Design of miniaturized multi-band hybrid-mode microstrip patch antenna for wireless communication

Yasameen F. Azeez[1], Maryam K. Abboud[2], Sara R. Qasim[3]
[1]Department of Computer Engineering, College of Engineering, Al-Farabi University College, Baghdad, Iraq
[2]Department of Computer Engineering Technical, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq
[3]Department of Computer Engineering, Al-Mustansiriya University, Baghdad, Iraq

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ABSTRACT

This research presents a small, compact microstrip patch antenna of multi-band antenna. The multi-band antenna can be scaled to higher frequencies, making it possibly useful in 5G applications. The antenna is made up of asymmetric scalene triangles slots on the right side of the patch, which is provided by the reference patch antenna. The modes of antenna, patch and slots are excited to obtain four bands. The antenna design is 25×25×1.4 mm^3 resonant at 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz. The simulated design shows a peak gain of 4.44 dB at 3.93 GHz, 5.63 dB at 4.25 GHz, 5.91 dB at 5.37 GHz and 5.2 dB at 6.18 GHz. The Total efficiency at 3.93 GHz and 4.25 GHz is -1.152 dB and -0.5174 dB, at 5.37 GHz and 6.18 GHz shows a total efficiency of -0.535 dB and -0.566 dB. Finally, the antenna is fabricated and measured. A good agreement shown between measurements and fabrication in terms of return loss.

Corresponding Author:

Yasameen F. Azeez
Department of Computer Engineering, College of Engineering, Al-Farabi University College
Baghdad, Iraq
Email: dr.yasmeen.fawzi@alfarabiuc.edu.iq

1. INTRODUCTION

Currently, wireless networking technologies are used to achieve high data rates. The millimeter and mid-wave bands are among the main technologies in 5G. Although mobile communication has improved, data collecting is still the main purpose of any antenna, so great consideration must be given when designing antennas. In recent years, the demand for small, compact, and inexpensive antennas has increased significantly. With the miniaturization and multi-functionality of communication equipment, built-in antennas are required to have strong integration capabilities [1]–[3]. The antenna design affects important variables like bandwidth and effectiveness, multiband microstrip patch antennas are the preferred type for most wireless applications. This is because of the benefits of compact size, simple structure, light weight, affordable price, flat, and multiband operation. It also replaces the use of multiple antennas for different resonant frequencies [4]–[6].

Many methods have been researched to obtain the multiband antenna, such as reconfigurable technologies [7]–[9], and coupling feed technologies [10], [11]. Unfortunately, these techniques are difficult to manufacture and complicated calculations. The patch antenna plays a major role in the development of numerous multiband and enhancement techniques. As a result, novel designs ought to be taken into consideration to simplify the structure and theoretical analysis. Dielectric material (ε_r) of the substrate determines the patch antenna's size. A lower size of antenna is produced by a substrate with a higher substrate dielectric constant [12], [13]. It is necessary to try to improve the antenna's bandwidth and gain to operate in multiple frequency bands [14]–[16]. Researchers are interested in compact printed monopole antennas for a variety of uses, including wireless local network, ultra-wideband, and radio frequency identification (WLAN, UWB, and RFID) applications [17]–[21]. They were suited for direct integration into the circuit boards of communication devices because of their compactness. MIMO antennas are helpful for 5G technologies, a novel 3-D aperture by importing a hexagonal-shaped patches [21]. Several substrate integrated waveguide (SIW) based antenna designs for broadband and multiband applications such as half mode SIW [22], [23], triangular ring slot [24], design of antenna multiplexer for medical things [25], design and analysis of Coax-Fed U-slot antenna for wireless application [26] and low-profile (SIW) cavity-backed self-triplexed slot antenna [27].

In this research paper, to achieve a multiband antenna, FR-4 is chosen as the dielectric substrate for the proposed antenna with dimensions 25×25 mm^2 and a thickness of 1.4 mm. The antenna is resonating at 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz. The main goal of this research is to examine how an antenna's performance changes as a function of different parameters and to suggest an improved design with multiple bands and better gain. To determine which parameter significantly affects an antenna's reflection coefficient, bandwidth, and resonant frequency, a parametric analysis of the antenna is carried out. The sections of this paper are as follows: The process for antenna design is described in section 2. Section 3 goes into further detail about the parametric analysis, the optimizations produced, and the effectiveness of the suggested antenna. The outcomes of the performance of gain are compiled in section 4. part 4 of this research study contains the conclusion, which is the final section. In addition, the proposed antenna might be useful for fifth-generation telecommunications systems as a multi-band antenna.

