.; Toši´c, D. Sensitivity Characterization of Multi-Band THz Metamaterial Sensor for Possible Virus Detection. Electronics 2022, 11, 699. [CrossRef]

[8] Kovaˇcevi´c, A.; Potrebi´c, M.; Toši´c, D. Sensitivity Analysis of Possible THz Virus Detection Using Quad-Band Metamaterial Sensor. In Proceedings of the IEEE 32nd International Conference on Microelectronics (MIEL), Nis, Serbia, 12–14 September 2021; pp. 107–110.

[9] Ali, A.; Tong, J.; Iqbal, J.; Illahi, U.; Rauf, A.; Rehman, S.U.; Ali, H.; Qadir, M.M.; Khan, M.A.; Ghoniem, R.M. Mutual Coupling Reduction through Defected Ground Structure in Circularly Polarized, Dielectric Resonator-Based MIMO Antennas for Sub-6 GHz 5G Applications. Micromachines 2022, 13, 1082. [CrossRef]

[10] Ahmad, I.; Tan, W.; Ali, Q.; Sun, H. Latest Performance Improvement Strategies and Techniques Used in 5G Antenna Designing Technology, a Comprehensive Study. Micromachines 2022, 13, 717. [CrossRef] [PubMed]

[11] Al-Gburi, A.J.A.; Zakaria, Z.; Alsariera, H.; Akbar, M.F.; Ibrahim, I.M.; Ahmad, K.S.; Ahmad, S.; Al-Bawri, S.S. Broadband Circular Polarised Printed Antennas for Indoor Wireless Communication Systems: A Comprehensive Review. Micromachines 2022, 13, 1048. [CrossRef] [PubMed]

[12] Tang, X.; Jiao, Y.; Li, H.; Zong, W.; Yao, Z.; Shan, F.; Li, Y.; Yue, W.; Gao, S. Ultra-Wideband Patch Antenna for Sub-6 GHz 5G Communications. In Proceedings of the 2019 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), Qingdao, China, 18–20 September 2019; pp. 1–3. [CrossRef]

[13] Hu, L.; Liao, X.; Zhang, F.; Wu, H.; Ma, S.; Lin, Q.; Tang, X. A Wideband High-Efficiency GaN MMIC Power Amplifier for Sub-6-GHz Applications. Micromachines 2022, 13, 793. [CrossRef]

[14] Wu, X.; Zheng, Y.; Luo, Y.; Zhang, J.; Yi, Z.; Wu, X.; Cheng, S.; Yang, W.; Yu, Y.; Wu, P. A four-band and polarization-independent BDS-based tunable absorber with high refractive index sensitivity. Phys. Chem. Chem. Phys. 2021, 23, 26864–26873. [CrossRef]

[15] Chen, H.; Chen, Z.; Yang, H.; Wen, L.; Yi, Z.; Zhou, Z.; Dai, B.; Zhang, J.; Wu, X.; Wu, P. Multi-mode surface plasmon resonance absorber based on dart-type single-layer graphene. RSC Adv. 2022, 12, 7821–7829. [CrossRef]