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ENHANCING MICROSTRIP ANTENNA EFFICIENCY WITH NOVEL SLOT-INTEGRATED PATCH CONFIGURATIONS

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Research Paper

Abstract: *This research presents a concept, for an elliptical ring patch microstrip antenna (ERPA) which was created tested and produced Employing types of materials, with varying permittivity values. The antenna is meant for X band use. In this study the substrates employed are FR4 (Design (1)) and RT5880 (Design (2)) having permittivity values of 4.4 and 2.2 respectively and thicknesses of 1.6 mm and 1.575 mm. The ERPA design includes four rings, with holes of different sizes. The Ansoft HFSS, a high-frequency structure simulator, is utilized to model the antenna design, which is crucial for optimizing the design and accurately predicting its performance. Moreover, simulation tools were integral in optimizing antenna characteristics before physical testing. Curiously, there is a significant consensus over the comparative outcomes. The research primarily examines key characteristics, including radiation pattern gain, return loss, and input impedance, which have been shown to fall below acceptable thresholds. The results show that relative permittivity and difference in the thickness of the substrate materials have a substantial impact on both bandwidth and gain. The analysis of efficiency showed the superior efficiency of 85.70% by RT-5880 in contrast to 69.96% efficiency gained via FR-4 substrate. The bandwidth of both proposed antennas is greater than 2 GHz which is 2.420 GHz and 3500 GHz for Design (1) and Design (2) respectively. The gain 3 is observed in both the Designs 1 and 2. The higher bandwidth and gain makes RT5880 substrate more efficient, and provide better design for X- band applications. Maintaining the X-band frequency range the proposed antenna design can be applied to wide range of applications.*

Keywords: *Microstrip, Bandwidth, Slot, Elliptical, X-Band.*

1. Introduction

The Wireless Operating Microstrip Patch Antennas (MSPAs) are very useful in some applications in the communication, remote sensing, medical devices, radar

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systems and hand handheld devices due to their weight and size (Gaid et al., 2024; Huang & Lee, 2024). Moreover, it is used in others such as vehicle speed identification, air traffic control and civil meteorological applications, marine vessel traffic control and even in military applications. Furthermore, in terms of wireless communication engineering design and optimization, the MSPA is considered a cornerstone because of its ability to be designed into different shapes and used at various frequencies according to the required device. Because of the benefits attributed to the fabrication processes, which are relatively simple, products are often lightweight and small in size, inexpensive, and compatible with advanced electronic systems (Roh et al., 2014).

But a major drawback of MPSAs is that they are not resource-efficient and have a rather small range of options (Andrews et al., 2014). This is understandable in light of the fact that electromagnetic fringing emanates only from two patch edges. The basic MSPA structure consists of three layers: a conductive ground plane, a dielectric substrate positioned above the ground plane, and a radiating patch on the bottom side of the substrate (Abdelghany et al., 2024; Mahbub et al., 2021). MSPA work at specific frequencies by resonating, where the length of the patch is approximately half the wavelength of the desired operating frequency (Khan et al., 2022; Kiani et al., 2022). The performance of MSPAs can be principally influenced by the dimensions and characteristics of the MSPAs. The patch can be made in various shapes, including rectangular, circular, elliptical, and more complex geometries. The dielectric substrate material separates the patch from the ground plane, and its properties (such as permittivity) significantly affect the antenna's performance (Zahid et al., 2022). It has been observed that although the overall structure of the printed circuit depends on the material used for the substrate, the material plays a significant role in the field of performance parameters. An increase in thickness of the substrate or a decrease of dielectric constant also leads to broad bandwidth and efficiency but possess loosely bound fields for radiation into space but entails large size of element (Sufian et al., 2021). However, if the substrate thickness is less than 0.05λ, the antenna's power delivery transitions from transverse waves to surface waves, thereby ceasing to radiate effectively. Another problem will appear due to the interaction between all these loops, which is also impacts on the efficiency of the antenna (Hussain et al., 2021). For higher dielectric constant, the area of the patch is small in comparison to that of the negative dielectric. Yet, at the same time, as the dielectric constant rises, not only bandwidth diminishes as well as radiation efficiency. But, as concluded, it is useful in determining the substrate selection in the methodology of antenna design. Also, the specific MPSA's patch geometry influences its performance as well. Therefore, several patch shapes have been proposed such as circular, triangular, rectangular, hexagonal, U-shaped, and bowtie-shaped, etc (Al-Bawri et al., 2021; Munir et al., 2024; Sharma & Kumar, 2023). Earlier works involved slots in circular or rectangular patch-shaped with a ground plane located in the backside of the given antenna (Mutashar et al., 2020). Consequently, we can identify a high level of potential when considering different slotted-patch designs and slot sizes, ground plane positions and feedline length/positioning options (Ullah et al., 2019).

