Received: June 18, 2024. Revised: August 7, 2024.

International Journal of
Intelligent Engineering & Systems

http://www.inass.org/

Design and Implementation of a Partially-Grounded Dual-Band Compact Patch Antenna with Enhanced Selectivity for Multiservice Wireless Communication Applications

Ahmed Lateef Khudaraham[1]* **Zaid M. Khudair[1]** **Abdullah Nasser Ibraheem[1]**

[1]*Department of Biomedical Engineering, College of Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq*
* Corresponding author's Email: ahmed.lateef771@nahrainuniv.edu.iq

Abstract: This paper presents a partially-grounded dual-band compact patch antenna with high selectivity for 2.4 GHz and 6.4 GHz wireless communication systems. The design concept is to achieve the 2.4 GHz resonance by using a simple patch, then introducing a U-shaped slot at the patch to grant the 6.4 GHz resonance. In order to minimize the design geometry without effecting the antenna performance, a center square cut-out is inserted into the center of the patch with two other cut-outs etched out from the upper part of the patch. For the selectivity enhancement, the partial ground plane is presented and studied. The proposed antenna reveals good performance and both bands can be independently controlled by tuning and adjusting various parts of the antenna. The proposed antenna is designed on a Rogers RT5880 substrate with thickness of 1.57 mm and overall dimension of 30x30 mm^2 using CST-MW package and the simulated results are verified experimentally with very good agreement between the two approaches. The impedance bandwidths are 0.4 GHz and 0.2 GHz at 2.4 GHz and 6.4 GHz, respectively. The gains of the proposed antenna are 1.2 dB and 1.21 dB, respectively with return loss of -37.70 dB and 36.90 dB, respectively. The proposed dual-band compact antenna exhibits omni-directional radiation patterns and achieves a better gain in comparison to monopole antennas.

Keywords: CST-MW, Rogers RT5880 (Lossy), Microstrip patch antenna, Multi-band, High selectivity, Partially grounded, Wireless applications.

1. Introduction

The increasing demand for wireless communication application system requires antennas that are cost-effective, lightweight, and have a low physical profile. Among the many antenna options available, microstrip patch antennas stand out for their suitability in wireless applications due to their simple design, various shapes, easy to install, and compatible with Microwave and Millimeter wave Integrated Circuits (MMIC). Despite these features, microstrip patch antennas have been the major topic of active research to address remarkable limitations, including narrow bandwidth, low efficiency, low gain, and limitations in power capabilities [1]. For achieving multiband operation, multiple antennas can be used, but this increases design complexity, cost, and size. In addition, using multiple antennas increase the coupling issues which in turn reduces antenna overall performance. A different approach is to manipulate and to perform adjustments to the antenna so that it can be used for multiband wireless communications [2]. This technique involves the adjustment of the antenna parameters to support multiband operation. Multiple techniques have been proposed for this purpose, including slots etching from the radiating patch, utilizing a tapered fed by coplanar waveguide, integrating metamaterials with antennas, utilizing a capacitive-coupled patch, and a multi-layered antenna geometry. Nevertheless, these approaches are primarily focused on adjusting the radiating patches and often fall short of achieving the required bandwidth that is crucial for multiband application systems [3].

Microstrip patch antennas are vastly used due to their overall simple profile, robustness, simplicity of fabrication, low cost, and many other privileges compared to conventional antennas. These antennas are widely used for short range and high frequency applications. A low-profile antenna has a small dimensions in terms of height and width, and can easily be integrated with a flat surface. Nevertheless, these microstrip patch antennas suffer from the drawbacks of a low directivity, limited bandwidth, and low gain, limiting its applications. For lower resonance frequencies, the patch size increases and higher wavelength is achieved, this means that antenna size is inversely proportional to the frequency and directly proportional to the wavelength [4]. Unlike the conventional antennas, microstrip patch antennas are known for their compact geometry and simplicity, and can be mounted on any plane surface within small areas. In addition, they also can exhibit good radiation properties with significant directivity and gain [5]. Multiple techniques for wireless dual- band frequency designs are reported and discussed, including the use of quarter-wavelength resonant slots in different shapes, coplanar fed, and defected ground plane [6].

In [7] the author presents a dual-band microstrip patch antenna design for Wi-Fi applications. The antenna design achieves bandwidths of 53.6 MHz at 2.41 GHz and 200.4 MHz at 5.8 GHz, these bandwidths are still insufficient for some applications that requires boarder bandwidths for high data rates. The use of FR-4 dielectric substrate has a dielectric loss compared to other materials such as Rogers or Teflon-based substrates. The antenna has a dimensions of (50 x 50 x 1.6 mm^3), these dimensions may still be large for some compact or portable devices that requires smaller antenna design. In [8] Dual-band microstrip rectangular patch antenna for Wi-Fi is designed to cover two specific frequency bands. One of the main limitations in this design is the narrow bandwidths which are appears between 2.5 GHz and 2.6 GHz, providing 100 MHz bandwidth, and between 5.7 GHz and 5.9 GHz, providing 200 MHz bandwidth. Using FR-4 substrate in this design can negatively affect the antenna performance, leading to lower radiation efficiency, lower bandwidth and high dielectric losses compared to other substrate materials. The antenna has dimensions of 44 mm × 41 mm, which may still be large for some compact wireless applications. In [9] a dual band patch antenna for Bluetooth and wireless local area networks applications was designed. The designer used slots and DGS in the design which may increase the complexity of the antenna structure. The increased complexity may lead to more challenges and expensive fabrication processes. The specific values of bandwidths are 82.926 MHz and 162.12 MHz may be still limiting for some high data rates applications. The antenna has a dimensions of (50 x 50 x 1.6 mm^3) which may be still large in size for application that required antenna smaller in size. In [10] the author proposed design of dual band microstrip patch antenna using metamaterial. Wide bandwidth is difficult to achieve when using metamaterial. Metamaterials are effectively operate over narrow bandwidth. Higher losses and reduced efficiency may be exhibited when using metamaterials. One of the major limitations in this design is that the narrow bandwidth and large dimensions (56mm × 82 mm). In [11] the author designed a dual-band antenna for LTE-R and 5G lower frequency operations. The proposed antenna dimensions are relatively large (180 × 60 mm), which may be a drawback for applications that required smaller antenna dimensions such as mobile devices. A narrow bandwidth was recorded for the antenna (130 MHz and 500 MHz) which is insufficient, especially for applications that requires high data rates. A dual-band antennas for wireless communication applications proposed in [12-14]. Fabricating the proposed antennas with precision may discompose challenges, especially in achieving the geometric parameters accurately. Small changes from the intended design could affect antenna performance. While some applications in wireless communications requires antenna compact in size, the proposed designs may still be considered large in size for certain applications. The proposed designs in [15-18] are suffering from design complexity, large size, narrow bandwidth and sensitivity to physical parameters. Each of these antenna designs, require an accurate manipulation of precise physical parameters and suspicious design processes to achieve the desired performance characteristics. This complexity can make the antennas challenging to optimize, fabricate, and reproduce consistently.

