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Compact Self-Quadplexing EMSIW Antenna with Small Frequency Ratio for C-Band Applications

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ABSTRACT: In this paper, a highly compact half mode substrate integrated waveguide (HMSIW)-based self-quadplexing antenna is proposed, employing four quarter-mode SIW (QMSIW) radiating elements integrated with rectangular slots. The antenna operates at four closely spaced resonant frequencies 3.68 GHz, 3.83 GHz, 4.04 GHz, and 4.17 GHz achieved by precisely tuning the slot dimensions. A minimum port isolation of 26 dB is maintained between any two ports, ensuring minimal mutual coupling. The proposed design exhibits a compact footprint of only $0.05\lambda_0^2$, where λ_0 is the free-space wavelength at the lowest resonant frequency. The simulated and measured gains exceed 5.5 dBi across all four bands, with a radiation efficiency of approximately 85%. Owing to its compact size, high isolation, and efficient radiation performance, the proposed antenna is well suited for the upper S-band (3.1–3.9 GHz) and lower C-band (4.0–4.2 GHz) which are widely allocated for fixed-satellite service (FSS) communications applications.

1. INTRODUCTION

In recent decades, advances in wireless communication technology have created a compelling requirement for low-profile, compact, and planar multiband antennas that can operate effectively in multiple frequency bands. Conventionally, multiband operation has been obtained through the assembly of single-band antennas on a substrate, each finely tuned to operate in a given frequency band. Although this approach obviates the requirement for external multiplexing hardware, it does so at the expense of much greater system complexity and a larger footprint, which complicates miniaturized platforms.

To overcome these challenges, researchers have investigated antenna structures with inherent self-multiplexing functions. These structures avoid the necessity for external multiplexers since they allow for multi-band operation in one radiating structure, presenting a space-conserving and efficient alternative. In parallel, the ongoing miniaturization trend in communication systems requires not only miniaturized but also high-performance electromagnetic antennas. Substrate integrated waveguide (SIW) technology has been recently cited as a promising solution in this area as it can supply a range of compact configurations, including half-mode, quarter-mode, and eight-mode SIW structures [1–4]. SIW-based antennas are recognized to possess inherent advantages in the form of good port isolation, better radiation characteristics, and smooth integration with planar circuitry [5, 6]. Additionally, SIW technology provides self-multiplexing characteristics along with smaller size and enhanced functional performance.

A key design parameter of SIW-based self-multiplexing antennas is the frequency ratio (FR) among various resonant bands. Obtaining a low frequency ratio is most beneficial since it enables resonant frequencies to be closely spaced within the assigned spectrum. Close spacing ensures efficient utilization of the spectrum by facilitating the inclusion of a higher number of communication channels in a limited frequency range [7]. Moreover, low frequency ratio antennas also improve spectral efficiency and enable greater data throughput, which makes them highly sought after in contemporary wireless systems. This has promoted more research towards the design of dual-band [8–13] and triple-band [14–19] SIW antennas with better performance. More recent developments involve the design of self-quadplexing antennas using half-mode and quarter-mode SIW techniques [7, 20–23]. These antennas tend to use a range of geometrical slot shapes, including V-shaped [24–26], U-shaped [27], and T-shaped slots [28], or utilize unequal patch resonators [29], in order to achieve multi-band operation.

Even with tremendous advancement, small frequency ratio (SFR) while having compact size for self-quadplexing antennas remains an impressing challenge of design. This is particularly challenging due to the larger number of ports involved than diplexing [30] or triplexing configurations. For example, in the design of [20, 27], high isolation values greater than 30 dB were obtained but at comparatively higher frequency ratios of 2.63 and 2.25, respectively, with a smaller foot print of $0.11\lambda_0^2$. On the other hand, such designs as [25, 28] achieved reduced frequency ratios of 1.34 but at the cost of reduced isolation, about 22 dB and 26 dB, respectively with large electrical size of the antenna of $0.81\lambda_0^2$. A simultaneous achievement of a small frequency ratio while keeping the footprint compact is another paramount design challenge in the design of

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efficient self-quadplexing antennas [31]. These compromises demonstrate the continued challenge of balancing a small footprint, SFR, high isolation, and good performance all at the same time. Thus, the design of self-quadplexing SIW antennas that simultaneously achieve small frequency ratios, high isolation, and compact size remains a technically demanding yet essential area of research for next-generation wireless communication systems.

Although metamaterial-based techniques, such as composite right/left-handed loading and engineered inclusions, have been extensively reported in recent years to improve efficiency and achieve miniaturization in SIW-based designs — particularly in the terahertz domain — our work follows a different innovation pathway that does not require such inclusions. This choice simplifies fabrication, reduces cost, and avoids the complexity of incorporating additional resonant elements. The novelty of the proposed design lies in: 1) Quadruplexing in a Compact QMSIW Structure: Achieving four well-separated resonances (3.68, 3.83, 4.04, and 4.17 GHz) within a compact footprint of $0.053\lambda_0^2$ without metamaterial loading. 2) Slot-Driven Frequency Control and Isolation Enhancement: A unique rectangular slot arrangement in QMSIW cavities enables the independent fine-tuning of resonances and significant isolation improvement ($>$ 26 dB) through localized field confinement — an approach not reported in metamaterial-based designs. 3) Direct Applicability to Upper S-Band and Lower C-Band: Covering both bands within the same compact antenna makes it suitable for a wide range of satellite communication and point-to-point link applications. These innovations are explicitly detailed in this work to distinguish our approach from conventional metamaterial-based methods while demonstrating competitive performance in terms of footprint, isolation, and frequency control.