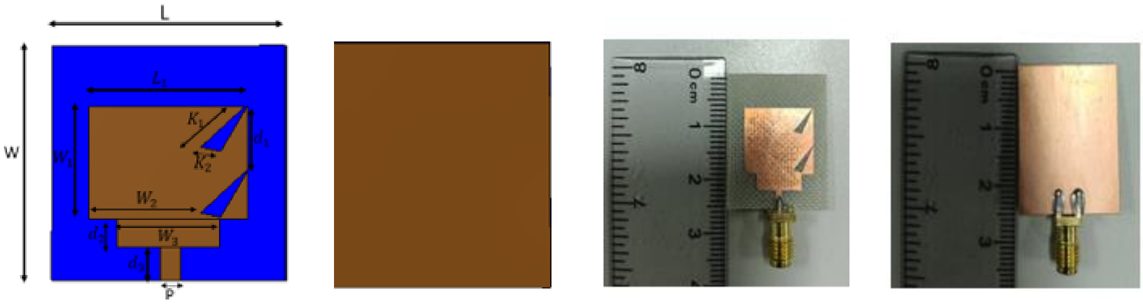
2. ANTENNA DESIGN

The suggested antenna is shown in Figure 1 and was developed, tooled, and simulated by 3D full-wave electromagnetic computer simulation design (CST). In the suggested designs, the substrate is constructed of FR4 material, on both sides, the conducting material is a perfect electrical conductor. Any shape can be used for the patch, but because a rectangle delivers more advantages in this instance, it was chosen over a circular one. The thickness of the substrate is 1.4 mm and a dielectric relative permittivity of $\varepsilon_r = 4.4$. The antenna design parameters are calculated using various formulas [28]. The complete dimensions of the proposed antenna are 25×25×1.4 mm^3. Figure 1 clearly shows that to implement the quadrable or multi-band antenna, the scalene triangle slots have been cut on the antenna's top surface to increase the effective aperture area without expanding the antenna's physical size. The slots affect the surface current and excite the electromagnetic fields [29]. It consists of a microstrip line with port1 that matches 50 Ω with a width of F=1.4 mm to achieve impedance matching and reduce feeding loss. The design is completed with an open waveguide SIW structure, where neither of the two ends has any metallic vias [30]. The parameters are tuned to achieve a multi-band antenna. Table 1 provides the suggested multi-band antenna's optimum design dimensions. Figures 1(a) and (b) shows the simulated design using (CST), Figures 1(c) and 1(d) shows the fabricated antenna top-view and bottom-view. The antenna is designed starting with a microstrip feed line and standard patch for better impedance matching. The addition of equal scalene triangles at one side of the upper plane of the patch provides multi-band resonant frequency. This design is working on hybrid-mode, two modes excited within a same radiating aperture. The hybrid mode antenna radiate in both resonance and anti-resonance frequencies.

Figures 2(a)-2(c) shows the three stages of the proposed antenna in order to radiate in multi-band antenna. Figure 3 shows the simulated design with only patch radiate at 5 GHz, adding one triangle in one side of the patch, the antenna radiates triple band 4 GHz, 4.23 GHz, and 5.58 GHz. The final antenna design radiate at multi-band 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz with return loss lower than 10 dB. Table 1 shows the final parametric dimensions to achieve S-parameter lower than 10 dB and multi-band antenna. This design is working on hybrid-mode, two modes excited within a same radiating aperture. The hybrid mode antenna radiate in both resonance and anti-resonance frequencies. To achieve the proposed geometry design, the resonant frequency for the TE_{mnp} was calculated using the following:

