Progress In Electromagnetics Research C, Vol. 110, 243–252, 2021

Compact Self-Quadruplexing Antenna Based on SIW Cavity-Backed with Enhanced Isolation

Abhay Kumar Singh* and Paras

Abstract—A self-quadruplexing antenna based on substrate integrated waveguide (SIW) is presented. A slot is engraved on its top surface of the SIW cavity, which generates four different resonant frequencies (around 6.54, 7.64, 8.30, and 9.60 GHz) when it is excited by four 50 Ω microstrip feed lines. Also, each resonant frequency can be controlled independently. Due to a quarter mode (QM) cavity, the antenna size becomes compact. The measured results show that the isolation between any two ports is more than 32 dB, and the estimated gain is more than 7.8 dBi at the operating frequencies. The proposed design is simple to fabricate, compact, and easy to integrate with the planner circuits.

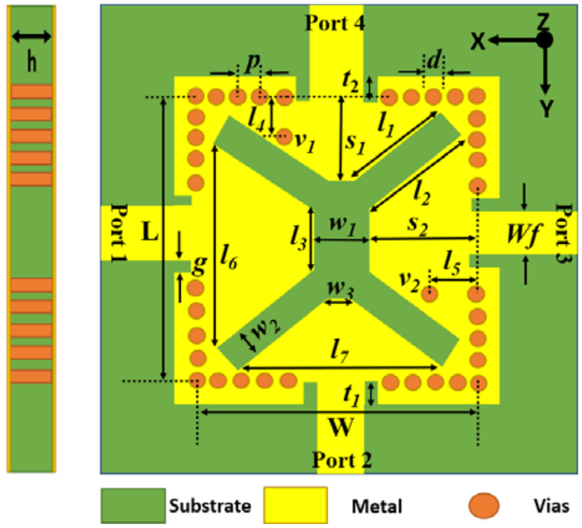
1. INTRODUCTION

The requirement for multi-band antennas in modern communication devices has been increasing in recent years. The multi-band antenna requires less space which is best suited for highly compact wireless devices. Isolation is low in multi-band antennas and compact devices among the ports that result in poor radiation performance and undesired interference among the components [1, 2]. A multiplexer is generally used to enhance the isolation level of ports, but this requires a large area and increases the device design complexity [3, 4]. To avoid this problem, recently the concept of diplexing antennas [7, 8], triplexing antennas [9–11, 14], and quadruplexing antennas [13] has been proposed, which does not require any extra circuitry to improve isolation. A self-isolated multiplex antenna requires a high gain and high front to back ratio (FTBR), which is satisfied by SIW antennas [5]. High isolation is difficult to achieve when the planner antennas have minimal space, extra structure, or circuitry required to provide high isolation between the ports, making the whole antenna system bulky and complicated. Compact planner antennas with four ports based on SIW cavity are illustrate in very few literary works. The most recent self-quadruplexing antenna using the SIW based cavity which provides circular polarization in four frequency bands has been proposed in [13]. To achieve isolation greater than 20 dB among the ports is still a challenge. In this proposed work, a SIW based self-isolated quadruplexing antenna is presented. Good matching and isolation are achieved at operating frequencies. Four simple microstrip lines are used to excite the cavity which creates four distinct resonant frequencies at 6.54, 7.64, 8.30, and 9.60 GHz for port1, port3, port2, and port4, respectively, and each port is well self-isolated from each other.

2. ANTENNA DESIGN AND ANALYSIS

Figure 1 illustrates the layout of the proposed self-quadruplexing antenna, which is made up of an engraving slot on the top metal surface of the substrate that provides four QM SIW cavities. Each QM SIW cavity radiates at four different resonant frequencies when the corresponding port is excited.

Received 1 February 2021, Accepted 3 March 2021, Scheduled 9 March 2021
* Corresponding author: Abhay Kumar Singh (abhays308@gmail.com).
The authors are with the Department of Electronics and Communication Engineering, GBPUAT, Pantnagar, Uttarakhand, India.



(a) (b)

Figure 1. (a) Side and (b) top view of the self-quadruplexing antenna.

Moreover, the antenna has been fabricated on a Duroid 5880 substrate with relative permittivity 2.2 and loss tangent 0.0009. Analysis of the proposed antenna is carried out by the Ansys HFSS 2020. The optimized dimensions of the proposed antenna are given in Table 1.

Table 1. The dimension of the proposed antenna.

