Design and Analysis of a Hexagonal Patch Antenna Operating at 3.5 GHz for Wireless Communication Applications

Yudi Barnadi[1], Ajeng Mayang Kurniaviep Sugeng [2], Ase Suryana [3], and Arief Budi Santiko[4*]

[1,2,3]*Jurusan Teknik Elektro, Universitas Widyatama Bandung*
Jl. Cikutra no.204A. Bandung 40125 Jawa Barat, Indonesia

[4]*Research Center for Telecommunication, National Research and Innovation Agency-BRIN*
Bandung,40135, Indonesia

[*]*Corresponding author. Email:* arie036@brin.go.id.

Abstract— Microstrip antennas are widely recognized for their compact structure, low profile, and ease of fabrication, making them highly suitable for modern wireless communication systems. Traditionally, these antennas incorporate a rectangular metallic patch as the radiating element. In this study, a novel microstrip antenna design featuring a hexagonal metal patch is proposed, specifically optimized to resonate at 3.5 GHz, a frequency band allocated for 5G wireless communication applications. The antenna is constructed on an F4BMX220 substrate with a thickness of 1.5 mm, chosen for its favorable dielectric properties and mechanical stability. The feeding mechanism employs an inset-fed microstrip line, enabling better impedance matching and improved power transfer. A full ground plane is used on the underside of the substrate to enhance isolation and minimize back radiation. The complete design, simulation, and optimization processes are carried out using CST Studio Suite, a professional electromagnetic simulation tool. Key performance parameters such as return loss (S_{11}), directivity, and gain are thoroughly analyzed. The design aims to achieve an S11 value below -10 dB, ensuring efficient radiation at the target frequency. With its optimized structure and favorable performance, the proposed antenna serves as a promising candidate for integration into next-generation 5G communication systems. Based on the fabricated prototype, the antenna demonstrates a gain of 4.5 dBi and a bandwidth of 24 MHz.

Keywords— Antenna 5G; Hexagonal patch antenna; Microstrip antenna

I. Introduction

An antenna is an essential RF/microwave device that converts electrical signals into electromagnetic waves and vice versa. Antennas play a vital role in wireless communication systems, functioning in both transmitting (Tx) and receiving (Rx) operations. One widely used type is the microstrip patch antenna, which offers several advantages. These include being lightweight, cost-effective, easy to manufacture, and conformable to various surfaces, as noted in [1].

Various types of patch antennas have been developed to suit a wide range of wireless communication applications. In [1], a patch antenna operating at 2.4 GHz is presented, featuring dimensions of 36 × 28.66 mm² and using Duroid 5880 as the dielectric substrate. Another design involves a patch antenna fabricated on FR-4, operating at 28 GHz, which achieves a simulated gain of 7.19 dBi and a bandwidth of 1.352 GHz. In [3], a rectangular microstrip antenna with an inset feed is used for WiMAX applications, employing an FR4 substrate with a thickness of 1.6 mm. Experimental results show that a 4×1 patch antenna array provides greater directivity compared to a single patch antenna. Additionally, in [4], a microstrip patch antenna is modified by truncating its corners, allowing it to resonate at 2.2 GHz. This technique is used to achieve circular polarization, which enhances signal stability and reception quality in dynamic environments.

Furthermore, various microstrip patch antenna designs have been developed to either reduce size or support dual- or multi-resonant frequency operation, as outlined in [5]–[11]. In [5], a fractal hexagonal antenna with a partially defective ground structure is presented, enabling multiband operation across multiple frequencies. For instance, [6] proposes a multilayer gap-coupled dual-band hexagonal microstrip patch antenna, designed to achieve compact size and support circular polarization. In [7], a miniaturized microstrip patch antenna is developed using a Genetic Algorithm, resulting in a size reduction of up to 60%. Meanwhile, [8] introduces a triangular microstrip antenna that incorporates a triangular split-ring resonator on the patch and slots on the ground plane, allowing it to resonate at frequencies ranging from 3.5 GHz to 9.7 GHz, with average peak gains between 0.6 dB and 2.09 dB. In [9], a triangular microstrip antenna with circular slots on the metallic patch is designed to operate at 5.8 GHz, offering a bandwidth of 100 MHz and a fractional bandwidth of 3%. Another design explored in [10] features a hexagonal microstrip antenna with a partial ground plane, intended to operate within the UHF range (470–806 MHz), achieving a size reduction of up to 60%.

