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Highly Miniaturized Self-Diplexed U-Shaped Slot Antenna Based on Shielded QMSIW

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ABSTRACT This article presents an efficient yet simple design approach to highly miniaturized cavity-backed self-diplexing antenna (SDA) with high-isolation. The structure employs a shielded quarter-mode substrate integrated waveguide (QMSIW). Two U-shaped slots are engraved on the top conducting plane, which realize two frequency bands and significant size reduction. The slots are excited by two independent 50Ω orthogonal feed-lines to achieve high isolation while enabling radiation at 3.5 GHz and 5.4 GHz. The proposed design approach allows us to design the two frequency bands independently from each other. The SDA structure is verified using an equivalent circuit model, full-wave electromagnetic (EM) analysis, and experimental validation of the antenna prototype. Excellent consistency between simulated and measured responses has been demonstrated. According to the measurement, the SDA has peak gains of 5.26/5.60 dBi at 3.5/5.4 GHz, and the return loss better than 21.6 dB. The isolation between ports is greater than 40 dB, whereas excellent front-to-back-ratio and co-to-cross polarization are obtained for the proposed SDA. Furthermore, the total size of the SDA is only 0.129 λ^2, with λ being the guided wavelength at 3.5 GHz.

INDEX TERMS Substrate-integrated waveguide, quarter-mode waveguide, shielding, antenna, self-diplexing.

I. INTRODUCTION

With the accelerated evolution of advanced wireless networking technologies, low cost, low-profile, and high-performance planar dual-band antennas are in greater demand. In multi-standard communication systems, a single antenna with multiband characteristic offers attractive features, including reduction of the overall cost and size. However, integration of transceiver circuitry with antennas imposes isolation limitations on multiple radiators, which requires additional frequency selective surfaces to improve isolation, increasing the design complexity and the size of the system. To preserve dual-band operation of the antenna, along with high isolation and compact size is a challenging endeavor. One of possible solution approaches are self-diplexing antennas (SDAs), which have become useful in achieving high isolation, size miniaturization, and the best overall microwave components for many applications [1].

Another potentially attractive approach is the substrate-integrated waveguide (SIW) technology. It has become of a paramount importance in the implementation of planar microwave components based on waveguide. SIW-based antennas are capable of rendering dual-band characteristics, small size, high gain, and excellent far-field performances [2]. As a matter of fact, many self-diplexing antennas that ensure sufficient isolation, size reduction, and radiation performance, are being developed in the SIW technology [3]–[12]. A rectangular-slot loaded SIW antenna excited by two orthogonal feed-lines has been demonstrated in [3]. In [4], a lightweight self-diplexing inverted U-shaped slot antenna has been realized on the SIW cavity for high isolation. In [5], a bow-tie-shaped slot has been engraved on

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the top conductor of SIW cavity for development of a SDA. In [6], a SDA has been realized by applying two rectangular-slots on the top surface of the SIW cavity for operation at 8.26 and 10.46 GHz; nevertheless, this structure offers low isolation, which hinders its application. In [7], a rectangular-ring slot has been loaded on the SIW cavity to build a compact SDA that radiates at 9.5 GHz and 10.5 GHz. A cavity-backed SIW antenna with an asymmetric cross-slot has been suggested to achieve SDA with circular polarization in [8]. In [9], a novel SIW cavity topology has been suggested for the development of a low-profile, extremely tunable SDA with frequency tuning range of 3.77 to 4.59 GHz in the lower frequency band, and 4.96 to 6.1 GHz in the upper band. In [10], a SDA has been implemented using SIW cavity loaded by a cross-shaped slot. A lightweight SIW-based SDA has been realized for Wi-Fi (5.2 GHz to 5.29 GHz) and ISM band (5.78 GHz to 5.83 GHz) applications in [11]. With 45° linear polarized (LP) and dual-band CP antennas, [12] develops a dual-band SIW antenna. A novel dual-frequency antenna architecture has been proposed utilizing HMSIW cavities for Ka-band applications in [13].

In the context of size reduction, self-diplexing characteristic, and isolation, the aforementioned design topologies have been often capable of achieving satisfactory performance. Considerable size reduction is possible by choosing the cavity structure at the beginning of the topology development process to ensure high isolation between the ports. Therein, appropriate design modifications are applied to the cavity topology, feed-lines and radiating slots. Quarter-mode SIW (QMSIW) derived from the full-mode SIW resonator, and including a shielded mechanism that offer highly size miniaturization has been reported in the literature [14]–[16]. Furthermore, the conventional half-mode SIW (HMSIW) [17] and QMSIW [9], [18] cavities are employed to design compact self-diplexing antennas. The abovementioned approach has been demonstrated successful in the development of miniaturized self-diplexing antennas but offers low isolation and does not provide equivalent model to validate their designs. Therefore, a new self-diplexing antenna is realized by using shielded QMSIW to achieve further size reduction, high isolation and equivalent model to validate the antenna.

This paper proposes a novel design procedure for highly-miniaturized self-diplexing antenna (SDA) with high isolation. Our approach relies on applying a shielded quarter-mode SIW (QMSIW). Two radiating patches are formed on the top of the shielded QMSIW by incorporating two U-shaped slots for radiation at 3.5 GHz and 5.4 GHz. These frequency bands can be tuned independently. The proposed SDA is validated through the lumped circuit model, EM simulation, as well as experimental validation.