To conclude, we utilize integrated slot MPSAs as a better approach to enhancing the performance of the MSPA (Yang & Alouini, 2020). This is one of the flexible procedures that ergo offer new design features thought to enhance some crucial antenna parameters such as return loss, operating frequency, and power gain

(Ojaroudi Parchin et al., 2019; Yang et al., 2023). Furthermore, besides changing the shapes of antennas, it is possible to introduce slots into the designs in order to enhance the performance of the structure. Some slots are engraved to form patches while others are carved out causing alteration of the antenna electromagnetic characteristics. These slots may usually decrease the excitation of the surface waves also, increase the bandwidth and furthermore make the impedance matching better since they add up more resonant frequencies (Deng et al., 2023; Krishna & Padmasine, 2023). It might be for specific performance goals, other slot configurations as well could be used as presented in (Saleh et al., 2023; Singh et al., 2024), like circular slots or annular ring slots.

This paper examines the influences of multiple dielectric materials on the performance characteristics of a new shape of ellipse rings elliptical micro strip antenna ERPA which consist circular slots on four-shaped ellipse ring patch of different size for X-band applications. The following designs should be proposed and simulated using two different substrate material namely FR4 and Rogers (RT-5880). Particular attention is paid to the analysis of the variety of slot geometries, dimensions, and their placement in order to influence the characteristics of antenna. This is a compact structure that boasts much better performance than a conventional MPAs employing contemporary simulation tools can as such better depict the benefits of this aiding method in optimizing the overall performance of micro strip antennas in the X-band frequency.

2. Antenna Design

MPSA structure has a ground plane, a dipolar dielectric substrate, and a radiating patch. The ground plane is a broad, conducting plane, which reflects the radio waves radiated by the remaining parts of the antenna. This is important in order to add support strength to the antenna through the substrate. Usually, a conductive substance like as copper or gold is used in the production of the patch. The configuration of the radiating patch has a substantial impact on performance of the developed antenna, as it affects the distribution of the surface current, the range of frequencies it can operate at, the amplification, the pattern of radiation, and the alignment of impedance. To enhance the performance of the antenna, different configurations of patch antennas are used for such purpose (Alsudani & Marhoon, 2023; Hussain et al., 2023; Rana, Hossain, et al., 2023; Rana, Sen, et al., 2023). The proposed MPA incorporates the micro strip line inset feeding technique, which ensures a sleek surface for the antenna. The HFSS was used to model the suggested antenna design.

The proposed antenna design begins with an ERPA, as shown in Figure 1a. A following stage entails doubling the number of ERPA in various diameters and loading them within the first ERPA. This is performed to produce the required radiation characteristics and bandwidth by altering the current distributions. To enlarge the bandwidth, the proposed antenna may be created by etching a circular hole into the ERPA, as seen in Figure (1e). Design 1 utilized a sublayer, with a dielectric substrate thickness of 1.60 mm and a relative permittivity of 4.4. In contrast Design (2) employed Rogers (RT 5880) material, with a thickness of 1.575 mm and a relative permittivity of 2.2. The layout of the proposed antennas is illustrated in Figure 3. The antennas are specifically engineered to operate at x-band frequencies. Hence, the objective of this research is to ascertain more effective and uncomplicated methods to achieve desired outcomes, such as a broad range of frequencies. Table 1 displays several details, including dielectric constant and substrate height.

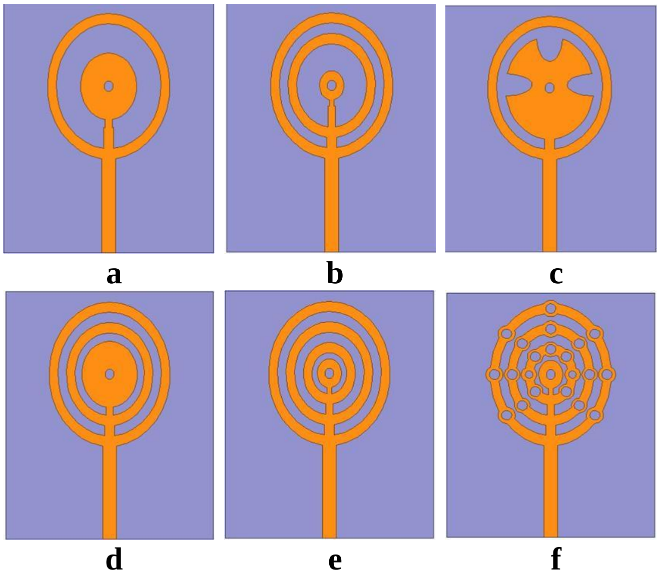


Figure 1: Illustration of the Sequential Stages involved in the Antenna Design.