A metamaterial patch antenna has been proposed for various applications, as shown in [11–16]. By incorporating metamaterials, patch antennas can be enhanced in terms of miniaturization, gain, bandwidth, circular polarization, and mutual coupling suppression in MIMO antenna systems [11]. In [12], a dual-band patch antenna was designed by adding a

Received 18 September 2024, Revised 16 June 2025, Accepted 28 June 2025.
DOI: https://doi.org/10.15294/jte.v16i2.13902

hexagonal-shaped Split Ring Resonator (SRR), intended to operate at frequencies above 28 GHz. The metamaterial, based on a hexagonal SRR, aims to improve isolation and gain. In [13] and [14], hexagonal-shaped metamaterials were used to enhance the gain and bandwidth of the proposed antennas. The antenna in [13], fabricated on an FR-4 substrate, operates over a frequency range of 1–12 GHz and achieves a peak gain of 6.92 dBi. Meanwhile, the antenna in [14], with a center frequency of 3.5 GHz, achieves a gain of 4.47 dBi and a bandwidth increase of 368% compared to the antenna without metamaterials. In [15], a new cascaded hexagonal ring-shaped metamaterial element is designed, and cross-shaped slots are etched on the ground plane of the microstrip antenna to widen the impedance bandwidth. Furthermore, the antenna proposed in [16] uses a metamaterial structure aimed at achieving triple-band operation. It incorporates a hexagonal SRR resonating at 1.9 GHz and 3.1 GHz, and a hexagonal Circular Ring Resonator (CRR) resonating at 5.2 GHz, 9.6 GHz, and 18.5 GHz.

Meanwhile, references [17–20] present the design of hexagonal or other shaped microstrip antenna arrays. In [17], a 1×2 array of hexagonal microstrip antennas is introduced for Bluetooth, WLAN, and WiMAX applications, operating in the 2.4–5 GHz range and offering a maximum directivity gain of 4 dBi. In [18], a 2×1 planar antenna array with hexagonal-shaped patches is designed to operate in the Ku-band for satellite TV broadcasting applications, with simulated results showing a maximum directivity of 4.4 dBi at the operating frequency. In [19], a performance comparison is presented between 2×4 circular and 2×2 rectangular microstrip patch arrays for satellite applications, based on simulation results. The antenna array proposed in [20] features a triangular-shaped patch and achieves a directivity of 11.4 dB at 10 GHz.

This study presents the design of a hexagonal microstrip antenna utilizing edge-feed and inset feed on the feeding line, optimized for a 3.5 GHz operating frequency pertinent to 5G applications. Circular antennas tend to give better results in terms of impedance reflection at an operated frequency, while hexagonal antennas can be more focused in terms of S_{11} control, wider bandwidth and higher gain antenna. Employing an RO5880 substrate with a thickness of 1.575 mm, the antenna utilizes the bottom substrate as the ground plane. The design and simulation aspects are illustrated using S-parameter graphs, gain analysis, and radiation pattern evaluations, with simulated results obtained from CST Studio Suite.

This paper is organized as follows: Section I provides an overview of the background and related works on microstrip antenna design. Section II describes the design methodology, including the theoretical framework and simulation parameters. Section III presents and discusses the simulation and measurement results, focusing on key performance metrics such as return loss, gain, and radiation pattern. Finally, Section IV concludes the study and offers suggestions for future research.

II. Method

A patch antenna is a common type of microstrip antenna that consists of two metal layers separated by a dielectric material, as shown in Figure 1. The top layer acts as the radiating patch, while the bottom layer serves as the ground plane. Between them, the dielectric substrate helps define how the antenna performs, things like its frequency, bandwidth, and overall efficiency. In this design, the antenna uses an edge-fed method, where the feed line connects directly to the edge of the patch. This approach is straightforward and effective, making it a popular choice for many wireless communication systems. It's especially useful when the feed and patch are properly matched in impedance, helping to ensure good signal transmission and minimal loss.