II. DESIGN PROCEDURE

This section provides a description of the antenna configuration, and the eigenmode analysis. Subsequently, the topology evolution and the design process flowchart are discussed. In order to verify the design, the RLC circuit model is derived for the proposed SDA and analyzed, along with full-wave EM simulation. The tunability of the proposed SDA is realized in a versatile manner by designing the two operating frequency bands independently from each other. The experimental validation and benchmarking against state-of-the-art antenna structures are discussed in Section III.

A. ANTENNA TOPOLOGY

Figure 1 shows the layout of the proposed self-diplexing antenna (SDA) featuring the size of $0.129\lambda^2$ at 3.5 GHz. The substrate used for this antenna has a thickness of 0.787 mm and permittivity 2.33. The proposed configuration comprises a shielded QMSIW, two U-shaped slots, and two orthogonal 50Ω lines. Figure 2 shows the design steps for realizing the proposed SDA. Initially, a full-mode SIW is developed for operating in the TE_{110} mode. The electric field distribution is shown in Fig. 3(a). Subsequently, the FMSIW is divided into four equal parts and each part is defined as QMSIW. Compared to full-mode SIW cavity, the conventional QMSIW cavity suffers from low Q factor due to leakage of wave through the magnetic walls shown in Fig. 3(b). To minimize this extra loss, a shielded QMSIW is developed by employing two rows of metallic vias near the open-ended edges of the conventional QMSIW, and the magnetic wall are recreated by engraving an open slot near the vias, as shown in Fig. 3(c). The wave propagation can be blocked partially by this shield walls, consequently, minimizing the loss [14]–[16]. Table 1 shows the Q-factor for different SIW cavities at TE110 mode. As it can be seen in Table 1, the Q factor of conventional QMSIW is smaller than the shielded QMSIW due to low loss [14]–[16]. Hence, the shielded QMSIW not only achieves compact size but also provides good overall performance.

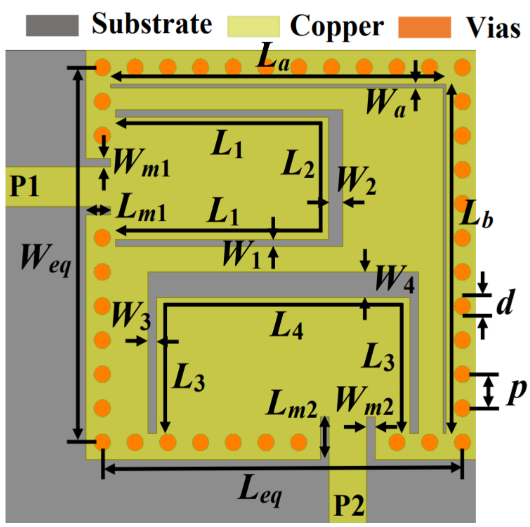

FIGURE 1. Schematic of shielded QMSIW cavity-backed slot antenna. Final dimensions: $L_{eq} = 22$, $W_{eq} = 22$, $L_a = 20.5$, $W_a = 0.2$, $L_b = 20.5$, $L_{m1} = 1.5$, $W_{m1} = 0.5$, $L_{m2} = 2.5$, $W_{m2} = 0.5$, $L_1 = 13.0$, $W_1 = 0.4$, $L_2 = 8.0$, $W_2 = 0.9$, $L_3 = 8.0$, $W_3 = 0.5$, $L_4 = 16.5$, $W_4 = 1.5$, $d = 1.0$, $p = 2.0$. (Units: Millimeters).

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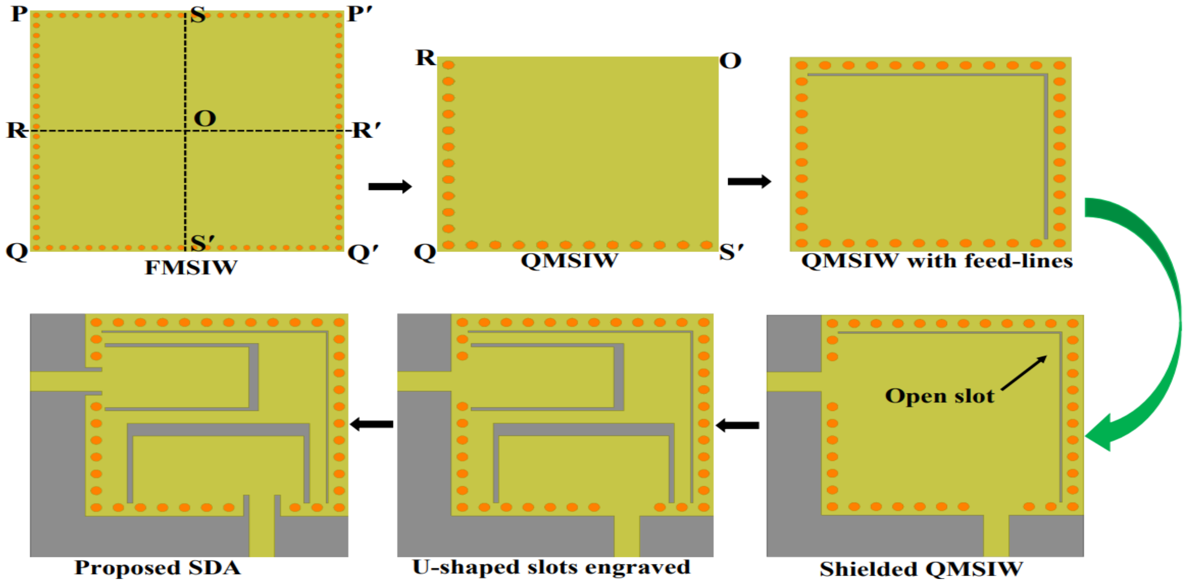

FIGURE 2. Design evolution of the proposed shielded QMSIW based SDA.

