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ENHANCED DESIGN OF A TRIPLE-BAND MICROSTRIP PATCH-ARRAY ANTENNA USING A MULTI-SPLIT RING RESONATOR

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ABSTRACT

We have experimentally demonstrated and simulated an enhanced design of a triple-band patch array. The proposed antenna design is enhanced by merging multiple split-ring resonators (SRR) on a single-layer dielectric substrate. The proposed design works on reducing the footprint size with improved return loss, gain, and bandwidth compared with related works. The simulated results show that the proposed antenna operates at 5.96 GHz, 7.96 GHz, and 14.94 GHz and it agrees with the experimental results. High gain values of 9 dB, 6.9 dB, and 7.6 dB were obtained from the designed antenna with split ring resonators at those frequencies, respectively. The return loss for each frequency was -45.77 dB, -33.21 dB, and -45 dB, respectively. The outcomes show an agreement between the simulated and measured results with the fabricated antenna. The suggested antenna outcomes and analysis show that the antenna can operate within the KU and C bands, therefore it has potential applications in Wi-Fi, microwave devices, radar, and satellite communications systems.

KEYWORDS

Microstrip Antenna (MSA), Patch Array Antenna, Voltage standing wave ratio (VSWR) · Split Ring Resonator (SRR), Triple-Band Antenna.

1. INTRODUCTION

The considerable demand for wideband and multi-band antennas in various communication fields, such as mobile communication, sensing applications, and radars, has increased rapidly (Ramahatla et al., 2022). The use of multiple resonance frequencies has attracted the researcher's attention to add the flexibility of frequency selectable based on the required application (Rai et al., 2023). Furthermore, Broadband and multi-band functionality being integrated into compact designs have been highly applicable in wireless communication systems (Kaur et al., 2022). Microstrip antenna (MSA) has been utilized extensively in contemporary wireless communication systems (Abbaoui et al., 2023). MSA has been utilized in several applications be- cause of the benefits of tiny compact size, lightweight, low manufacturing cost, and low profile, such applications are cellular communication systems (Chung, M.A. & Chuang, B.R., 2021), satellite systems (Kumar et al., 2023), GPS (Global positioning system) and Wi-max (Jain et al., 2024). MSA consists of, the patch, dielectric substrate, and ground layer (AL- Amoudi et al., 2021). There are multiple techniques to feed the MSA, the most common ones are coaxial probe feed, line feed, aperture couple feed, and proximity couple feed (Kashyap et al., 2022). The shape of the patches can be circular, rectangular, or square (Ghosh & Swati, 2022).

Previously, triple-band antenna characteristics have been investigated to enhance various performance parameters of the triple-band microstrip array patch antenna, Such as compact size, gain, bandwidth (Deng et al., 2022). A triple-band antenna was studied by etching a complementary design to reduce the particle size of a split ring resonator with a defective ground structure (Abdalla et al., 2020). In another work, to obtain triple-band characteristics, A dielectric resonator antenna (DRA) with dual polarization was investigated by using a feeding mechanism based on aperture coupling, resulting in obtaining a triple-band antenna for fourth-generation (4G) and fifth-generation (5G) (Anuar et al., 2020). In addition, a rectangular triple-band antenna was suggested and developed by using an extra strip and a slot of U and H shapes embedded in the patch which was fed by a line feed and a partial ground plane to achieve the optimization of bandwidth at a lower resonance frequency (Pandey et al., 2022). Furthermore, an antenna with two dielectric substrates, a textile substrate, and a rigid one by utilizing a single-by-double power divider feeding technique printed on a rigid dielectric substrate with low-loss and two open ring radiators was proposed to achieve a triple- band antenna for wearable applications (Le et al., 2021). Moreover, to achieve the fifth-generation standards for multiple-input multiple-output characteristics, four modules of patch antenna with three bands were investigated concerning the patch antenna in half-mode, to cover the three Chinese 5G bands, the initial three TM 1/2,0, TM 1/2,1, and TM 3/2,0 modes were analyzed and investigated (Chang et al., 2021). The proposed designs showed a large footprint size as in (Chang et al., 2021, Pandey et al., 2022, Anuar et al., 2020, Abdalla et al., 2020 & Deng et al., 2022), and, some designs show a narrow bandwidth (Le et al., 2021), low gain (Le et al, Pandey et al., 2022, Chang et al., 2021), and low return loss (Pandey et al., 2022 & Anuar et al., 2020).