The patch antenna is designed with a hexagonal-shaped metallic patch on the upper side of the substrate, and a ground plane on the lower side, illustrated in Figure 2. It operates at a frequency of 3.5 GHz and utilizes an F4BMX220 dielectric substrate with ε_r of 2.2, Tanδ of 0.001, and substrate thickness (h) of 1.5 mm. The F4BMX220 substrate is chosen because it is more cost-effective than the Rogers substrate and has lower loss compared to FR4, as indicated by its low loss tangent (Tan δ) value. The antenna design process initiates with calculations using equation 1 to determine the radius dimensions of the circular patch at the desired resonance frequency (f_0) [10]-[11].

$$a_h = \frac{c}{\sqrt{\left\{1+\frac{2h}{\pi \varepsilon_r F}\left[\ln\frac{\pi F}{2h}+1.7726\right]\right\}}} \tag{1}$$

$$F = \frac{8.791 \times 10^9}{fo\sqrt{\varepsilon_r}} \tag{2}$$

After obtaining the dimensions of the circular patch radius, the length of the side (s) of the hexagonal patch antenna is calculated using the following equation 2:

$$\pi {a_h}^2 = \frac{3\sqrt{3}}{2} S^2 \tag{3}$$

Meanwhile, for calculating the length (W) and width (L) of the substrate, and the area of the length (W_g) and width (L_g) of the ground plane area, you can use the following equations (4-10):

$$w = \frac{c}{\sqrt{\frac{\varepsilon_{re}+1}{2}}} \tag{4}$$

$$w = \frac{\varepsilon_{re}+1}{2} + \frac{\varepsilon_{re}-1}{2}\left[1+\frac{12h}{2}\right]^{-0.5} \tag{5}$$

$$L = L_{eff} - 2\Delta L \tag{6}$$

$$L_{eff} = 0.5\frac{\lambda}{\sqrt{\varepsilon_r}} \tag{7}$$

$$\Delta L = 0.412\left(\frac{\varepsilon_{re}+0.3}{\varepsilon_{re}-0.3}\right)\frac{\left[\frac{w}{t}+0.264\right]h}{\left[\frac{w}{t}+0.8\right]} \tag{8}$$

$$W_g = W + 6_h \tag{9}$$

$$L_g = L + 6_h \tag{10}$$

Next, equations (7-8) can be used to determine the dimensions of the feeding line, specifically its length (L_f) and width (W_f).

$$Z = \frac{120\,\pi}{\sqrt{\varepsilon_{re}\left[\frac{h}{w_f}+1.393+0.667\ln\left(\frac{h}{w_f}+1.444\right)\right]}} \tag{11}$$

$$F = \frac{\lambda}{4} = \frac{\lambda_o}{4\sqrt{\varepsilon_{re}}} \tag{12}$$

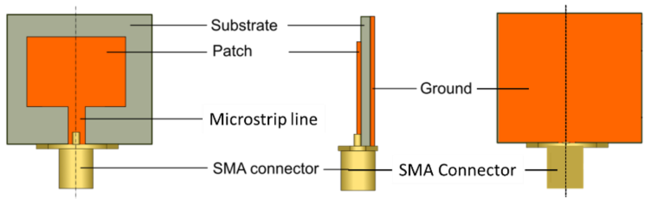


Figure 1. Microstrip patch antenna with edge feed techniques.

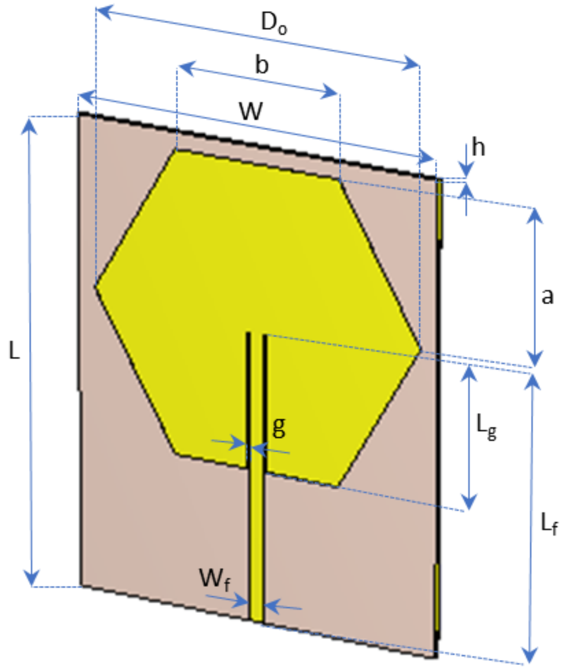


Figure 2. The optimized hexagonal antenna design.