This paper presents a self-quadplexing antenna consisting of four quarter-mode substrate integrated waveguide (QMSIW) cavities. Individual cavities are excited independently by a 50 Ω microstrip line and loaded with a precisely designed rectangular slot to achieve resonance at a specific frequency. The incorporation of rectangular slots allows for the careful control of every resonant mode by merely adjusting the slot size, allowing for separate frequency band selection in a small-sized structure. The designed structure naturally supports self-quadplexing operation, negating the use of external multiplexers or decoupling networks. This yields a simplified structure with elevated isolation between successive ports, an SFR between the operating bands, and improved gain performance for all channels. These features render the antenna a suitable contender for future multi-band communication systems where miniaturization, channel separation, and high performance are necessary requirements.

2. ANTENNA STRUCTURE AND FUNCTIONAL PERFORMANCE ANALYSIS

The top and side planes of the self-quadplexing antenna are shown in Figs. 1(a) and (b), respectively. The antenna structure is implemented on a middle substrate layer made of Rogers RT/Duroid 5870 having a thickness of 0.787 mm, a relative permittivity of 2.33, and a low dielectric loss tangent of 0.0012. Copper is employed to form the top and bottom conducting surfaces. To minimize electromagnetic leakage between adjacent metallic vias, via diameter and separation are selected according to the condition $0.5p \leq d \leq 0.1\lambda_0$ [6], where p denotes the center-to-center pitch (spacing) between two adjacent metallic vias in the substrate integrated waveguide structure, and d represents the diameter of each via. The condition is applied to provide minimum leakage losses between vias while maintaining structural integrity, thereby ensuring effective wave confinement. The optimized structural parameters of the antenna are: $L_{eff} = 28$ mm, $W_{eff} = 12.6$ mm, $l_1 = 3$ mm, $l_2 = 2.75$ mm, $l_3 = 2.5$ mm, $l_4 = 3$ mm, $l_5 = 5$ mm, $l_6 = 4.75$ mm, $l_7 = 5.25$ mm, and $l_8 = 5.5$ mm.

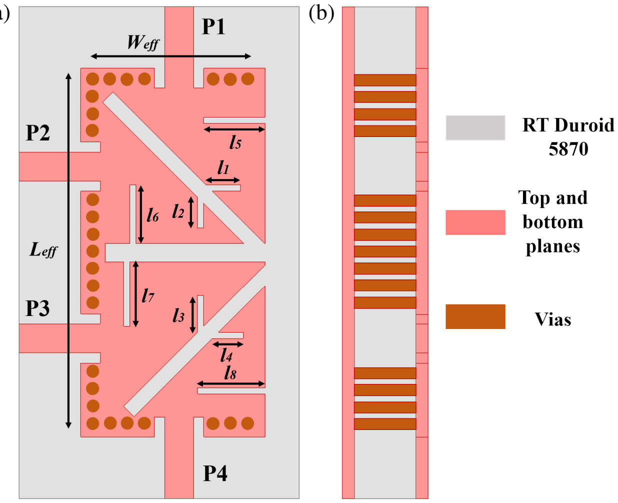

FIGURE 1. (a) Front-view, (b) Side-view of the self-quadplexing antenna.

The design stages of the proposed self-quadplexing antenna is shown in Fig. 2. A conventional HMSIW resonator (Structure 1) as shown in Fig. 2(a) is designed using the expression given in Equation (1)

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

L_{eff} represents the effective length of the half-mode SIW cavity after accounting for the effect of the via walls and fringe fields, and W_{eff} represents the effective width of the HMSIW cavity after similar corrections for via placement and fringe effects. These effective dimensions are obtained from the physical length (L) and width (W) of the cavity given by

$$L_{eff} = L - \frac{d^2}{0.93s} + \frac{10d^2}{L} \tag{2}$$

$$W_{eff} = W - \frac{d^2}{0.93s} + \frac{10d^2}{W} \tag{3}$$

Using (1) along with the design specifications of the antenna, the calculated resonant frequency is found to be 5.24 GHz. The HMSIW cavity split into four QMSIW cavities in order