The previous designs indicate less efficient power transfer in some resonant frequencies (Chang et al., 2021, Pandey et al., 2022 & Anuar et al., 2020). The proposed work focuses on enhancing these parameters, including reducing the design footprint size and return loss, and having an enhanced antenna gain with good bandwidth.

In our work, a new design of an array patch with a line-feeding technique has been proposed to achieve triple-band antenna characteristics with several features that aim to enhance the antenna performance. First, we have made efforts to decrease the antenna’s overall size. Second, the suggested antenna has a highly optimized return loss. Thirdly, the antenna’s gain has been improved across its three bands. The voltage standing wave ratio reaches its highest value. The frequencies at which the suggested antenna operates are 5.96 GHz, 7.96 GHz, and 14.94 GHz. The suggested antenna’s performance is improved by placing several split ring resonators (SRRs) on the dielectric layer. The CST studio suite simulator program has been utilized in the implementation of the design. The present research is organized as follows: our antenna design is proposed in Section 2. The results and discussion are covered in Section 3, and the paper’s conclusion, remarks, and future work are covered in Section 4.

2. THE PATCH-ARRAY ANTENNA’S PROPOSED STRUCTURE

The recommended antenna’s design targets potential applications in Wi-Fi, microwave devices, radar, and satellite communications systems (Singh & Sharma, 2021). It is optimized to operate within the C and KU bands. In the physical dimension, both the substrate and the ground layer are carefully selected to support the antenna operation. The proposed design is achieved and analyzed using a studio suite simulator program (CST).

2.1. Antenna Design without Split Ring Resonators (SRRs)

Firstly, a copper material was chosen to design a ground plane with a dimension of 53 x 67 mm and 0.1 mm in thickness. The antenna’s thickness is mostly deter- mined by the substrate. Thus, FR-4 material with a dimension of 52.5 x 67.1 x 1.48 mmm has been selected to be mounted on the ground layer with a relative permittivity of 4.3. The third most important layer of the antenna is the patch layer, situated on the dielectric substrate layer, possessing measurements of 16.5 x 10.53 mm and is responsible for radiating, and various Techniques for feeding it are available (Christin et al., 2022).

One of the patch antenna's most important feeding techniques is line feeding (Ghimire et al., 2023). The lines support the patch with current from one of its ends and should be connected to the ground. It has been noticed that the matching impedance can be improved by modifying the position of the inset (Choudhary et al., 2023), as shown in Fig. 1.

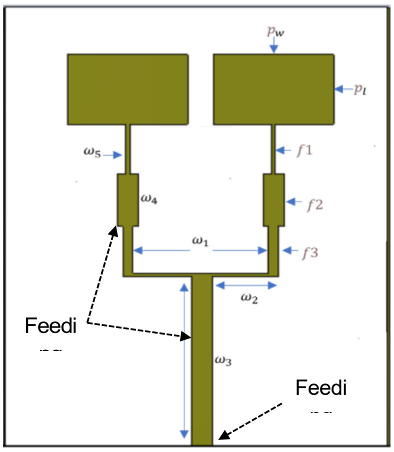

Fig. 1 The initial design of patch array without using split ring resonators.

2.2. Antenna Design with Split Ring Resonators (SRRs)

To optimize the antenna design and characteristics, split- ring resonators have been placed on the substrate layer. The split ring resonators (SRRs) and the array patch antenna have been designed with the dimensions shown in Table 1.

Table 1 The planned antenna's parameterized dimensions

Symbol	Dimensions $[mm]$
RL_1, Rg_1	20, 10
pw_1	16
P1	10
f1, f2, f3	7.5, 8, 7.5
fg1 = fg2	1
w1, w2, w3, w4, w5	18.5, 9, 2.9, 2.9, 0.5
fr_1	7.5
$fw_1 = fw_2$	1

Among the different kinds of metamaterial structures is the split ring resonator (SRR) that can be used to impact electromagnetic waves (Anitha et al., 2024). It consists of two concentric metallic rings with small gaps in the middle and can be placed on the dielectric substrate (Kaur et al., 2022). The final designed shape of this antenna as in Fig. 2, the antenna is constructed from two patch components with six split ring resonators.