W	L	l_1	l_2	l_3	l_4	l_5	l_6	l_7	w_1	h
19.78	19.78	8.64	7.74	3.97	3	3	12.4	17	4	1.575
w_2	w_3	t_1	t_2	d	p	W_f	g	s_1	s_2	
2.15	2.5	0.6	1	1	1.5	5	0.5	5.89	7.89	

units: millimetres

The cavity dimensions determine the resonant frequencies (f_{mn}) of the QM cavities. Each QM cavity gives a distinct frequency when being fed by four 50 Ω microstrips lines. Due to the QM cavity, resonant frequency requires only one-quarter of the SIW cavity [12]. The length of the slot approximately $\lambda_0/2$ at that resonant frequency, where λ_0 is the free-space wavelength. f_{mn} of the QM SIW cavity without any slot can be calculated using formulas [6];

$$f_{mn} = \frac{1}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m\pi}{L_{eff}}\right)^2 + \left(\frac{n\pi}{W_{eff}}\right)^2} \tag{1}$$

and the resonant frequency can be determined by the following equations:

$$f_{mn}^{QM} = \frac{1}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m\pi}{l_6}\right)^2 + \left(\frac{n\pi}{2s_2}\right)^2} \tag{2}$$

$$f_{mn}^{QM} = \frac{1}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m\pi}{l_7}\right)^2 + \left(\frac{n\pi}{2s_1}\right)^2} \tag{3}$$

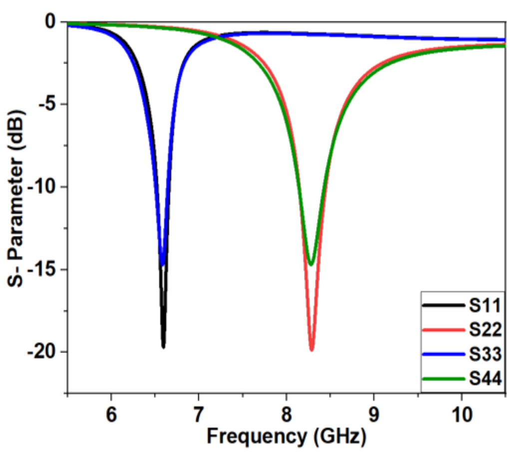
where m and n are integers, and μ_r = relative permeability, ε_r = relative permittivity. The effective length (L_{eff}) and width (W_{eff}) of the SIW cavity can be calculated as

$$L_{eff} = L - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{L} \tag{4}$$

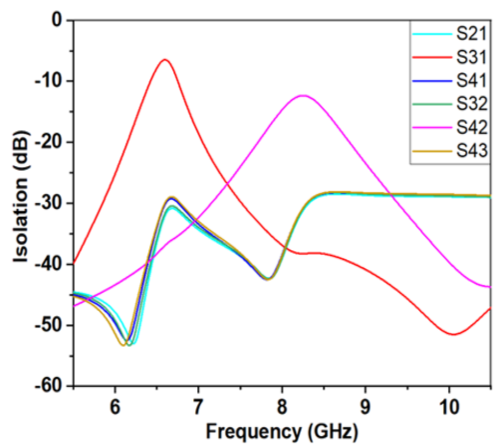
$$W_{eff} = W - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{W} \tag{5}$$

The parameters of diameter (d) and pitch (p) are to be designed in such a way as to minimize leakage between the vias. Two wide V-shaped slots are joined by the middle slot with width w_1 and length l_3 etched on the top plane of the SIW cavity as shown in Figure 1(b). These V-shaped slots and the middle slot divide the cavity into four QM cavities. Each QM cavity is excited by four 50 Ω microstrip lines, and each cavity produces four different resonate frequencies. Generally, to increase the isolation among the QM cavities, the widths of the slots w_1 and w_2 are kept wide. However, an increase in slot width (w_1, w_2, and w_3) worsens the cross-polarization level.

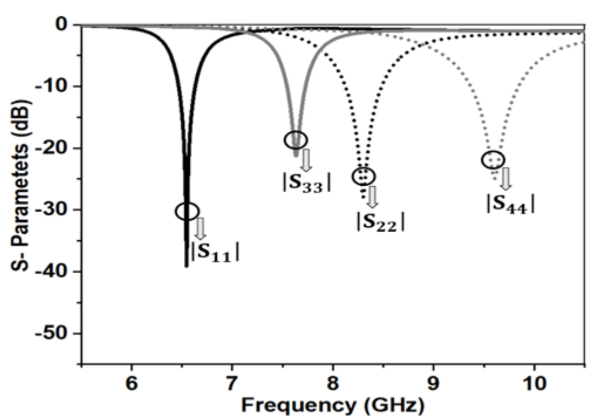
The resonant frequency calculated from Equation (2) and Equation (3) is slightly higher due to the fringing field and unequal shape of the cavities. Due to symmetry in QM cavity size, the resonant frequencies for port1, port3, and port2, port4 are equal as shown in Figure 2(a), and due to this isolation S_{31} and S_{42} are poor as shown in Figure 2(b). Further, to change the resonating frequencies for port3 and port4, two metallic vias v_1 and v_2 are placed in the corresponding cavities of port3 and port4. These two vias added the shunt inductance and perturbed the electric field distribution in the corresponding



