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A Compact Four Port High-Isolation SIW-Backed Self-Quadruplexing Antenna with a Swastik Shaped Slot for C Band Applications

Anil Kumar Katta[1,*] and Praveen Babu Choppala[2]

[1]Department of ECE, Trans-Disciplinary Research Hub - Andhra University (A.U. TDR-HUB) Visakhapatnam, Andhra Pradesh, India
[2]Department of ECE, AU College of Engineering (A), Andhra University, Visakhapatnam, Andhra Pradesh, India

ABSTRACT: A compact planar self-quadruplexing antenna backed with the SIW technology with high isolation between the input ports is designed and demonstrated for the simultaneous quad-band operation of the antenna. The SIW cavity is integrated with a Swastik shaped slot and two metallic vias to generate four distinct frequency bands with high gain and low cross polarization. Utilizing four distinct orthogonal patches with different lengths, each independently connected to a 50-Ω microstrip feed line, makes the antenna operate at four frequency bands of 4.8, 5.5, 6.6, and 7.6 GHz. The minimum value of Front-To-Back-Ratio (FTBR) is 18 dB, and the minimum isolation between the input ports is 28.4 dB. The measured values of peak gains in the frequency bands 4.8, 5.5, 6.6, and 7.6 GHz are 5.05, 6.20, 6.45, and 6.32 dBi, respectively. Hence, a single antenna consists of four signals transmitting or receiving simultaneously from four individual input ports without interfering with each other and with high isolation between the input ports confirms the self-quadruplexing property of the antenna. This antenna configuration enables the independent tuning of each resonant frequency according to specific application needs by manipulating a single parameter, that is the length of the patch and without disturbing other performance parameters of the antenna. To validate the simulation results, the antenna is fabricated and tested. The measurement findings match the simulation results closely, which confirms the quad-band operation of the antenna design. Simple configuration, compact size, high gain, and low cross polarization of the antenna make the proposed planar antenna suitable for practical multiband applications and for handheld transceivers with high isolation between the input ports.

1. INTRODUCTION

With the advancements in wireless communication applications, such as handheld mobile devices, there has been an increased demand for compact and planar multiband antennas. They can operate at multiple frequency bands with a single antenna, thus avoiding the need for multiple antennas within a single device, thereby reducing the overall device size [1–3]. Nevertheless, to achieve independent transmission and reception across all bands, an external multiplexer circuit is necessary, which increases the overall size and makes the antenna less useful for practical applications. Hence, self-multiplexing antennas which do not require additional components and allow simultaneous multiband operation are of growing interest, such as self-diplexing antennas [4–7]. Alternatively, researchers have shown interest in substrate integrated waveguide (SIW) due to its distinct characteristics such as unidirectional radiation, high gain, and ease of integration with planar circuits [8–10]. Self-multiplexing antennas are listed as follows: self-diplexing antennas [11–13], self-triplexing antennas [14–16], and self-quadruplexing antennas [17–19] from the existing literature. The self-diplexing antenna, as presented in [11], employs a bow-tie shaped slot and is fed by two 50 Ω microstrip lines to resonate at 9 and 11.2 GHz frequencies and achieves an isolation better than 25 dB between the two input ports. In [12], a plus-shaped slot is utilized, enabling self-diplexing operation at two frequency bands (8.55 GHz and 9.7 GHz) with an isolation of better than 20 dB. A rectangular slot is utilized in [13] for the radiation simultaneously at two frequency bands, achieving a peak gain of 5.95 dBi. A self triplexing antenna shown in [14] utilizes a pair of bow-tie slots for triple band operation, achieving good cross polarization better than 24.45 dB. A half-mode circular SIW, a half-mode rectangular SIW, radiating slot, and matching feed lines are employed in [15] to generate triple resonances, achieving isolation better than 20 dB. An I-shaped structure is configured in [16] to produce three distinct patches oriented towards three input ports, each emitting radiation at frequencies of 4.14, 6.1, and 8.32 GHz, respectively. As the number of ports increases, maintaining isolation between them becomes increasingly challenging. Nonetheless, in order to satisfy the growing demands of future communication, the development of self-multiplexing antennas with multiple ports are imperative. The self-quadruplexing antenna, as described in [17], employs four quarter-mode cavity resonators functioning at resonant frequencies of 3.5, 5.2, 5.5, and 5.8 GHz. In [18], an antenna configuration with four V-shaped slots of varying dimensions is employed. Each slot is supported by a quarter-mode substrate integrated waveguide and is con-

* Corresponding author: Anil K. Katta (anilecedepartment@gmail.com).