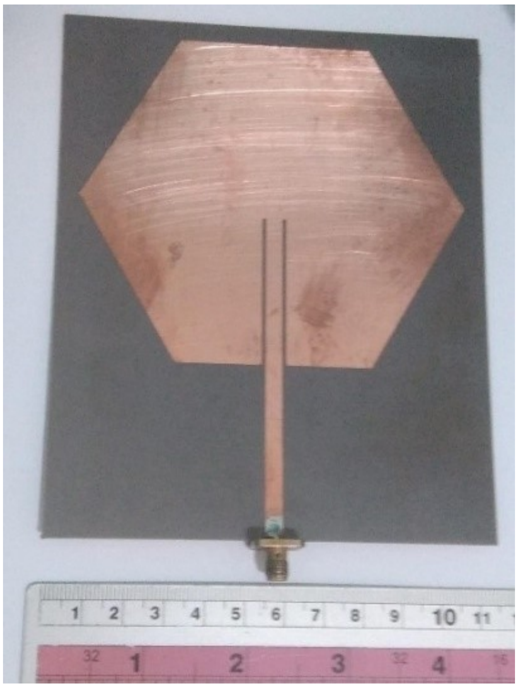


Figure 3. Fabrication of the hexagonal antenna.

Once the dimensions of the hexagonal microstrip antenna are determined using the equations mentioned earlier, the design will undergo simulation to assess its performance using CST Studio Suite, a 3D electromagnetic simulation software as shown in Figure 2.

The parameters optimized and displayed in Table 1 were derived through multiple simulations aimed at achieving a hexagonal antenna design resonating at approximately 3.5 GHz frequency. Adjusting the diameter of the circular patch impacts both the side length of the hexagonal patch antenna and the desired resonance frequency. Similarly, modifying the length and width of the feeding line affects the value of S_{11} or the antenna's return loss.

III. Results and Discussion

The hexagonal antenna is fabricated on a F4BMX220 substrate, which is 1.5 mm thick, and utilizes an SMA connector for its input. The printed dimensions of this antenna are 140.25 mm x 114.40 mm as shown in Figure 3.

TABLE I. The optimized parameters design of the hexagonal antenna.

Parameter	Value (mm)
W	114
L	140
h	1.5
W_f	4.37
L_f	85.36
L_g	40.35
a, b	51.53
D_o	103.06
g	1

Based on the S-parameter measurements shown in Figure 4, the measured S11 value is -14.7 dB at 3.527 GHz, while the simulated S11 value is -23.06 dB at 3.5 GHz. This indicates a minor frequency shift of 0.027 GHz and a slight discrepancy of 8.36 dB in the S11 magnitude between the measured and simulated results.

When calculating the antenna bandwidth using an S_{11} value below -10 dB, the measured bandwidth is approximately 0.024 GHz, whereas the simulated bandwidth is about 0.036 GHz. The slight difference in overall S_{11} values and bandwidth between the simulated and measured results is attributed to material property tolerances and parasitic effects on the patch. The material property tolerances mean the actual dielectric constant (ε_r) and loss tangent (Tanδ) of the substrate used in fabrication may differ slightly from the ideal values assumed in simulation. While in patch antennas, nearby metallic structures or elements that are not electrically connected but influence the antenna's radiation pattern or impedance are considered parasitic.

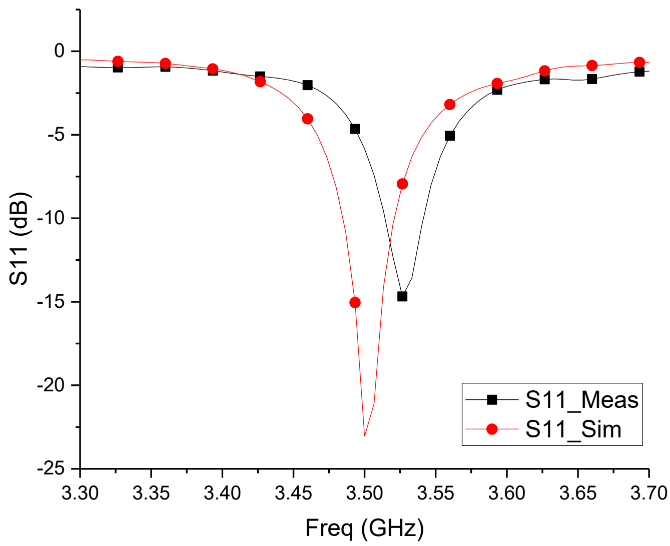


Figure 4. S_{11} graph between the simulated and measured results.