(a)



(b)



(c)

Figure 2. Simulated S-parameters, (a) reflection coefficients without vias, (b) isolation without vias, (c) reflection coefficients with vias.

cavities. As a result, the resonant frequencies of port3 and port4 shifted to a higher-value (or lower-value) at a fixed position of vias v_1 and v_2. Now the resonating frequency of port3 is 7.64 GHz and for port4 is 9.60 GHz as shown in Figure 2(c). Basically, these vias (v_1 and v_2) change the magnitude and phase of the electric fields on the opposite sides of slots. Because of this, slot radiates in the free space without transmitting the incident power to the other ports. Further, we studied the effect of l_4, l_5, and l_2 on S-parameters, as shown in Figures 3–4. Starting with l_4 and l_5, as both vias v_1 and v_2 move

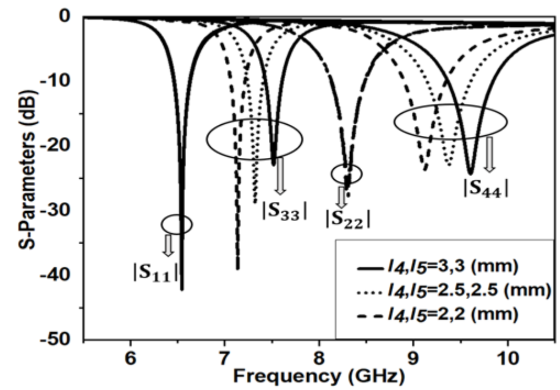


Figure 3. Simulated S-parameters variation with vias location.

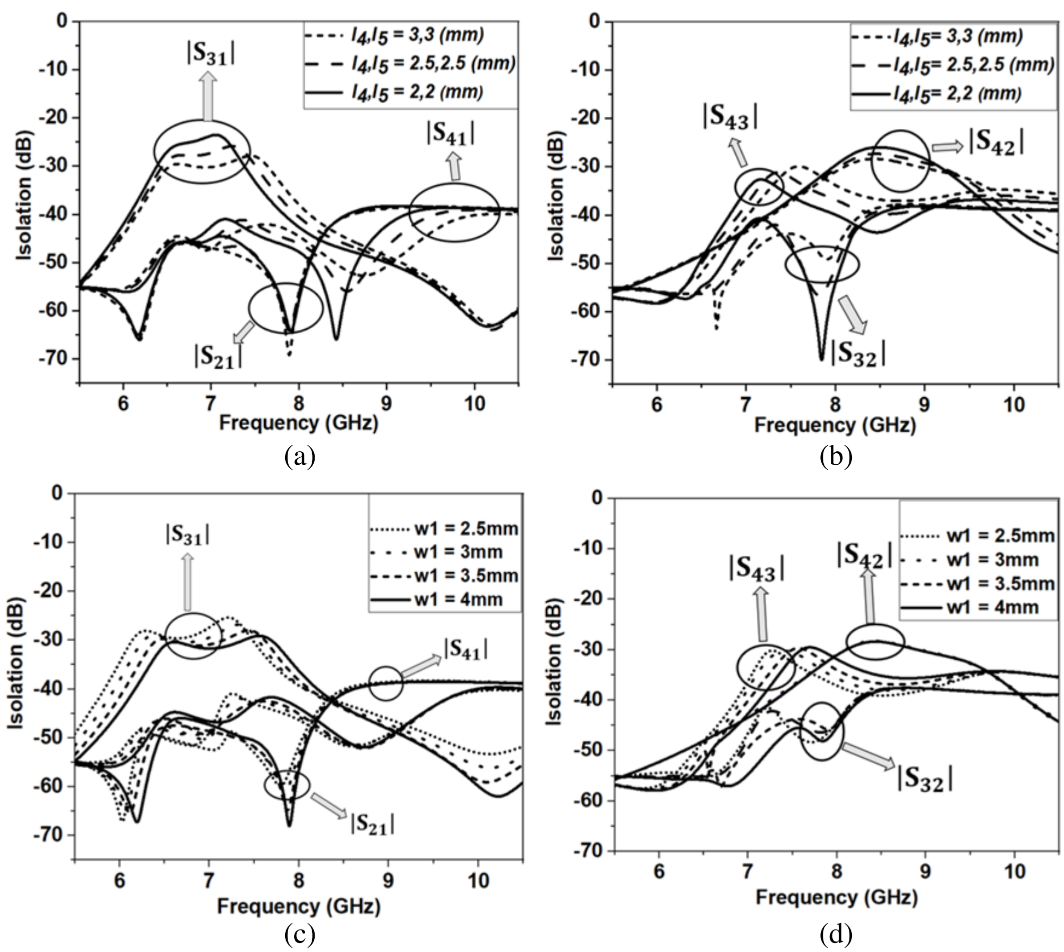


Figure 4. (a), (b) Effects of l_4 and l_5 on isolation. (c), (d) Effects of w_1 on isolation.