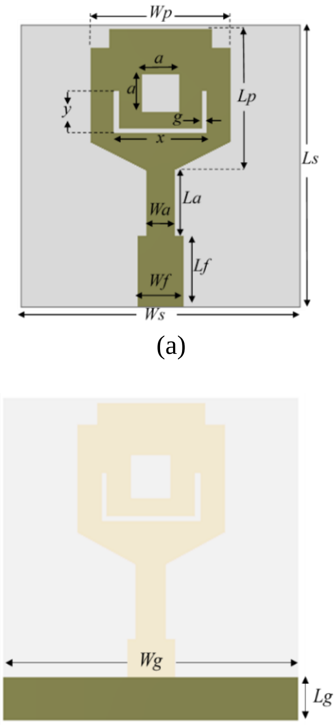
In this paper, a dual-band microstrip patch antenna is designed having a dimension of 30×30 mm^2 on a 1.57 mm thick Rogers RT5880 substrate for wireless applications. The antenna consists of a square patch with a U-shaped slot placed at the center of the patch, and multiple cut-outs to achieve antenna compactness. The slot placement specifies the antenna operating frequencies which are 2.4 GHz with the return loss of -37.07 dB, and 6.4 GHz with the return loss of -36.90 dB. The inclusion of the slots and cut-outs on the patch tunes the operating frequencies. This optimizes antenna performance within the desired bands. The proposed design significantly offers higher selectivity and compactness while maintaining simplicity.

Received: June 18, 2024. Revised: August 7, 2024.

Compared to existing works, it achieves high selectivity, enabling it to be more precise in differentiating between desired signals and potential interference. This high selectivity enhances the overall performance and reliability of communication systems. Another aspect is used to enhance the antenna performance is the introduction of a partial-ground structure that increases the compactness of the proposed design. The methodology and design of the dual-band antenna, parametric study, simulation, and implementation results for the proposed design are discussed.

2. Design concepts of the proposed compact dual-band antenna

In this section, the design geometry of a compact dual-band microstrip antenna is detailed. The concept of a microstrip patch antenna (MPA), slots, and partially grounded structures are presented in this design to attain the dual-band operating frequencies. Firstly, the design approach starts with a straight forward MPA and a 50 Ω feed-line with a partially ground plane, aiming to resonate at 2.4 GHz. Then, the patch is enhanced with a U-shaped slot to produce the second resonance frequency at 6.4 GHz. Adding to that, the miniaturization of the design is optimized by introducing some cut-outs in the patch to achieve more compactness without effecting the overall performance of the proposed antenna.



(a)

(b)

Figure. 1 The proposed dual-band antenna geometry: (a) Front View and (b) Back View

2.1 Antenna geometry

The final proposed antenna is illustrated in Figure 1. As can be noticed, the antenna is comprised of a square slotted patch, with a feedline and a partially grounded plane for performance maximization. The overall dimensions of the antenna (*Ls* x *Ws*) is 30 x 30 mm^2 and its simulated using CST-MW studio on a Rogers RT5880 substrate with thickness (*h*) of 1.57 mm, and dielectric constant (ε_r) of 2.2. The dimensions of the feed line (*Lf* x *Wf*) are chosen to satisfy the 50Ω transmission line matching impedance. The patch of the antenna is designed with dimensions (*Lp* x *Ws*) and the partially grounded plane is shown with dimensions (*Lg* x *Wg*). As can be seen, the slots are represented to produce the dual-band operation and to minimize the overall geometry of the proposed design and more details are explained in the following sections. Table 1 shows the optimized dimensions of the proposed antenna.

2.2 Design stages

Figure 2 demonstrates the procedure for the three design stages applied to design the proposed antenna, namely:

Table 1. Geometric dimensions of the optimized proposed antenna

Parameter	Description	Value (mm)
Ls	Substrate length	30
Ws	Substrate width	30
Lp	Patch length	15
Wp	Patch width	15
Lf	Feedline length (50Ω)	7.5
Wf	Feedline width (50Ω)	4.86
La	Patch stripline length	7
Wa	Patch stripline width	3
Lg	Partial ground length	4
Wg	Partial ground width	30
g	U-slot (gap) width	0.5
x	U-slot length	10
y	U-slot height	4.5
a	Center square notch	4

Received: June 18, 2024. Revised: August 7, 2024.