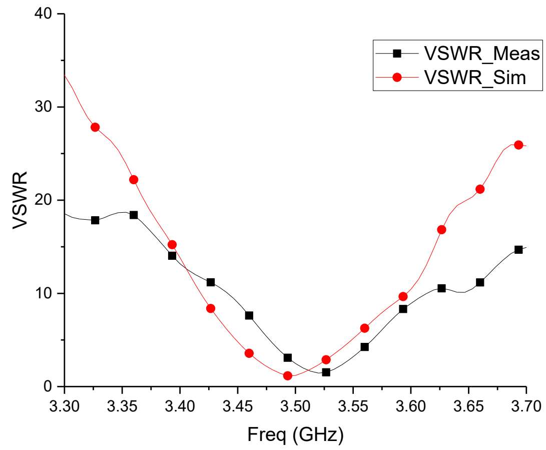


Figure 5. VSWR between simulated and measured results.

Figure 5 presents the VSWR of the hexagonal antenna, comparing the simulated and measured results. The VSWR indicates how well the antenna is impedance-matched to the transmission line or source port (typically 50 ohms). According to the graph, the simulated VSWR is 1.15 at 3.5 GHz, while the measured VSWR is 1.53 at 3.527 GHz. Although there is a small difference of approximately 0.38 between the two values, both are below or close to 1.5, indicating a good impedance match between the proposed antenna and the 50-ohm transmission line.

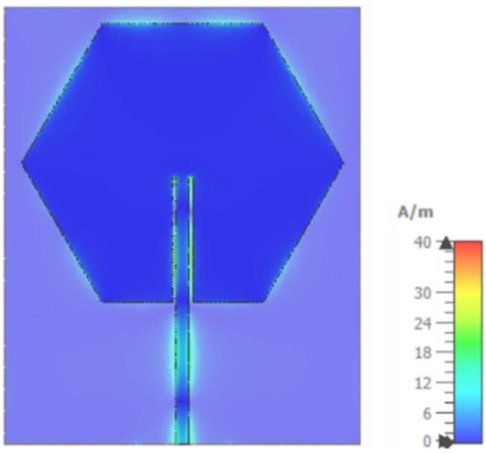


Figure 6. Current distribution of the proposed antenna.

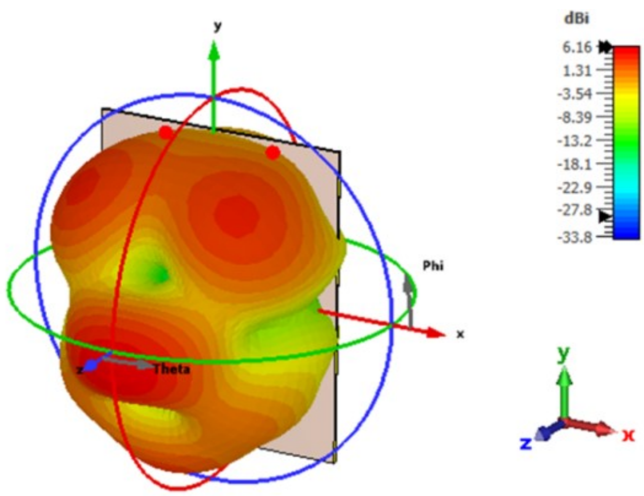


Figure 7. Gain simulated result of the hexagonal antenna.

The current distribution of the proposed antenna is shown in Figure 6, where strong current concentration appears along the feeding line and gradually decreases toward the edges. This indicates excitation of the fundamental resonant mode, resulting in symmetrical and efficient radiation. The gradual tapering of current across the patch suggests good impedance matching and supports wideband performance.

The simulated gain of the hexagonal antenna shows approximately 6.16 dBi at 3.5 GHz, as depicted in Figure 7, but after measurement of the fabricated antenna, the achieved gain is only 4.5 dBi at the center frequency. Additionally, according to the simulation results depicted in Figure 8, the radiation pattern of this antenna reveals that in the E-plane, the main lobe has a magnitude of 5.64 dBi with a side lobe level of -14.5 dB, whereas in the H-plane, the main lobe registers a magnitude of 6.17 dBi with a side lobe level of -3.0 dB.