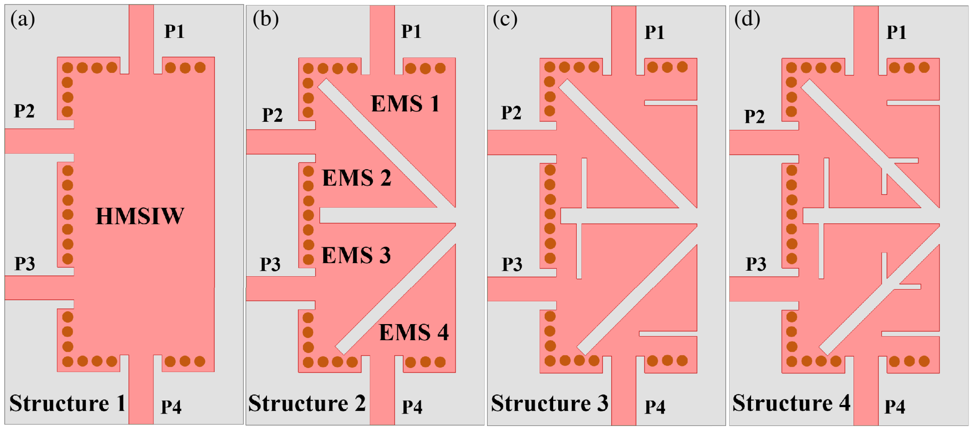

FIGURE 2. (a) HMSIW, (b) four EMSIW resonating elements, (c) with single rectangular slots on each of the resonating elements, and (d) with a pair of rectangular slots on each EMSIW elements.

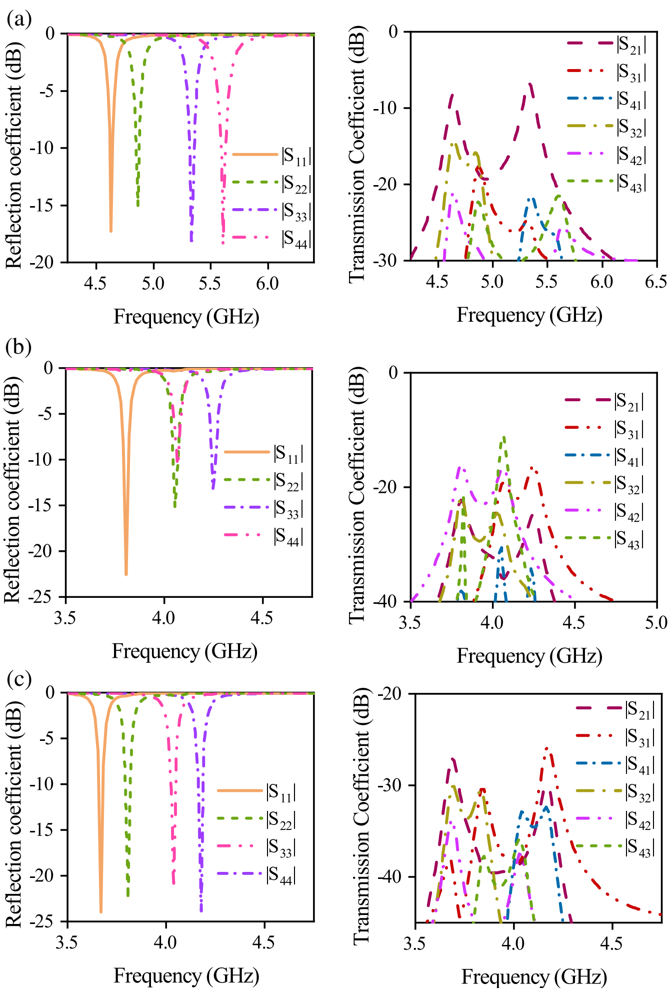

FIGURE 3. $|S|$-Parameters of the antennas in design steps, (a) Structure 2, (b) Structure 3, and (c) Structure 4.

to achieve self-quadplexing characteristics, one for each designated radiating element. Structure 2 operates at four different frequencies 4.63 GHz, 4.86 GHz, 5.33 GHz, and 5.61 GHz as shown in Fig. 3(a). In the initial stage, high mutual coupling of < 7.69 dB occurs between the radiating elements, resulting in poor isolation between consecutive ports. To overcome this limitation, in the second design stage, a single rectangular slot was introduced to each QMSIW resonant element as depicted in Fig. 2(c). This addition changed the current distribution and consequently reduced the resonant area, leading to miniaturization of the antenna structure as shown in Fig. 3(b). Even though the addition of the slot successfully tuned the resonant frequency and optimized the cavity size, the port-to-port isolation continued to be suboptimal.

Structure 3 resonates at 3.81 GHz, 4.05 GHz, 4.06 GHz, and 4.24 GHz with a port isolation of > 11.54 dB. For the final step, a second rectangular slot was inserted within every QMSIW cavity as illustrated in Fig. 2(d). This double-slot structure effectively improved the field localization within every resonator, hence reducing unwanted coupling between the adjacent elements. The E-field plots also show that before introducing slots, the strong electric fields extend toward adjacent cavities, allowing higher mutual coupling. The presence of the slot confines the high-field region around the slot and reduces field leakage toward neighboring cavities. With the addition of a second slot, the fields become even more localized, further minimizing interaction between cavities. This localization reduces evanescent field overlap and results in the measured port-to-port isolation exceeding 26 dB across all four operating frequencies. The first slot primarily perturbs the surface current path in each cavity, producing a noticeable downward shift in the resonant frequency with modest improvement in isolation. The second slot further localizes the electric fields within each cavity, reducing the near-field coupling to adjacent resonators and thus producing a significant isolation enhancement, while causing only a minor additional frequency shift. This progressive improvement is evident from the simulated S-parameter results in Figs. 3(a)–(c), and the corresponding electric field distributions are illustrated in Figs. 5(a)–(c).