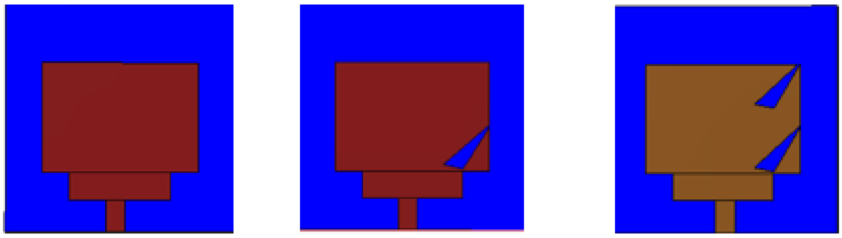
$$f_{mnp}=\frac{c}{2\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m}{L_1}\right)^2+\left(\frac{n}{w_1+d_2}\right)^2+\left(\frac{p}{h}\right)^2} \quad (1)$$

where c is the velocity of light μ_r, ε_r is the dielectric relative permeability and relative permittivity 4.4 respectively, of the substrate. Due to the significant loading effect in the antenna, the triangular slots produces two hybrid modes, between the TE_{100}(m=1, n=0, p=1) and TE_{110} (m=1, n=1, p=0) cavity modes as shown in Figure 4. The modified-slot helps tuning each hybrid's resonance frequency below 10 dB, Figure 4 shows the real impedance between the modes $TE_{100}$and TE_{110} at 3.9 GHz and 6.16 GHz respectively.



(a) (b) (c) (d)

Figure 1. Schematic view of the proposed multi-band antenna: (a) simulation (front-view), (b) simulation (back-view), (c) fabrication (front-view), and (d) fabrication (back-view)



(a) (b) (c)

Figure 2. Design stages of the proposed antenna (a) antenna 1 with only patch, (b) antenna 2, adding one scalene triangle, and (c) final design with two symmetric triangles