The resonant frequency of the conventional QMSIW for the TE_{110} mode is determined as [2]

$$f_{mn0}^{QMSIW} = \frac{1}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{2W_S^{QMSIW}}\right)^2 + \left(\frac{n\pi}{2L_S^{QMSIW}}\right)^2} \quad (1)$$

The SIW equivalent width W_S and length L_S are determined as [2]

$$\begin{cases} W_S^{QMSIW} = W_{eq} - 1.08\dfrac{d^2}{p} + 0.1\dfrac{d^2}{W_{eq}} \\ L_S^{QMSIW} = L_{eq} - 1.08\dfrac{d^2}{p} + 0.1\dfrac{d^2}{L_{eq}} \end{cases} \quad (2)$$

In order to minimize the energy leakage, the diameter d and the distance p between the vias are chosen using the following relationship: $d/\lambda \leq 0.1$ and $d/p \geq 0.5$ [2]. The open-ended edges of the QWSIW causes the unwanted radiation loss, which can be mitigated by enclosing the open-ended edges by two rows of metallic vias and open-slot. Finally, two U-shaped slots are created on the top conductor to realize dual-band operation.

TABLE 1. Q-factor for FMSIW, QMSIW and shielded QMSIW cavities.

Cavities	Q factor
FMSIW	371
QMSIW	186
Shielded QMSIW	292

B. CIRCUIT MODEL ANALYSIS

Figure 4 shows an equivalent RLC circuit model of the proposed SDA, where each cavity resonator is represented by a parallel RLC tank, and each U-shaped slot is modeled by a shunt capacitance. Size reduction is accounted for by increasing the extra capacitance produced due to the slots. Furthermore, the transformers are used in order to achieve good matching between the cavity resonators and the input signals. The coupling between the two cavity resonators is represented by M_{12}, and modeled by an LC circuit. The resonant frequency of the QMSIW, which operates below the waveguide cutoff frequency is expressed as

$$f_{0i} = \frac{1}{2\pi\sqrt{L_{ai}C_{bi}}} \quad (3)$$

The input impedance can be determined as

$$Z_{input} = \frac{jw_0 L_{ai}}{1 - w_0^2 C_{bi} L_{ai}} \quad (4)$$

Equation (4) indicates that the operating frequency f_{0i} of the antenna depends on L_{ai} and C_{bi}, where $i = 1, 2$.

The capacitance C_{bi} increases by enlarging the slot dimension and shifting operating frequency toward lower values, which is beneficial from miniaturization standpoint. The lumped circuit model is optimized using Keysight Advanced Design System (ADS), and the optimized values of the components are given in Table 2. The circuit-simulated

TABLE 2. Component values of proposed QMSIW SDA.

Components	Values	Components	Values
R_{a1} (Ω)	221	R_{a2} (Ω)	307
L_{a1} (nH)	0.27	L_{a2} (nH)	0.37
C_{a1} (pF)	0.02	C_{a2} (pF)	0.001
C_{b1} (pF)	7.6	C_{b2} (pF)	2.31
L_m (nH)	0.57	$T1$	0.4696
C_m (pF)	0.035	$T2$	0.4097

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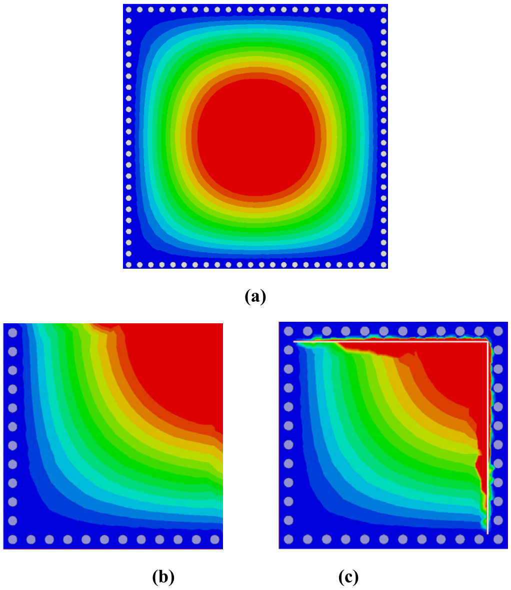

FIGURE 3. Electric-field distributions for (a) full-mode SIW; (b) conventional QMSIW, and (c) shielded QMSIW cavities.

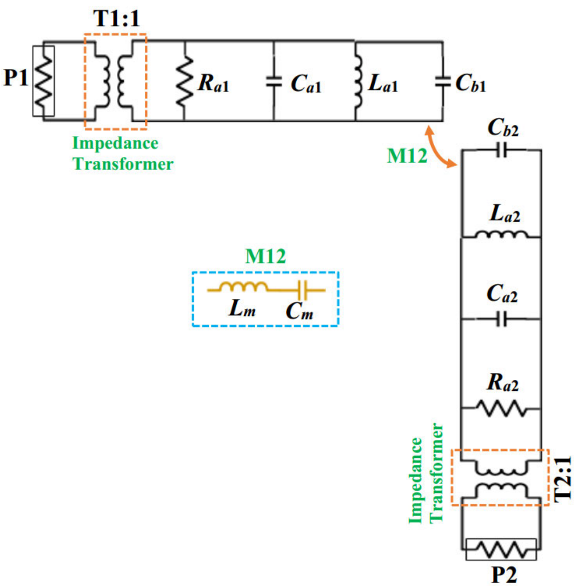

FIGURE 4. RLC circuit model for shielded QMSIW SDA.