Consequently, the antenna attained both frequency miniaturization and significant improvement in isolation performance with enhanced inter-port isolation levels across all operating bands. The control over the resonance of each cavity was optimally achieved through the careful tuning of rectangu-

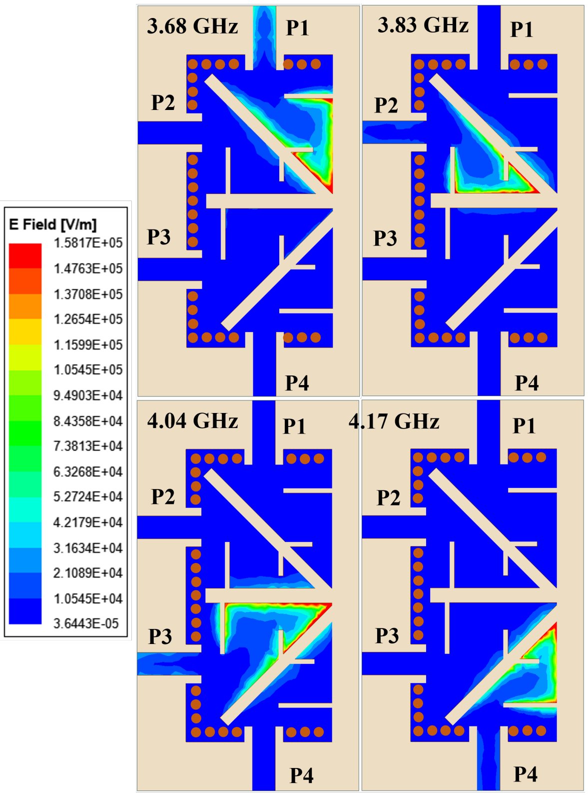

FIGURE 4. Simulated electric field (E-field) distributions of the proposed self-quadplexing SIW antenna at its four resonant frequencies: 3.68 GHz, 3.83 GHz, 4.04 GHz, and 4.17 GHz.

lar slots dimensions, allowing the antenna to be used at four well-separated frequencies 3.68 GHz, 3.83 GHz, 4.04 GHz, and 4.17 GHz with high isolation $>$ 26 dB and compact size of $0.053\lambda_0^2$.

The systematic design process of the proposed self-quadplexing antenna shown in Fig. 6 is as follows:

1. Begin with desired frequency bands of operation and selection of suitable dielectric material with its relative permittivity and loss tangent. Determine the cavity size for the SIW structure based on desired frequencies.

2. Design a half-mode SIW cavity from calculated dimensions.

3. Introduce a magnetic walls on the HMSIW cavity to obtain four quarter mode SIW cavities to obtain resonant frequencies necessary for self-quadplexing operation.

4. Next insert rectangular slots at four resonating elements. Each slot will be designed with enough spacing to target specific frequencies to resonate at desired operating frequencies.

5. Tune the position and dimensions of these eight slots to obtain the desired operating frequencies. The challenge is to achieve the desired resonating frequencies while maintaining low mutual coupling between adjacent ports.

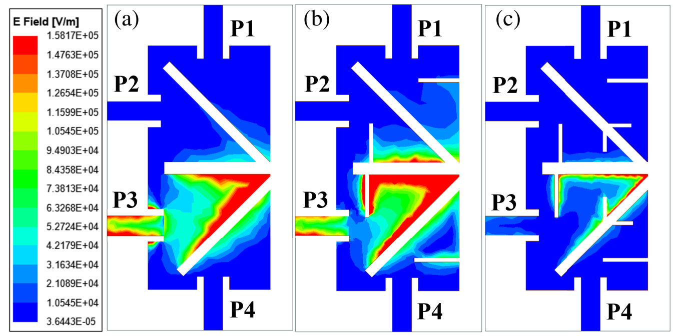

FIGURE 5. E-field distributions of the proposed self-quadplexing SIW antenna: (a) without slot, (b) with single slot, and (c) with double slot, showing improved field confinement and reduced coupling between ports.

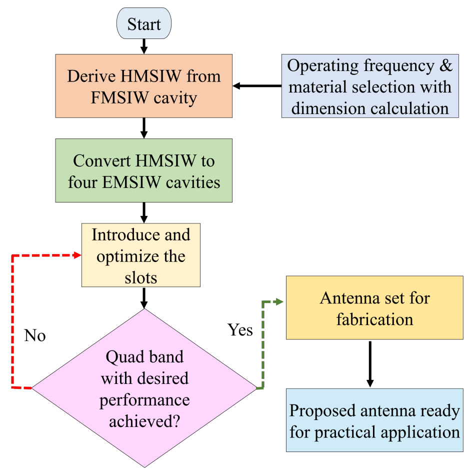

FIGURE 6. Design flow of the proposed self-quadplexing antenna.

