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Highly Isolated Self-Quadplexing Antenna Based on Quarter-Mode Substrate Integrated Waveguide Cavity

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ABSTRACT: In this paper, a substrate integrated waveguide based self-quadplexing antenna with modified U-shaped slots is presented. The quadplexing antenna resonates at four distinct frequencies 4.02 GHz, 4.37 GHz, 4.78 GHz, and 5.26 GHz by adjusting the length of U-shaped slots. The antenna shows a minimum port isolation of > 34 dB between any two ports. The self-quadplexing antenna gives the frequency tunability and shows an unidirectional radiation pattern at the corresponding operating frequencies. The simulated (measured) gains of the antenna are 5.18 dBi (5.24 dBi), 5.51 dBi (5.57 dBi), 5.03 dBi (5.14 dBi), and 5.12 dBi (5.19 dBi). The proposed antenna is independent of frequency tunability by the excitation of four ports with an antenna size of $0.12\ \lambda_0^2$, where λ_0 is the free space wavelength at the lowest resonant frequency. These features make the proposed antenna suitable for WLAN, ISM, INSAT C, Wi-Fi applications.

1. INTRODUCTION

The evolution of recent wireless communication systems has created an increasing demand for planar, low-profile, multiband antennas. In order to meet the demands of different frequency bands, it is necessary to mount several antennas on a single platform. These antennas can be precisely tuned to the requirements of modern communication systems. But practical implementation usually requires external multiplexers for frequency band selection, and these require additional space for accommodation. To solve these problems, new antenna topologies with inherent multiplexing have been proposed. These configurations facilitate multi-band operation without requiring external multiplexer circuits. Also, the trend towards miniaturization requires these devices to be small in size. Substrate Integrated Waveguide (SIW) technology is efficient in miniaturizing antenna systems [1, 2]. The method also offers other advantages, such as better isolation between the ports, better radiation properties, and easy integration [3–6]. With the integration of SIW technology and self-multiplexing antennas, it is possible to attain compactness and improved performance.

One of the most important requirements for self-multiplexing SIW antennas is the frequency ratio between the operating frequency bands. The frequency ratio should be low because it allows the close spacing of different frequency bands in the operating range with the antenna. It makes the efficient use of existing sub-bands possible, making the allocation of more frequency channels within the given frequency range easier [7]. Additionally, a low frequency ratio increases capacity for data rates, fully utilizing a comparatively small frequency spectrum. High demand exists for multiband antennas that have a low frequency ratio (FR) since they support several frequencies within one band, maximizing the utilization of existing frequency spectra. Substantial research work in the past few years has been centered on the design of antennas that include SIW technology. Dual-band [8–13] and triple-band [14–18] antennas have been presented. Self-quadplexing antennas utilizing SIW have been presented by the use of modes like half-mode SIW [19, 20] and quarter-mode SIW [7, 21]. These antennas are designed using various shapes of slots, i.e., V-shaped slots [22, 23], U-shaped slots [24], unequal patch resonators [25], and T-shaped slots [26].

To have low frequency ratio (LFR) with high isolation is a challenge as more ports are available in quadplexing antennas [22, 27, 28] than in diplexing [29] and triplexing antennas. For instance, in [19, 24], the quadplexing antennas attained high isolation of > 30 dB but with frequency ratio of 2.25 [24] and 2.63 [19]. In contrast, the designs presented in [23, 26] had a frequency ratio of 1.34 [23] and 1.38 [26], respectively. In addition, in [11] there was a high isolation of 30.5 dB with a frequency ratio of 1.46 using V-shaped slots, but with a huge antenna size of $0.42\lambda_0^2$. Though the reported designs have high performance characteristics, they are restricted by having either a high frequency ratio and size or a low frequency ratio and isolation. Hence, it is difficult to design a self-quadplexing antenna with high isolation, low frequency ratio, small size, and high performance characteristics.

An SIW based self-quadplexing antenna is designed in this paper on the basis of the four QMSIW cavities excited by $50\,\Omega$ microstrip lines. Modified U-shaped slots are used to load the antenna for resonating four different frequencies in order to get the self-quadplexing characteristics. Here, the advantage of this design is that independent frequency bands can be controlled by altering the lengths of these slots. The Key bene-