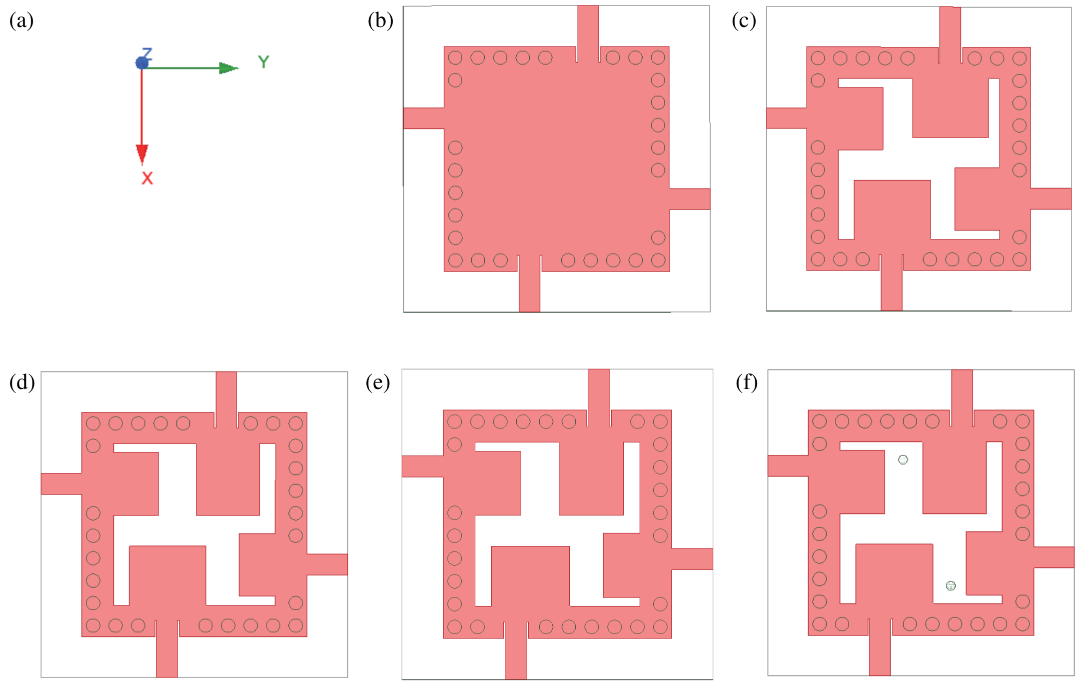


FIGURE 1. Design Evolution of antenna of the proposed antenna: (a) Reference directions for the antenna, (b) Stage-I: SIW Cavity, (c) Stage-II: SIW Cavity with swastik shaped slot with equal patches, (d) Stage-III: SIW Cavity with modified swastik shaped slot with center feed with unequal patches, (e) Stage-IV: SIW Cavity with modified swastik shaped slot with offset feed, (f) Stage-V-Proposed antenna: With modified swastik shaped slot with offset feed and metallic vias.

nected with 50 Ω feed lines. The antenna operates at frequencies of 8.19, 8.8, 9.71, and 11 GHz. It exhibits measured isolation of over 22 dB among the ports, with a minimum value of cross polarization 24.7 dB and front to back ratio (FTBR) better than 18.2 dB. However, a highly desirable solution is a planar self-quadruplexing antenna with compact size and enhanced isolations between the ports.

In this context, a new self-quadruplexing antenna design backed with a substrate integrated waveguide (SIW) cavity for the operation across four frequency bands within the C-band range is proposed. The design incorporates four mutually perpendicular patches with two metallic vias, along with four planar microstrip-feeding ports, enabling operation at 4.8, 5.5, 6.6, and 7.6 GHz with the peak gains of 5.05, 6.20, 6.45, and 6.32 dBi, respectively, while maintaining the minimum isolation of 28.4 dB. The prototype of the design is fabricated and analyzed for validation purposes. This article is organized as follows. Section 2 delves into the antenna configuration and principle of operation, while Section 3 discusses independent frequency tuning and frequency ratio design. The experimental results are outlined in Section 4 followed by the conclusion in Section 5.

2. ANTENNA STRUCTURE AND PRINCIPLE OF OPERATION

Figure 1 illustrates the design evolution stages of the suggested antenna, developed across five stages. SIW unperturbed cavity (Stage-I) is implemented on an RT/Duroid 5870 substrate with $\epsilon_r = 2.33$, $\tan\delta = 0.0012$, and height of the substrate (hs) $= 0.787$ mm. The antenna configuration, along with detailed dimensions, is provided in Figure 3.

The resonant frequency (f_{mn0}) of the SIW cavity can be calculated utilizing the formula [16]:

$$f_{mn0} = \left(\frac{1}{2\pi\sqrt{\mu\epsilon}}\right)\sqrt{\left(\frac{m\pi}{L_{eff}}\right)^2 + \left(\frac{n\pi}{W_{eff}}\right)^2} \tag{1}$$

where μ is the permeability, and ϵ is the permittivity of the substrate.

The effective length of the cavity,

$$L_{eff} = L_{cav} - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{L_{cav}} \tag{2}$$

The effective width of the cavity,

$$W_{eff} = W_{cav} - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{W_{cav}} \tag{3}$$

L_{cav} and W_{cav} are the cavity length and width, respectively.

A series of metallic vias arranged along the edges of the SIW cavity serve as the sidewalls of the conventional rectangular cavity. The diameter (d) and pitch (p) of the cylindrical vias are carefully selected such that $d/\lambda0 \leq 0.1$ and $d/p \geq 0.5$, to lower the leakage energy [9], where $\lambda0$ is the wavelength corresponding to the first resonant frequency. Figure 2 displays the electric field (E-field) distributions of the unperturbed cavity,

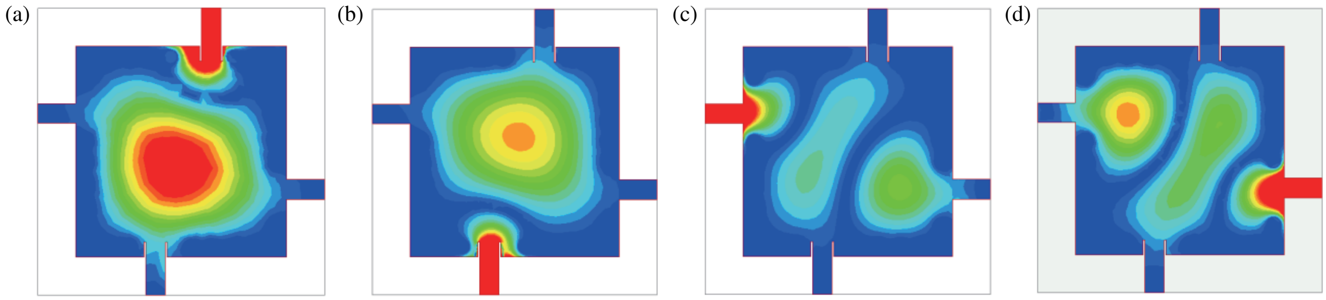


FIGURE 2. E-field distributions of the unperturbed cavity resonator. (a) TE_{110} mode at 6.83 GHz with input at port 1, (b) TE_{110} mode at 6.83 GHz with input at port 2, (c) TE_{120} mode at 11 GHz with input at port 3, (d) TE_{120} mode at 11 GHz with input at port 4.

