

Research Article

Design of Dual-Band, 4-Ports MIMO Antenna-Diplexer Based on Quarter-Mode Substrate Integrated Waveguide

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Received 14 August 2022; Accepted 10 September 2022; Published 23 September 2022

Academic Editor: Arvind Kumar

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Here, a compact, dual band, 4-elements multi-input and multi-output (MIMO) antenna diplexer is designed to use in wireless local area network (WLAN) applications. The antenna is accomplished in a planar profile by employing Substrate Integrated Waveguide (SIW) technology. To reduce the size of a single element by 75%, a quarter-mode substrate integrated waveguide (QMSIW) technology is introduced. The QMSIW is realized by bisecting the full-mode SIW along the two magnetic walls and considering the quarter-mode for the operation. Initially, two-QMSIW cavities of distinct dimensions are designed to operate in two frequency bands, 5.2 GHz and 5.8 GHz, respectively. Later, two more radiating elements operating at the same frequencies are integrated with a 2-elements antenna. For better polarization decoupling, the identical elements are placed perpendicular to each other, and a parasitic metallic strip loaded with shorting vias is placed between two identical frequency band while 2.2% in the upper frequency band. The antenna prototype is fabricated, and its results are verified with experimental data. It is observed that the measured results are closely following the simulated results.

1. Introduction

Wireless communication channel environment is a densely populated area as the links are more susceptible to fading and co-channel interference, hence, due to this reason, power falls substantially with space. Thus, it becomes challenging for the antenna designer to design a system with higher spectral efficiency, higher quality of service, and wide bandwidth [1-4]. Therefore, the wireless communication parameters in a complex setting can be enhanced by employing spatial multiplexing and diversity techniques. Multiplexing techniques mainly improve the channel capacity, which leads to enhanced data rate, while diversity techniques improve the reliability of communication. Thus, the MIMO antenna is an optimum alternative to mitigate the fading by employing receiver and transmit diversity. In the modern world, electronic devices are dropping in size every day; thus, there is a need for a compact system. In this

concern, the antenna plays a vital role. The next stringent requirement is good isolation levels between the radiating elements because they are very close to a compact structure. There are various techniques suggested by the researchers to enhance the isolation level [5-9]. In [5], photonic band gap structures are placed between transmitting and receiving antennas, a metamaterial mushroom structure is used between 4 closed-spaced antennas in [6], two cross-neutralization lines are used in [7], and a meandering slot along with an inverted *T* slot is etched in the ground plane in [8].

In the past two decades, Substrate Integrated Waveguide (SIW) based cavity-backed antennas have played a vital role in developing self-diplexing antennas [9–11]. The overall size of the SIW antenna can be substantially condensed by retaining similar bandwidth and radiation characteristics by employing half-mode (HM) SIW [12–14], quarter-mode (QM) SIW [15], and eight mode (EM) SIW [16] topologies. Many multiple antenna systems were investigated [17–25]. However, only a few of them discussed the MIMO properties. In [17], the dual-band performance is realized by coupling a parasitic rectangular patch with the HMSIW cavity; however, the antenna suffers from narrow bandwidth. To improve bandwidth with compact size, the HMSIW cavities are loaded with rectangular slots to split the dominant mode into odd- and even-half modes [18]. To improve the bandwidth and gain in each operating band, a half-split cylindrical dielectric resonator is realized in [19]. To realize a small dual-band MIMO antenna, a split ring resonator (SRR) slot is employed, but the isolation level in the inter-elements becomes poor [20].