The antenna shown in Figure 1(f) was selected to be ideal design. Figure 1(f), was selected based on the favourable simulation results for radiation pattern and return loss, which are discussed in the next section. The HFSS programme was used to optimise the size of the antenna and study parameterization derived from the highest level of achievement, as seen in Figure 2. This antenna is both simulated and constructed using a cost-effective-method. The dielectric substrate used is FR4 epoxy with a dielectric constant (εr) of 4.4. The volume of the substrate is 36.0 * 24.0 * 1.6 mm3. The annular patch has a major axis diameter of rv = 7 mm and a minor axis dimension of rh = 5.18 mm. The ERPA has the same width. The ground plane has an area of 285.12 mm2. Table 1 displays the characteristics and dimensions used in the fabrication and the design of the recommended antenna. A fabricated antenna is connected to a vector network analyser (VNA) via cable, as shown in Figure 3, to measure the VSWR and S11 (dB) graphs.

Table 1: The Proposed Antenna Geometric Measurements

Parameters	Dimensions(mm)	Parameters	Dimensions(mm)
L	36	l_g	11.83
W	24	w_g	24
dro	1	dri	1.1
W_f	1.6	L_f	11.83
L_i	6.7	r_s	1
h Design (1)	1.6	h Design (2)	1.575
ε_r Design (1)	4.4	ε_rDesign (2)	2.2

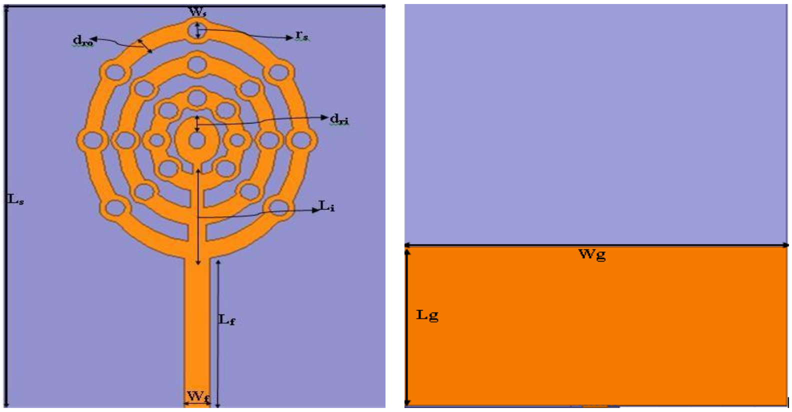


Figure 2: Geometrical Characteristics of the Most Efficient Antenna Design.

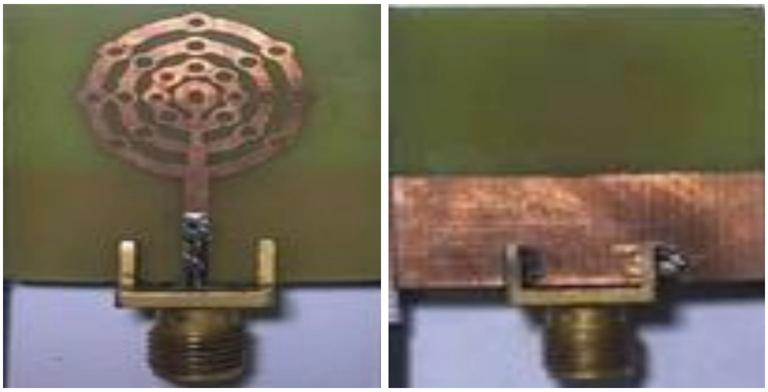


Figure 3: The Constructed Antenna Prototype as Seen from the Top and Bottom Perspectives.

Table 2: Specifications of the Proposed Antennas' Design.

Specification Values Frequency	C- and x-band
Coefficient of Reflection, S11	Less than 10 dB
Input of VSWR	1:2
Impedance, Z	50 Ohms
Thickness of Copper	0.035 mm
Range of Bandwidth-	≥ 2 GHz

3. Results and Discussion

The antenna was designed with a particular purpose or function in mind. Conducted tests on Xband frequency using different substrate materials with varying relative permittivity values. A MSPA design was created by integrating a ring patch (ERPA) decorated with circular slots. The ERPA is available in several diameters, as seen in the Figure 2. The precise measurements of the slots' diameters. Their arrangement plays a role in achieving the required radiation patterns at certain frequencies by effectively controlling the reversal of phase in surface currents. The proposed antenna's performance has been optimised by selecting the phase reversal in surface currents, based on simulation findings related to return loss. Integrating ERPA leads to modifications in the surface route, resulting in enhanced impedance matching.

The planned antenna, referred to as design (1), was executed via the use of Ansoft HFSS software. The object was created using a FR4 substrate that has a consistent dielectric constant (εr = 4.4). The antenna has dimensions of 36.0*24.0*1.6 mm. The strip line in Figure 2 is used to provide power, and it has a typical impedance of 50 ohms. Table 1 provides precise measurements of the recommended antenna. The FR4 substrate is considered because using an FR4 substrate for antenna design provides a balance of electrical, mechanical, and cost-related advantages that make it a popular choice in many engineering applications. This graphic illustrates that the optimal design produces the most advantageous results in terms of coefficient of reflection. Figure 1(e) shows the optimal design, with a bandwidth of 2.420 GHz and a resonance frequency of 7.58 GHz.