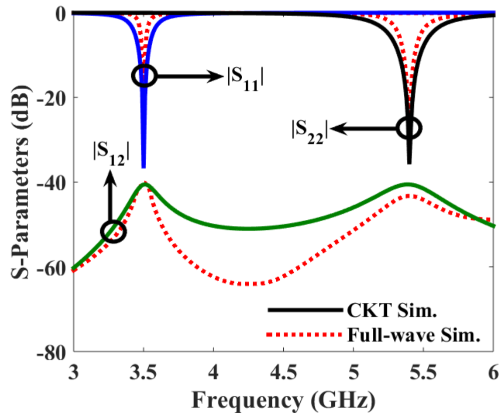

FIGURE 5. Circuit and EM simulation responses of the proposed shielded QMSIW SDA.

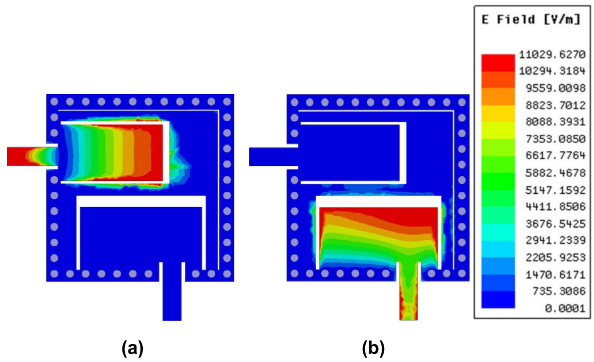

FIGURE 6. Electric-field distributions. (a) At 3.5 GHz (port 1 is ON); (b) At 5.4 GHz (port 2 is ON).

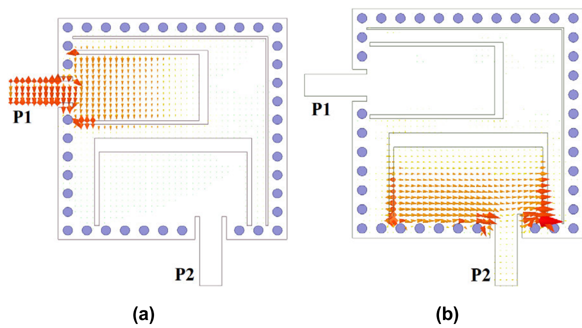

FIGURE 7. Magnetic-field distributions. (a) At 3.5 GHz (port 1 is ON); (b) At 5.4 GHz (port 2 is ON).

S-parameters are also obtained from EM simulation. The comparison thereof is shown in Fig. 5.

C. ELECTRIC FIELD DISTRIBUTION

Figures 6 and 7 portray the electric and magnetic field distributions of the proposed antenna, respectively. The excitation is applied to one port (ON), whereas the other port is terminated (OFF) by a 50-ohm load, and vice versa. The maximum field strength is observed at the inner-edges of the slots by exciting the ports as shown in Fig. 6, whereas the magnetic field strength is maximum at the inside area enclosed by the slots, which is depicted in Fig. 7.

D. TUNABILITY AND PARAMETRIC ANALYSIS

The proposed antenna configuration offers a flexibility of designing each frequency band independently. It has been found in the previous section that the frequency is in a direct relationship with the slot dimension. The allocation of the frequency bands can be controlled by increasing/decreasing the total capacitance, which is achieved by varying the slot length. The first (f_{01}) and the second (f_{02}) operating bands are controlled by varying the parameters L_1 and L_3, respectively. As shown in Fig. 8(a), the first band frequency f_{01} is shifted

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towards higher values as L_1 decreases due to the decrease in capacitance. Therefore, f_{01} can be designed independently in the range of 3.5-3.87 GHz by varying the parameter L_1 from 12.0 mm to 12.9 mm. Similarly, the second operating frequency is moved towards higher values by decreasing the value of L_3, which is shown in Fig. 8(b). The frequency f_{02} can be tuned independently in the range of 5.4-6.1 GHz by varying the parameter L_3 from 7.0 mm to 7.9 mm. It is noted that when L_3 varies, the capacitive loading due to the slot changes significantly, which makes the second operating frequency tunable to a larger extent than the first band. Consequently, the proposed SDA offers excellent flexibility in terms of frequency tunability, which is essential in many applications.

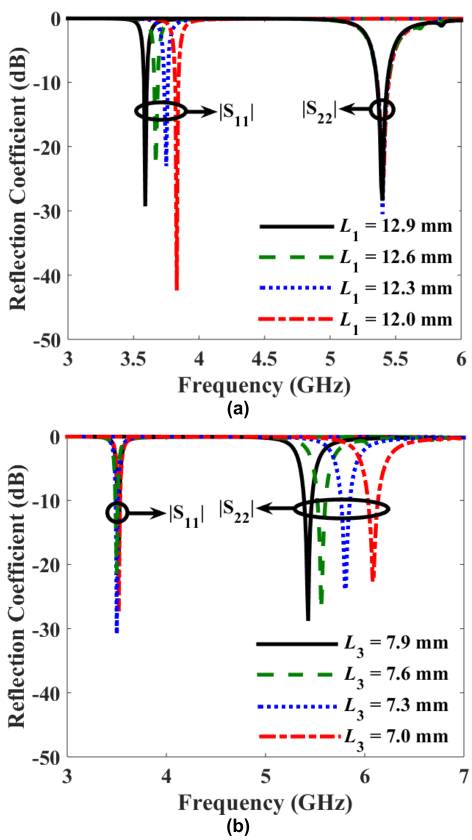

FIGURE 8. Design of frequency bands independently. (a) First band and (b) second band.