In this article, a dual-band 4-elements-self-diplexing MIMO antenna is developed to operate in the lower frequency band around 5.2 GHz (5.15-5.26 GHz, 110 MHz) and the higher frequency band around 5.8 GHz (5.75-5.88 GHz, 130 MHz) for wireless local area network (WLAN) bands. The size of the proposed design is minimized to a quarter by employing the QMSIW cavity. The proposed MIMO antenna has potential use in enhancing data transmission speed by twice compared to a 2-elements antenna. In a complex communication environment, this antenna also can be considered to improve the reliability of data links. The MIMO properties of a 2×2 elements antenna diplexer have been evaluated in terms of the Envelop Correlation Coefficient (ECC) and diversity gain (DG). The exclusive and modest proposed antenna shape maintains isolation between any two ports below -25 dB just by employing rectangular metallic strips loaded with shorting vias. Both the lower and upper resonant frequencies can be scaled individually by altering the QMSIW cavity length. This article is divided into three sections. Section 2 presents the design methodology of a 4-elements self-diplexing MIMO antenna system, Section 3 presents simulated and measured results, and Section 4 has concluded the proposed idea.

2. 4-Ports Self-Diplexing Antenna Design Process

Figure 1 shows the geometrical view of the proposed QMSIW cavity-backed slot antenna. The various stages used in the design progression from the full-mode SIW to the QM SIW cavity resonators are explained in Figure 2. The design of the proposed antenna is modeled with the help of a Computer Simulation Technology (CST) Microwave studio simulator [11]. The first step is calculating the dominant mode resonant frequency of the rectangular cavity at around 5.2 GHz using (1) [12]. The dimensions of the rectangular cavity are evaluated as $27.4 \times 27.4 \text{ mm}^2$. The QMSIW cavity is achieved by firstly bisecting the FMSIW cavity along two magnetic walls, then preserving the quarter-part of the fulldominant mode. By using the abovementioned steps, two QM planar cavities are designed where the first cavity (i.e., Cav1) operates at 5.2 GHz and the second cavity (i.e., Cav2) operates at 5.8 GHz, as shown in Figure 2(a). The operating frequency equation for the FMSIW cavity can be calculated using (1) [9, 15] shown below.



FIGURE 1: Schematic diagram of 4-ports self-diplexing antenna (dimensions, $w_1 = w_2 = 25$, $l_1 = 15.7$, $l_2 = 17.4$, g = 2.5, $w_f = 5$, $k_1 = k_2 = 16$, $p_1 = 1.6$, $m_2 = 3.2$, d = 0.8, s = 1.6, L = W = 44.2) (unit: mm).



FIGURE 2: Design evolution to accomplish a dual element 4-ports antenna-diplexer.

$$f_{110}(\text{FM}) = \frac{c}{2\sqrt{\varepsilon_{reff}}} \sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{l_{eff}}\right)^2}, \qquad (1)$$

where l_{eff} or $W_{eff} = W$ or $L - 1.08 d^2/p$, w_{eff} and l_{eff} are the effective width and length of the full-mode cavity, d is the diameter, and s is the pitch distance between two shorting vias. The electric walls on each side of the SIW cavity are accomplished by inserting the number of shorting vias, which attach the top and bottom planes of the metallic cladding. In the proposed design, firstly a full-mode SIW is divided into two equal parts along the magnetic walls to achieve a half-mode (HM) SIW. In the next step, the HMSIW cavity resonator operating in the dominant mode is split into two unequal parts by carving one open-end tilted rectangular slot. Necessarily, this slot translates the HMSIW cavity resonator into two patchy quarter-mode like cavity structures. The QMSIW conserves the lowest operating mode of FMSIW due to its uniform and symmetrical field distribution. 50 Ω microstrip line is adopted for excitation. Each QM cavity operates at a different resonant frequency due to unequal size. To realize better impedance matching characteristics, feed location can be optimized. Three metallic vias, covering a distance of "m," are implanted near the short end of the slot to reduce the inter-element mutual coupling. The dimensions of the QMSIW cavities are optimized to achieve a lower frequency band of around 5.2 GHz and an upper-frequency band of around 5.8 GHz. The final dimensions of this design are tabulated in Table 1 and are symbolized in Figure 1. To achieve a complete planar configuration, microstrip feed line techniques are used to feed the QM cavities. The feed characteristic impedance and the antenna input impedance are matched by optimizing the location of the feed. To avoid leakage loss through vias, the diameter and spacing between the shorting vias are obtained using the design guidelines mentioned in [12]. The 2-element antenna illustrates adequate isolation of around -25 dB between two cavities, as shown in Figure 3. A MIMO diplexing antenna system is achieved by replicating two more similar elements [19]. However, after adding the elements, there is no variation in the reflection coefficient parameters, but the isolation level (S_{ij}) is degraded by around 5 dB.