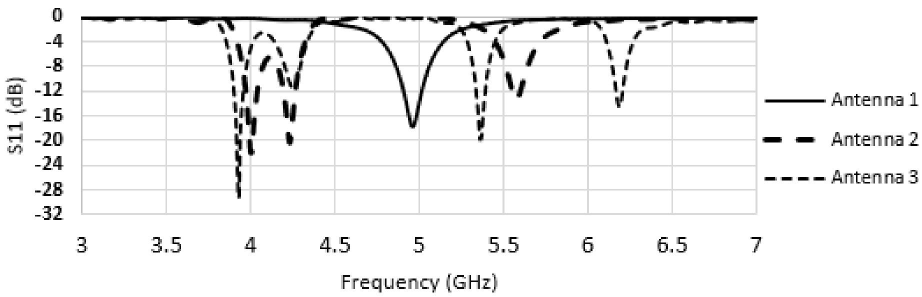


Figure 3. Simulated |S11| responses corresponding to various design stages

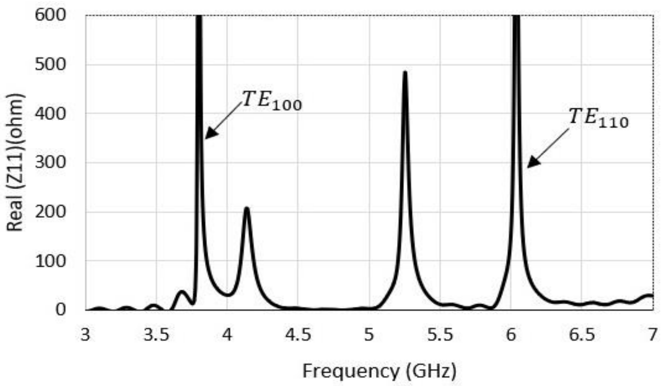


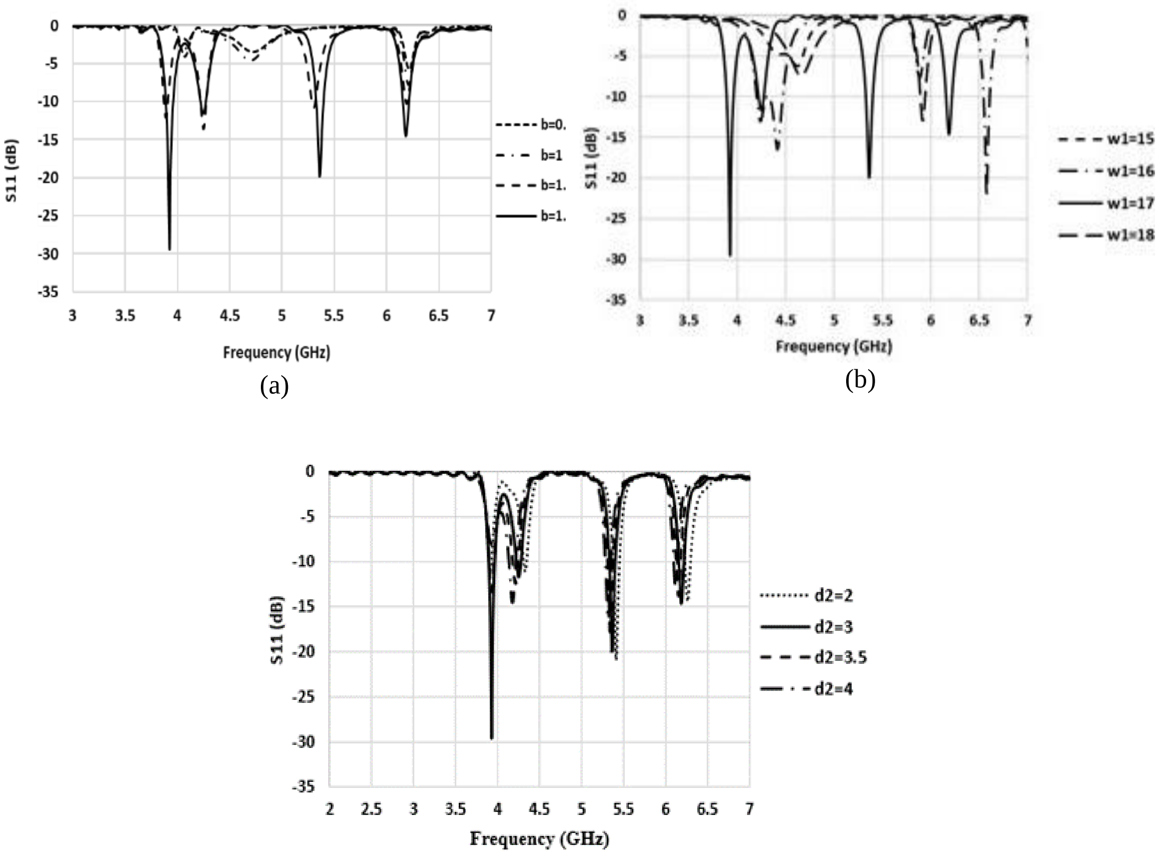
Figure 4. Real impedance (Z_{11}) for antenna design

Table 1. Optimized antenna dimensions of the proposed SIW

Parameters	L	L_1	W	W_1	W_2	W_3	K_1	K_2	d_1
Value (mm)	25	17	25	12	12	9	4.8	2	6.8
Parameters	d_2	d_3	P	b (thickness)					
Value (mm)	3	3.5	1.4	1.4					

3. PARAMETRIC STUDY FOR THE PROPOSED DESIGN

The antenna has been simulated using CST and studied the parameter's effect on matching, frequency change, bandwidth, and gain. Figure 5 shows the parameters change effect on the reflection coefficient. Figure 5(a) shows that when the thickness is 0.8 mm and 1 mm the reflection coefficient radiate at 3.9 GHz, 4.8 GHz, 5.37 GHz, and 6.18 GHz. When increasing the thickness, the return loss will increase. Figure 5(b) shows when the width of the substrate increases the resonance of frequency decrease. Figure 5(c) shows that the change of the microstrip length part affects the resonance frequency tuning.



(c)

Figure 5. Effect parameters change on reflection coefficient: (a) thickness change, (b) length of the patch change, and (c) microstrip length change

4. RESULTS AND DISCUSSION

The reflection coefficient S11 of our antenna, which is -30 dB, -12 dB, -19.9, and -14.6 dB at the minimum points of supported bands 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz, respectively, is shown in Figure 6. After the design has been simulated, the design has been fabricated and a comparison of return loss against frequency has been made. Figure 6 shows that the simulation radiates at 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz while the measurements radiation was at resonance frequencies 3.97 GHz, 4.32 GHz, 5.3 GHz, and 6.18 GHz. In all the simulations and measurements the return loss is below 10 dB. The bandwidth for the simulation at 3.93 GHz is 70 MHz while the measurements are 85 MHz, and the bandwidth at 4.25 GHz is 50 MHz while the measurement is 96 MHz. The bandwidth at 5.37 GHz is 73 MHz while the measurement is 90 MHz. The bandwidth at 6.18 GHz is the same for simulation and measurements is 60 MHz.