Stage-1 (Ant. A): The construction of a single band antenna is illustrated in Figure 2(a). The antenna consists of a simple straight forward patch with a 50Ω matched feedline. The patch width and length are found using the below formulas [19]:

$$w_p = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{2}$$

Where c is the speed of light, f_r is the resonant frequency, ε_r is the relative dielectric constant and ΔL is the variation in the length.

$$\Delta L = 0.412(h)\,\frac{(\varepsilon_{eff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{w}{h}+0.8\right)} \tag{3}$$

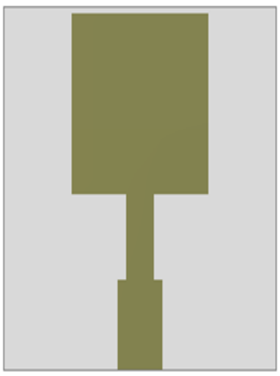
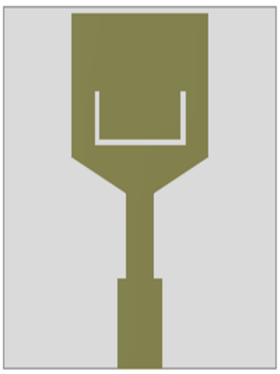
The effective dielectric constant, ε_{eff} is formulated using [20]:

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\;\frac{1}{\sqrt{1+12\left(\frac{w}{h}\right)}} \tag{4}$$

Where h is the substrate thickness.

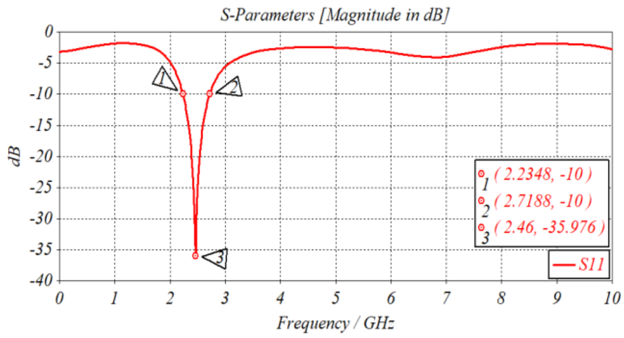
The obtained resonance frequency f_0 is 2.4 GHz with a bandwidth of 500 MHz. The reflection coefficient (S11) of this antenna is shown in Figure 3(a) with a return loss of -35.9 dB.

Stage-2 (Ant. B): In this step, the reference antenna has been modified by cutting a U-shaped slot in the patch as shown in Figure 2(b). This antenna, namely Ant. B provides a second band operation at 6.4 GHz with a bandwidth of 200 MHz and a return loss of -29.8 without effecting the first band ensuring the high selectivity of the proposed antenna as illustrated in Figure 3(b).

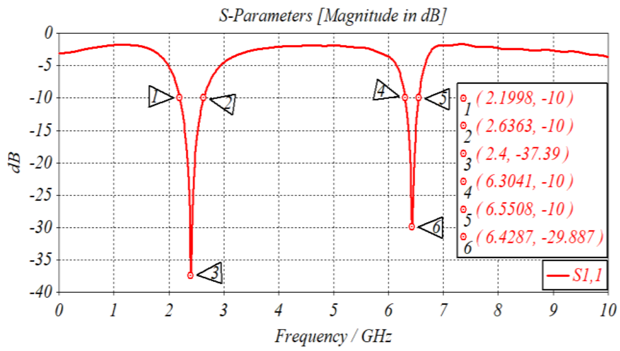



(a) (b)

Figure. 2 Design stages: (a) Ant. A (Ref. antenna) and (b) Ant. B

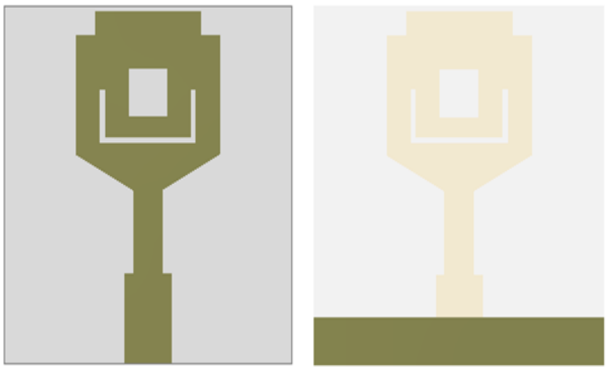


(a)

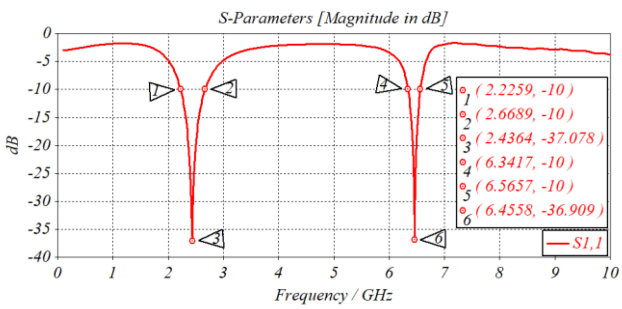


(b)

Figure. 3 S-parameter for the antenna design stages



(a)



(b)

Figure. 4 Proposed antenna: (a) Optimized geometry. (b) S-parameter

As can be seen from Figure 2(b), a slight cut has been presented on both lower sides of the patch, this adds

Received: June 18, 2024. Revised: August 7, 2024.

more compactness to the antenna without effecting the operation frequencies.