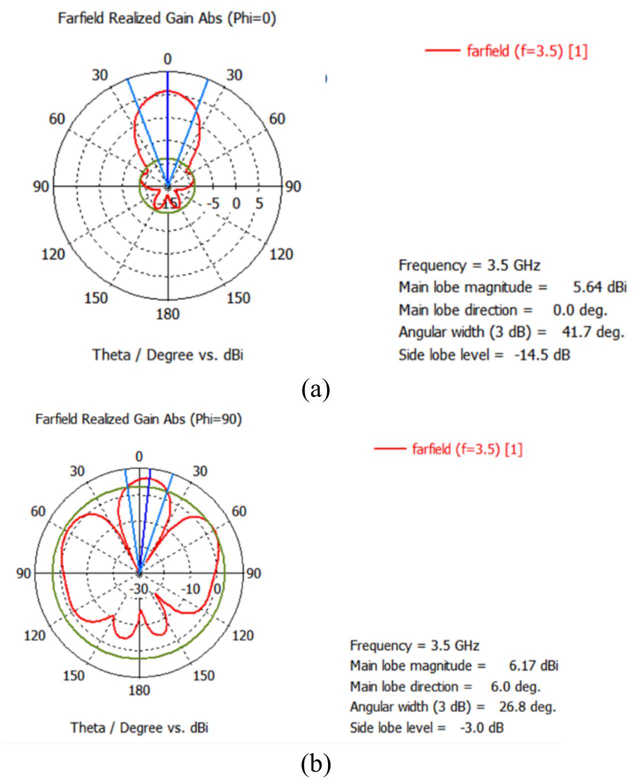


Figure 8. Simulation results of radiation pattern for the hexagonal antenna. a) E-Plane (Phi = 0) (b) H-Plane (Phi = 90)

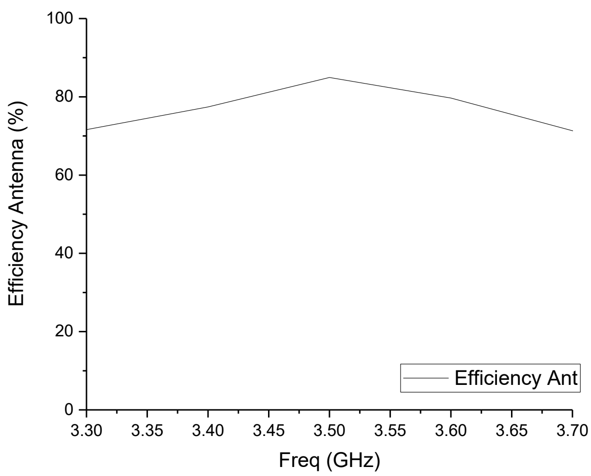
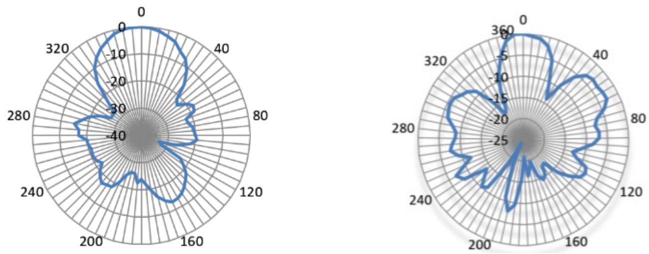


Figure 9. Efficiency antenna of the hexagonal antenna.

The antenna efficiency, as shown in Figure 9, indicates how effectively the antenna converts input power (from a transmitter) into radiated electromagnetic waves. Higher efficiency means less power is lost as heat, resulting in stronger signals, better communication range, and improved battery life in wireless devices. Poor efficiency leads to wasted power, weak transmission, and potential overheating. In the proposed antenna design, the efficiency reaches 84.94% at 3.5 GHz, indicating minimal mismatch losses and demonstrating strong performance for a microstrip patch antenna.

Figure 10 displays the radiation pattern measurements of the hexagonal antenna. Generally, the measurements in the E-plane and H-plane exhibit radiation patterns that resemble those from the simulations, albeit with minor variations attributable to the data collection intervals of every 5 degrees. In the E-field radiation pattern, the main lobe indicates a directional antenna, while the side lobe level (SLL) is very small at approximately -17 dBi. However, the hexagonal antenna appears to be omnidirectional in the H-field radiation pattern, with an SLL of around -5 dBi. The measured and simulated radiation patterns are generally consistent, with slight differences likely caused by measurement errors.

For the overall results, the hexagonal antenna is one of many variant shapes of the microstrip patch antenna. The hexagonal antenna offers higher gain due to its directional coverage, a slightly broader bandwidth, but its size is slightly larger due to the geometrical arrangement of this shape.