towards the slot (increasing the l_4 and l_5), the resonating frequencies of respective ports shifted towards higher values without affecting the matching performance S_{11} and S_{22} as shown in Figure 3. The resonant frequency at port4 can be tuned in the frequency range 9.20–9.60 GHz by varying the location of 'v_1'l_4 from 2 to 3 mm. Similarly, the resonant frequency at port3 can be tuned in the frequency range 7.20–7.64 GHz by varying l_5 of 'v_2' from 2 to 3 mm. The gaps between the vias and slots are chosen to be very small. Hence, minimum energy passes through these little gaps. Here, the primary concern of the proposed work is enhancing the isolation among the ports. Therefore, l_4, l_5, and w_1 are the critical parameters for increasing the isolation performance.

Furthermore, by changing l_4 and l_5 simultaneously, the isolation level increases to 32 dB, as shown in Figures 4(a)–(b). As the values of l_4 and l_5 increase from 2 to 3 mm, isolation $|S_{31}|$ keeps improving. Similarly, for port2 and port4, $|S_{42}|$ improves as both l_4 and l_5 increase from 2 to 3 mm. So vias presence not only shifts the resonate frequencies but also enhances the isolation among the ports. Furthermore, parameters w_1, w_2, and w_3 affect the capacitive coupling between QM SIW cavities; hence, isolation performance is affected. The effect of w_1 on isolation is illustrated in Figures 4(c)–(d). As w_1 increases from 2.5 to 4 mm, the isolation between port1 and port3 (S_{31}) increases up to 32 dB, and further increases in w_1 worsen the antenna cross-polarization performance. Additionally, due to the orthogonal orientation of adjacent ports, the isolation parameters $|S_{21}|$, $|S_{32}|$, $|S_{43}|$ achieve greater dip, more than 35 dB. The isolation $|S_{31}|$ (> 30 dB), $|S_{42}|$ (> 30 dB) is comparatively weaker than $|S_{32}|$ (> 40 dB), $|S_{21}|$ (> 40 dB) and $|S_{43}|$ (> 35 dB), which is due to the direct coupling of port1 with port3, and port2 with port4. Parameters t_1 and t_2 are optimized for improving the matching level. Figures 5(a)–(d) illustrate the electric field distribution in the cavities when the particular port of the antenna is excited. It can be seen that the maximum intensity of the electric-field dominates mostly between the corresponding excited cavities. At the same time, a negligible portion of the electric field is observed towards another cavity.

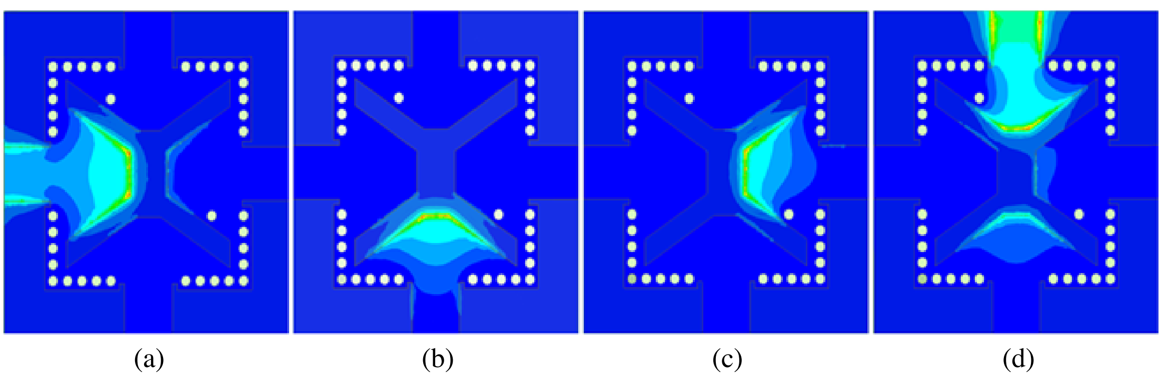
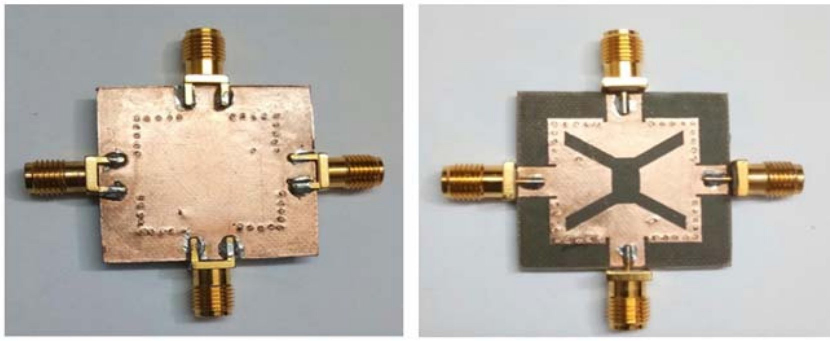


Figure 5. Electric-field distributions at (a) 6.54 GHz, (port1: on), (b) 8.30 GHz, (port2: on), (c) 7.64 GHz, (port3: on) and (d) 9.60 GHz, (port4: on).