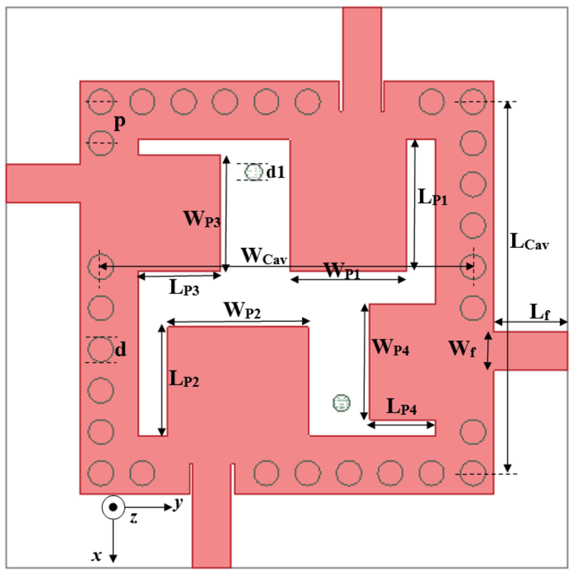


FIGURE 3. Structure of the antenna ($L_{Cav} = W_{Cav} = 22.5$, $p = 2.5$, $d = 1.5$, $d1 = 1$, $L_{P1} = 8$, $L_{P2} = 6.6$, $L_{P3} = 5$, $L_{P4} = 4$, $W_{P1} = W_{P3} = W_{P4} = 7$, $W_{P2} = 8.5$, $L_f = 4.5$, $W_f = 2.33$, $hs = 0.787$) (all dimensions are in millimeters).

and it can be observed that it supports TE_{110} mode (excited at Port 1 or Port 2) at 6.83 GHz and TE_{120} mode (excited at Port 1 or Port 2) at 11 GHz.

The SIW cavity is loaded with a modified swastik shaped slot (Stage-II) as shown in Figure 1(c), which creates four orthogonal radiating patches, where patch 1 and patch 2 have equal length and widths, and patch 3 and patch 4 have equal length and widths. As a result, antenna resonates at two distinct frequencies, which are 5.5 GHz and 6.7 GHz as shown in Figure 4(a), and the minimum isolation between the ports is around 8 dB. It is observed that because of the capacitive loading of the slot, the resonant frequencies are moved down below the cutoff frequency which helps to achieve a compact size of the antenna. Here the antenna is required to resonate at four different resonant frequencies from the individual input ports and to improve isolation beyond 20 dB to make it useful for practical multiband applications. Therefore, the dimensions of the patches are adjusted in a manner that results in the creation of four patches with unequal sizes (Stage-III) as shown in Figure 1(d). As a result, antenna resonates at four distinct frequencies of 4.8, 5.5, 6.6, and 7.6 GHz, and the minimum isolation (S_{12}) of 26 dB is achieved as shown in Figure 4(b). Offset feeding is employed (Stage-IV), which improves the impedance matching as shown in Figure 4(c). Two metallic vias of radius 0.5 mm are placed (Stage-V, proposed antenna, as shown in Figure 3) which act as parasitic elements further improving the impedance matching and improving isolation (S_{12}) to 28.4 dB. The isolations achieved at four resonant frequencies of 4.8, 5.5, 6.6, and 7.6 GHz are -31.1, -28.4, -30.5, and -32.8 dB, respectively. Here, the suggested antenna resonates at four distinct frequencies of 4.8, 5.5, 6.6, and 7.6 GHz. The minimum achieved isolation is 28.4 dB, ensuring simultaneous transmission and reception of the four different frequencies from the individual patches. This is achieved with a small square cavity measuring 22.5 mm in length and 22.5 mm in width, making the antenna suitable for practical multiband applications without the need for any external multiplexing circuit. Structure of the antenna with the detailed dimensions is presented in Figure 3.