6. Finally, validate the performance characteristics of the antenna by comparing the simulated and measured results to check the accuracy of the proposed quadplexing antenna.

In order to understand the physical mechanism of the antenna self-quadplexing action, the distribution of the electric field was analyzed at the four different resonant frequencies that correspond to the excitation of every single port as shown in Fig. 4. It can be observed that at each of these resonances, the maximum electric field intensity is mainly concentrated around the edges of the rectangular slots located near the corresponding excited port. This intense field confinement at the slot edges emphasizes the function of every rectangular slot in the production of a particular resonance, ensuring selective frequency operation. Spatial separation of such high-field region not only establishes the uniqueness of every radiating element but also testifies to the antennas ability to provide effective port-to-port isolation, essential for consistent multi-band operation.

2.1. Design Analysis and Tunability

Figure 7 illustrates the frequency tuning capability of the proposed self-quadplexing antenna, enabling support for C-band applications. Independent frequency tuning is achieved by modifying the lengths of the rectangular slots labeled as l_1, l_2, l_3, and l_4, corresponding to the four QMSIW resonators. As

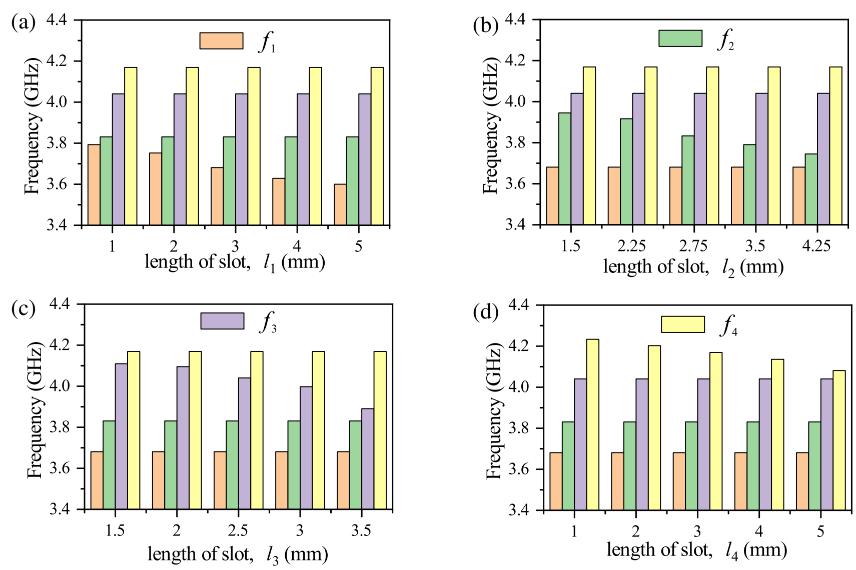

FIGURE 7. Parametric analysis of slot lengths on the resonant frequencies of the proposed self-quadplexing SIW antenna. (a) Effect of varying l_1 on f_1, (b) effect of varying l_2 on f_2, (c) effect of varying l_3 on f_3, and (d) effect of varying l_4 on f_4. The results illustrate the tunability of each frequency by adjusting the corresponding slot length independently.

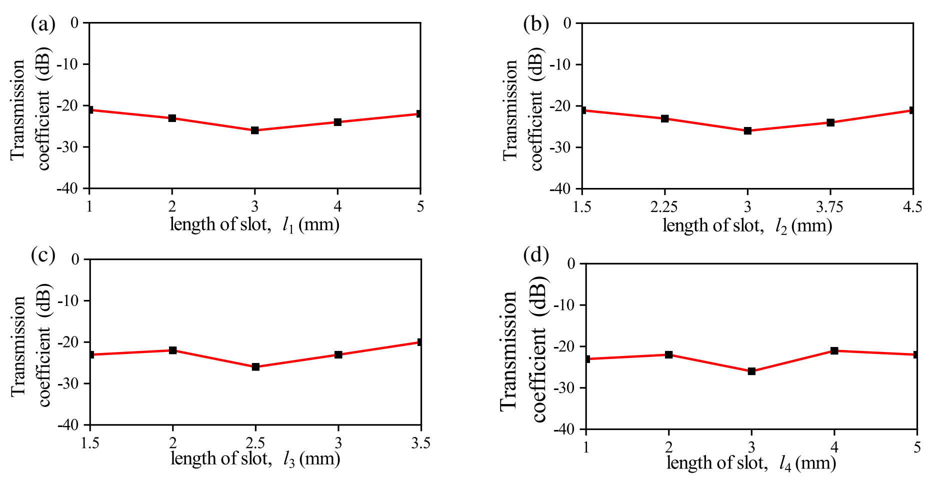

FIGURE 8. Variation of isolation with slot length for (a) l_1, (b) l_2, (c) l_3, and (d) l_4 in the proposed self-quadplexing antenna.