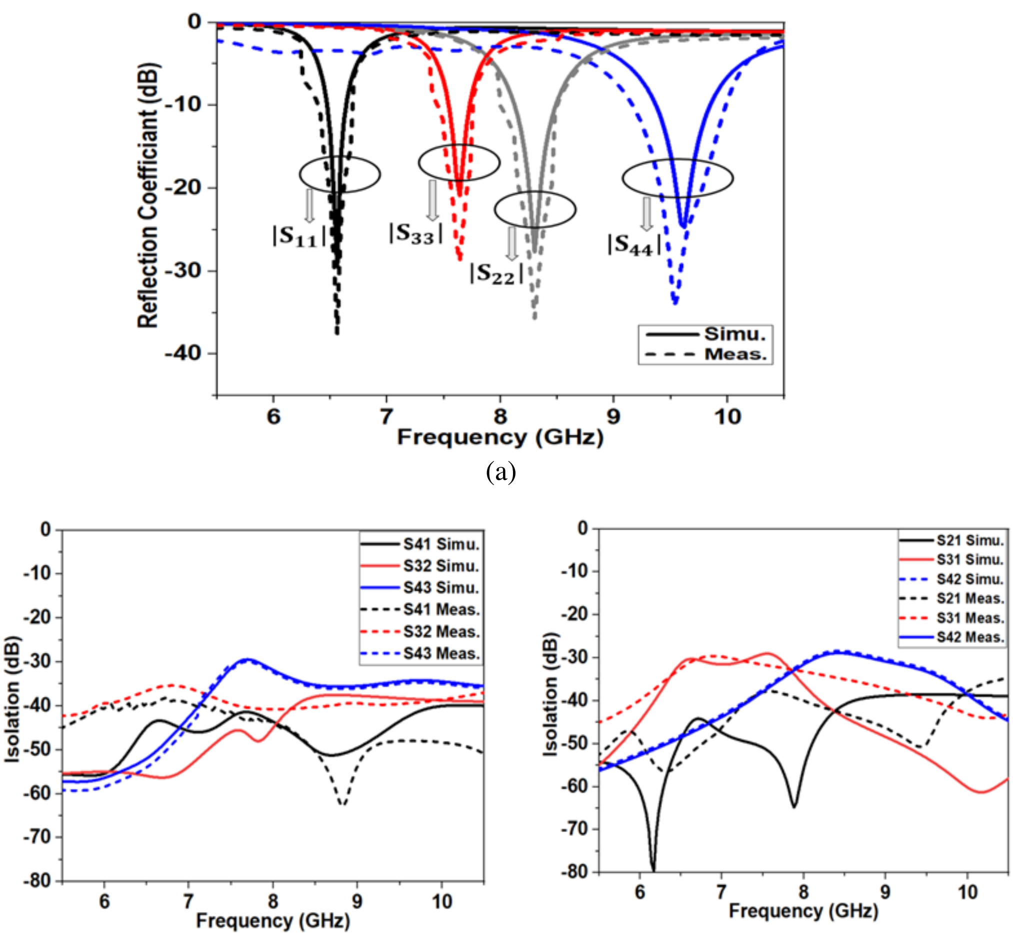
3. EXPERIMENTAL VALIDATION

The fabricated antenna is shown in Figure 6. Figure 7(a) shows the comparison between measured and simulated S-parameters. The measured resonant frequency of 6.54 GHz is obtained when port1 is excited, and the remaining ports are terminated with a matched load of 50 Ω. Similarly, other resonating frequencies obtained are 8.30, 7.64, and 9.60 GHz when port2, port3, and port4 are excited, respectively, and the remaining ports are connected to 50 Ω load. In all cases, the measured minimum isolation among the ports has been obtained more than 32 dB, as shown in Figure 7(c). The simulated and measured normalized radiation patterns in E ($\varphi = 0°$) and H ($\varphi = 90°$) planes at the four operating frequencies are shown in Figure 8. It can be observed that the measured radiation patterns show good agreement with the simulation results. Here, the radiation characteristics of the SIW antenna are unidirectional due to the cavity-backed structure. Cross-polarization is more than 19 dB at the operating frequencies. Figure 9 shows a measured gain of 8.1, 8.0, 7.8, and 7.9 dBi at 6.54, 7.64, 8.30, and 9.60 GHz, respectively, when only one port is excited and remaining ports terminated with $50\,\Omega$ match load. The measured efficiency obtained is more than 88% at each resonant frequency. However, measured results slightly deviate from the simulated ones due to the fabrication tolerance, limitation of the simulation environment, or imperfection in soldering. The measured antenna performance parameters at the resonant frequencies are given in Table 2. It can be observed that the measured isolation, gain, and FTBR are better than



(a) (b)

Figure 6. Fabricated antenna. (a) Bottom and (b) top view.