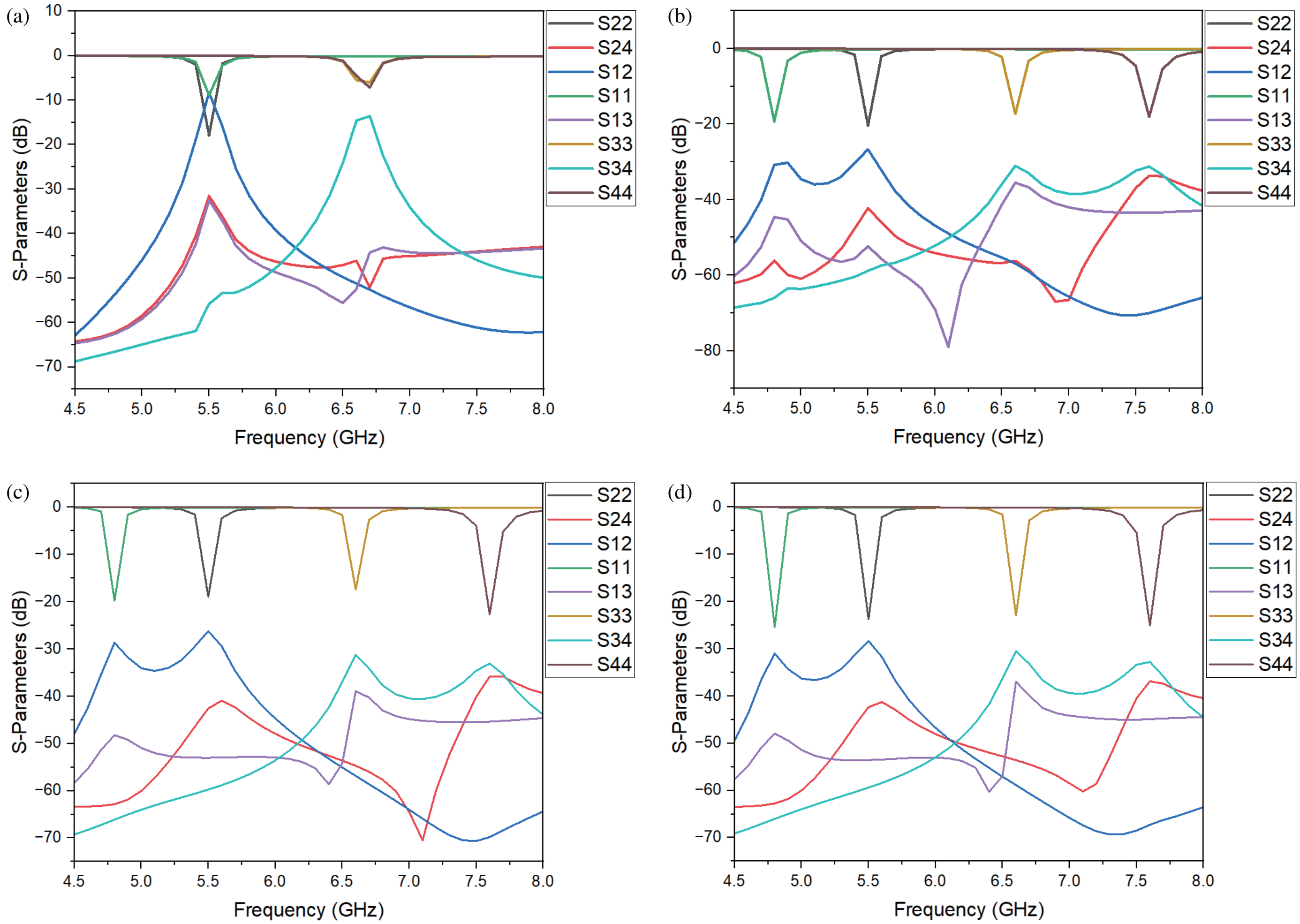


FIGURE 4. S-Parameters of the various design stages of the antenna: (a) Stage II, (b) Stage III, (c) Stage IV, (d) Stage V (proposed antenna).

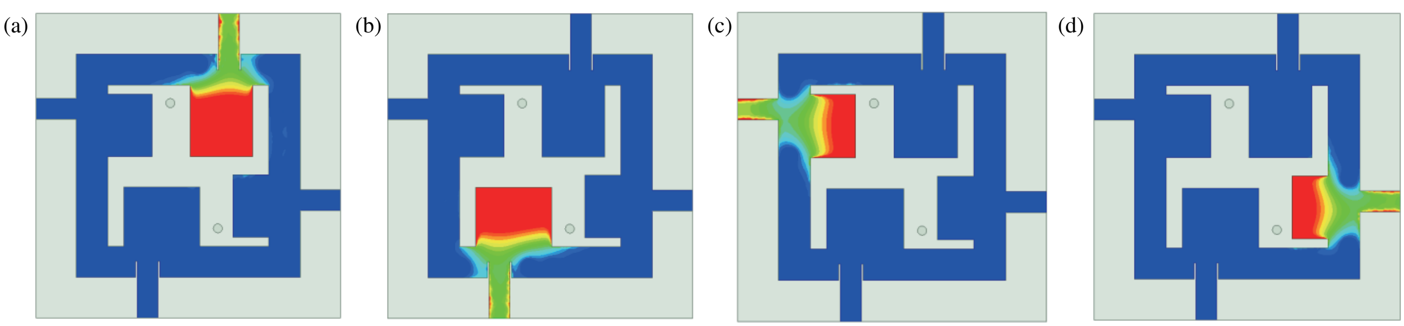


FIGURE 5. Electric field distribution of the proposed antenna (a) at 4.8 GHz when the input is applied at port 1, (b) at 5.5 GHz when the input is applied at port 2, (c) at 6.6 GHz when the input is applied at port 3, (d) at 7.6 GHz when the input is applied at port 4. (Note: Red colour indicates the maximum electric field intensity and blue colour indicates the minimum electric field intensity).

The patches with orthogonal arrangement within the small square cavity, along with the inclusion of two metallic vias between the patches, serve as reflective parasitic elements. This configuration enables high isolation between ports, good impedance matching, and ensures a compact antenna size. Figure 5 indicates that the proposed antenna supports TE_{110} modes at 4.8 GHz (input applied at Port 1) and 5.5 GHz (input applied at Port 2), with the highest intensity at the slot edges facing Port 1 and Port 2, respectively. Furthermore, it exhibits TE_{120} modes at 6.6 GHz (input applied at Port 3) and 7.6 GHz (input applied at Port 4), with the maximum intensity observed at the slot edges facing Port 3 and Port 4, respectively. It is