3. INVESTIGATION OF THE PERFORMANCE RESULTS

The microstrip's central layer is the conducting patch that affects the antenna performance by altering band- width, surface current distribution, return loss, radiation pattern, and impedance matching (Mukta et al., 2021). A PEC material has been chosen for the patch layer due to its high electrical connectivity . The selected PEC results in efficient radiation of the electromagnetic field (Wadday, et al., 2016). The FR-4 substrate material is a good choice for printed circuit boards due to its features of easy fabrication, low cost, and good electrical properties (Wadday, et al., 2016). In our suggested design, the radiation of the patch has been enhanced by merging a new design of patch array and split ring resonators (SRRs).

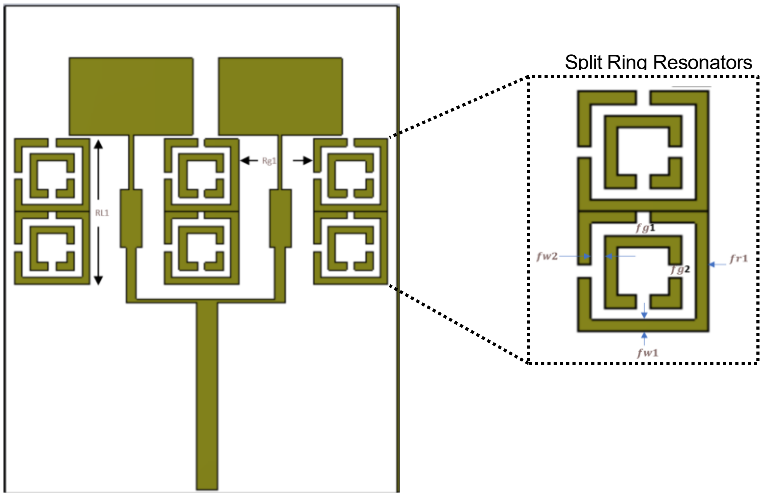

Fig. 2 The suggested patch antenna's ultimate design consists of 2 patches fed by a feed line technique and six split ring resonators (SRRs) had been placed on the antenna designed to achieve high performance at triple band characteristics.

3.1. Performance of MSA without SRRs

Initially, the S-parameters of the initial design of the antenna are investigated without using (SRRs) as shown in Fig. 3. A resonant frequency of 6.0 and 8.0 GHz with -25.53 and -31.89 dB of return loss and a gain of 8.6 and 5.58 dB were produced, respectively. Thus, the feature of dual-band has been achieved in this antenna. The simulated data demonstrate that the bandwidth of the first resonance frequency, which is 6.0 GHz, is 257.8 MHz, while the second resonant frequency, which is 8.0 GHz, is 128.2 MHz. At the resonant frequencies of 6.0 and 8.0 GHz, this antenna's voltage standing wave ratio (VSWR) is 1.13 and 1.31, respectively.

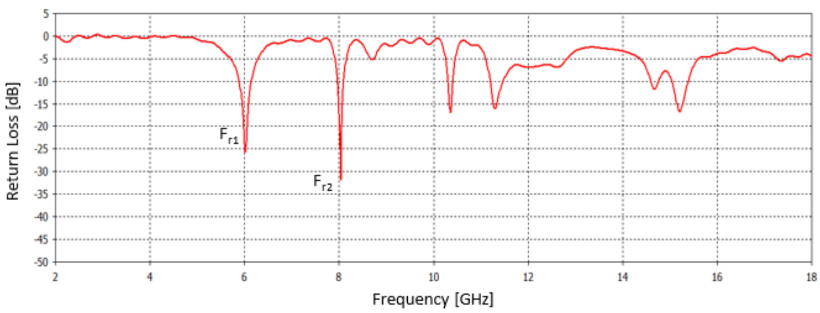

Fig. 3 The suggested patch array antenna's S-parameters without utilizing split ring resonators (SRRs). This design shows a good performance only at two frequencies (Fr1 and Fr2).