(a)

(b) (c)

Figure 7. Simulated and measured (a) reflection coefficients, (b) and (c) isolation.

the previous works are presented in Table 3. The proposed antenna total geometrical size, including the feed-network, is 30 mm × 30 mm.

Table 2. The measured antenna characteristics.

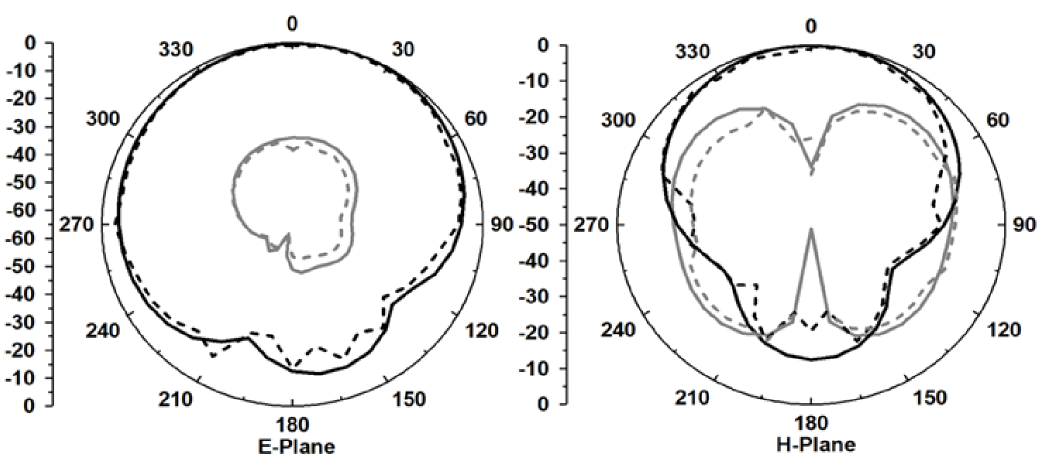
Excitation	Freq. (GHz)	Minimum isolation (dB)	Gain (dBi)	Cross-Pol. (dB)	FTBR (dB)
Port1	6.54	> 32.5	8.10	30	20
Port2	8.30	> 33	7.8	35	19.5
Port3	7.64	> 32	8	19	20.5
Port4	9.60	> 37	7.9	25	20

Table 3. Comparison of proposed work with the previous antennas.

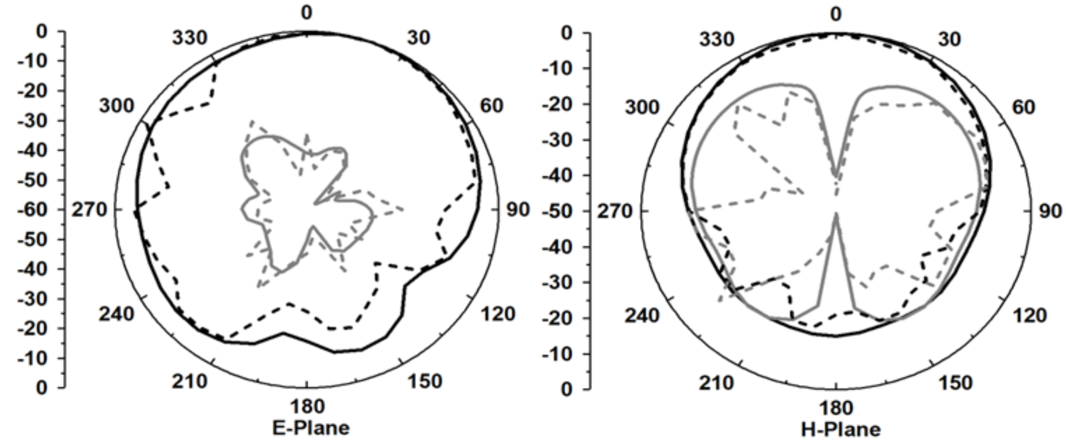
Parameters	[3]	[13]	[10]	[14]	[11]	Proposed Work
Freq. (GHz)	1.2/2.4/3.5/5.2	12.23/10.04/8.85/11.4	7.8/9.4/9.87	6.5/7.6/9.0	4.2/5.2/5.8	6.54/7.64/8.30/9.60
Gain (dBi)	5.47/5.88/2/3.56	6.5/6.1/5.25/6.35	7.2/7.2/7.2	3.68/4.76/4.5	6.56/4.2/5.85	**8.1/8.0/7.8/7.9**
Isolation (dB)	NA	26	22.5	18	23	> **32**
FTBR (dB)	NA	> 15	> 17.3	> 13	> 19	> **19.5**
Size	$0.36\lambda_0 \times 0.24\lambda_0$	$0.82\lambda_0 \times 0.82\lambda_0$	$1.3\lambda_0 \times 1.3\lambda_0$	$1.0\lambda_0 \times 1.0\lambda_0$	$1.2\lambda_0 \times 0.9\lambda_0$	$\mathbf{0.65\lambda_0 \times 0.65\lambda_0}$
Design Layout	Quad-Band*	Self-Quadruplexing	Self-triplexing	Self-triplexing	Self-triplexing	Self-Quadruplexing