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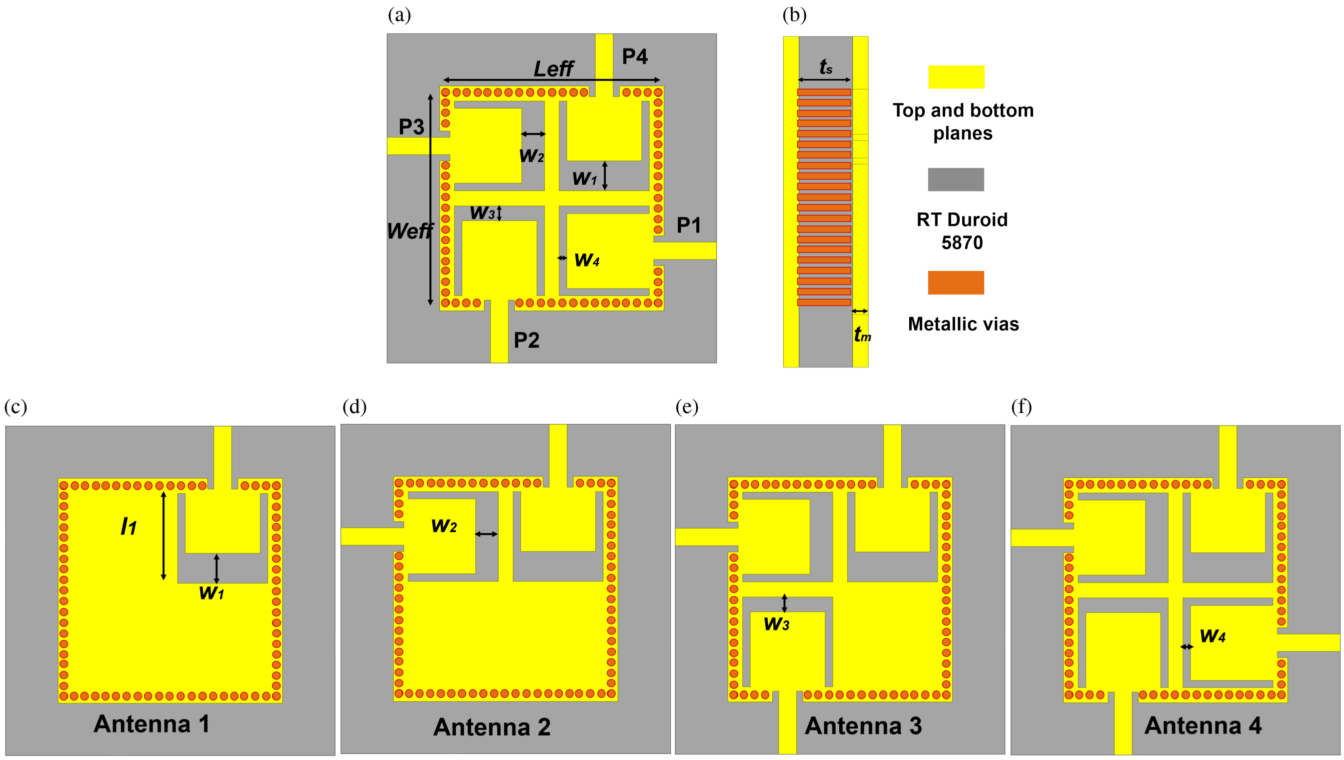

FIGURE 1. (a) Schematic-view. (b) Side-view pf the antenna. Design steps of the proposed antenna. (c) With single U-shaped slot. (d) With two U-shaped slots. (e) With three U-shaped slots, and (f) With four modified U-shaped slots.

fits of the antenna are high isolation between neighboring ports without requiring extra decoupling networks, a low frequency ratio (LFR), and high gain, and with these performance parameters, the proposed antenna is appropriate for real-world applications. Thus, the proposed quadplexing antenna simultaneously operate at four distinct frequency bands, each with good isolation and stable radiation performance. This enables the antenna to handle four independent channels or functionalities concurrently, effectively acting as a self-multiplexing system.

2. STRUCTURAL DESIGN AND FUNCTIONAL ANALYSIS OF PROPOSED ANTENNA

The top and side views of the self-quadplexing antenna are shown in Figs. 1(a) and (b), respectively. The middle substrate layer of the antenna is made using Rogers RT/Duroid 5870 with a thickness of 0.787 mm, relative permittivity of 2.33, and dielectric loss tangent of 0.0012. Top and bottom metallic surfaces are formed using copper layers with each layer having a thickness of 0.035 mm. In order to reduce electromagnetic leakage between the metal vias, the via diameter and distance are chosen such that $0.5p \leq d \leq 0.1\lambda_0$ [5]. The optimized structural parameters of the antenna are: $L_{\mathit{eff}} = 26$ mm, $W_{\mathit{eff}} = 26$ mm, $w_1 = 4$ mm, $w_2 = 3$ mm, $w_3 = 2$ mm, and $w_4 = 1$ mm (all in millimeters).

A conventional square SIW resonator is first designed using the expression given in Equation (1)

$$f_{110} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1}{l_{\mathit{eff}}}\right)^2 + \left(\frac{1}{w_{\mathit{eff}}}\right)^2} \tag{1}$$

Here, c represents the speed of light in free space, ϵ_r the substrate's relative permittivity, *leff* the effective length, and *weff* the effective width of the SIW cavity resonator. Based on Equation (1) and the antenna's design parameters, the resonant frequency is calculated to be 5.38 GHz.

The design process of the SIW quadplexer is shown in Fig. 1. A single U-shaped slot of slot length $w_1 = 4$ mm is first added on the traditional SIW square cavity resonator. It can be seen from Fig. 1(c) that this slot decreases the effective area of the patch, and Structure 1 resonates at 5.26 GHz which can be observed from Fig. 2(a). The loading of the slot forms a quarter-mode SIW cavity [30]. In order to further observe the influence of the slot, the distribution of electric fields is shown Fig. 3(a). When port 1 is driven, the field is focused around the U-shaped slot edge as indicated in Fig. 3(a). For realizing two dissimilar resonant frequencies, another U-shaped slot of length $w_2 = 3$ mm is loaded on the SIW cavity as illustrated in Fig. 1(d).