Stage-3 (Proposed antenna): As depicted in the prior step, the dual-band operation has been achieved, but more compactness can be granted by making some manipulations on the design. The main goal is to optimize the miniaturization process while keeping the resonance frequencies not affected as well as the selectivity of the proposed design. This miniaturization is done by cutting a square portion at both ends of the upper sides of the patch, and inserting a square notch in the middle as shown in Figure 4(a). The S-parameter is also illustrated in Figure 4(b). As mentioned earlier, the dual-band operation are centered at 2.4 GHz and 6.4 GHz respectively and the antenna presented a high return loss of -37.07 dB and -36.90 dB respectively.

3. Parametric study

The parametric study is essential to optimize antenna dimensions and performance and to observe the effect of each part on the frequency response. The antenna performance is mainly effected by the patch length (*Lp*), patch width (*Wp*), U-slot height (*y*), partial ground length (*Lg*), and U-slot length (*x*). In the following sub-sections, all the aforementioned parameters are studied.

3.1 Effect of *Lp* and *Wp*

Figure 5(a) and (b) shows the effect of varying Lp and Wp on the S-parameter. As can be seen, its effect is on both bands that it facilitates the fine tuning for the resonance frequencies to obtain the optimum required antenna performance.

3.2 Effect of *y* and *x*

The U-slot configuration in the patch has given the second band, thus it's important to study the effect of the U-slot parameters. Figure 5(c) and (d) reveals the effect of tuning y and x. As can be seen, these two parameters have effected only the second band when taking multiple values for y and x, which confirms the high selectivity properties of the proposed antenna.

3.3 Effect of *Lg*

The impact of the ground layer is demonstrated in Figure 5(e). It is evident that both bands are simultaneously impacted, exhibiting synchronized upward and downward shifts as this parameter is tuned.

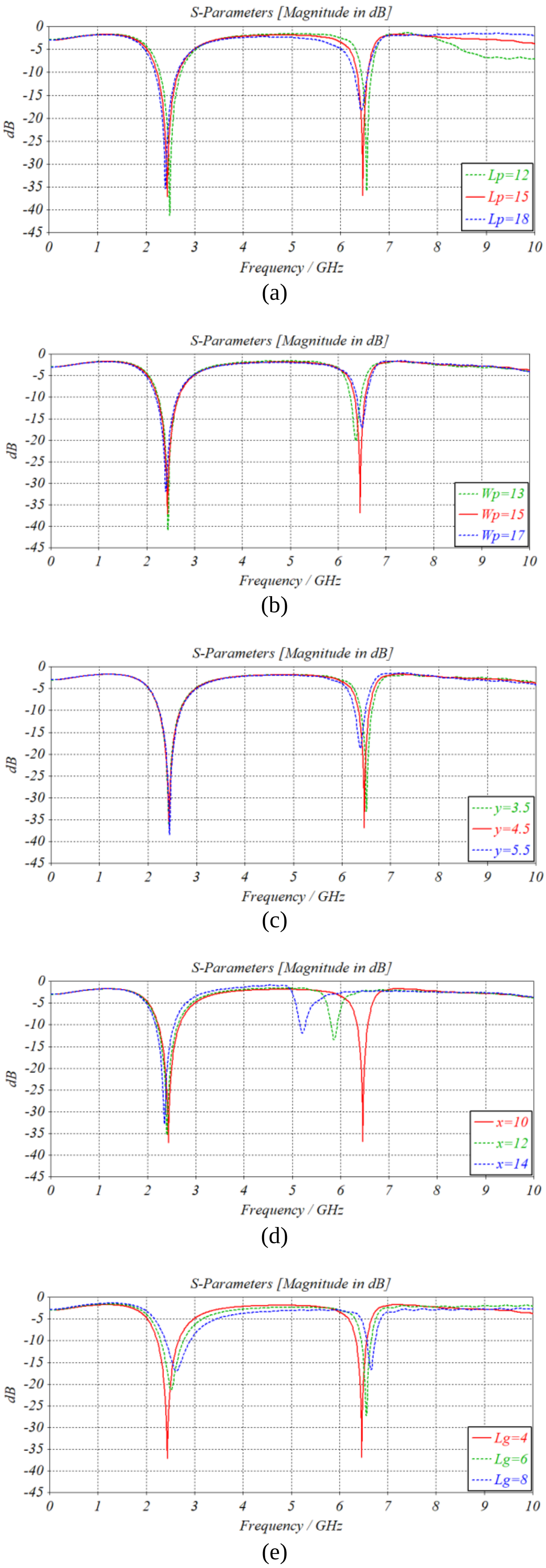


Figure. 5 Parameters effect on S11: (a) *Wp*, (b) *Lp*, (c) *y* (d) *x* and (e) *Lg*

Received: June 18, 2024. Revised: August 7, 2024.

For a clearer and more understandable presentation for the effect of these four parameters, Table 2 shows the iterations of each parameter with their effect on the center frequency (f0), and the return loss (RL) at f0.

4. Simulation results

4.1 Radiation pattern

The 2D farfield directivity of the proposed design at the dual-band operation of 2.4 and 6.4 GHz, as illustrated in Figure (6), delivers an inclusive understanding of the antenna's radiation pattern and performance. Figure (6) displays the directivity in both the elevation and azimuth planes, highlighting the regions where the antenna radiates most efficiently. Peaks in the directivity plots indicate directions with maximum radiation, while nulls correspond to directions with less radiation. The main lobe denotes the primary direction of radiation, which is critical for targeted communication, while the side lobes display secondary radiation directions Figure (7) shows the 3D radiation patterns and the directional characteristics of the proposed antenna. These simulated patterns were obtained from the CST software providing a broad view of the antenna's performance across different angles for the dual resonance frequencies of 2.4 and 6.4 GHz. The visual representations in this figure focuses on the main lobe magnitude and direction, side lobe levels, and angular width.