NA = Not Available

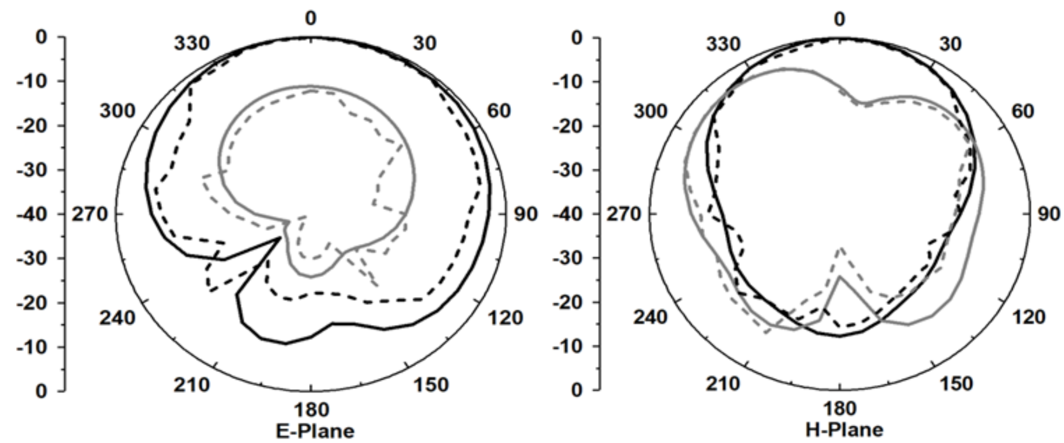
*Requires extra circuitry for isolation



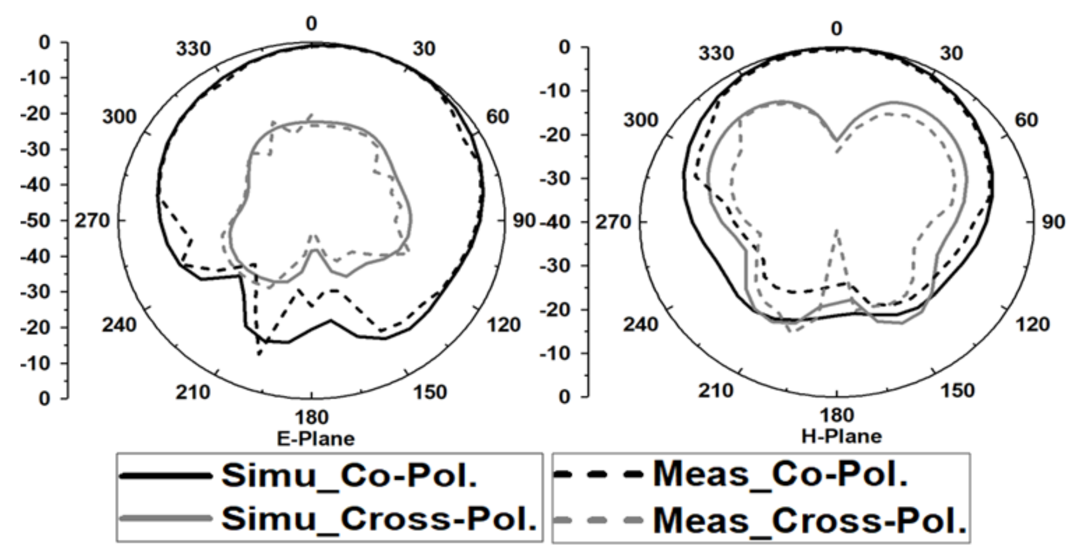
(a)



(b)



(c)



(d)

Figure 8. Radiation patterns at (a) 6.54 GHz, (b) 8.30 GHz, (c) 7.64 GHz, and (d) 9.60 GHz.