3.2. Performance of MSA with SRRs

To optimize the antenna design and characteristics, split- ring resonators (SRRs) have been placed on the substrate. Split resonators consist of thick multiple rings with spaces, causing inductance and capacitive effects. The metal ring produces induction, and the interval between the spaces causes the capacitance. The resonance frequency of SRR is determined by its inductance (L) and capacitance (C) according to the LC resonance formula (SK Patel & Y Kosta, 2018).

$$f = \frac{1}{\left(2\Pi\sqrt{(Lc)}\right)} \qquad (1)$$

The inductance of the SRR can be approximated using the formula from a loop inductor:

$$\mathrm{L} \approx \mu_0 \mathrm{r}\left[\ln\left(\frac{8\mathrm{r}}{\mathrm{a}}\right) - 2\right] \qquad (2)$$

Where, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m). r is the radius of the loop. a is the radius of the wire. The capacitance of the SRR is primarily due to the gap between the splits, modeled as a parallel plate capacitor (SK Patel & Y Kosta, 2018):

$$\mathrm{C} = \varepsilon_0 \varepsilon_r (\mathrm{Ad}) \qquad (3)$$

where ϵ is the permittivity of the medium, A is the area of the gap, and d is the separation between the splits (SK Patel & Y Kosta, 2018).

A patch antenna design with integrated SRR creates a paired resonance system. A patch antenna has its own resonance frequency determined by its physical dimensions and substrate properties. Integration of SRR introduces an extra resonance, causing a double-band or multi-band operation; Also, the SRR has the effect of enhancing the gain of the antenna by focusing the electromagnetic energy (SK Patel & Y Kosta, 2018).

When placing the SRR between the patch layer and the transmission line, this technique has a massive role in modifying the current path, enhancing resonance, and improving the impedance matching of the antenna by reducing the reflections, thus improving the power transfer of the antenna. It also offers an opportunity to affect the antenna's resonant frequency and radiation characteristics. After many adjustments and tests, the SRR has been strategically placed in a position to obtain the best results to achieve the desired performance in the proposed design (SK Patel & Y Kosta, 2018).

Fig. 4, shows the S-parameters of the pro-posed antenna design after adding SRRs to the initial antenna design. The S-parameters show that the antenna operates at triple band frequency. A resonant frequency of (5.96, 7.96, and 14.94) GHz with a return loss of (-45.77, -33.21, and -45.10) dB has been achieved, respectively. Therefore, the features of the triple-band have been gained and enhanced in this antenna, furthermore, the return loss values have improved due to the effect of the (SRRs), as demonstrated in Fig.4. The simulated data results demonstrate that first resonant frequency (5.96) GHz has a bandwidth of (282.5) MHz; second resonant frequency (7.96) GHz has a bandwidth of (121.6) MHz, and the bandwidth of the third resonant frequency (14.94) GHz is (1.175) GHz, this mean that this antenna can support high data rate with multiple applications.

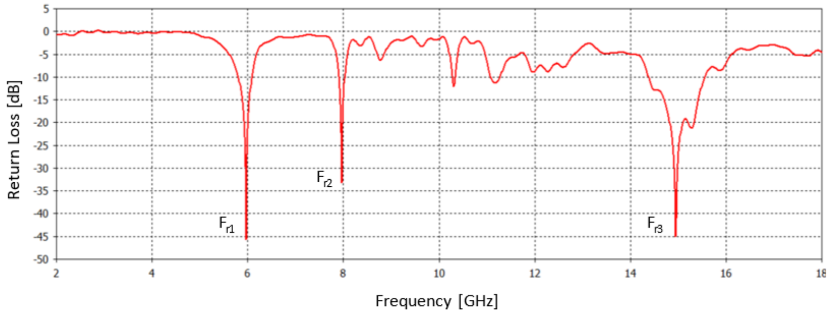

Fig. 4 The S- parameters of the proposed enhanced microstrip array antenna after adding the split ring resonators (SRRs). This design shows high performance at triple band frequencies (Fr1, Fr2, and Fr3).