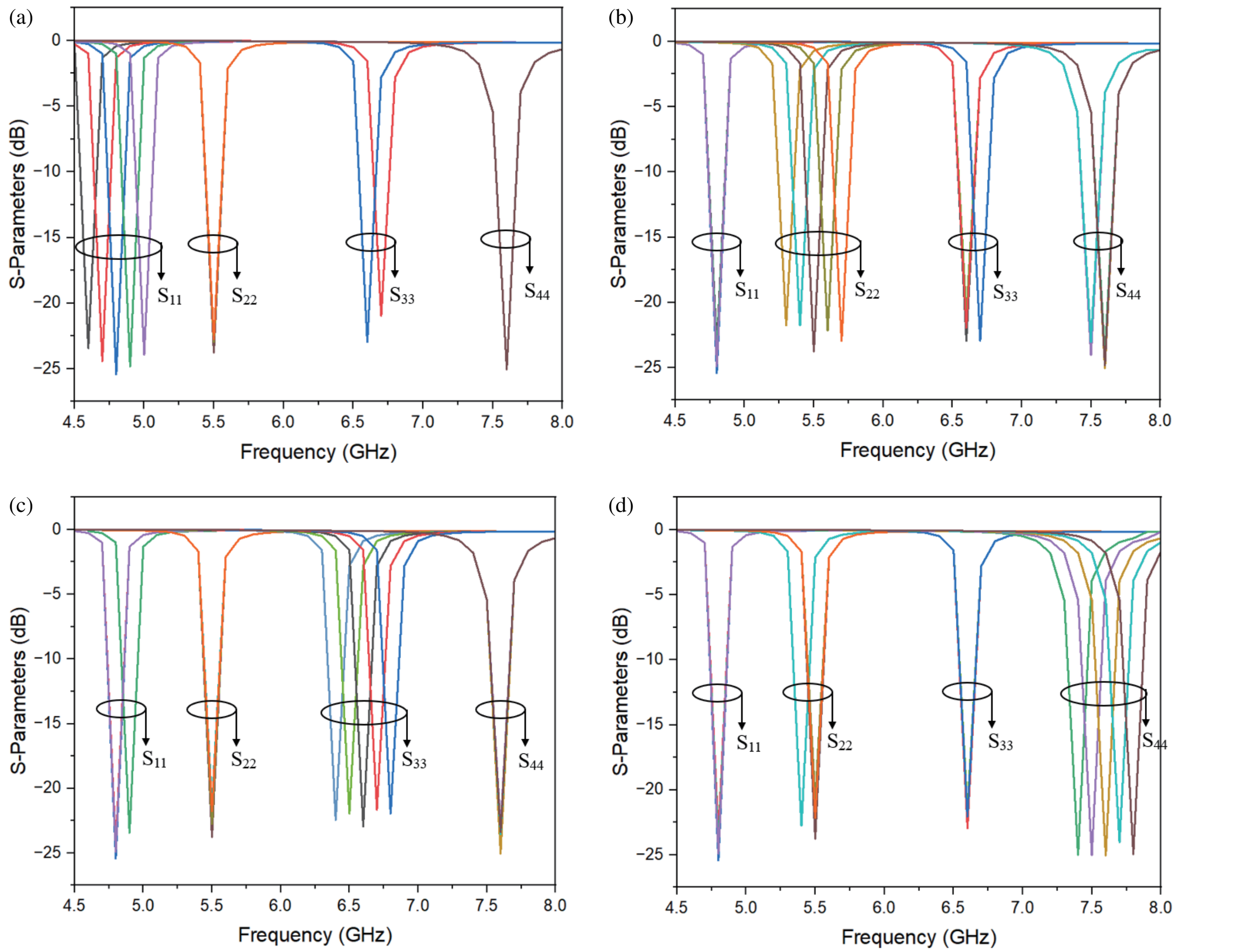


FIGURE 6. Independent frequency tuning using single parameter. (a) S_{11} using L_{P1}, (b) S_{22} using L_{P2}, (c) S_{33} using L_{P3}, (d) S_{44} using L_{P4}.

also clear that the transmission from one patch does not affect the remaining patches. Hence, the proposed antenna is suitable for practical multiband applications with high isolation between the ports.

3. INDEPENDENT FREQUENCY TUNING

Each frequency band can be tuned individually using the proposed antenna configuration. The frequency bands' locations may be adjusted by varying the total capacitance, which is accomplished by changing the slot length. The resonant frequencies of the suggested antenna depend on the lengths of the respective patches, and width of the patch has no effect on the location of the frequency. Therefore, the resonating frequencies $f1$, $f2$, $f3$, $f4$ can be tuned independently by modifying their respective patch lengths L_{P1}, L_{P2}, L_{P3}, L_{P4}. The reflection coefficient values (S-parameter: S_{11}, S_{22}, S_{33}, S_{44}) at each port with the variation in corresponding patch lengths L_{P1}, L_{P2}, L_{P3}, L_{P4} are shown in Figure 6. It is evident that $f1$, $f2$, $f3$, $f4$ increase as the patch lengths L_{P1}, L_{P2}, L_{P3}, L_{P4} increase. The detailed frequency ranges and patch lengths are presented in Table 1.

The suitable applications for the above frequency ranges of the antenna are: IEEE 802.11a for Wi-Fi applications in the frequency range 4.82 to 5.5 GHz, ISM band (Industrial, Scientific and Medical) frequency range: 5.4 to 5.8 GHz, Russian C-Band: 5.8 to 7.31 GHz, Metrological Satellite: 7.12 to 9.1 GHz.

3.1. Frequency Ratio Design

In addition to the independent frequency tuning, it is also possible to design the frequency ratio between any two resonant frequencies. This flexibility enables the antenna to fine tune its operating frequency to the desired nearby frequency ranges. To better describe this, the frequency ratio vs $L_{P1}/L_{P2}/L_{P3}/L_{P4}$ is plotted in Figure 7.

By varying the length of patch 1 (L_{P1}) from 7.6 to 8.4 mm in steps of 0.2 mm, frequencies $f1$ are relocated to 4.6, 4.7, 4.8, 4.9, and 5 GHz. Hence, the frequency ratios associated with $f1$, i.e., $f4/f1$, $f3/f1$, and $f2/f1$, are changed from 1.652 to 1.52, from 1.435 to 1.32, and from 1.196 to 1.1, respectively, as shown in Figure 7(a). By varying the length of patch 2 (L_{P2}) from 6.2 to 7 mm in steps of 0.2 mm, frequencies $f2$ are relocated to 5.3, 5.4, 5.5, 5.6, and 5.7 GHz. Hence, the frequency

TABLE 1. Variation of the resonant frequencies ($f1$, $f2$, $f3$, $f4$) with the corresponding patch lengths (L_{P1}, L_{P2}, L_{P3}, L_{P4}).

L_{P1} (mm)	$f1$ (GHz)
7.6	4.6
7.8	4.7
8	4.8
8.2	4.9
8.4	5

(i)

L_{P2} (mm)	$f2$ (GHz)
6.2	5.3
6.4	5.4
6.6	5.5
6.8	5.6
7	5.7

(ii)

L_{P3} (mm)	$f3$ (GHz)
4.6	6.4
4.8	6.5
5	6.6
5.2	6.7
5.4	6.8

(iii)

L_{P4} (mm)	$f4$ (GHz)
3.6	7.4
3.8	7.5
4	7.6
4.2	7.7
4.4	7.8

(iv)