The suggested multi-band antenna design's allocation of current surface distribution is shown in Figure 7. Figures 7(a)-7(d) shows the graphs make clear that the current distributions are close to the slots and feed line. The far-field radiation pattern in the 3-D plot and polar plot is shown in Figure 8. Figure 8(a)-(d), the gain at 3.93 GHz is 4.44 dB and at 4.25 GHz is 5.62 dB. Figures 8(e)-8(h) at 5.37 GHz is 5.91 dB and the gain at 6.11 GHz is 5.21 dB as shown in Figures 8(a)-(h). Figure 9 shows the peak gain and efficiency with a range of frequencies (3.9-7 GHz).

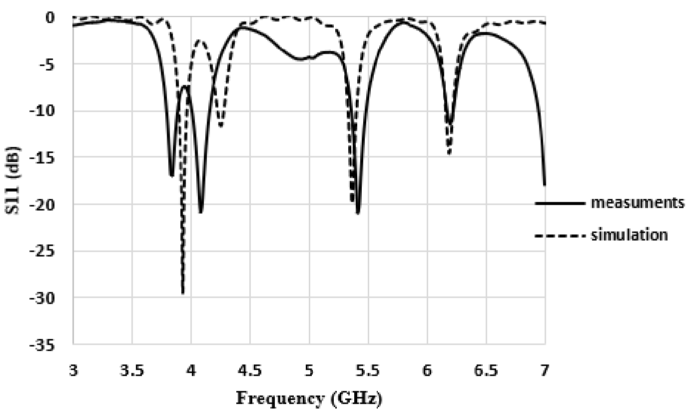


Figure 6. Comparison of return loss against frequency between measurements and simulation