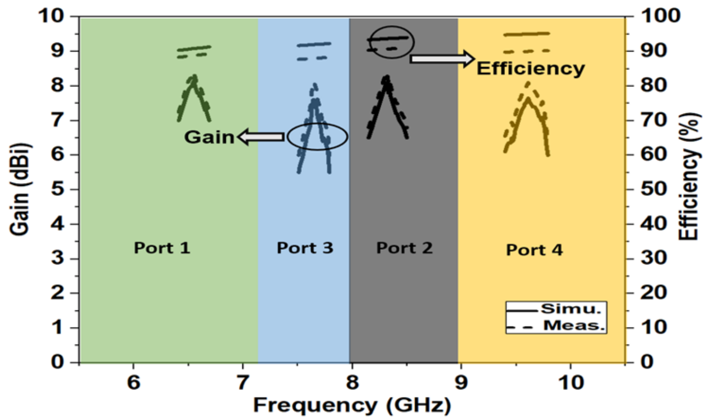


Figure 9. Simulated and measured gains and efficiencies.

4. CONCLUSIONS

A compact SIW self-quadruplexing antenna is presented. Two wide V-shaped slots joined by the middle slot divide the entire cavity into four QM cavities. These four QM cavities generate four resonant frequencies, and a single variable can tune each resonant frequency. The isolation between the ports is greater than 32 dB. The measured gain at the operating frequencies is more than 7.8 dBi. Moreover, the size of the antenna is $0.65\lambda_0 \times 0.65\lambda_0$. Radiation efficiency and FTBR are more than 88% and 18 dB in all the bands, respectively. Due to high isolation among the ports, the proposed antenna is the right candidate for quad-band antennas. There is no requirement for an extra circuit for isolating the operating frequencies.

REFERENCES

1. Hu, W., Y. Z. Yin, X. Yang, and P. Fei, "Compact multi-resonator-loaded planar antenna for multi-band operation," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 5, 2838–2841, May 2013.
2. Lu, Y. C. and Y. C. Lin, "A mode-based design method for dual-band and self-diplexing antennas using double T-stubs loaded aperture," *IEEE Trans. Antennas Propag.*, Vol. 60, No. 12, 5596–5603, Dec. 2012.
3. Liu, H., P. Wen, S. Zhu, B. Ren, X. Gua, and H. Yu, "Quad-band CPW-fed monopole antenna based on flexible pentangle-loop radiator," *IEEE Antennas Wireless Propag. Lett.*, Vol. 14, 1373–1376, 2015.
4. Zeng, S. J., J. Y. Wu, and W. H. Tu, "Compact and high isolation quadruplexes using distributed coupling technique," *IEEE Microw. Wireless Compon. Lett.*, Vol. 21, No. 4, 197–199, Apr. 2011.
5. Mukherjee, S., A. Biswas, and K. V. Srivastava, "Substrate integrated waveguide cavity-backed dumbbell-shaped slot antenna for dual-frequency applications," *IEEE Antennas Wireless Propag. Lett.*, Vol. 14, 1314–1317, 2015.
6. Xu, F. and K. Wu, "Guided-wave and leakage characteristics of substrate integrated waveguide," *IEEE Trans. Microw. Theory Techn.*, Vol. 53, No. 1, 66–73, Jan. 2005.
7. Kumar, A. and S. Raghavan, "Planar cavity-backed self-diplexing antenna using two-layered structure," *Progress In Electromagnetics Research Letters*, Vol. 76, 91–96, 2018.
8. Nandi, S. and A. Mohan, "An SIW cavity-backed self-diplexing antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 16, 2708–2711, 2017.
9. Cheong, P., K. F. Chang, W. W. Choi, and K. W. Tam, "A highly integrated antenna-triplexer with simultaneous three-port isolations based on multimode excitation," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 1, 363–368, Jan. 2015.

10. Kumar, K. and S. Dwari, "Substrate integrated waveguide cavity-backed self-triplexing slot antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 16, 3249–3252, 2017.
11. Chaturvedi, D., A. Kumar, and S. Raghavan, "An integrated SIW cavity-backed slot antenna-triplexer," *IEEE Antennas Wireless Propag. Lett.*, Vol. 17, No. 8, 1557–1560, Aug. 2018.
12. Jin, C., R. Li, A. Alphones, and X. Bao, "Quarter-mode substrate integrated waveguide and its application to antennas design," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 6, 2921–2928, Jun. 2013.
13. Kumar, K., S. Priya, S. Dwari, and M. K. Mandal, "Self-quadruplexing circularly polarized SIW cavity-backed slot antennas," *IEEE Trans. Antennas Propag.*, Vol. 68, No. 8, 6419–6423, Aug. 2020.
14. Kumar, A. and S. Raghava, "Self-triplexing SIW cavity-backed slot antenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 17, No. 5, 772–775, 2018.