Table 2. Parameters effect on antenna performance

Parameter	*Value mm*	*f_{01} GHz*	*f_{02} GHz*	*RL1 dB*	*RL2 dB*
Lp	12	2.5	6.5	-41.17	-35.88
	15	2.4	6.4	-37.07	-36.90
	18	2.4	6.4	-35.40	-18.29
Wp	13	2.4	6.3	-40.56	-20.10
	15	2.4	6.4	-37.07	-36.90
	17	2.4	6.5	-31.79	-17.18
y	3.5	2.4	6.5	-35.99	-33.15
	4.5	2.4	6.4	-37.07	-36.90
	5.5	2.4	6.3	-38.36	-18.61
x	10	2.4	6.4	-37.07	-36.90
	12	2.4	5.8	-35.36	-13.44
	14	2.3	5.2	-32.93	-11.81
Lg	4	2.4	6.4	-37.07	-36.90
	6	2.5	6.5	-21.30	-27.27
	8	2.6	6.6	-16.80	-16.72

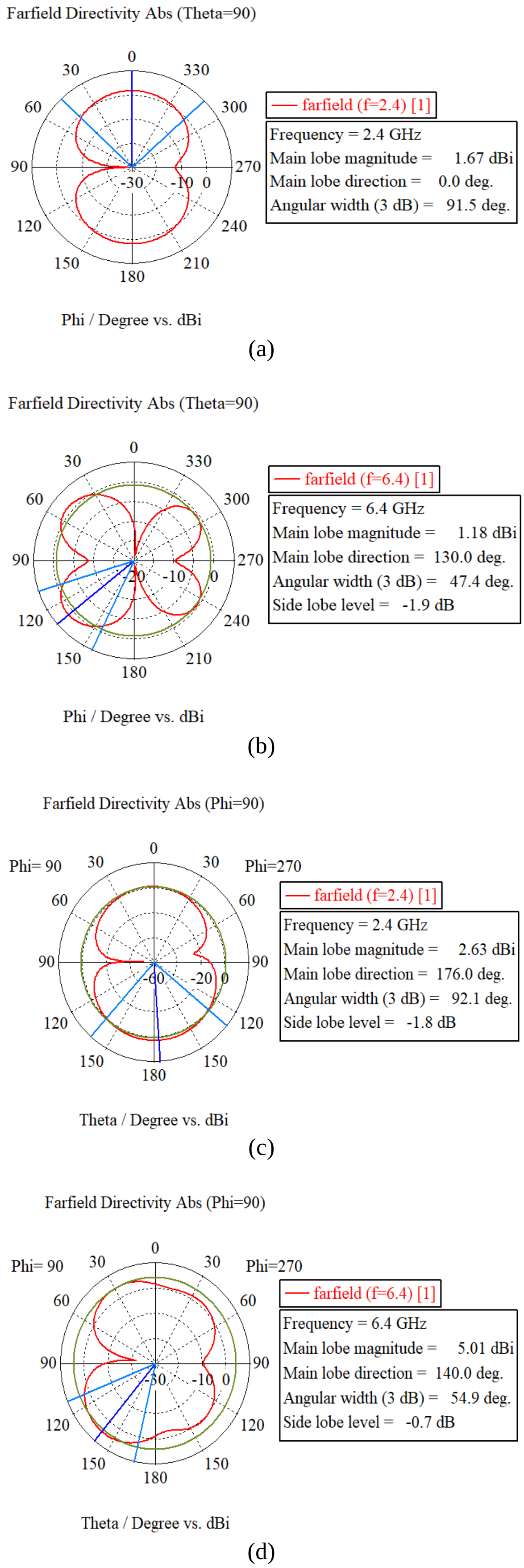
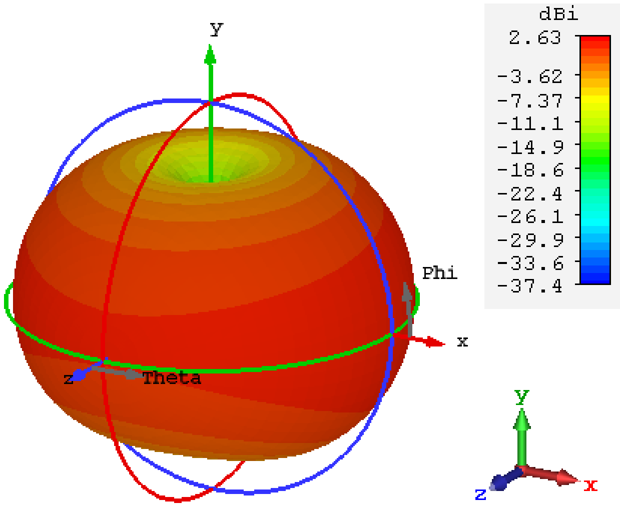
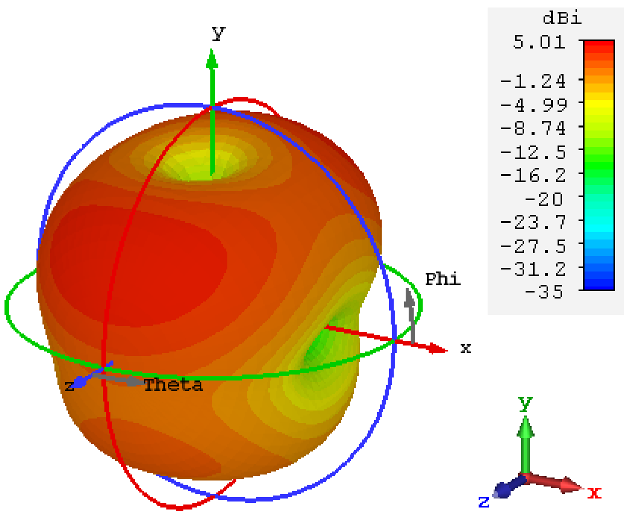


Figure. 6 Farfield directivity: (a) 2.4 GHz (Theta=90), (b) 6.4 GHz (Theta=90), (c) 2.4 GHz (Phi=90), and (d) 6.4 GHz (Phi=90)

Received: June 18, 2024. Revised: August 7, 2024.