The addition of the second slot makes the patch's effective area smaller, and resonant frequency is 4.78 GHz, while the first resonant frequency is the same. The U-shaped notches achieve a high isolation thanks to their geometric symmetry, reducing electromagnetic coupling among neighboring ports as well

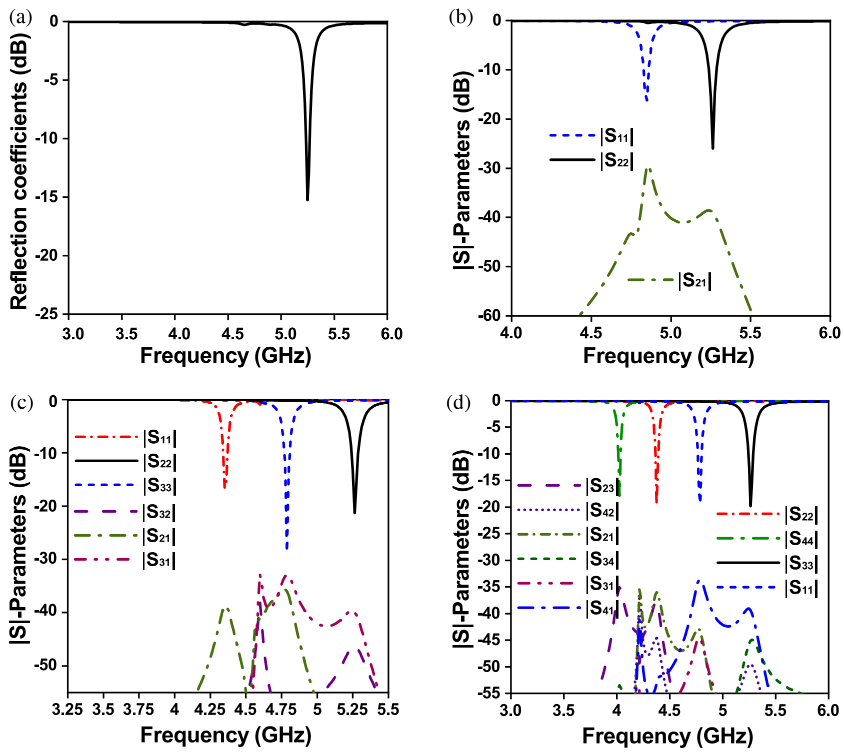

FIGURE 2. $|S|$-parameters of the antennas at different design steps, (a) Antenna 1, (b) Antenna 2, (c) Antenna 3, and (d) Antenna 4.

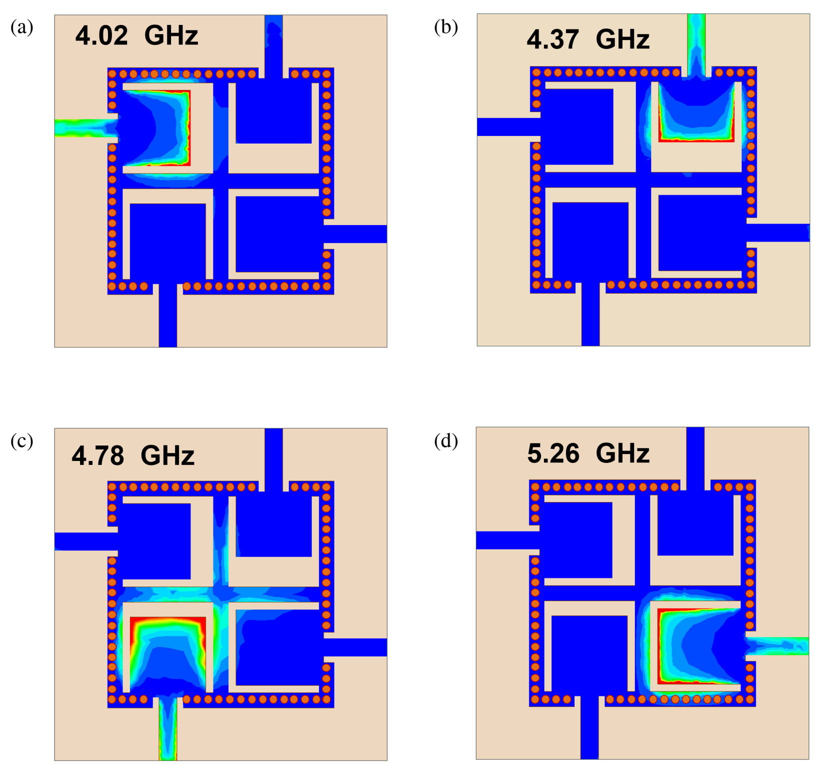

FIGURE 3. Electric field distributions of proposed antenna at four different resonant frequencies.