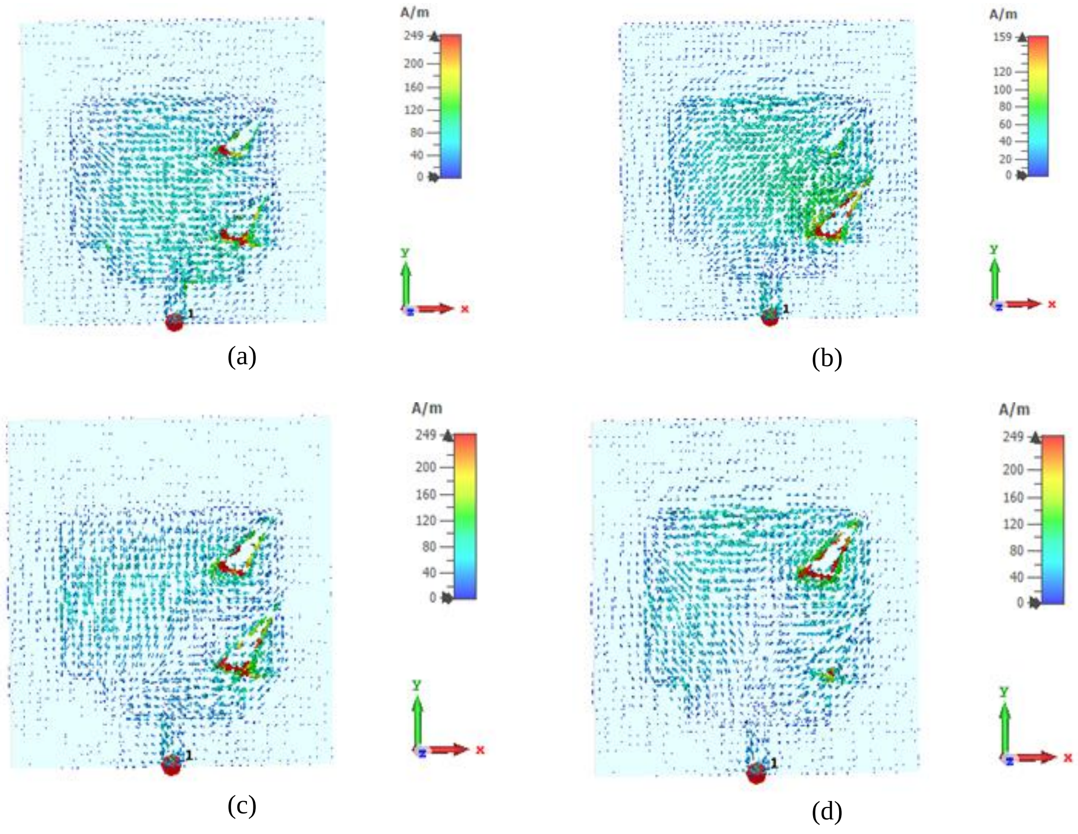


Figure 7. Simulated surface current distribution at the resonant frequencies: (a) 3.93 GHz, (b) 4.25 GHz, (c) 5.37 GHz, and (d) 6.18 GHz