Figure 9 shows the variation of the peak gain with respect to the parameters L_1 and L_3. As shown in Fig. 9(a), the peak gain is obtained at f_{01} by applying excitation to Port 1 and terminating Port 2 with 50-ohm load. Similarly, the peak gain is computed at f_{02} by applying excitation to Port 2 and terminating Port 2 with 50-ohm load, as shown in Fig. 9(b). From this study, it is found that the variation of peak gain is about 5 to 7% at both operating bands.

The proposed shielded QMSIW SDA is realized on a single-layer printed circuit board using the metallic vias, which results in a significant reduction of surface-wave transmission within the substrate. This improves the antenna

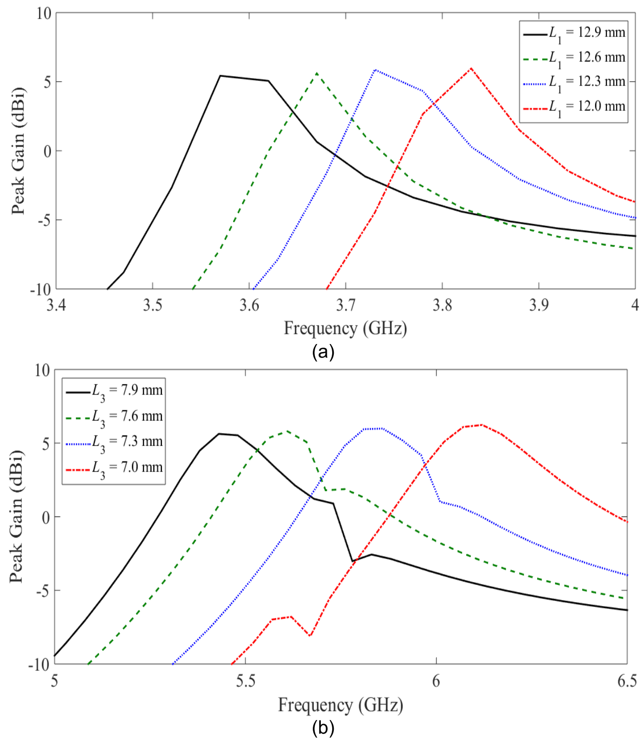

FIGURE 9. Variation of peak gain with respect to (a) L_1 and (b) L_3.

performance due to the suppression of the edge diffraction effects, and reduction of power dissipation [2]. The SIW based antenna shows unidirectional radiation, which results in elimination of the back side radiation, leading to a good far field performance [2]. This SIW antenna is designed at TE_{110} mode, which offers a reasonable amount of gain. However, the gain of this antenna can be increased when operated at higher order modes without increasing the physical size of the antenna. Also, the gain can be increased by thickening the substrate height [19].

It should be noted that the antenna gain has a direct relationship with the effective aperture of antenna. Considering the above facts, the gain of the antenna based on SIW does not only depend on the size, but also other parameters such as mode of operation and substrate height. In this design, we achieved a reasonable gain while ensuring a compact size of the antenna, which is realized at TE_{110} mode. As mentioned before, the gain of this particular antenna can be increased by realizing at higher order mode without increasing the physical size of the antenna.

Based on the above study, a detailed design flowchart is provided in Fig. 10, which includes optimization and characterization of the proposed QMSIW-based.

III. FABRICATION, RESULTS AND DISCUSSION

To validate the proposed design approach, EM simulation and circuit model analysis, a prototype of the shielded QMSIW-based SDA has been fabricated and demonstrated for WiMAX and WLAN applications. The antenna is fabricated