The developed antenna with SRRs has improved its gain values to be 9, 6.7, and 7.5 dB for the three resonant frequencies (5.96, 7.96, and 14.94) GHz, respectively, due to the effect of the SRRs. The voltage standing wave ratio must typically fall between (1 and 2), indicating the perfect impedance matching, which means that there is no reflected power and all the signal has been transmitted to the antenna. The VSWR is formulated in Eq. 1 (Kimura et al., 2021).

$$VSWR = \frac{V_{max}}{V_{min}} \tag{4}$$

where V_{max} and V_{min} are the maximum and minimum amplitudes of the standing wave, respectively. In our work, the results of the simulation indicate that the proposed antenna's (VSWR) with SRRs has a value of 1.01, 1.05, and 1.01 for the three resonant frequencies (5.96, 7.96, and 14.94 GHz), resulting in high impedance matching and low reflected power, as shown in Fig.5.

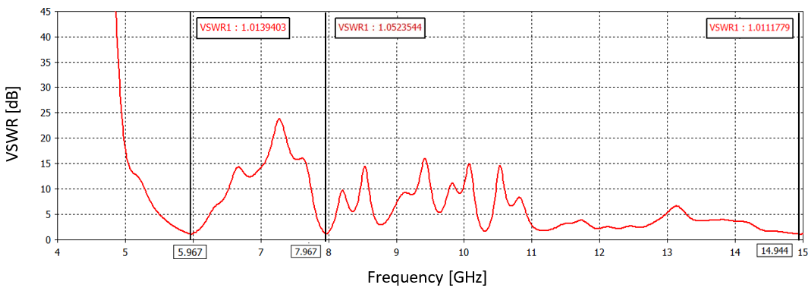

Fig. 5 The intended antenna's voltage standing wave ratio with SRRs at the three resonant frequencies 5.96 GHz, 7.96 GHz, and 14.94 GHz. The VSWR shows optimum values of 1.01, 1.05, and 1.01 for resonant frequencies, respectively.

To clarify the performance of the designed array patch antenna, Fig. 6 and Table 2 highlight the antenna performance and characteristics with and without using SRRs. For example, the merged design with SRRs enhanced the gain of the first and second resonant frequencies (F_{r1}, F_{r2}) by 0.4 dB and 1.32 dB, respectively, in addition to obtaining a high gain of 7.5 dB at the frequency of resonance 3. (F_{r3}).

Fig.7 provides further information about the con- structed antenna by displaying the simulated radiation pattern and the surface current distribution of the three resonant frequencies. For the three resonant frequencies—5.96 GHz, 7.96 GHz, and 14.94 GHz—the radiation patterns are in the E-plane. The acquired outcomes demonstrate that the antenna can operate within the C, and KU bands, thus, it has the potential to be used in Wi-Fi, microwave devices, radar, and satellite communications systems.

Table 2 An analysis of the differences between the simulated results of the suggested antenna with and without merging SRRs in terms of gain, fractional bandwidth, VSWR, BW, Fr, and RL.

	Number of bands	RF (GHz)	RL (dB)	BW (MHz)	VSWR	Fractional BW (%)	Gain (dB)
Without SRRs	2	6.0	-25.53	257.8	1.13	4.29	8.6
		8.0	-31.89	128.2	1.31	1.60	5.58
with SRRs	3	5.96	-45.77	282.5	1.01	4.73	9.0
		7.96	-33.21	121.6	1.05	1.52	6.9
		14.94	-45.10	1175	1.01	7.86	7.5

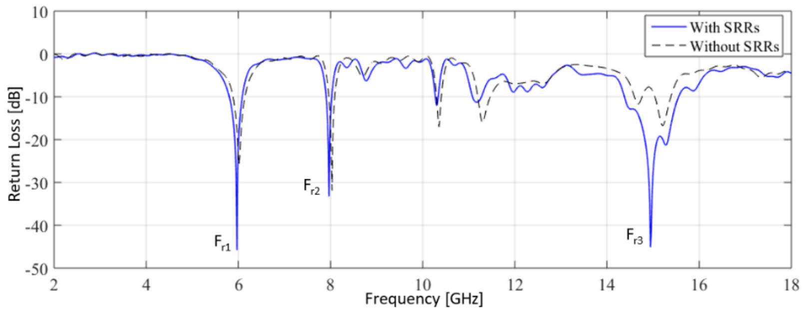

Fig. 6 The evaluated antenna's return loss at the three resonant frequencies (a) 5.96 GHz, (b) 7.96 GHz, and (c) 14.94 GHz, both with and without the use of SRRs.