as making controlled current distribution and localized electric fields possible such that the isolation between these two ports is $>$ 30 dB as depicted in Fig. 2(b). The electric fields are confined inside the slot from the excitation of 2 as shown in Fig. 3(b). The same process is used to obtain two other resonant frequencies. Increasing the number of slots as shown in Figs. 1(e) and 1(f) the effective area of the patch decreases, which leads to two lower resonant frequencies of 4.02 GHz and

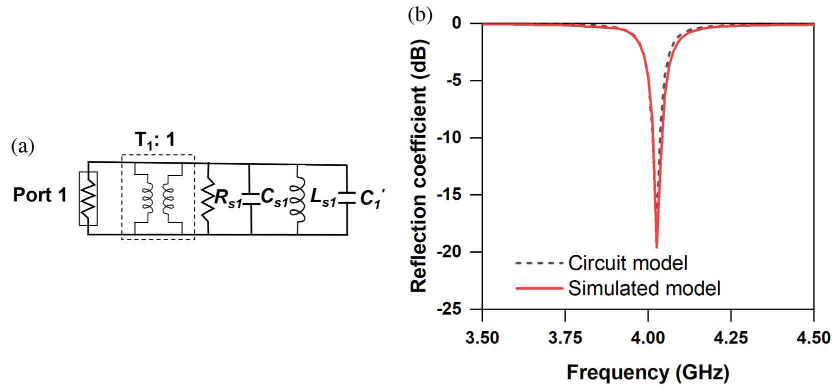

FIGURE 4. (a) Equivalent circuit model of the first resonating element, (b) Reflection coefficient of the simulated and circuit model of the antenna by the excitation of port 1.

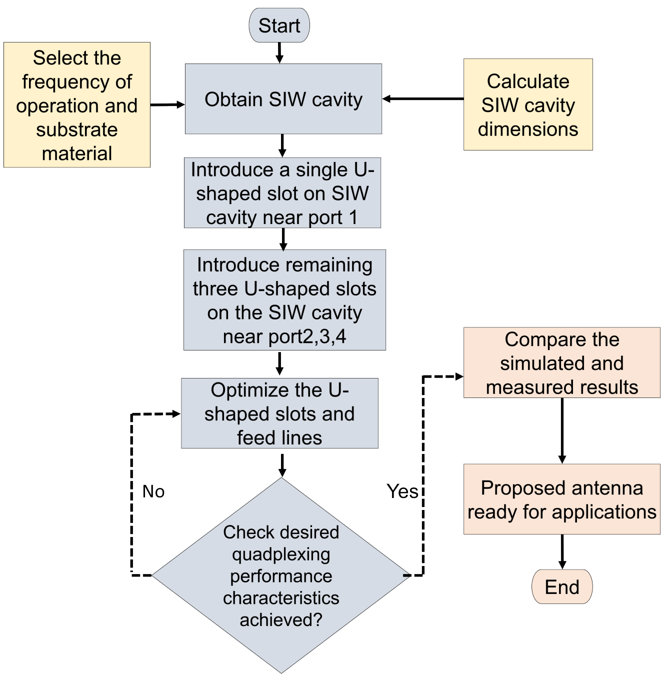

FIGURE 5. Design flowchart of the proposed self-quadplexing SIW antenna.

4.37 GHz. The isolation between any two ports is still > 34 dB, as can be seen in Figs. 2(c) and 2(d), whose corresponding electric field distributions are presented in Figs. 3(c) and 3(d) by exciting ports 3 and 4, respectively. Therefore, by incorporating modified U-shaped slots, the SIW cavity resonates at four operating frequencies: $f_1 = 4.08$ GHz, $f_2 = 4.37$ GHz, $f_3 = 4.61$ GHz, and $f_4 = 4.97$ GHz, as indicated in Fig. 2(d).

The equivalent circuit model of the first resonating element of the proposed self-quadplexing antenna is depicted in Fig. 4. This model depicts the cavity resonator in terms of a shunt combination of resistance, inductance, and capacitance. Furthermore, the slot connecting Port 1 has an additional shunt capacitance. This circuit is simulated for validation with Advanced Design System, and the obtained S-parameters are presented in Fig. 4. The analysis confirms that the circuit model closely follows the simulated response, particularly around the first resonant frequency. Additionally, we have now specified that the circuit model analysis was performed at the first resonant frequency of 4.02 GHz, corresponding to the excitation at Port 1. The RLC values in the circuit were optimized using ADS to match the behavior observed in the HFSS-based full-wave simulation. The same can be derived and validated for the rest of the ports. The systematic design process of the proposed self-quadplexing antenna, as outlined in the flowchart given in Fig. 5, is as follows:

1. Begin with defining the target frequency bands of operation and selecting a suitable dielectric material with its relative permittivity and loss tangent in mind. Determine the cavity size for the SIW structure based on the target frequencies and substrate's properties.
2. Design a square-shaped full-mode substrate integrated waveguide (FMSIW) cavity from the calculated dimensions.
3. Introduce a single U-shaped slot on the SIW cavity near port 1. The slot is tasked with generating one of the several resonant frequencies necessary for self-quadplexing operation.
4. Next insert three more U-shaped slots around 2, 3, and 4 ports. Each strip will be designed with enough spacing to target specific frequencies to resonate at desired operating frequencies.
5. Tune the position and dimensions of these four slots to obtain the desired operating frequencies. The challenge is to achieve the desired resonating frequencies while maintaining low mutual coupling between adjacent ports.
6. Finally, validate the performance characteristics of the antenna by comparing the simulated and measured results to check the accuracy of the proposed design.