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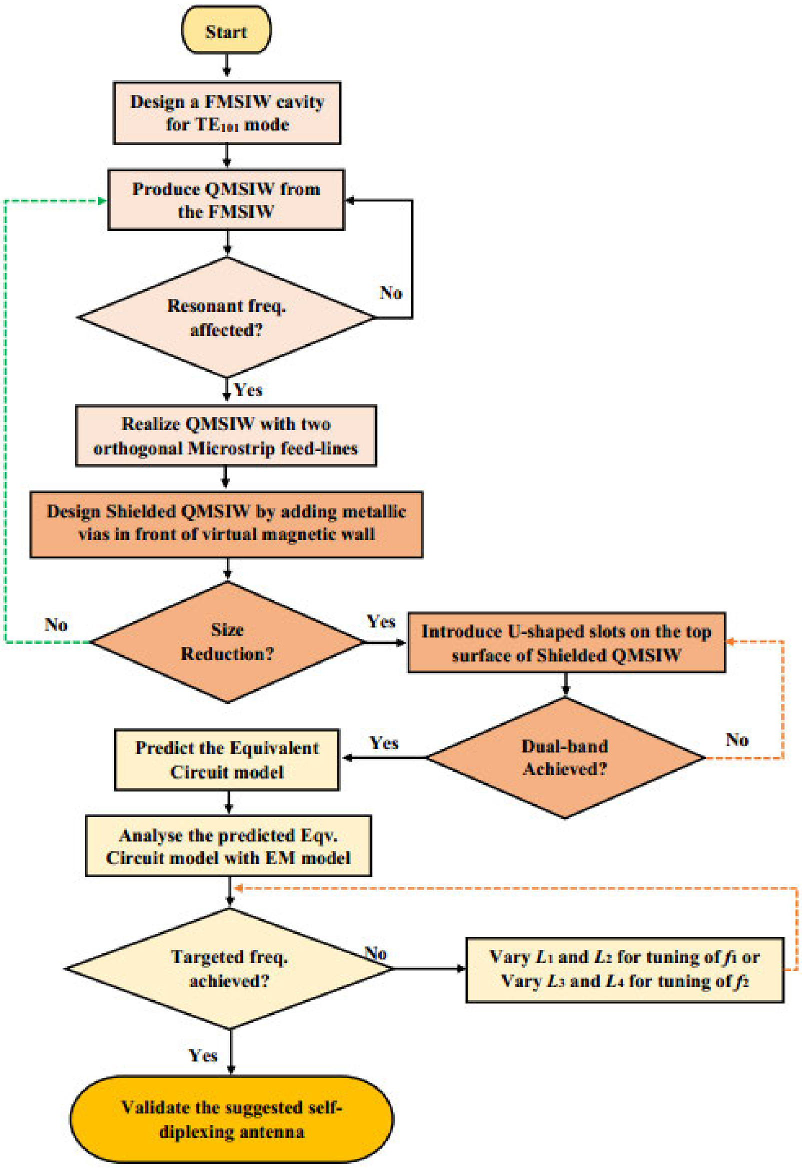

FIGURE 10. Design flowchart for the proposed SDA.

on the RT/Duroid substrate ($\varepsilon_r = 2.33$, H = 0.787 mm, $\tan\delta = 0.0012$). The photograph of the manufactured SDA is shown in Fig. 11(a). All of the tests are carried out by applying the excitation at Port 1 and terminating Port 2 by a 50Ω load, and vice-versa. The S-parameters are recorded by a two-port Rohde & Schwarz vector network analyzer.

Figure 11(b) illustrates the EM-simulated and measured return losses ($|S_{11}|$ and $|S_{22}|$) and port-isolation ($|S_{12}|$). The far-field responses of the manufactured SDA are recorded inside an anechoic chamber in two-orthogonal planes of $\Phi = 0°$ and $\Phi = 90°$ at 3.5 GHz and 5.4 GHz. Figures 12 and 13 show the EM-simulated and measured peak gains and radiation efficiency, respectively. The simulated and measured radiation patterns of the manufactured SDA are shown in Fig. 14. As predicted, the simulation and measurement data are well aligned. Slight differences are due to fabrication tolerance and connector losses. The following is a description of the fabricated prototype's performance:

EM Simulation:

- The input return losses $|S_{11}|$ and $|S_{22}|$ of the SDA are -33.5 dB and -34.9 dB, respectively;
- The port isolations are 40.1 dB and 43.27 dB at 3.5 and 5.4 GHz, respectively.
- The full-wave peak gains of the SDA are 5.47 and 5.69 dBi at 3.5 and 5.4 GHz, respectively.
- The radiation efficiencies of the suggested SDA are 84.5% and 88% at 3.5 and 5.4 GHz, respectively.
- The co-to-cross polarization level and front-to-back-ratio (FTBR) are better than 21 dB and 20 dB, respectively.

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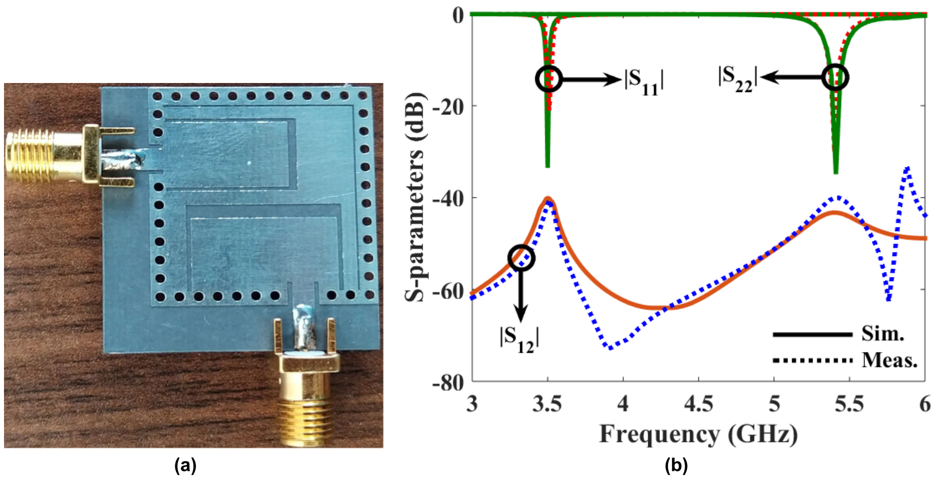

FIGURE 11. (a) A photo of proposed SDA; (b) Simulated and tested S-parameter responses of the shielded QMSIW antenna prototype.