The design executes the operating bandwidth of around 1.8% in a lower frequency band and 2.2% in an upperfrequency band. The operating principle of the 2-port diplexing antenna is demonstrated in Figure 2. When *Cav1* is fed with microstrip feed while *Cav2* is terminated with a 50 Ω matched termination, the *Cav1* resonates at 5.2 GHz due to its quarter fundamental mode TE110, as presented in [15]. Similarly, when *Cav2* is fed with microstrip feed and Cav1 is ended with matched termination, *Cav2* operates at 5.8 GHz. To reduce the port decoupling, the cavities operating at the same resonant frequency are placed orthogonal to each other. Thus, inherent isolation is achieved at around -20 dB, as shown in Figure 4. However, the isolation level is insufficient for high-powered wireless communication. Furthermore, to improve the isolation.

Rectangular parasitic metallic strips loaded with shorting vias are placed among the QM cavities. The parasitic strips reduce mutual coupling between the cavities of distinct resonant frequencies, which are oriented parallel to each other. The shorting vias make the electric wall by making the electric field zero. Thus, the inter-element isolation levels are getting improved and obtained -25 dB. Figure 5 illustrates clearly how the metallic strip plays an essential role in reducing the field coupling. The scalar electric field plots have been shown in Figure 6(a) without metallic strips and Figure 6(b) including metallic strips. The E-field plots are presented at each operating frequency when the corresponding port is excited. It can be observed in Figure 6(b)

TABLE 1: The dimensions of the antenna structure. All dimensions are in millimeters (Mm).

w_1	w_2	l_1	l_2	9
25	25	15.7	17.4	2.5
w_f	k_{1}	k ₂	p _1	m_2
5	16	16	1.6	3.2
d	\$	L	W	h
0.8	1.6	44.2	44.2	1.57



FIGURE 3: S-parameters of dual-band dual element diplexing antenna.



FIGURE 4: S-parameters of dual-band quad elements diplexing antenna without a metallic strip.



FIGURE 5: S-parameters of dual-band quad elements diplexing antenna with a metallic strip.



FIGURE 6: Scalar E-field when corresponding port is powered (a) without parasitic metallic strips (b) with metallic strips.

that mutual coupling with other elements can be reduced significantly.

The operating frequencies of a 4-element diplexing antenna configuration can be rescaled for different bands by simply altering the length of the cavities. It can be observed in Figure 7 that by varying the length a1 of Cav1 in the range of 11.8–12.4 mm, the resonant frequencies can be tuned from 5.3–5.1 GHz. Similarly, it can be observed in Figure 8 that by varying the length a2 of Cav2 in the range of 10.8–11.4 mm, the corresponding resonant frequency can be tuned in the frequency range of 5.9–5.7 GHz.

The resonant frequency can be adjusted individually in both operating bands in a straightforward manner. The scaling of one resonance has no impact on another resonance, which proves the flexibility of the MIMO-antenna system. This antenna design maintains the ground plane integrity, which makes it easy to integrate with other elements. All radiating elements are placed on the top plane. All four cavities share the same ground, making the design simpler and more compact.