2.1. Design Analysis and Tunability

Figure 6 shows the frequency tuning ability of the designed self-quadplexing antenna to support different communication standards, such as but not limited to C-band, NR bands (n46, n77,

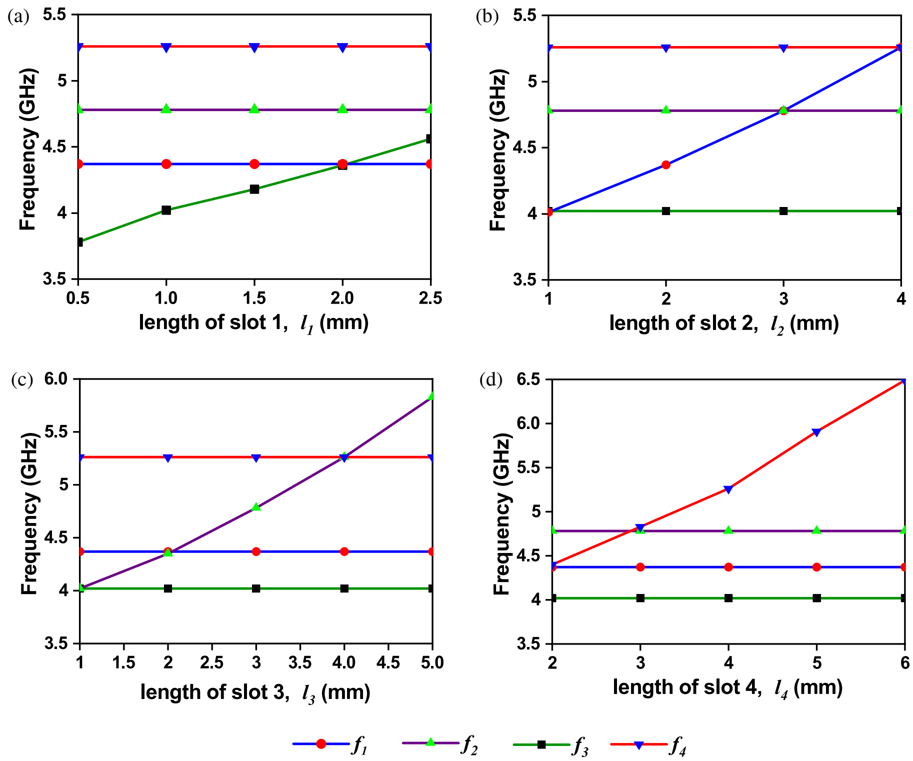

FIGURE 6. Independent frequency tunability of the antenna by the variation of (a) l_1, (b) l_2, (c) l_3, and (d) l_4.

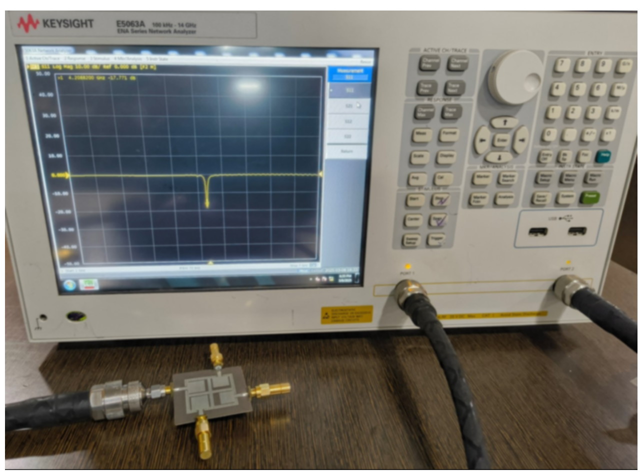

FIGURE 7. Measurement of the reflection coefficient of the proposed antenna.

n79), ISM, Wi-Fi, Wi-MAX, LTE, and 5G applications. Independent frequency tuning is realized by varying parameters w_1, w_2, w_3, and w_4. In particular, the lower resonant frequency f_1 can be tuned from 3.78 GHz to 4.56 GHz by sweeping w_1 from 0.5 mm to 2.5 mm as indicated by Fig. 6(a).

It can be seen that changing w_1 has a significant effect on the first resonant frequency f_1, whereas the other resonant modes are not affected much. The second resonant frequency, f_2, can be adjusted between 4.01 GHz and 5.26 GHz by changing w_2 from 1 mm to 4 mm, as shown in Fig.,6(b).

Similarly, the slot length, w_3, is adjusted to obtain tuning of the third resonant frequency, f_3. By changing w_3 from 1 mm to 5 mm, the frequency f_3 varies from 4.02 GHz to 5.83 GHz, as shown in Fig. 6(c). Lastly, Fig. 6(d) illustrates that the fourth resonant frequency, f_4, can be tuned from 4.4 GHz to 5.89 GHz by varying w_4 from 2 mm to 6 mm.