(a)



(b)

Figure. 7 Three dimensional radiation pattern: (a) 2.4 GHz and (b) 6.4 GHz

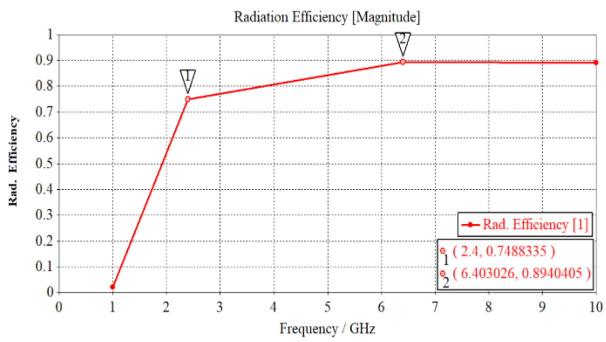


Figure. 8 Radiation efficiency

4.2 Radiation pattern

Figure 8 illustrates the radiation efficiency of the antenna. At 2.4 GHz, the efficiency is about 75%, while at 6.4 GHz is around 89%.

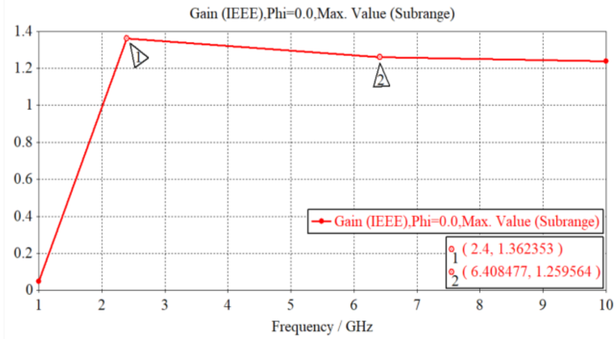


Figure. 9 Antenna gain

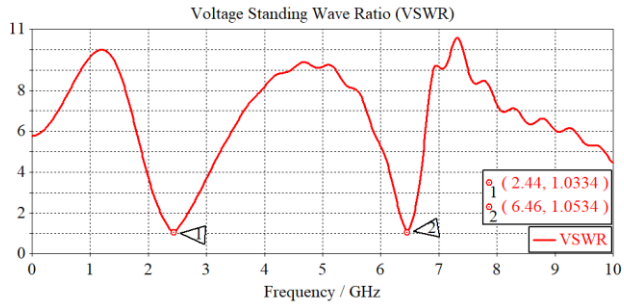


Figure. 10 Voltage Standing Wave Ratio (VSWR)

4.3 Gain

The antenna gain through both bands is shown in Figure 9. The gain values appeared to be positive of 1.36 at 2.4 GHz and 1.25 at 6.4 GHz.

4.4 VSWR

Figure 10 shows the Voltage Standing Wave Ratio VSWR at the operating frequencies of 2.4 GHz and 6.4 GHz, both of which are shown to be 1.

4.5 Surface current distribution

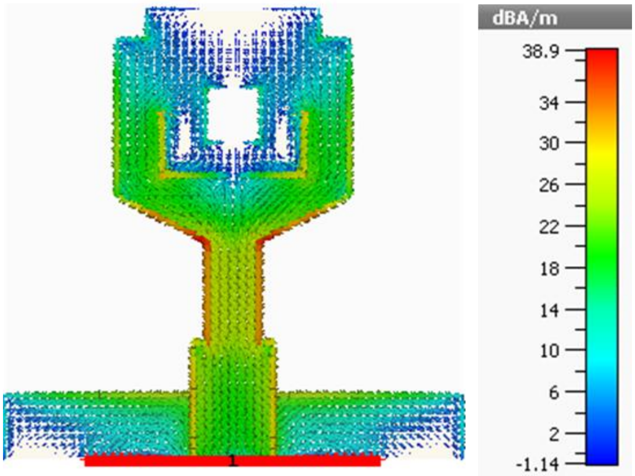
Figure 11 demonstrate the current distribution of the suggested antenna at 2.4 and 6.4 GHz. The red colour is the indication of higher current density, whereas the blue colour is the indication of lowest current density. As can be seen in Figure 11a, that is the 2.4 GHz, the current vectors are mostly along the lower part of the patch and the feeding line. Whilst at 6.4 GHz (Figure 11b), the current vectors lie the most at the U-slot part of the patch which has been proved earlier that this part is responsible for the second band.

5. Fabrication and verification

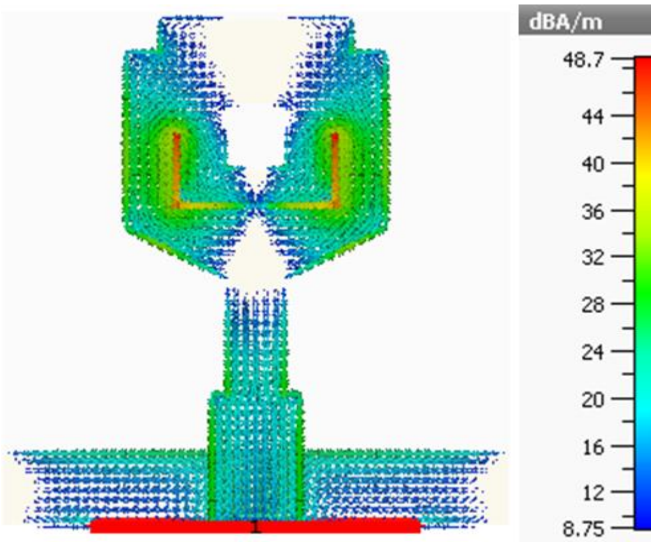
Figure 12 shows the manufactured proposed antenna. The results of the S11 measured by the Vector Network Analyzer (VNA) E5071C is shown in Figure 13. As can be seen in Figure 13, the return loss and the center frequency of both bands have a slight deviation in comparison with the simulated