The red line in Fig. 7 a-c, shows the radiation pattern of the antenna in the far field at the three resonant frequencies, and the blue line shows the gain and the directivity of the antenna at each of the obtained resonant frequencies, which indicate the main direction of the radiation. We can notice that the gain and the directivity increase with the frequency of this antenna, which indicates the antenna is becoming more efficient at focusing the power in the required direction.

From Fig. 7 we can also notice the current distribution of the antenna at the three resonant frequencies, we can observe from the first resonant frequency that the current is focused around the SRRs which mean the SRRs is heavily excited thus play an important part in mapping the antenna's radiation characteristics. At the second and the third resonant frequency, the patch and the SRRs playing a significant role where we can notice that the current is flowing broadly into the patch and the SRRs and the antenna structure which also contribute to the radiation of these frequencies. Overall, we can observe the SRRs had played a significant role in influencing the current distribution of this antenna.

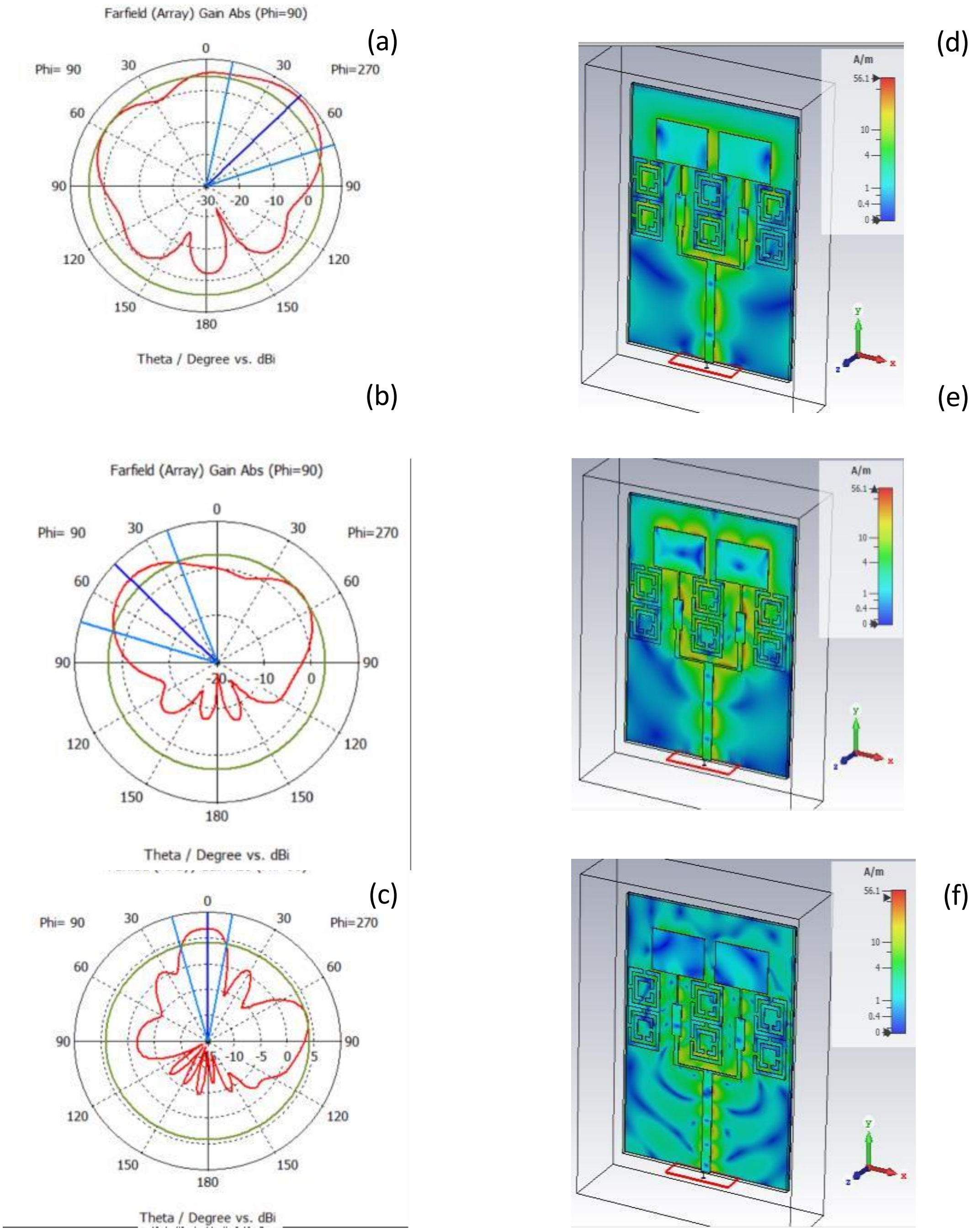

Fig. 7 The suggested antenna with SRRs at the three resonant frequencies (a and d) 5.96 GHz, (b and e) 7.96 GHz, and (c and f) 14.94 GHz, as well as the simulated radiation pattern and surface current distribution.