Tuning one frequency band does not really have much influence on the other ones so as to make precise and independent frequency tuning. Such broad tuning range (3.78–5.89 GHz) allows the presented antenna to operate for several wireless standards. Therefore, the proposed antenna can obtain a minimum frequency ratio of 1.3, while maintaining the other frequencies constant, and demonstrates the effective design and optimization of the antenna.

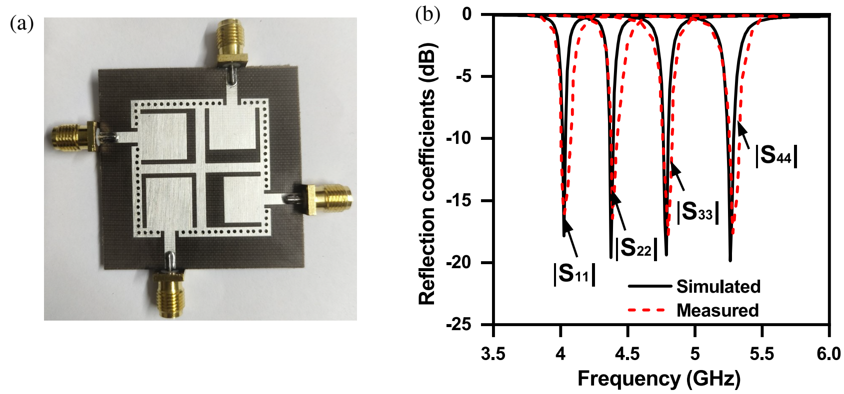

FIGURE 8. (a) Fabricated photograph of the antenna. (b) Simulated and measured values of the reflection coefficient.

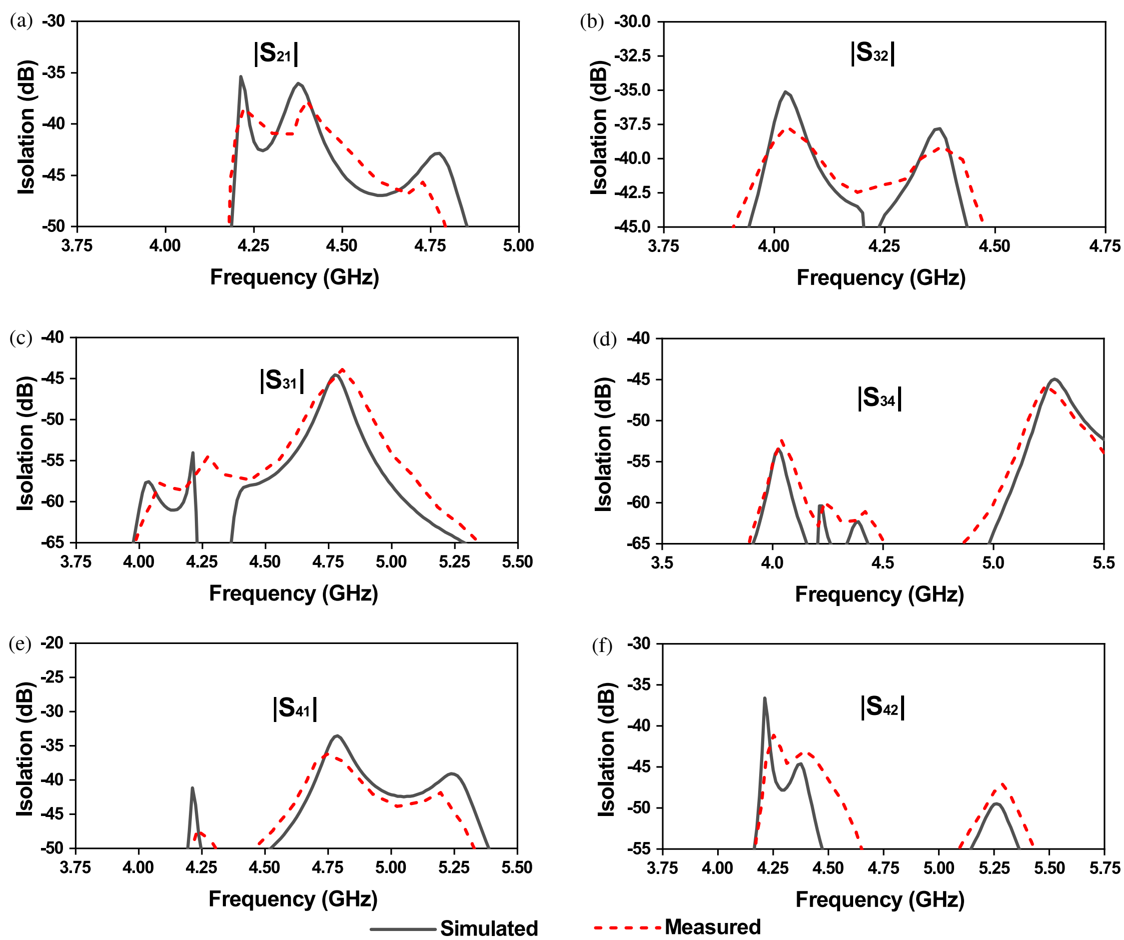

FIGURE 9. Simulated and measured values of the isolation of the proposed antenna.