(a) (b)

Figure 10. Measurement results of radiation pattern for the hexagonal antenna. (a) E-Plane (b) H-Plane

TABLE II. COMPARISON WITH PREVIOUS WORKS

Ref.	Patch Shaped Antenna	Freq (GHz)	Gain (dBi)
[1]	Square	2.39	6.7 (simulated)
[2]	Square	28	7.2 (simulated)
[3]	Triangular	10.3	2.5 (simulated)
[5]	Fractal Hexagonal		2.1 (simulated)
[6]	Hexagonal-Triangular Combinatoria	1.176 & 1.575	3.4 (measured) & 3.6 (measured)
[8]	Triangular with circular slotted	5.8	1.5 (simulated)
This work	Hexagonal	3.5	6.6 (simulated) 4.5 (measured)

The table presents a comparison of different patch-shaped antennas, highlighting their operational frequencies and corresponding gains, either simulated or measured. Square patch antennas [1] and [2] exhibit relatively high simulated gains of 6.7 dBi and 7.2 dBi at 2.39 GHz and 28 GHz, respectively. In contrast, triangular designs generally show lower gains, such as 2.5 dBi at 10.3 GHz [3] and 1.5 dBi at 5.8 GHz for the slotted version [8]. The fractal hexagonal design in [5] also yields a relatively low gain of 2.1 dBi. Meanwhile, [6] investigates a dual-band hexagonal-triangular combination with moderate measured gains of 3.4 dBi and 3.6 dBi. Compared to these, the proposed hexagonal patch in "This work" at 3.5 GHz achieves the highest simulated gain of 6.6 dBi and a strong measured gain of 4.5 dBi, indicating both high design efficiency and practical performance improvements over previous designs.

CONCLUSION

The hexagonal antenna has been designed, simulated, and measured to operate at 3.5 GHz on an F4BMX220 substrate. The measured gain of the hexagonal antenna is 4.5 dBi, showing directional characteristics in its radiation pattern. The simulated and measured results differ slightly due to material properties and parasitic effects on the patch, causing frequency shifts and degraded gain. The measured bandwidth is approximately 24 MHz. In future applications and research, the proposed design could be adapted for a phased array antenna, increasing its gain.

ACKNOWLEDGEMENT

This journal article research funded by Widyatama University through the OLOPOY-2 (One Lecture One Paper One Year) Research Program in 2024.

REFERENCES

[1] M. S. Rana and M. M. Rahman, "Study of Microstrip Patch Antenna for Wireless Communication System," 2022 International Conference for Advancement in Technology (ICONAT), Goa, India, 2022, pp. 1-4, doi: 10.1109/ICONAT53423.2022.9726110.

[2] Md Sohel Rana, et all, "Design of 28 GHz Microstrip Patch Antenna for Wireless Applications," Indonesian Journal of Electrical Engineering and Informatics (IJEEI), Vol. 11, No. 4, December 2023, doi: 10.52549/ijeei.v11i4.4942.

[3] N. A. Wahab, S. A. Nordin, W. N. W. Muhamad and S. S. Sarnin, "Microstrip Rectangular Inset-Fed Patch Array Antenna for WiMax Application," 2020 IEEE International RF and Microwave Conference (RFM), Kuala Lumpur, Malaysia, 2020. pp. 1-4. doi: 10.1109/RFM50841.2020.9344799.

[4] F. Armin, A. Noer, Kamirul and S. Prasetya, "Modification of 2.2 GHz S-Band Rectangular Patch Microstrip Antenna using Truncated Corner Method for Satellite Applications," 2020 3rd International Seminar on Research of Information Technology and Intelligent Systems (ISRITI), Yogyakarta, Indonesia, 2020, pp. 284-288. doi: 10.1109/ISRITI51436.2020.9315475.

[5] R. Koniammal, G. P. Ramesh and G. G. Naidu, "Design a Multiband Frequency of Partial Defected Ground for Hexagonal Fractal Antenna," 2023 International Conference on Data Science and Network Security (ICDSNS), Tiptur, India, 2023, pp. 1-7, doi: 10.1109/ICDSNS58469.2023.10244918.

[6] C. Sahana, M. Nirmala Devi and M. Jayakumar, "Hexagonal-Triangular Combinatorial Structure Based Dual-Band Circularly Polarized Patch Antenna for GAGAN Receivers," in IEEE Access, vol. 11. pp. 23205-23216. 2023. doi: 10.1109/ACCESS.2023.3252913.