3.3. Experimental Results

The enhanced design of a triple-band patch array antenna along with multiple split-ring resonators is demonstrated as shown in Fig. 8. An Agilent N5242A Vector Network Analyzer is used to measure S11 outcomes, and the results demonstrate a high agreement between the simulated and measured results. The measured S11 plot shows resonance frequencies of (5.94 GHz, 7.97 GHz and 15 GHz). Also the measured S11 shows an impedance bandwidth of (200 MHz, 150 MHz, 800 MHZ) for the obtained resonance frequencies.

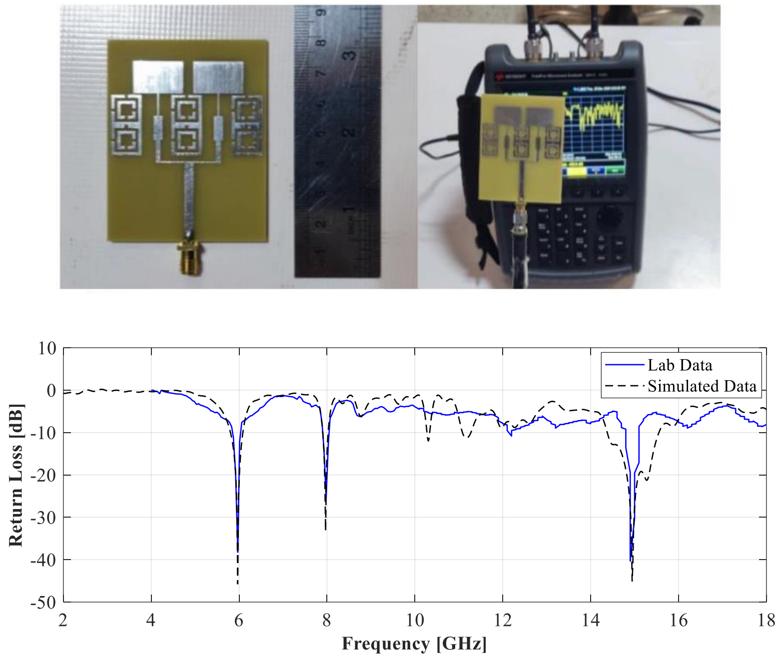

Fig. 8 The demonstrated the simulated and experimented results of the antenna at the three resonant frequencies 5.94 GHz, 7.97 GHz, and 15 GHz.

From Fig. 8 we can see that the S11 is still below the threshold (-10 dB) which means that the antenna has a good impedance matching, we can also notice a minimum difference between the S11 values at each resonant frequency for both measured and simulated results, this demonstrate how the antenna is matched at the center frequencies, plus the number of bands are ideally matched. Also, the shape of the curves are highly identical in the first and the second band with small insignificant shift in third band which consider within the fabrication tolerance.