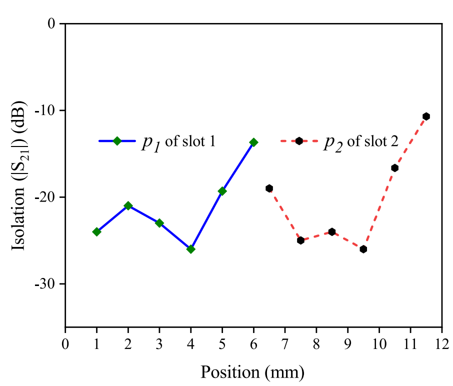

FIGURE 9. Effect of position of slot 1 and slot 2 on isolation in the proposed self-quadplexing antenna.

illustrated in Fig. 7(a), the lowest resonant frequency f_1 can be tuned from 3.6 to 3.79 GHz by varying l_1 from 1 mm to 5 mm. It is evident that changes in l_1 have a prominent effect on f_1, while the remaining resonant frequencies remain unaffected, indicating a high degree of frequency isolation. Similarly, Fig. 7(b) shows that adjusting l_2 from 1.5 mm to 4.25 mm shifts the second resonant frequency f_2 from 3.74 to 3.95 GHz. The third resonant frequency f_3, as depicted in Fig. 7(c), is tunable from 3.89 to 4.11 GHz when l_3 is varied between 1.5 mm and 3.5 mm. Finally, Fig. 7(d) presents the tuning behavior of f_4, which can be adjusted from 4.08 to 4.23 GHz by varying l_4 in the range of 1 mm to 5 mm. These results confirm that each resonant frequency can be precisely tuned by altering its corresponding slot length without significantly affecting the others. The isolation variation with respect to slot length has been plotted in Fig. 8. It can be observed that the isolation remains consistently > 26 dB for all four resonators across their respective tuning ranges, indicating that slot-length adjustments have minimal effect on mutual coupling. It confirms that the proposed design maintains excellent port-to-port isolation while enabling precise and independent frequency tuning for each channel.

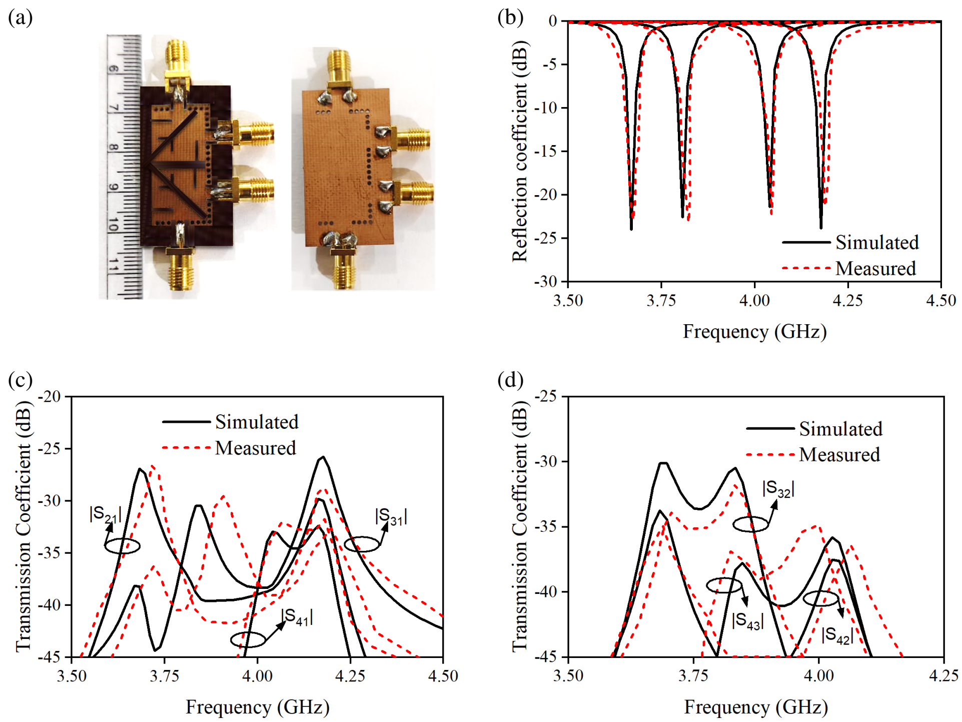

FIGURE 10. (a) Fabricated prototype of the proposed self-quadplexing antenna. (b) Simulated and measured reflection coefficient (S_{11}, S_{22}, S_{33}, S_{44}). (c) Simulated and measured transmission coefficients $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$. (d) Simulated and measured transmission coefficients $|S_{32}|$, $|S_{42}|$, and $|S_{43}|$.