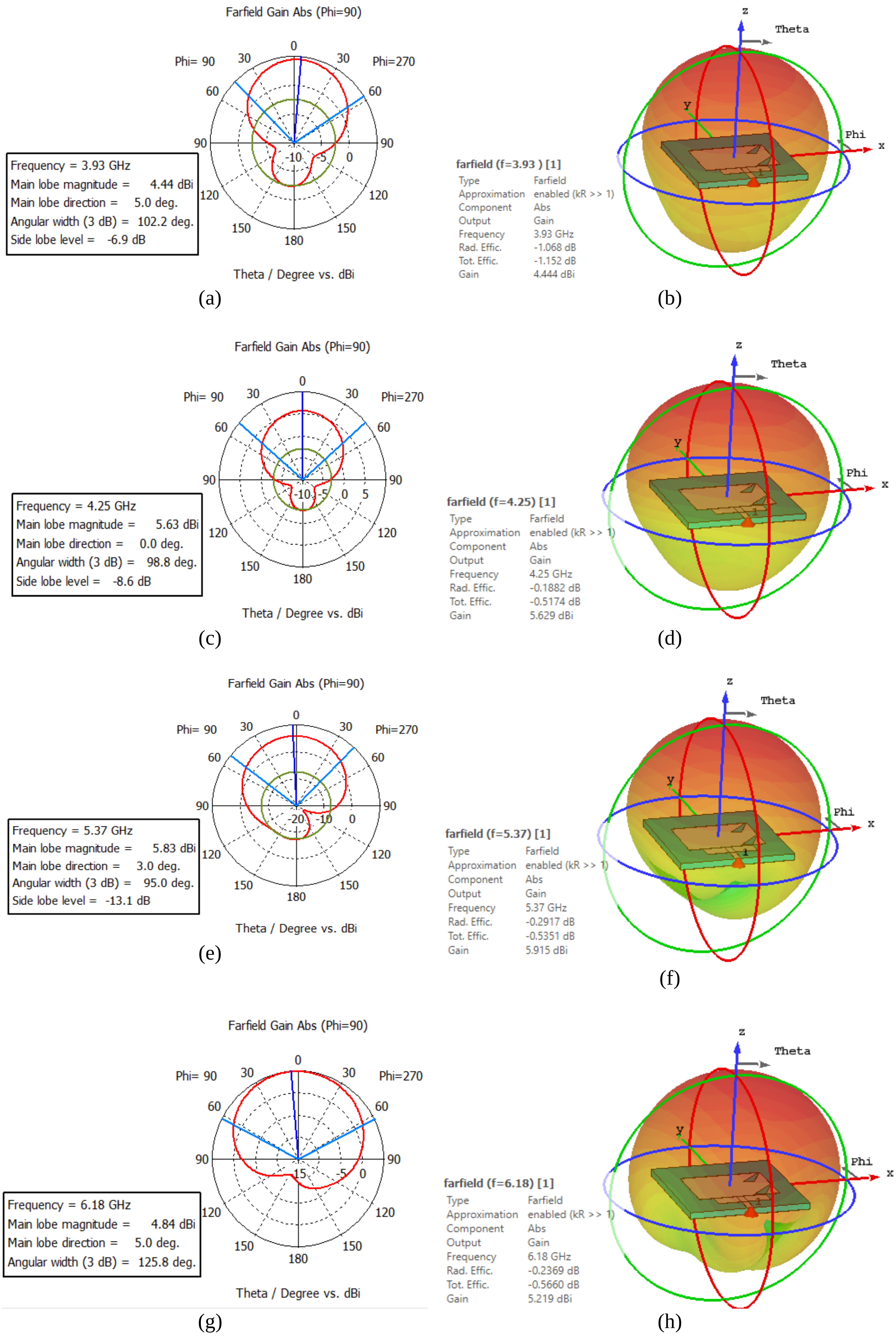


Figure 8. Electromagnetic radiation pattern plot for the simulated design (a) 3.93 GHz (E-field), (b) 3.93 GHz (3-D plot), (c) 4.25 GHz (E-Field), (d) 4.25 GHz (3-D plot), (e) 5.37 GHz (E-field), (f) 5.37 GHz (3-D plot), (g) 6.18 GHz (E-field), and (h) 6.18 GHz (3-D plot)

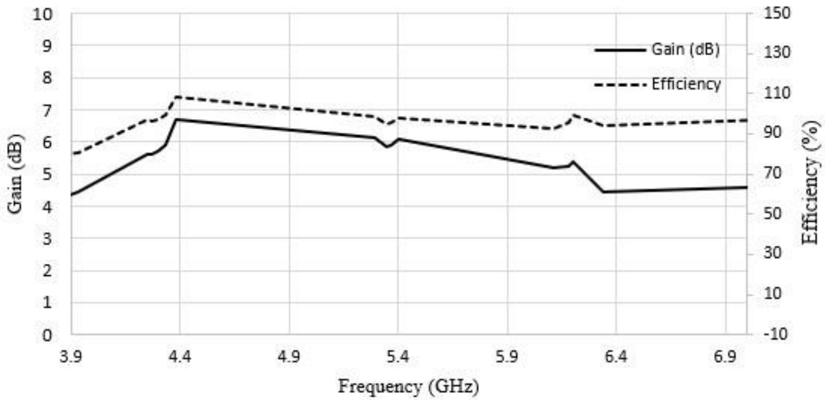


Figure 9. Gain and efficiency against frequency

5. CONCLUSION

Asymmetric scalene triangles slots on the right side of the patch antenna are presented. The modes including patch mode and slot mode are excited to achieve four bands 3.93 GHz, 4.25 GHz, 5.37 GHz, and 6.18 GHz. The gain achieved between the range of 4.4 dB to 6 dB, the total efficiency has the range between -0.5 dB to -1 dB. Simulation and measurement show that the proposed antenna has good agreement in terms of impedance matching and reflection coefficients at the four distinct frequency bands. The multi-band antenna might be useful in 5G applications and can be rescaled to higher frequencies.

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BIOGRAPHIES OF AUTHORS

Yasameen F. Azeez received B.Sc. and M.Sc. degrees from the department of electronics and communications engineering. Al-Nahrain University, Baghdad, Iraq in 2005 and 2009, respectively. The Ph.D. degree from the University of Kent, Canterbury, U.K. Her research interest include; microwave, wireless communication, antennas, and substrate integrated waveguide antenna. She can be contacted at email: dr.yasmeen.fawzi@alfarabiuc.edu.iq.

Maryam K. Abboud received her B.Sc. in Information and Communication Engineering from Al-Khwarizmy College of Engineering, Baghdad University, Baghdad, Iraq in 2012, the M.S and Ph.D. in Information and Communication Engineering from College of Information Engineering, Al-Nahrain University, Baghdad, Iraq in 2016 and 2020 respectively. Her research interest includes; signal processing, wireless communication, communication security, network, and channel coding. She can be contacted at email: Maryam.Khalifa@mtu.edu.iq.

Sara R. Qasim received her B.Sc. in Computer Engineering from the College of Engineering, Baghdad University, Baghdad, Iraq in 2007, and her M.Sc in Electrical Engineering-Computer and Control from the College of Engineering, Baghdad University, Baghdad, Iraq in 2014. Her research interests include; image processing, AI, security, and robotics. She can be contacted at email: sararaad.cac@gmail.com.