Received: June 18, 2024. Revised: August 7, 2024.

results fetched from the CST. The reason for that might be caused by manufacturing accuracy and the SMA connector. However, the results show a very good match between simulation and measurement as illustrated in Figure 14. For more comparison details between simulation and measurement results, see Table 3.

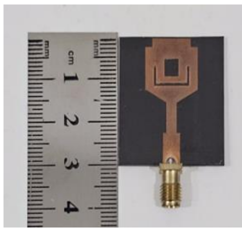


(a)

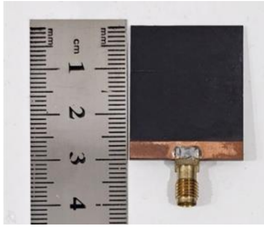


(b)

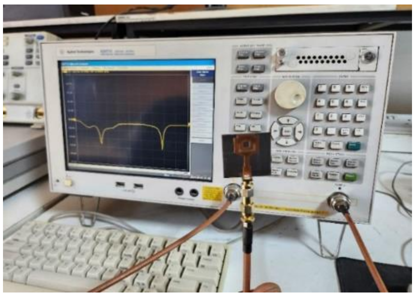
Figure. 11 Surface current distribution: (a) at 2.4 GHz and (b) at 6.4 GHz



(a)



(b)



(c)

Figure. 12 The fabricated proposed antenna: (a) front view, (b) back view and (c) antenna with the VNA

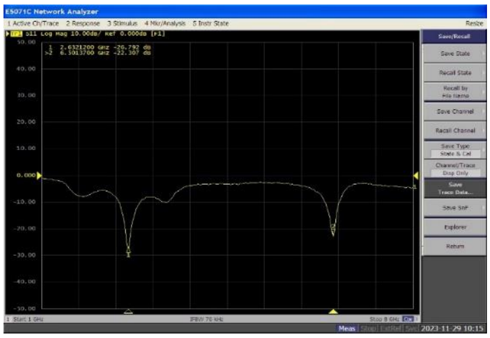


Figure. 13 S11 of the proposed antenna from the VNA

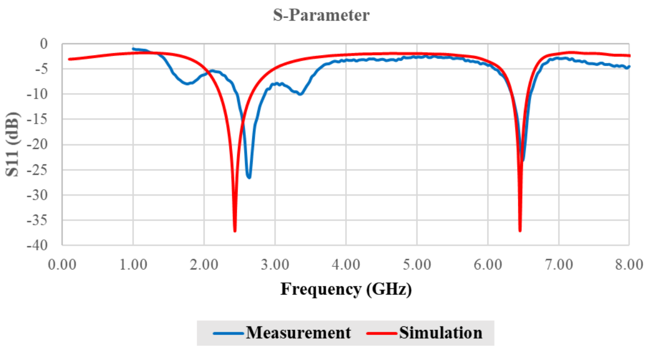


Figure. 14 Simulation and measurement S11.

Table 3. Simulation results vs. measurement results

	Simulation		Measurement	
Center frequency GHz	2.4	6.4	2.6	6.5
Bandwidth GHz	0.4	0.2	0.5	0.2
Return loss dB	-37.07	-36.9	-26.79	-22.3

Table 4 Comparison between reported dual-band antennas and the proposed antenna

Reference No	Size (mm^2)	Substrate Type	Bandwidth (GHz)	Resonant Frequency (GHz)	Reflection Coefficient (dB)
[7]	50×50	FR-4	0.05 0.2	2.4 5.8	-14.1 -27.5
[8]	44×41	FR-4	0.1 0.2	2.5 5.8	-29.9 -15.1
[9]	50×50	FR-4	0.08 0.16	2.4 5.8	-25 -19.1
[10]	56×82	FR-4	NA	1.8 2.4	-25 -23.5
[11]	180×60	FR-4	0.1 0.5	0.7 3.5	-13 -29.5
[12]	60×60	FR-4	0.06 0.07	2.3 3.5	-23.1 -24
[13]	40×40	FR-4	0.06 0.14	2.4 5.3	-24.9 -18.1
[14]	70×70	FR-4	0.11 0.48	2.4 5.6	-29.7 -26.3
[15]	50×50	FR-4	0.01 0.05 0.14	1.2 2.4 5.6	-14 -20 -19
Proposed Design	30×30	Rogers RT5880	0.4 0.2	2.4 6.4	-37.07 -36.90

6. Comparison with reported antennas

The summary of the previously reported antennas that have been published in recent years in comparison with the proposed antenna in terms of specifications is represented in Table 4.

7. Conclusions

This research depicts the development of a dual-band patch antenna, compact in size, and optimized for various wireless communication applications, operating at both 2.4 GHz and 6.4 GHz frequencies. Its design combines the use of square slots, slits, and a partial ground plane to achieve enhanced selectivity. The results demonstrate satisfying reflection coefficient and gain, with a reflection coefficient of -10 dB deemed favourable. To validate the simulated design, a physical model of the antenna was fabricated and its performance was verified via Vector Network Analyzer (VNA) E5071C. With its dual-band capabilities, the antenna shows promise for a wide range of wireless communication application systems.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Ahmed Lateef Khudaraham and Zaid M. Khudair; methodology, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; software, Ahmed Lateef Khudaraham and Zaid M. Khudair; validation, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid

M. Khudair; formal analysis, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; investigation, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; resources, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; data curation, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; writing—original draft preparation, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; writing—review and editing, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; visualization, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; supervision, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; project administration, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair; funding acquisition, Ahmed Lateef Khudaraham, Abdullah Nasser Ibraheem and Zaid M. Khudair.