[7] M. Boudjerda, A. Reddaf, A. Kacha, K.H. Cherif, T.E.A. Alharbi, M.S. Alzaidi, M. Alsharef, S.S.M. Ghoneim, " Design and Optimization of Miniaturized Microstrip Patch Antennas Using a Genetic Algorithm". Electronics 2022, 11. 2023, doi: 10.3390/electronics11142123.

[8] K. Mahendran, R. Gayathri, and H. Sudarsan, "Design of multi band triangular microstrip patch antenna with triangular split ring resonator for S band, C band and X band applications," Microprocess. Microsyst. 80, C (Feb 2021), doi: 10.1016/j.micpro.2020.103400.

[9] A. Atif, A. Majid, M. Zahid, Y. Amin, “Circular Slotted Triangular Patch Antenna for 5.8 GHz ISM Band Applications,” Eng. Proc. 2023, 46, 10, doi: 10.3390/engproc2023046010.

[10] R. Sharma, N. S. Raghava and A. De, "Design of Compact Circular Microstrip Patch Antenna using Parasitic Patch," 2021 6th International Conference for Convergence in Technology (I2CT), Maharashtra, India, 2021, pp. 1-4, doi: 10.1109/I2CT51068.2021.9418104.

[11] P. Kumar, T. Ali and M. M. M. Pai, "Electromagnetic Metamaterials: A New Paradigm of Antenna Design," in IEEE Access, vol. 9, pp. 18722-18751, 2021, doi: 10.1109/ACCESS.2021.3053100.

[12] Talari, S. and Sekhar, P.C. 2024. A High Gain Dual Band Hexagonal Metamaterial Inspired Antenna for 5G Applications. Engineering, Technology & Applied Science Research. 14, 6 (Dec. 2024), 18029–18035, doi: 10.48084/etasr.8575.

[13] Meshari Alsharari, Raj Agravat, Sunil Lavadiya, Ammar Armghan, Khaled Aliqab, Shobhit K. Patel, “Design and development of hexagonal-shaped copper and liquid metamaterial-loaded superstrate patch antenna for 5G, WLAN, tracking and detection applications, “ Ain Shams Engineering Journal, Volume 16, Issue 1, 2025, ISSN 2090-4479, doi: 10.1016/j.asej.2024.103236.

[14] H. Ryanu, “A Bandwidth and Gain Enhanced Hexagonal Patch Antenna using Hexagonal Shape SRR”, INFOTEL, vol. 16, no. 2, pp. 457-473, May 2024.

[15] Cui, Cheng, Yingnan Ren, Pengfei Tao, and Binzhao Cao. 2021. "Microstrip Antenna with High Gain and Strong Directivity Loaded with Cascaded Hexagonal Ring-Shaped Metamaterial" *Materials* 14, no. 23: 7289. https://doi.org/10.3390/ma14237289.

[16] Saranya, S., Sharmila, B., Jeyakumar, P. et al., “Design and Analysis of Metaresonator-Based Tri-Band Antenna for Biosensing Applications,” Plasmonics 18, 1799–1811 (2023), doi: 10.1007/s11468-023-01873-2.

[17] K. Koesmarijanto, N. A. P. Alifia, and H. Darmono, “Design and Implementation of 2x4 Element Hexagonal Array Microstrip Antenna with DGS Method in the Shape of Dumbbell Circle Head for 2.4 GHz Frequency Wi-Fi Applications”, Jartel. Vol. 12, no. 4. Dec. 2022. pp. 232-238.

[18] C. G. L. N. Moukengue, et al., “Design of A New Hexagonal Patch Antenna Array”, Int Res J Adv Engg Hub, vol. 2, no. 06, pp. 1692–1697, Jun. 2024, doi: 10.47392/IRJAEH.2024.0234.

[19] S. Kesana, et al., “2x4 Circular and 2x2 Rectangular Microstrip Patch Antenna Array of 4.2 GHz for Satellite Applications, “National Journal of Antennas and Propagation, Vol. 3, Issue 2, ISSN 2582-2659, doi: 10.31838/NJAP/03.02.03.

[20] Mohd Asaduddin, Shaik Seif Shah, Mohd Asim Siddiqui, "Design of Microstrip Patch Antenna Array", International Journal of Wireless and Microwave Technologies(IJWMT), Vol.13, No.3, pp. 39-48, 2023, doi:10.5815/ijwmt.2023.03.04.