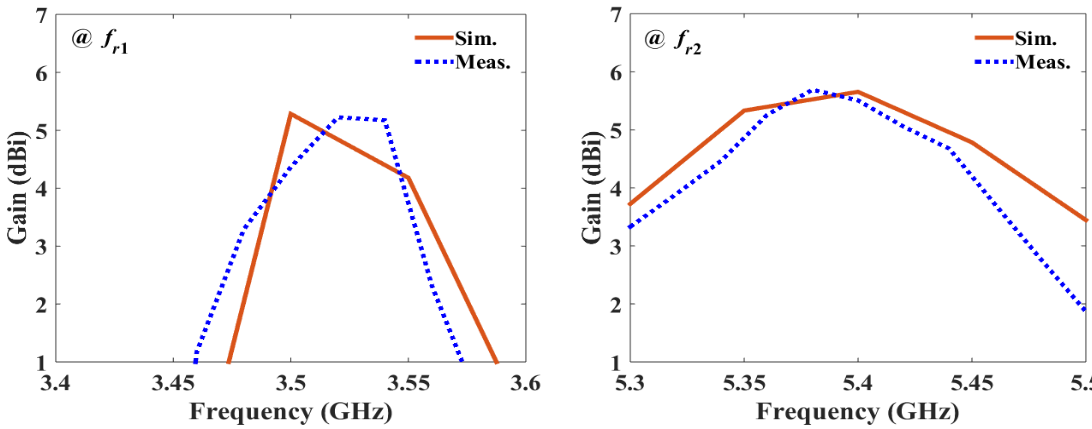

FIGURE 12. Simulated and measured peak gains of the proposed SDA.

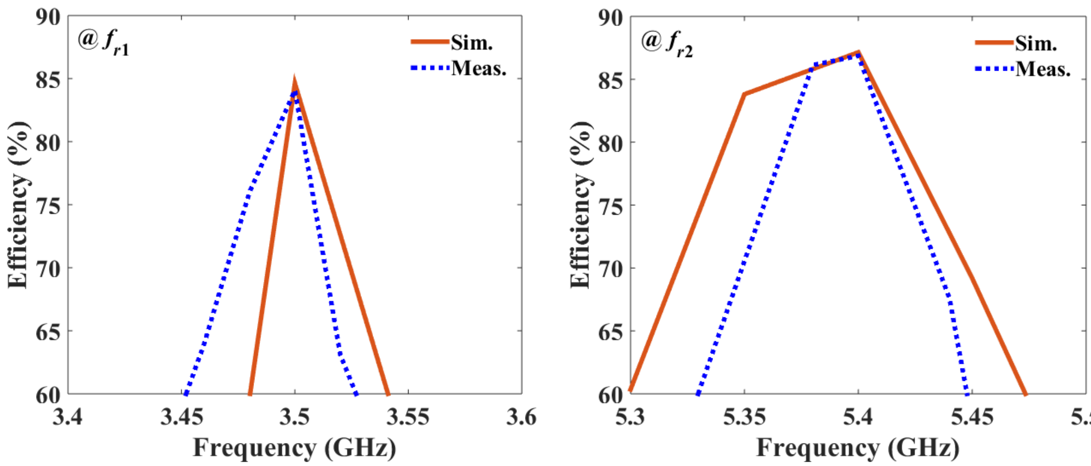

FIGURE 13. Simulated and measured efficiency of the proposed SDA.

Measurement:

- The return losses $|S_{11}|$ and $|S_{22}|$ of the fabricated SDA are greater than −21.6 dB and −30.1 dB at 3.5 and 5.4 GHz, respectively.
- The port isolations ($|S_{12}|$) of the fabricated antenna are found to be 40.54 dB and 40.08 dB at 3.5 and 5.4 GHz, respectively.
- The measured peak gains of the fabricated SDA are 5.46 dBi and 5.60 dBi at 3.5 GHz and 5.4 GHz, respectively.
- The measured radiation efficiencies of the fabricated SDA are 84% and 86.8% at 3.5 GHz and 5.4 GHz, respectively.

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TABLE 3. Performance comparison of SIW self-diplexing antennas.

Ref.	Tech./Sub (ε_r)	Freq. (GHz)	ISL (dB)	Gain (dBi)	FTBR (dB)	Size (λ_g^2)	Equivalent model
[3]	SIW/2.33	6.62/11.18	>29.3	5.42/5.66	23, 21	0.462	No
[4]	SIW/2.33	4.29/7.52	>32.5	5.38/5.82	23,22	0.23	No
[5]	SIW/2.2	9/11.2	>25	4.3/4.2	21,16	0.95	No
[6]	SIW/2.2	8.26/10.46	>27.9	3.56/5.24	23, 20	0.43	No
[7]	SIW/2.2	9.5/10.5	>29	5.55/5.75	NR	0.796	No
[8]	SIW/2.2	11.23/11.72	>14	5.8/5.85	>14	NR	No
[9]	SIW/4.4	4.59/6.1	>21	4.85/4.96	NR	0.294	No
[10]	SIW/2.2	8.55/9.77	>20	5.7/5.94	12, 23	1.02	No
[11]	SIW/2.33	5.23/5.8	>27.6	5.22/5.1	>17	0.28	No
[17]	HMSIW/2.2	6.44/7.09	>30.3	3.1/4.8	>16.5	0.35	No
[9]	QMSIW/4.4	3.77/4.96	>21	5.87/6.5	-	0.29	No
[18]	QMSIW/-	28/38	>18	9.5/11	>17	1.15	No
This work	**Shielded QMSIW/2.33**	**3.5/5.4**	**>40**	**5.26/5.60**	**>20**	**0.13**	**Yes**

FTBR: Front-to-back ratio, ISL: Isolation, NR: Not reported.