3. RESULTS AND DISCUSSION

The reflection coefficients and isolation of the antenna are measured using a Keysight E5063A two-port vector network analyzer shown in Fig. 7. The image of the simulated model of top-view of the designed self-quadplexing is presented in Fig. 8. The reflection coefficients are determined by exciting port 1, port 2, port 3, and port 4, respectively, and the isolation is determined between the ports (1 and 2), (2 and 3), (3 and 4), (4 and 2), (4 and 1), and (4 and 3). The simulated and calculated values of the reflection coefficients S_{11}, S_{22}, S_{33}, and S_{44} at ports 1, 2, 3, and 4, respectively, are presented in Fig. 8.

The simulated resonant frequencies are 4.02 GHz, 4.37 GHz, 4.78 GHz, and 5.26 GHz, while the measured frequencies are 4.03 GHz, 4.38 GHz, 4.79 GHz, and 5.28 GHz. The observed variation is within 1%, which is typical and acceptable in practical antenna fabrication. The simulated and measured isolations between Port 1 and Port 2 (S_{21}) is $>$ 35 dB; S_{32} is $>$ 36 dB; S_{31} is $>$ 44 dB; S_{34} is $>$ 45 dB; S_{41} is $>$ 34 dB; and S_{42} is $>$ 37 dB.

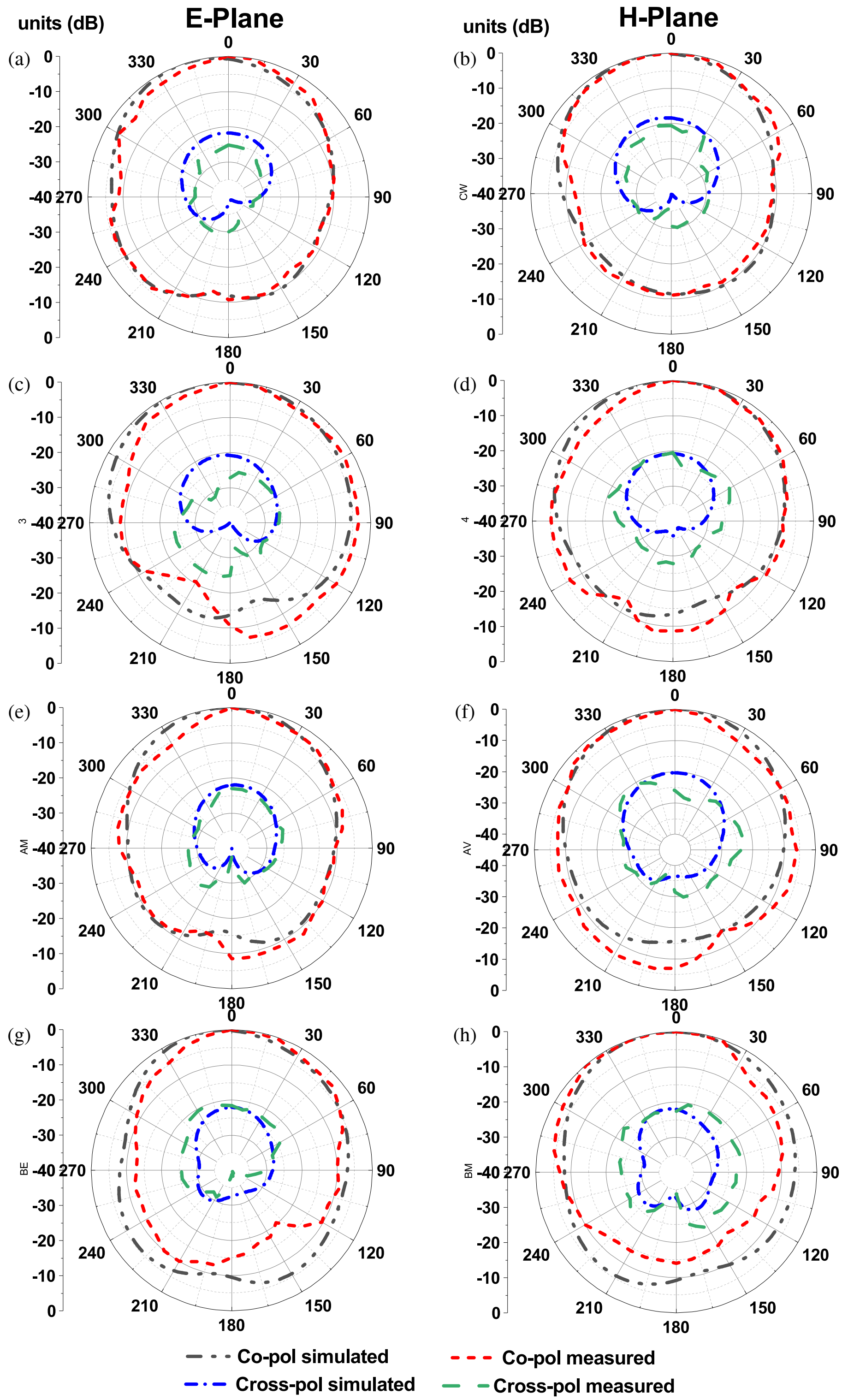

FIGURE 10. Normalized simulated and measured radiation patterns of the proposed antenna in the E-plane and H-plane.