2.1. MIMO Properties of Self-Diplexing Antenna. The MIMO features of the proposed design are verified in terms of envelope correlation coefficient (ECC) and diversity gain (DG). ECC governs the correlation in radiation patterns between two independent antennas [8]. Typically, its value should be <0.5. The ECC can be derived from S-parameters and far-field gain. The ECC from S-parameters can be extracted from (2). The ECC performance of the proposed design is shown in Figure 9. When Port-1 and Port-3 are fed with a microstrip feed line while Port-2 and Port-4 are ended with the matched terminations, the peak value of ECC is observed as 0.02. On the other hand, when Port-2 and Port-4 are fed and the rest are terminated with matched loads, the peak value of ECC is obtained as 0.03. The ECC can be evaluated from S-parameters using (2) [19] when Port-1 and Port-3 are excited.

$$ECC = \frac{|S_{11*} S_{13} + S_{13} * S_{33}|^2}{\left(1 - \left(|S_{11}|^2 + |S_{31}|^2\right)\right)\left(1 - \left(|S_{31}|^2 + |S_{13}|^2\right)\right)}.$$
 (2)



FIGURE 7: S 11 against frequency with different lengths of Cav1.



FIGURE 8: S $_{22}$ against frequency with different lengths of Cav_2 .

Similarly, the ECC in the upper-frequency band can be evaluated using (2) just by replacing *Port 1* with *Port 2* and *Port 3* with *Port 4*. The ECC values from far-field gain are evaluated and displayed in Figure 9. It shows the peak value in the lower frequency band is around 0.08, while in the upper-frequency band it is around 0.18.

The diversity gain (DG) signifies a rise in the antenna gain with the addition of multiple elements [9]. The DG values are evaluated and presented in Figure 10. After inserting the other cavities, the DG value of the MIMO antenna approaches around 9.94 dB, which approaches its typical value of 10, and it can be obtained by (3) [19].



FIGURE 9: ECC-graphs against frequency from S-parameters and far field.



FIGURE 10: DG against frequency when same cavities are fed simultaneously.

$$DG = 10\sqrt{1 - |0.99 Ecc|^2}.$$
 (3)

2.2. Design Steps. The design guidelines for the proposed MIMO systems are as follows:

- (a) Design a square cavity resonator (SIW).
- (b) Split the FMSIW cavity into two equal parts along the central magnetic wall.
- (c) Insert an open-ended slanted rectangular slot in the HMSIW cavity to convert into two unequal QMSIW cavity resonators (Cav₁ and Cav₂).
- (d) Excite each cavity with a microstrip feed line and optimize the dimensions of Cav₁ and Cav₂ to achieve

FIGURE 11: Fabricated prototype of 2 × 2 MIMO antenna-diplexer.



FIGURE 12: Simulated and measured S-parameters against frequency response (solid curve represents simulated graph and dashed curve signify the measured responses).



FIGURE 13: Simulated and measured gain and efficiency against frequency.

the fundamental mode around 5.2 GHz and 5.8 GHz, respectively.

- (e) Replicate the 2-elements in the diplexing antenna to achieve a 2×2 MIMO antenna.
- (f) Optimise the isolation of the relevant dimensions. Evaluate the MIMO performance.

3. Results-Validation and Discussions

A prototype of the proposed dual-band self-diplexing 2×2 MIMO antenna system is fabricated using a Rogers-5880 copper laminated dielectric substrate, as shown in Figure 11. The dielectric substrate has a thickness of 1.578 mm and a relative permittivity of 2.2. The simulated scattering parameter responses have been revealed in Figure 12. The operating frequency bands show the port isolation as better than -25 dB. The measurements are performed using the E5080A VNA. The antenna generates resonant frequencies from simulations at 5.2 GHz when Port-1 or Port-3 is fed, and *Port-2/Port-4* is terminated with matched loads, while it vields resonant frequencies at 5.2 GHz when Port-2 or Port-4 is fed, and Port-1/Port-3 is matched terminated. On the other hand, the antenna shows the measured results at 5.25 and 5.84 GHz when the corresponding port is excited, respectively. The antenna generates the peak simulated values of gain of 4.75 and 4.9 dBi and measured values of gain of 4.7 and 4.67 dBi in the lower and upper-frequency bands, respectively. Also, the antenna demonstrates a flat response of the gain curve in both operating frequency bands as the quarter fundamental mode is used for the operation. The radiation efficiency varies in the range of 78%~82% in the frequency band of 5.1~5.35 GHz, while it varies 81%~87% in the upper-frequency band of 5.7~5.89 GHz, as shown in Figure 13. The simulated results closely follow the measured results.