Table 3 demonstrates the comparison between the previous works and our work regarding the dimensions of the antenna, resonance frequency, return loss, BW, fractional bandwidth, VSWR, and gain of each antenna design mentioned in (Le et al., 2021; Pandey et al., 2022; Anuar et al., 2020; Abdalla et al., 2020; Chang et al., 2021). Table 3 shows that our antenna provides a compact size, triple bands, the highest RL, maximum (VSWR), and higher gain than other previously designed antennas.

Table 3 Comparison between the proposed antenna with the previous papers on triple band operation

Ref	Overall Size (mm)	Frequency (GHz)	Return Loss (dB)	Fractional BW (%)	Gain (dB)
(Le et al., 2021)	60 x 60	2.45 3 3.45	≈ -23 ≈ -12 ≈ -27	4.4 4 6.2	4.2 6.6 5
(Pandey et al., 2022)	80 x 78.93	1.275-2.84 33.333-3.767 6.79-8.25	-13 -17 -20	76 12.2 19.4	2.85 2.9 3
(Anuar et al., 2020)	100 x 100	1.63–1.84 2.43–2.71 3.28–3.73	-17 -19 -22	12.10 10.89 12.84	5.5 5.9 6.9
(Abdalla et al., 2020)	100 x 100	2.4 2.9 4.38	-12 -30 -12	22 36.3 41	3.28 4.5 3.1
(Chang et al., 2021)	71 x 71	2.60 3.48 4.87	-17 -13 -28	10.7 6 8.4	3.53 4.19 4.09
Our work	53 x 67.1	5.96 7.96 14.94	-45.77 -33.21 -45.10	4.73 1.52 7.86	9 6.9 7.5

As shown in Table 3, the proposed design shows a good improvement in crucial aspects of the antenna performance, including size, return loss, gain, and bandwidth. The proposed design accomplishes a smaller overall size compared to the previous designs. The design footprint size provides a significant benefit for modern communication devices, as miniaturization is quite preferable.

Additionally, the return loss is optimized in the proposed design with an excellent improvement compared with previous works. All three resonant frequencies in our work exhibit return loss values (−45.77 dB, −33.21 dB, and −45.10 dB) and show a high impedance matching of our antenna, resulting in efficient power transfer. Furthermore, we have obtained high gain values compared to previous works that offer advantages in increasing the signal strength, resulting in longer transmission range with low losses. Regarding antenna bandwidth enhancement, the proposed work shows relatively competitive bandwidth values, which can be considered for future optimization.

The proposed antenna shows three resonant frequencies that have potential applications in wireless systems, including a 5.96 GHz frequency that could be used for high-speed data transfer and fall within the upper range of the 5 GHz Wi-Fi band. A 7.96 GHz frequency that would be used in satellite communication and weather radar, which falls within the X-band. Additionally, a 14.94 GHz frequency falls within the KU-band and can be used in satellite communication and 5G applications.

4. CONCLUSION

An enhanced design of the triple-band antenna with two array patches is presented. A multi-split ring resonator (SRR) has been used to enhance the antenna characteristics. The triple-band frequencies are measured at 5.96 GHz, 7.96 GHz, and 14.94 GHz with a corresponding gain of 9, 6.7, and 7.5 dB, respectively.

The antenna's voltage standing wave ratio with SRRs has been enhanced to become 1.01, 1.05, and 1.01 as obtained in the simulation for the three resonant frequencies, resulting in high impedance matching and low reflected power. The return loss has been analyzed and enhanced in this work by -45.77 dB, -33.21 dB, and -45 dB. The features of multi-band have been achieved and optimized. The results demonstrate a high agreement between the simulated and measured results. The obtained results show that the antenna can operate within C, and Ku bands, thus it has the potential to be used in Wi-Fi, microwave devices, radar, and satellite communications systems. For future work, it is desirable to improve the shape of the radiation pattern of the third band to achieve the targeted coverage and minimize noise, plus the presented design could also respond to other frequencies by changing the position of the split ring resonators in the antenna.

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