The parametric study was performed by fixing the position of one slot (p_1) and varying the position of the second slot (p_2), and vice versa. The results show that when the spacing between the two slots increases, the electric field becomes concentrated near the slot vertices. It reduces the effective electrical length of the cavity, which in turn causes a shift in the resonant frequency and leads to degraded isolation. On the other hand, placing the slots too close together introduces impedance mismatch, which negatively affects both the reflection coefficient and isolation. By careful optimization, a spacing of 5 mm between the slots was chosen, since this provides proper impedance matching while maintaining high isolation at the desired resonant frequencies. The effect of slot positioning on isolation is summarized in Fig. 9, where maximum isolation is achieved for $p_1 = 4$ mm and $p_2 = 9.5$ mm, which were selected as the final slot positions in the proposed design as shown in Fig. 9. This independent tuning capability enables the antenna to cover a broad operational frequency range from 3.6 GHz to 4.23 GHz, aligning with S-band and C-band standards. Moreover, the antenna achieves a minimum frequency ratio of approximately 1.13 while maintaining the remaining bands stable, which further demonstrates the efficiency and flexibility of the proposed design.

3. RESULTS AND DISCUSSION

The top and bottom views of a photograph of the fabricated self-quadplexing antenna are presented in Fig. 10(a). The reflection coefficients were measured by separately exciting port 1, port 2, port 3, and port 4. Isolation was measured between port pairs (1 and 2), (2 and 3), (3 and 4), (4 and 2), (4 and 1), and (4 and 3). The calculated and simulated values of reflection coefficients S_{11}, S_{22}, S_{33}, and S_{44} at ports 1, 2, 3, and 4, respectively, are shown in Fig. 10(b).

The measured operating frequencies of the proposed self-quadplexing antenna are 3.67 GHz, 3.82 GHz, 4.04 GHz, and 4.18 GHz as shown in Fig. 10(b). These values show excellent agreement with the simulated results, exhibiting a deviation of $< 1\%$, which confirms the accuracy of the design and fabrication. The isolation between ports was evaluated through both simulation and measurement. The results indicate that the isolation is > 26 dB between any two ports as shown in Fig. 10(c).

The radiation characteristics of the antenna, both simulated and measured, exhibit a directional pattern with maximum radiation directed toward the broadside. The normalized radiation patterns, shown in Fig. 11, confirm that the antenna delivers unidirectional performance at each resonant frequency, with a cross-polarization level greater than 22 dB. The gain performance of the antenna, as shown in Fig. 12, is also consistent between simulation and measurement. The simulated/measured gains are 5.38/5.34 dBi at 3.68 GHz, 5.55/5.62 dBi at 3.83 GHz, 5.35/5.28 dBi at 4.04 GHz, and 5.43/5.38 dBi at 4.17 GHz. Furthermore, the antenna exhibits a radiation efficiency exceeding 85% when any of the four ports is activated as shown in Fig. 13. A detailed comparison presented in Table 1 highlights the superior performance of the proposed design over other reported SIW-based self-quadplexing antennas in terms of small frequency ratio and significant isolation with compact size. It is evident from Table 1 that the proposed antenna achieves a gain of 5.3–5.5 dBi within the smallest footprint of $0.05\lambda_0^2$, clearly demonstrating its superior gain-to-size trade-off compared to other reported works.