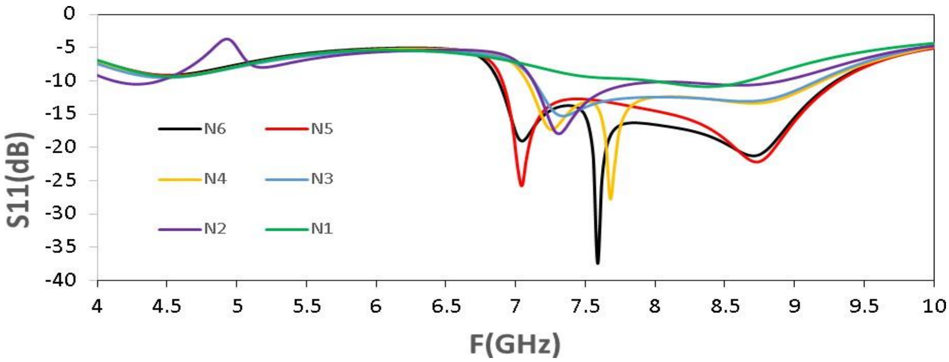


Figure 4: The Return Loss Results of the Developed Antennas as Displayed in Figure 1.

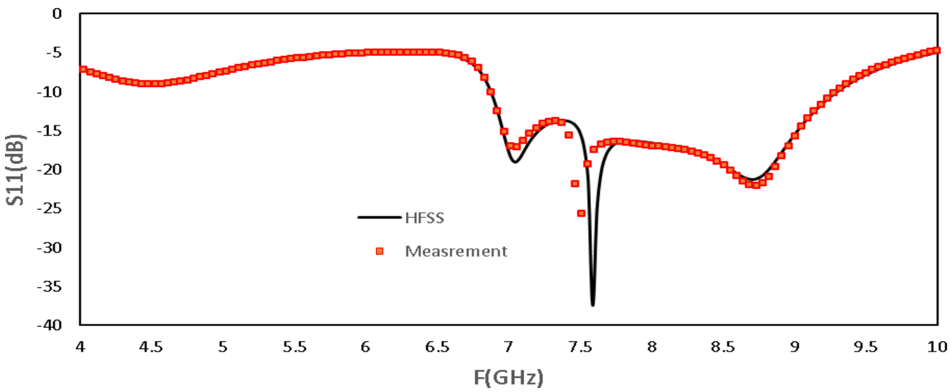


Figure 5: The Return-Loss of the Recommended Antenna.

This image demonstrates that the ideal design yields the most favourable outcomes in terms of coefficient of reflection. Figure 1(e) shows the most efficient antenna design, with a bandwidth of 2.420 GHz and a resonance frequency of 7.58 GHz. The graph in Figure 5 illustrates a positive connection between the calculated and measured values of the return loss parameter for the proposed antenna. The use of soldering effects in SMA connections, which are often overlooked in simulation designs, might potentially lead to slight discrepancies between the measured and simulated outcomes. The measured and modelled data show a bandwidth of 2.420 GHz, spanning from 6.87 GHz to 9.29 GHz, and a resonance frequency of 7.58 GHz and 7.5 GHz, respectively. The antenna Design (2) was developed and simulated using Ansoft HFSS software on a Roger RT (Duroid 5870) substrate with a relative permittivity (εr) of 2.2 and a thickness (h) of 1.575 mm. The Design-1 used components of same dimensions, including the feeding technique. The feeding method included the use of a tapered strip line with a 50-ohm impedance, as shown in Figure 2. Table 1 displays the measurements of the suggested antenna.

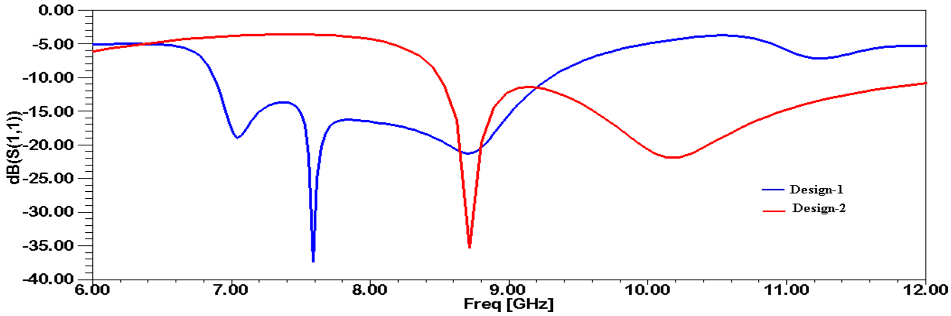


Figure 6: Simulation Findings for the Return Loss of Antenna Design (1) and Design (2).