References

[1] I. Ali and R. Y. Chang, "Design of Dual-Band Microstrip Patch Antenna with Defected Ground Plane for Modern Wireless Applications", In: *Proc. of 2015 IEEE 82nd Vehicular Technology Conference* (VTC2015-Fall), Boston, MA, USA, 2015, pp. 1-5.

[2] M. R. Ahsan, M. T. Islam, M. Habib Ullah, H. Arshad, and M. F. Mansor, "Low-cost dielectric substrate for designing low profile multiband monopole microstrip antenna", *Scientific World Journal, 2014*.

[3] M. P. Joshi, and V. J. Gond, "Design and Analysis of Microstrip Patch Antenna for WLAN and Vehicular Communication", *Progress in Electromagnetics Research C*, Vol. 97, 2019.

[4] M. N. Kumar, M. V. Narayana, G. Immadi, P. Satyanarayana, and A. Navya, "Analysis of a low-profile, dual band patch antenna for wireless applications", *AIMS Electronics and Electrical Engineering*, Vol. 7, No. 2, pp. 171–186, 2023.

[5] J. U. Yoo, and H. W. Son, "A Simple Compact Wideband Microstrip Antenna Consisting of Three Staggered Patches", *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 12, pp. 2038–2042, 2020.

[6] L. Januszkiewicz, P. di Barba, L. Jopek, and S. Hausman, "Many-objective automated optimization of a four-band antenna for multiband wireless sensor networks", *Sensors (Switzerland)*, Vol. 18, No. 10, 2018.

[7] S. KÜÇÜKCAN and A. KAYA, "Dual-Band Microstrip Patch Antenna Design for Wi-Fi Applications", *European Journal of Science and Technology*. 2022.

[8] R. S. Uqaili, J. A. Uqaili, S. Zahra, F. B. Soomro, and A. Akbar, "A Study on Dual-band Microstrip Rectangular Patch Antenna for Wi-Fi", *Proceedings of Engineering and Technology Innovation*, Vol. 16, pp. 1–12, 2020.

[9] M. Mabaso, and P. Kumar, "A Dual Band Patch Antenna for Bluetooth and Wireless Local Area Networks Applications", *International Journal of Microwave and Optical Technology*, 2018.

[10] M. R. Islam, A. A. A. Adel, A. W. Mimi, M. S. Yasmin and F. A. M Norun, "Design of Dual Band Microstrip Patch Antenna using Metamaterial", *IOP Conference Series: Materials Science and Engineering*, Vol. 260, No. 1, 2017.

[11] A. Kumar Arya, S. J. Kim and S. Kim, "A Dual-Band Antenna for LTE-R and 5G Lower Frequency Operations", *Progress In Electromagnetics Research Letters*, Vol. 88, 2020.

[12] N. Ismail, F. Oktafiani, F. Makmur, F. D. Ramadhan, M. A. Ramdhani and I. Taufik, "Dual-band Rectangular Microstrip Patch Antenna for LTE and BWA Application", *IOP Conference Series: Materials Science and Engineering*, Vol. 434, No. 1, 2018.

[13] S. J. Pawar and M. P. Joshi, "Design Of Dual Band Circular Microstrip Patch Antenna for ISM and WLAN", In: *Proc. of International Conference on Automatic Control & Dynamic Optimization Techniques (ICACDOT 2016): 9th & 10th*, 2016.

[14] J. Kaur, Nitika and R. Panwar, "Design and optimization of a dual-band slotted microstrip patch antenna using Differential Evolution Algorithm with improved cross polarization characteristics for wireless applications", *Journal of Electromagnetic Waves and Applications*, *33*(11), 1427–1442, 2019.

[15] M. Mabaso and P. Kumar, "A microstrip patch antenna with defected ground structure for triple band wireless communications", *Journal of Communications*, Vol. 14, No. 8, pp. 684–688, 2019.

[16] A. K. Nghaimesh, A. K. Jassim and W. K. A. Ali, "Design and analysis several band antenna for wireless communication", *Bulletin of Electrical Engineering and Informatics*, Vol. 12, No. 1, pp. 207–214, 2023.

[17] A. Khidre, F. Yang and A. Z. Elsherbeni, "A patch antenna with a varactor-loaded slot for reconfigurable dual-band operation", *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 2, pp. 755–760, 2015.

[18] P. G. A. Murti, L. O. Nur and T. Yunita, "Antena Mikrostrip Dual Band Bahan Fleksibel Frekuensi 2, 45 Ghz Dan 5, 85 Ghz Untuk Aplikasi Telemedis", *eProceedings of Engineering*, Vol. 6, No. 2, 2019.

[19] S. Liu, W. Wu and D. G. Fang, "Single-Feed Dual-Layer Dual-Band E-Shaped and U-Slot Patch Antenna for Wireless Communication Application", *IEEE Antennas and Wireless*

Propagation Letters, Vol. 15, pp. 468–471, 2016.

[20] S. K. Hassan and Z. M. Khudair, "Circular Patch Antenna with Quintuple Band Operation Design Analysis and Performance Evaluation for Multi-Frequency Applications", *International Journal of Intelligent Engineering and Systems*, Vol. 17, No. 3, 671–681, 2024, doi: 10.22266/ijies2024.0630.52.