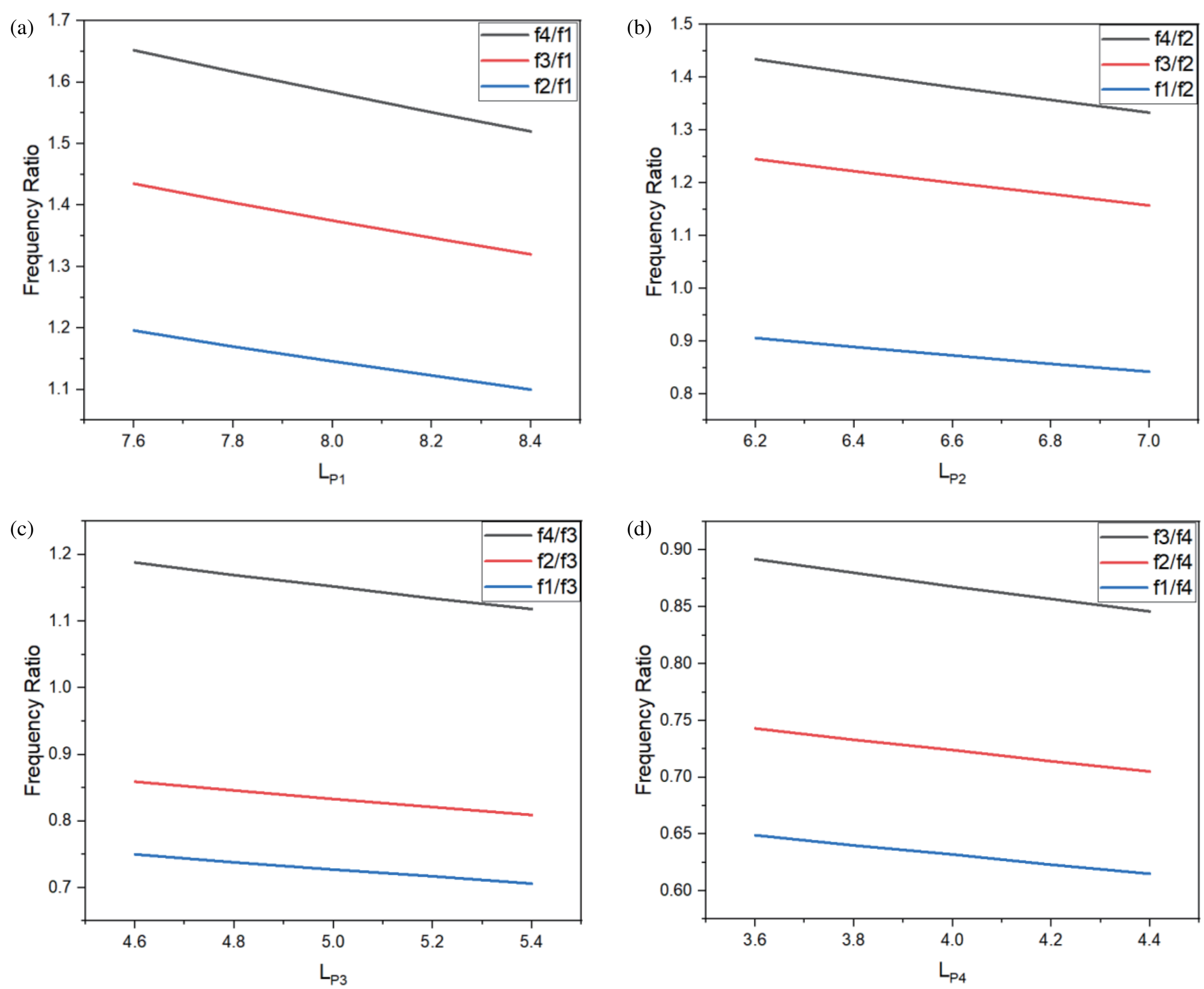


FIGURE 7. Design of frequency ratio using a single variable (length of the patch): (a) Frequency ratio related to $f1$ using L_{P1}. (b) Frequency ratio related to $f2$ using L_{P2}. (c) Frequency ratio related to $f3$ using L_{P3}. (d) Frequency ratio related to $f4$ using L_{P4}.

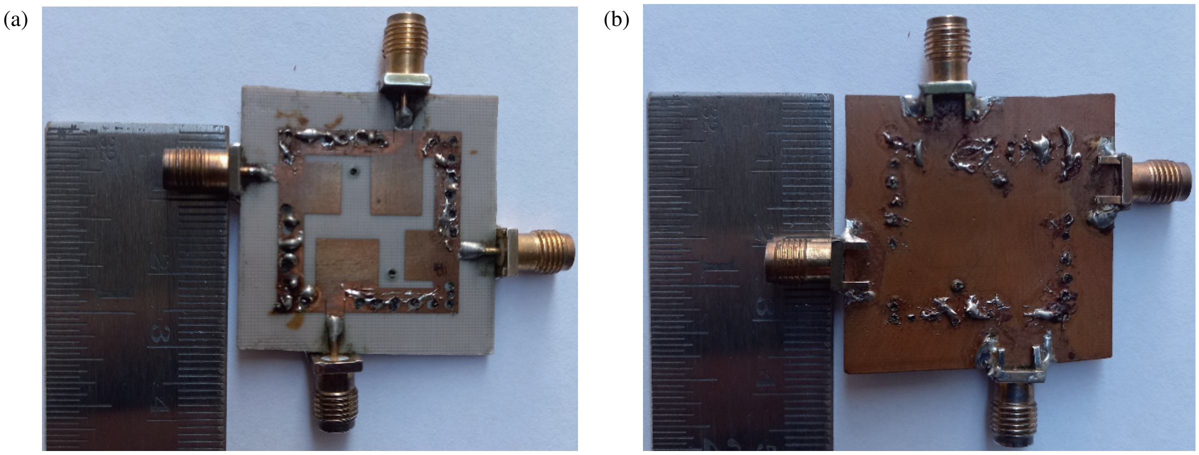


FIGURE 8. (a) Top and (b) Bottom faces of the fabricated prototype of the antenna.

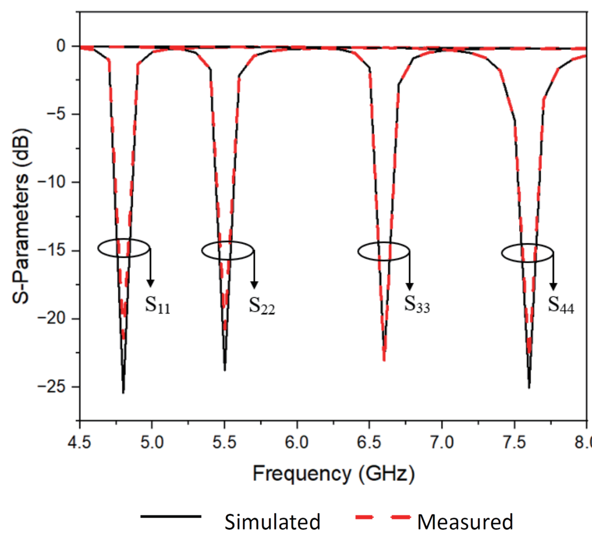


FIGURE 9. Simulated vs Measured Values of S-Parameters (Reflection Coefficient — S_{11}, S_{22}, S_{33}, S_{44}).