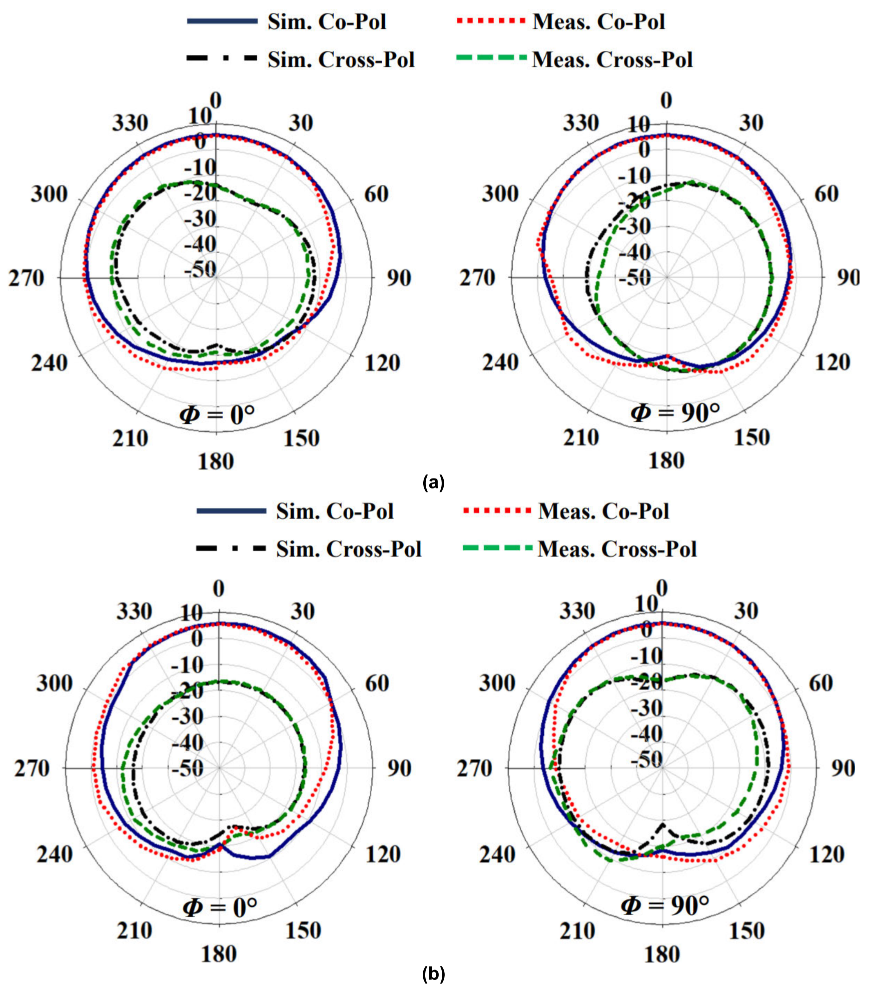

FIGURE 14. Simulated and measured radiation pattern of the proposed SDA at $\Phi = 0°$ and $\Phi = 0°$. (a) At 3.5 GHz; (b) At 5.4 GHz.

A comparison between the proposed SDA and the previously reported state-of-the-art antennas based on full-mode SIW [3]–[11], HMSIW [17] and QMSIW [9], [18] has been discussed based on performance indicators (size, isolation, peak gain and FTBR) as shown in Table 3. Compared to [3]–[11] and [9], [17], [18], the proposed SDA is highly

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miniaturized. The manufactured antenna is almost 44% smaller than the most compact SDA reported in [4]. The proposed SDA achieves higher isolation when compared with [3]–[11] and [9], [17], [18]. The antenna reported in [18] offers high gain compared to the proposed antenna due to use of 2 × 2 array. However, this antenna occupies larger size and suffers from low isolation. Also, it does not provide any equivalent circuit model to validate the EM simulation. The proposed antenna exhibits good peak gain, FTBR and co-to-cross polarization level when compared with existing works. Based on this analysis, it can be concluded that the proposed self-diplexing cavity-backed shielded QMSIW slot antenna is suitable for dual-frequency communication systems.

IV. CONCLUSION

In this paper, a novel design of highly miniaturized cavity-backed self-diplexing antenna (SDA) employing shielded quarter-mode SIW for WiMAX and WLAN applications has been presented. The design employs a shielded QMSIW, two U-shaped slots, and two orthogonal 50Ω feed lines. The U-shaped slots are loaded on the top conductor plane of the shielded QMSIW to produce two radiating patches for the antenna to operate at 3.5 GHz and 5.4 GHz. These frequency bands can be designed individually by varying the dimensions of the U-shaped slots. The slots are excited by two orthogonal 50 Ω feed lines, which creates a weak cross-coupling path resulting in high element isolation. An equivalent LC circuit model is used to validate design along with full-wave EM analysis. Furthermore, the SDA has been fabricated and measured. Good alignment between simulations and measurements has been observed. The SDA prototype offers peak gains of 5.26/5.60 dBi at 3.5/5.4 GHz and a return loss of better than 21.6 dB, according to the tested results. The proposed SDA exhibits a better than 40 dB isolation between ports, as well as outstanding front-to-back ratio and co-to-cross polarization.

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