Thus, the overall isolation between any two ports (S_{21}, S_{31}, S_{41}, S_{23}, S_{24}, S_{34}) is > 34 dB shown in Fig. 9.

The simulated and measured self-quadplexing antennas have a directional radiation pattern with maximum radiation in the broadside direction. The radiation pattern plots for both simulated and measured results in the E-plane and H-plane at different frequencies have been analyzed. These patterns consistently exhibit a dominant main lobe directed in the forward direction ($\theta = 0°$), with significantly reduced back lobes and low cross-polarization levels. Such characteristics are indicative of a unidirectional radiation pattern. The normalized simulated and measured radiation patterns are shown in Fig. 10. The

TABLE 1. Performance comparison of SIW based self-quadplexing antennas.

Ref	Type of slot	Overall size (λ_0^2)	Frequencies f_1, f_2, f_3, f_4 (GHz)	Minimum isolation (dB)	Gain (dBi)	f_h/f_l (FR*)
[20]	Rectangular-slots	0.14	4.8, 5.4, 28, 30	20	5.4, 5.2, 8, 8.7	6.25
[23]	V-shaped slots	0.81	8.19, 8.8, 9.71, 11	22	5.5, 6.9, 7.47, 7.45	1.34
[21]	Rectangular-slots	0.2	3.5, 5.2, 5.5, 5.8	23.6	5.43, 4.10, 3.56, 3.6	1.65
[26]	T-shaped slots	0.31	8.85, 10.4, 11.4, 12.23	26	> 6	1.38
[25]	Rectangular-slots	0.14	5.14, 5.78, 6.74, 7.74	28	4.1, 4.96, 6.2, 6.1	1.5
[24]	U-shaped slots	0.11	3.2, 4.1, 5.8, 7.2	30.5	5.8, 5.3, 3.9, 3.4	2.25
[22]	V-shaped slots	0.42	6.54, 7.64, 8.3, 9.6	30.5	5.8, 5.3, 3.9, 3.4	1.46
[19]	U-shaped slots	0.12	2.33, 2.96, 5.43, 6.15	32.5	4.21, 3.39, 6.1, 4.34	2.63
PW	Modified U-shaped slots	0.12	4.02, 4.37, 4.78, 5.26	34	5.18, 5.51, 5.03, 5.12	1.3

PW = Proposed work

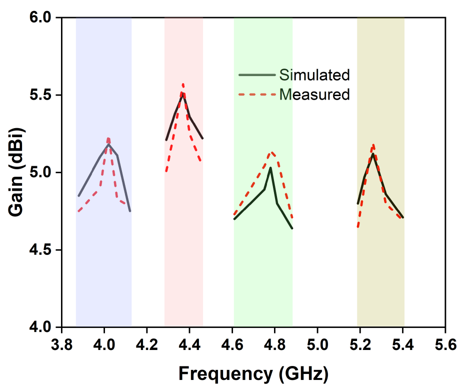

FIGURE 11. Simulated and measured gains.

proposed self-quadplexing antenna demonstrates unidirectional radiation behavior with a cross-polarization level > 20 dB at the resonant frequencies. The measured and simulated gains for the antenna at frequencies 4.02 GHz, 4.37 GHz, 4.78 GHz, and 5.26 GHz are 5.18/5.24 dBi, 5.51/5.57 dBi, 5.03/5.14 dBi, and 5.12/5.19 dBi, respectively, as represented in Fig. 11. The self-quadplexing antenna proposed has a radiation efficiency of $> 80\%$ with the excitation of ports 1, 2, 3, and 4. Table 1 compares the output of the proposed quadplexing antenna with other presented designs, and the proposed antenna in this work outperforms other SIW-based quadplexing antennas.

4. CONCLUSION

A U-slot-based self-quadplexing antenna is proposed in this paper. The antenna was made quadplexing in nature by selecting various slot lengths. The proper placement and alignment of these slots within the SIW structure provide unique resonances with minimal overlap, which aids in minimizing mutual coupling and improving isolation between ports. The antenna resonates at four different frequencies: 4.02 GHz, 4.37 GHz, 4.78 GHz, and 5.26 GHz with a minimum port isolation of more than 34 dB. With a small footprint of 0.12 λ_0^2 (and corresponding to an actual physical size of 26 mm $\times$ 26 mm.), a frequency ratio of 1.3, and gain in excess of 5 dBi, the $|S|$-parameters and radiation patterns of the antenna, as seen from both simulated and measured results, are acceptable. One of the major benefits of the suggested quadplexer is its independent frequency tunability over the operating bands, which makes it highly suitable for real-world applications.

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