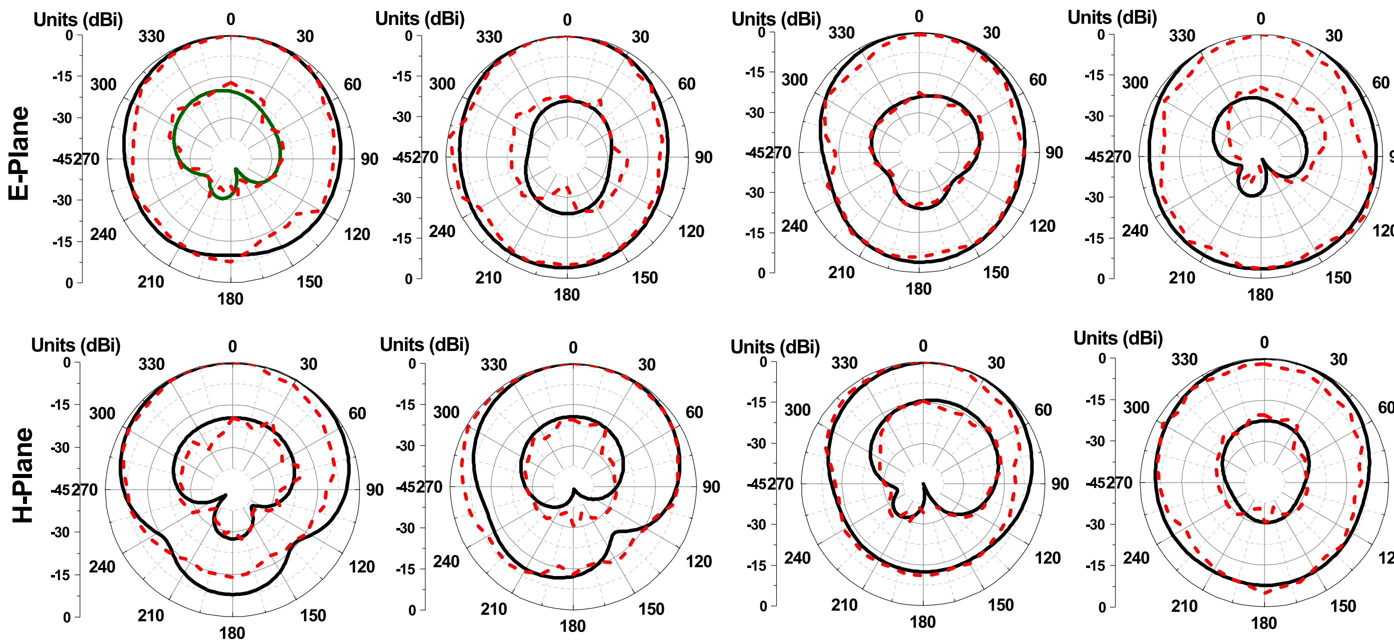

FIGURE 11. Simulated and measured normalized radiation patterns of the proposed self-quadplexing SIW antenna at four resonant frequencies. Top row: E-plane patterns at (a) f_1, (b) f_2, (c) f_3, and (d) f_4. Bottom row: H-plane patterns at (e) f_1, (f) f_2, (g) f_3, and (h) f_4. Solid black lines represent simulated results, and red dashed lines indicate measured results.

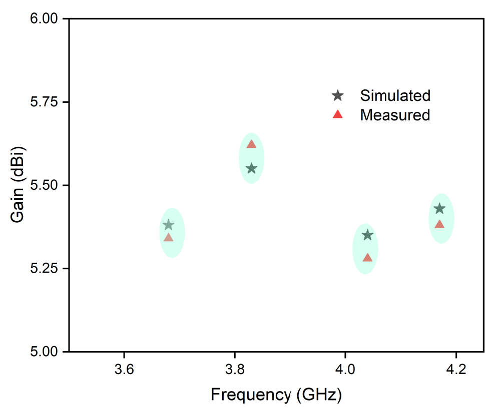

FIGURE 12. Simulated and measured gain values of the proposed antenna at different resonant frequencies.

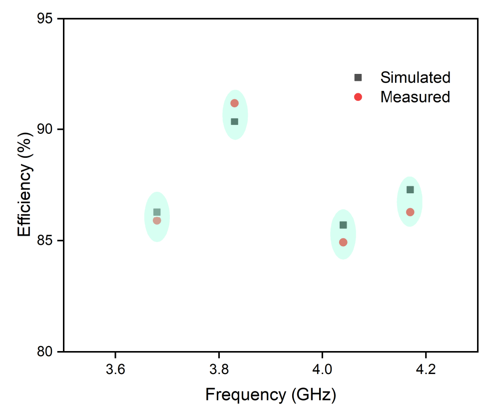

FIGURE 13. Simulated and measured efficiency values of the proposed antenna at different resonant frequencies.

TABLE 1. Performance comparison of proposed SIW-based self-quadplexing antenna with reported works. The proposed antenna (PW) achieves relatively high gain while maintaining the smallest footprint.

Ref	Slot type	Size (λ_0^2)	Frequencies f_1–f_4 (GHz)	Minimum Port isolation (dB)	Gain (dBi)	SFR
[26]	Rectangular-slots	0.14	4.8, 5.4, 28, 30	20	5.4, 5.2, 8, 8.7	6.25
[20]	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
[27]	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
[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
[29]	Rectangular-slots	0.14	5.14, 5.78, 6.74, 7.74	28	4.1, 4.96, 6.2, 6.1	1.5
[24]	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
[28]	T-shaped slots	0.31	8.85, 10.4, 11.4, 12.23	26	> 6	1.38
[25]	V-shaped slots	0.81	8.19, 8.8, 9.71, 11	22	5.5, 6.9, 7.47, 7.45	1.34
PW	rectangular slots	0.05	3.68, 3.83, 4.04, 4.17	26	5.38, 5.55, 5.35, 5.43	1.13

PW = Proposed work, SFR — Small frequency ratio

4. CONCLUSION

A novel self-quadplexing antenna based on quarter-mode substrate integrated waveguide (QMSIW) cavities with rectangular slot perturbations has been successfully designed, simulated, and validated. The proposed antenna operates at four closely spaced C-band frequencies 3.68 GHz, 3.83 GHz, 4.04 GHz, and 4.17 GHz achieved by independently exciting four QMSIW radiators with carefully optimized slot lengths. The design demonstrates effective self-quadplexing functionality with a minimum port isolation of 26 dB, thereby ensuring low mutual coupling among the ports. With a highly compact footprint of only $0.05\lambda_0^2$, the antenna achieves excellent size reduction compared to existing counterparts. Moreover, simulated and measured gain values consistently exceed 5.5 dBi across all operating bands, with a stable unidirectional radiation pattern and an average radiation efficiency of approximately 85%. These performance metrics indicate the antenna's suitability for the integration into modern wireless systems where multi-band operation, compactness, and efficiency are critical requirements. Overall, the proposed structure offers a promising solution for next-generation compact RF front-ends in S-band and C-band applications such as wireless communication systems, radar front-ends, and frequency-division multiplexed platforms.

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