ratio associated with $f2$, i.e., $f4/f2$, $f3/f2$, and $f1/f2$ are changed from 1.434 to 1.333, from 1.245 to 1.157, and from 0.96 to 0.842, respectively, as shown in Figure 7(b). By varying the length of patch 3 (L_{P3}) from 4.6 to 5.4 mm in steps of 0.2 mm, the frequencies $f3$ are relocated to 6.4, 6.5, 6.6, 6.7, and 6.8 GHz. Hence, the frequency ratio associated with $f3$, i.e., $f4/f3$, $f2/f3$, and $f1/f3$ are changed from 1.188 to 1.118, from 0.859 to 0.809, and from 0.750 to 0.706, respectively, as shown in Figure 7(c). Similarly, by varying the length of patch 4 (L_{P4}) from 3.6 to 4.4 mm in steps of 0.2 mm, frequencies $f4$ are relocated to 7.4, 7.5, 7.6, 7.7, and 7.8 GHz. Hence, the frequency ratios associated with $f4$, i.e., $f3/f4$, $f2/f4$, and $f1/f4$ are changed from 0.892 to 0.846, from 0.743 to 0.705, and from 0.649 to 0.615, respectively, as shown in Figure 7(d). While observing the variation in one frequency, the remaining parameters are held at a constant value. The Figure 7 illustrates how the frequency ratio varies with the length of the patch (L_{P1} or L_{P2} or L_{P3} or L_{P4}).

Design procedure of the proposed antenna:

Step 1: Design an SIW cavity (with the length and width: 22.5 mm and 22.5 mm, which are $0.5\lambda_g$ and $0.5\lambda_g$, respectively) using Equations (1)–(3) [16].

Step 2: The top face of the cavity is loaded with a swastik shaped slot to create four distinct resonating pathes, with lengths of L_{P1}, L_{P2}, L_{P3}, L_{P4}.

Step 3. To achieve high impedance bandwidth, two metallic vias of diameter 1 mm are incorporated between the patches as shown in Figure 3. Metallic vias act as parasitic elements for further improved impedance matching and improved isolation to 28.4 dB.

Step 4. The resonating frequencies $f1$, $f2$, $f3$, $f4$ can be tuned independently by modifying their respective patch lengths L_{P1}, L_{P2}, L_{P3}, L_{P4}.

4. EXPERIMENTAL RESULTS

Figure 8 displays the prototype of the suggested antenna, which underwent characterization using a Vector Network Analyzer

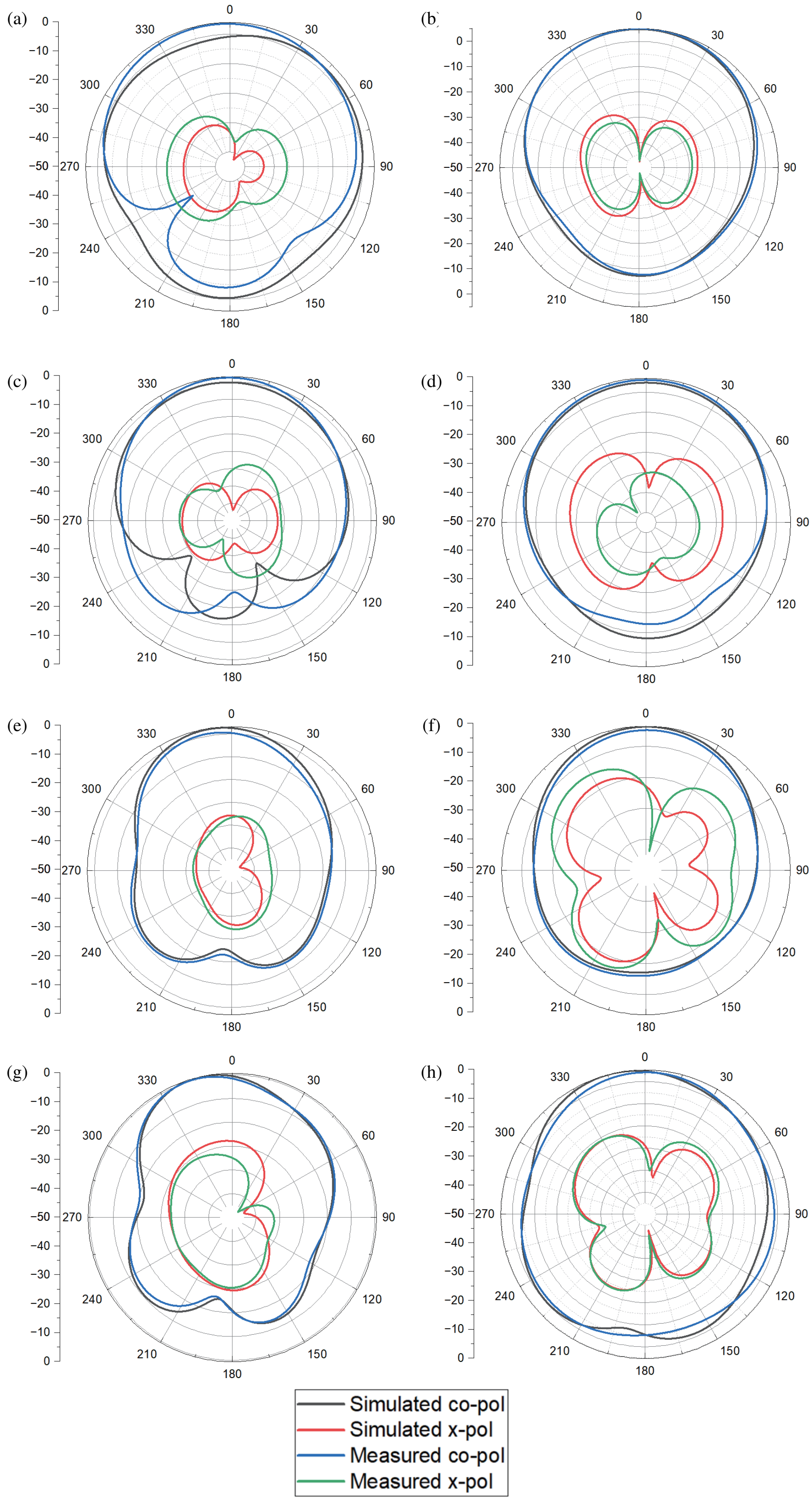


FIGURE 10. Simulated and measured normalized radiation patterns at resonant frequencies of: (a) 4.8 GHz ($\Phi = 0°$), (b) 4.8 GHz ($\Phi = 90°$), (c) 5.5 GHz ($\Phi = 0°$), (d) 5.5 GHz ($\Phi = 90°$), (e) 6.6 GHz ($\Phi = 0°$), (f) 6.6 GHz ($\Phi = 90°$), (g) 7.6 GHz ($\Phi = 0°$), (h) 7.6 GHz ($\Phi = 90°$).