Figure 6 demonstrates the coefficient of reflection (S11), for both Design 1 and Design 2. In Figure 5 Design 1 had an S11 value of 37.42 dB at 7.58 GHz with a bandwidth of 2.420 GHz from 6.87 GHz, to 9.29 GHz. During optimization Design 1 demonstrated results in terms of S11. Bandwidth. However, Design 2 surpassed Design 1 in both S11 and bandwidth performance. Design 2 achieved an S11 value of 35.34 dB at a frequency of 8.711 GHz with a bandwidth of 3.500 GHz, spanning from 8.5 GHz to 12.0 GHz. Figure 5 emphasizes the performance of Antenna Design 2. The simulation results of VSWR for Design (1) and Design-(2) are shown on Figure 7. The proposed antenna meets the criteria of the intended applications. The criteria for these applications include satellite communication and wireless communication in x band applications, with a VSWR (Voltage Standing Wave Ratio) of less than 2. The VSWR values for Design (1) and Design (2) were 1.027 and 1.034, respectively.

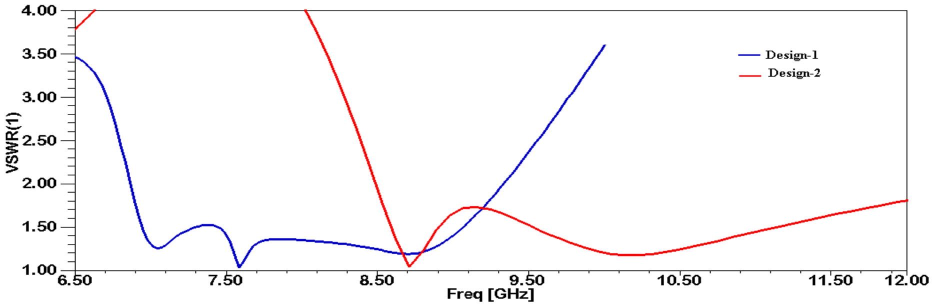
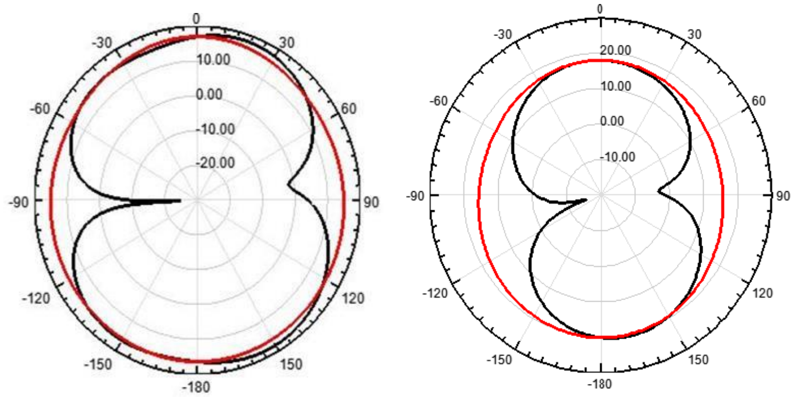


Figure 7: VSWR Simulation Findings for the Return Loss of Antenna Design (1) and Design (2).

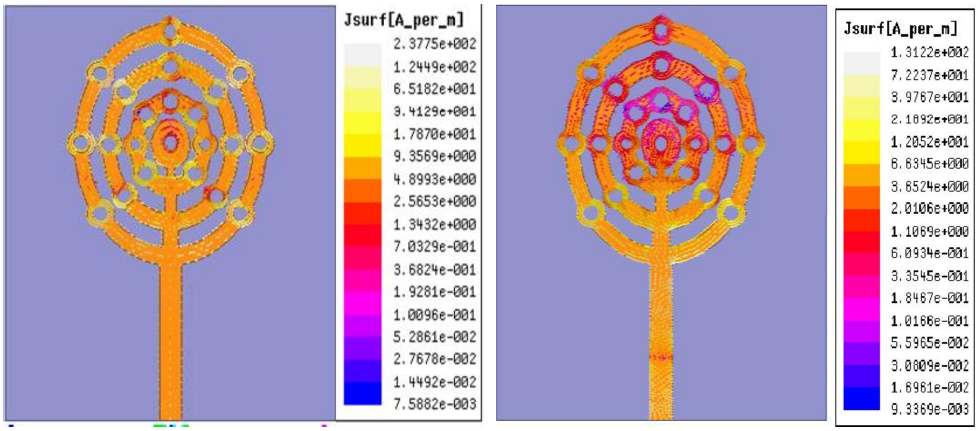


a **b**

Figure 8: The Patterns of Radiation of the Proposed Two-dimensional Antenna Design. The red colour represents the E-plane, while the black colour represents the H-plane. These patterns were seen at the resonance frequency for both Design (1) and Design (2)

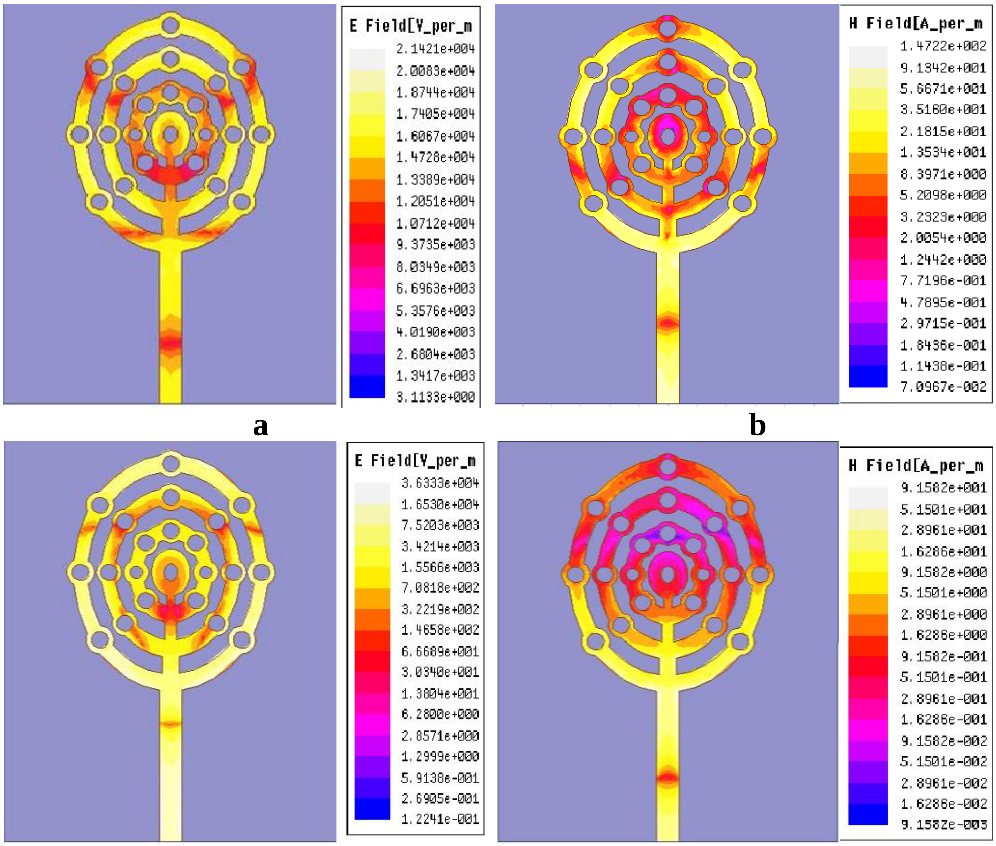
Figure 8 displays the simulated radiation patterns for Design (1) and Design (2). The patterns were acquired at the resonant frequencies of 7.58 GHz and 8.71 GHz, respectively. The radiation patterns are partitioned into two planes: vertical plane (E-Plane) and the horizontal plane (H-Plane). The broadside direction demonstrates the largest intensity of radiation among all the configurations shown. When frequencies resonate, the E-plane pattern is evenly dispersed in all directions. The E-plane pattern is characterised by a rectangular shape, whereas the H-plane pattern has a dumbbell shape. Moreover, the antenna transmits radiation uniformly in all directions, ensuring complete coverage of the surrounding region. The efficacy of the proposed antenna may be assessed by analysing the distributions of the surface current. Figure 9 illustrates the current distribution of Design (1) and Design (2) for the resonance frequencies of 7.56 GHz and 8.71 GHz, respectively. The slots on the ERPA patch possess the capacity to modify this distribution, hence impacting the radiation properties of the antenna.

To be more specific, the circular ring slots modify the trajectory of electric currents on the patch's surface, resulting in the currents being concentrated or deflected along the edges of the slots. This alteration significantly influences the antenna's radiation pattern, as illustrated in Figure 9. Moreover, Figure 9 displays the depicted current flow. The magnetic and electric fields of the suggested antenna design validate the behaviour of the relevant surface currents. Consequently, at certain locations throughout the perimeter of ERPA, the currents will synchronise, resulting in the maximum dose of radiation. In contrast, at different locations along the boundary, the currents will be asynchronous, leading to the minimum degree of radiation. Figure 10(a) and 10(b) show the spatial arrangement of electric and magnetic fields on ERPA at the resonance frequencies of 7.56 GHz and 8.71 GHz for Design (1) and Design (2), respectively. Heightened fluctuations in the electric and magnetic fields will result in an impact on the surface.



a **b**

Figure 9: Surface Currents on the Recommended Antenna at Its Resonance Frequencies. The Currents are Shown for Two Different Designs: Design (1) and Design (2).



c **b**

Figure 10: The Magnetic (H) and the Electric (E) Fields on the Patch of an ERPA Antenna for Two Different Designs: Design (1) and Design (2).