TABLE 2. Performance comparison of the suggested antenna with the recently reported designs.

Reference No.	Resonant Frequencies	Gain (dBi)	Size of the antenna ($\lambda_g \times \lambda_g$)	Isolation (dB)	Minimum FTBR**	Frequency Tuning	Type of Antenna	External Multiplexing circuit-Required (Yes/No)
[1]	2.4, 3.5, 5.2, 5.8	1.3, 3.2, 1.5, 1.8	0.110	NA*	NA	Not Possible	Quad-Band	Yes
[2]	2.4, 3.5, 5.2, 5.8	2.8, 2.1, 3.5, 3.2	0.104	NA	NA	Not Possible	Quad-Band	Yes
[3]	1.2, 2.4, 3.5, 5.2	5.47, 5.88, 1.97, 3.56	0.156	NA	NA	Not Possible	Quad-Band	Yes
[12]	8.55, 9.77	5.7, 5.94	0.59	> 18	12	Possible	SIW Self-Diplexing	No
[14]	7.8, 9.4, 9.8	7.2, 7.2, 7.0	0.94	> 22.5	17.3	Possible	SIW Self-Triplexing	No
[15]	5.57, 7.17, 7.65	4.10, 3.95, 3.54	0.42	> 21.3	14.1	Possible	SIW Self-Triplexing	No
[17]	3.5, 5.2, 5.5, 5.8	5.43, 4.1, 3.56, 3.6	NA	> 23.6	NA	Possible	SIW Self-Quadruplexing	No
[18]	8.1, 8.78, 9.71, 11	5.5, 6.9, 7.47, 7.45	0.792	> 22.6	17	Possible	SIW Self-Quadruplexing	No
This Work	4.8, 5.5, 6.6, 7.6	5.05, 6.20, 6.45, 6.32	0.25	> 28.4	18	Possible	SIW Self-Quadruplexing	No

*NA-Not Available or not given
**FTBR-Front To Back Ratio

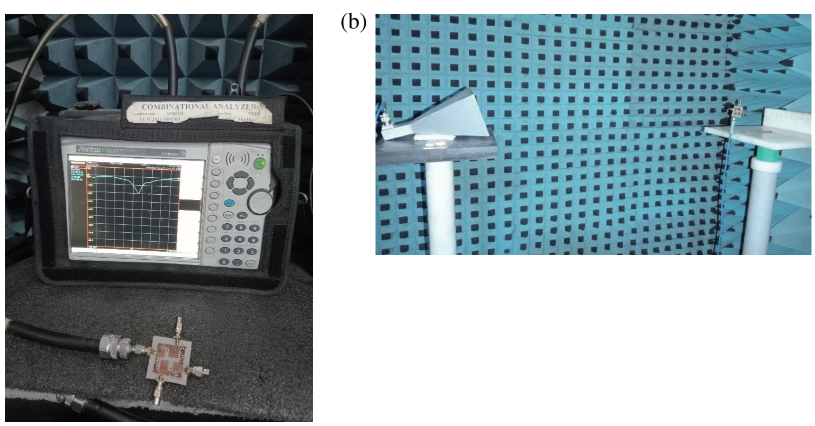
(a) (b)


FIGURE 11. (a) Antenna connected with vector network analyzer and (b) Antenna in anechoic chamber for the radiation measurement.

(Anritsu-MS2037C). Each port is individually excited while the other ports are terminated with a 50-ohm load during measurements, as the suggested antenna is a multiport device. Figure 9 illustrates the comparison between simulated and measured values of reflection coefficients S_{11}, S_{22}, S_{33}, S_{44}. The measured values of the peak gains are recorded as 5.05, 6.20, 6.45, and 6.32 dBi at four resonant frequencies of 4.8, 5.5, 6.6, and 7.6 GHz respectively. The antenna's radiation patterns in two orthogonal planes $\phi = 0°$ and $\phi = 90°$ are measured at all resonant frequencies and depicted in Figure 10. Minimum cross polarization values in the radiating directions of the antenna in four frequency bands are -27.9, -25.2, -28.2, and

−21 dBi, respectively, and the difference between co pol and cross pol values is maximum which can be verified from the radiation patterns (Figure 10). Performance of the suggested antenna is compared with recently reported one port non-SIW quadband antennas from [1] to [3], as well as various SIW based self-multiplexing antennas cited in [12, 14, 15, 17, 18], as summarized in Table 2. The antenna sizes provided in [1–3] exclude the dimensions of the external multiplexing circuit, and the self-multiplexing antennas do not necessitate external multiplexing circuits and enable independent frequency tuning. Compared to the self-diplexing antenna [12], self-triplexing antennas [14, 15], and self-quadruplexing antennas [17, 18], the suggested self-quadruplexing antenna has achieved enhanced performance in terms of antenna configuration, size, and isolation. Figure 11 displays the antenna connected to a Vector Network Analyzer and the antenna placed in an anechoic chamber for radiation measurement. The measured results match the simulated ones closely, with minor discrepancies which are due to the fabrication and measurement errors.

5. CONCLUSION

This paper presents an SIW based self-quadruplexing antenna, providing quad-band operation from four input ports, and it does not require any additional multiplexing circuits. It integrates four antenna elements in a single antenna called self-quadruplexer, offering independent frequency tuning at all input ports. The suggested antenna exhibits quad-band operation with simultaneous transmission and reception at 4.8, 5.5, 6.6, and 7.6 GHz frequencies by perturbing the cavity with a modified swastik shaped slot and two metallic vias. The measured values of the peak gains at the four resonant frequencies are 5.05, 6.20, 6.45, and 6.32 dBi, respectively. Independent frequency tuning and the design of frequency ratio are possible by changing a single variable, length of the patch. The performance of the self-quadruplexing antenna is confirmed through the measurement results. The antenna demonstrates a compact size, high isolation ($>$ 28.4 dB), good Front To Back Ratio (FTBR) ($>$ 18 dB), and eliminates the need for an external multiplexing circuit, making it an ideal choice for C-band applications.

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