4. Conclusion

This study demonstrates that the proposed antenna, equipped with an ERPA and loaded circular slot, is well-suited for X-band applications. The choice of substrate significantly impacts antenna performance, affecting characteristics such as bandwidth, return loss, and radiation efficiency. Higher dielectric constants negatively affect both bandwidth and radiation efficiency. Both antennas showed excellent performance with wide bandwidth. Design (1) and Design (2) achieved efficiencies of 60.13% and 61.51%, respectively. Design (2) (RT-5880) is thus more suitable for X-band applications. The developed antenna is applicable in vast fields of practical wireless and many other engineering applications where a minimum frequency of 2 GHz and a reflection coefficient less than -10 dB are required.

4.1 Study Limitations and Implications

In this study, the comparison took place only between two substrate material (FR4 and RT5880), thus making it less generalizability of findings across a broader range of materials. The focus on X-band applications limits insights into how antenna performance might vary at different frequency ranges. Moreover, static simulation conditions used may not fully reflect dynamic real-world operational environments, which may impact the accuracy of performance predictions. The findings highlight the critical role of substrate material selection in optimizing antenna performance for X-band applications, suggesting potential improvements in future antenna designs by focusing on materials with favourable dielectric properties. The developed antenna configurations, particularly with RT5880 substrate, demonstrate promising efficiency and bandwidth characteristics suitable for radar systems, military applications, satellite communications, and beyond, indicating practical implications for advancing wireless communication engineering technologies.

4.2 Future Research Directions

The future research directions involve the integration of the device with advanced materials that will improve the antenna's performance and provide more efficient bandwidth. Moreover, advanced beamforming algorithms and beam steering techniques should be considered for further enhancement of the antenna's radiation pattern in operational design. Additionally, efforts should be made to miniaturize it for integration into smaller and more compact devices.

References

Abdelghany, M. A., Ibrahim, A. A., Mohamed, H. A., & Tammam, E. (2024). Compact sub-6 GHz four-element flexible antenna for 5G applications. *Electronics*, *13*(3), 537. https://doi.org/10.3390/electronics13030537

Al-Bawri, S. S., Islam, M. T., Singh, M. J., Alyan, E., Jusoh, M., Sabapathy, T., Padmanathan, S., & Hossain, K. (2021). Broadband Sub-6GHz Slot-based MIMO antenna for 5G NR bands mobile applications. Journal of Physics: Conference Series, http://dx.doi.org/10.1088/1742-6596/1962/1/012038

Alsudani, A., & Marhoon, H. M. (2023). Design and Enhancement of Microstrip Patch Antenna Utilizing Mushroom Like-EBG for 5G Communications. *J. Commun.*, *18*(3), 156-163. http://dx.doi.org/10.12720/jcm.18.3.156-163

Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C., & Zhang, J. C. (2014). What will 5G be? *IEEE Journal on selected areas in communications*, *32*(6), 1065-1082. https://doi.org/10.1109/JSAC.2014.2328098

Deng, Q. J., Pan, Y. M., Liu, X. Y., & Leung, K. W. (2023). A singly-fed dual-band aperture-sharing siw cavity-backed slot antenna with large frequency ratio. *IEEE Transactions on Antennas and Propagation*, *71*(2), 1971-1976. https://doi.org/10.1109/TAP.2022.3232208

Gaid, A. S., Ali, M. A., Saif, A., & Mohammed, W. A. (2024). Design and analysis of a low profile, high gain rectangular microstrip patch antenna for 28 GHz applications. *Cogent Engineering*, *11*(1), 2322827. https://doi.org/10.1080/23311916.2024.2322827

Huang, T.-Y., & Lee, Y.-J. (2024). Design of Microstrip Antenna Arrays with Rotated Elements Using Wilkinson Power Dividers for 5 G Customer Premise Equipment Applications. *International Journal of Antennas and Propagation*, *2024*(1), 2945195. https://doi.org/10.1155/2024/2945195

Hussain, M., Awan, W. A., Alzaidi, M. S., Hussain, N., Ali, E. M., & Falcone, F. (2023). Metamaterials and their application in the performance enhancement of reconfigurable antennas: A review. *Micromachines*, *14*(2), 349. https://doi.org/10.3390/mi14020349

Hussain, N., Awan, W. A., Ali, W., Naqvi, S. I., Zaidi, A., & Le, T. T. (2021). Compact wideband patch antenna and its MIMO configuration for 28 GHz applications. *AEU-International Journal of Electronics and Communications*, *132*, 153612. https://doi.org/10.1016/j.aeue.2021.153612

Khan, M. I., Khan, S., Kiani, S. H., Ojaroudi Parchin, N., Mahmood, K., Rafique, U., & Qadir, M. M. (2022). A compact mmWave MIMO antenna for future wireless networks. *Electronics*, *11*(15), 2450. https://doi.org/10.3390/electronics11152450

Kiani, S. H., Alharbi, A. G., Khan, S., Marey, M., Mostafa, H., & Khan, M. A. (2022). Wideband three loop element antenna array for future 5G mmWave devices. *IEEE Access*, *10*, 22472-22479. https://doi.org/10.1109/ACCESS.2022.3152769

Krishna, N., & Padmasine, K. (2023). A review on microwave band pass filters: Materials and design optimization techniques for wireless communication systems. *Materials Science in Semiconductor Processing*, *154*, 107181. https://doi.org/10.1016/j.mssp.2022.107181

Mahbub, F., Islam, R., Al-Nahiun, S. A. K., Akash, S. B., Hasan, R. R., & Rahman, M. A. (2021). A single-band 28.5 GHz rectangular microstrip patch antenna for 5G Communications Technology. 2021 IEEE 11th Annual Computing and Communication Workshop and Conference (CCWC), https://doi.org/10.1109/CCWC51732.2021.9376047

Munir, M. E., Nasralla, M. M., & Esmail, M. A. (2024). Four port tri-circular ring MIMO antenna with wide-band characteristics for future 5G and mmWave applications. *Heliyon*, *10*(8). https://doi.org/10.1016/j.heliyon.2024.e28714

Mutashar, R. A., Wa'il, A., & Tahir, A. S. (2020). Design and Simulation of Triple Band Circular Patch Microstrip Antenna Based on Shape of Ring and Rectangular Slots. *Open Access J Sci Technol*, *3*, 245-252. http://dx.doi.org/10.31580/ojst.v3i3.1666

Ojaroudi Parchin, N., Jahanbakhsh Basherlou, H., Al-Yasir, Y. I., Abd-Alhameed, R. A., Abdulkhaleq, A. M., & Noras, J. M. (2019). Recent developments of reconfigurable antennas for current and future wireless communication systems. *Electronics*, *8*(2), 128. https://doi.org/10.3390/electronics8020128

Rana, M. S., Hossain, S., Rana, S. B., & Rahman, M. M. (2023). Microstrip patch antennas for various applications: a review. *Indonesian journal of Electrical Engineering and computer science*, *29*(3), 1511-1519. http://dx.doi.org/10.11591/ijeecs.v29.i3.pp1511-1519

Rana, M. S., Sen, B. K., Tanjil-Al Mamun, M., Mahmud, M. S., & Rahman, M. M. (2023). A 2.45 GHz microstrip patch antenna design, simulation, and analysis for wireless applications. *Bulletin of Electrical Engineering and Informatics*, *12*(4), 2173-2184. https://doi.org/10.11591/eei.v12i4.4770

Roh, W., Seol, J.-Y., Park, J., Lee, B., Lee, J., Kim, Y., Cho, J., Cheun, K., & Aryanfar, F. (2014). Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results. *IEEE communications magazine*, *52*(2), 106-113. https://doi.org/10.1109/MCOM.2014.6736750

Saleh, S., Jamaluddin, M. H., Razzaz, F., Saeed, S. M., Timmons, N., & Morrison, J. (2023). Compactness and performance enhancement techniques of ultra-wideband tapered slot antenna: A comprehensive review. *Alexandria Engineering Journal*, *74*, 195-229. https://doi.org/10.1016/j.aej.2023.05.020

Sharma, S., & Kumar, M. (2023). Design and analysis of a 4-port MIMO microstrip patch antenna for 5G mid band applications. *Prog. Electromagn. Res. C*, *129*(2022), 231-243. http://dx.doi.org/10.2528/PIERC22120104

Singh, A. K., Padhy, B., & Ray, K. (2024). Design of high-performance miniaturised circular slotted microstrip power dividers. *AEU-International Journal of Electronics and Communications*, *174*, 155013. https://doi.org/10.1016/j.aeue.2023.155013

Sufian, M. A., Hussain, N., Askari, H., Park, S. G., Shin, K. S., & Kim, N. (2021). Isolation enhancement of a metasurface-based MIMO antenna using slots and shorting pins. *IEEE Access*, *9*, 73533-73543. https://doi.org/10.1109/ACCESS.2021.3079965

Ullah, S., Ruan, C., Sadiq, M. S., Haq, T. U., & He, W. (2019). High efficient and ultra wide band monopole antenna for microwave imaging and communication applications. *Sensors*, *20*(1), 115. https://doi.org/10.3390/s20010115

Yang, H.-C., & Alouini, M.-S. (2020). *Advanced Wireless Transmission Technologies: Analysis and Design*. Cambridge University Press. https://doi.org/10.1017/9781108332835

Yang, Y., Wei, X., Yao, W., & Lan, J. (2023). Broadband electrical impedance matching of sandwiched piezoelectric ultrasonic transducers for structural health monitoring of the rail in-service. *Sensors and Actuators A: Physical*, *364*, 114819. https://doi.org/10.1016/j.sna.2023.114819

Zahid, M. N., Gaofeng, Z., Kiani, S. H., Rafique, U., Abbas, S. M., Alibakhshikenari, M., & Dalarsson, M. (2022). H-shaped eight-element dual-band MIMO antenna for sub-6 GHz 5G smartphone applications. *IEEE Access*, *10*, 85619-85629. https://doi.org/10.1109/ACCESS.2022.3189658