However, a slight difference is witnessed due to the shared coupling of fields generated by the adjoining elements. However, the impact of field coupling on antenna performance is minor. The 2D-radiation patterns of the antenna are plotted at two planes ($\phi = 0^{\circ}$) and ($\phi = 90^{\circ}$) in Figure 14. The simulated and measured 2D radiation patterns are plotted at 5.2 GHz in the lower frequency band and at 5.8 GHz in the upper-frequency band. The co/cross-polarization ratio is better than 18 dB in the lower frequency band, while 16 dB is in the higher frequency bands. The proposed design contributes primarily to radiation unidirectional with a front-to-back ratio of better than 18 dB for both operating frequency bands. Additionally, the antenna radiates highest in the broadside direction and has a unidirectional radiation pattern at each resonance due to the involvement of the SIW-backed cavity with the complete ground plane. The proposed MIMO antenna is remarkably compliant in adjusting the resonant frequency in the desired frequency bands. The operating bands can be shifted on either side of the resonant dip individually without affecting performance merely by modifying the dimensions of the QMSIW cavities. The design of the proposed antenna is straightforward, low-profile, small, and easily tunable. The



FIGURE 14: Simulated and measured radiation patterns at 5.2 GHz. (a) *E*-plane ($\phi = 0^{\circ}$), (b) H-plane ($\phi = 90^{\circ}$), and 2D radiation patterns at 5.8 GHz, (c) *E*-plane ad (d) *H*-plane.

TABLE 2:	Comparison	of pro	posed	mimo	antenna	with	other	existing	works.
	1								

Ref	MIMO elements	fr (GHz)	Gain (dBi)	Fractional bandwidth	Isolation (dB)	Size in (electrical length)
[4]	2×2	2.5	2.6	2	28	2.5 $\lambda_1 \times 2.5 \lambda_1$
[16]	2×2	3.27	4.8	6.6	20	1.42 $\lambda_I \times 1.42 \lambda_I$
		5.4	5.3	2.6	20	
[17]	2×2	3.5	2.7	1.7	18.4	0.65 $\lambda_1 imes 0.65 \lambda_1$
		5.2	2.8	1.2		
[18]	2×2	4.43	6	2.5	35	1.7 $\lambda_1 imes 0.8 \ \lambda_1$
		5.39	6.4	1.8		
[20]	2×2	2.93	4	35	14	0.8 $\lambda_1 imes 0.8 \ \lambda_1$
		5.68	4	6.86	14	
[21]	2×2	3.51	4.9	≈ 2.7	14	0.35 $\lambda_1 \times 0.86 \lambda_1$
This work	2×2	5.2	4.85	1.8	25	0.7 $\lambda_1 imes 0.7 \ \lambda_1$
		5.8	4.6	2.2		

proposed design is an efficient alternative to enhance the data speed by offering spatial diversity/spatial multiplexing for WLAN communication.

The novel features of the proposed 4-element MIMO antenna are associated with other similar research works, summarized in Table 2. The dual-band self-diplexing antenna shows compact size, better isolation, and comparable gain.

Profile with other similar works. The antennas presented in [16, 20, and 21] show better fractional bandwidth; however, the isolation level is poor. The antennas present similar gain and bandwidth features to [17, 18], and [21] in a more compact design. The port decoupling is better than many other works without using the defected ground structure (DGS) element in the ground plane, which makes this design configuration simple and unique.

4. Conclusion

This paper represents a simple and compact quarter-mode SIW cavity-backed MIMO antenna for two-channel frequency applications. By employing the quarter-mode cavity, the overall size of the proposed structure is miniaturized by around 75% compared to the full-mode cavity. The dualband operations are achieved by employing two-QMSIW cavities of different dimensions. Later, the cavities are replicated with two more cavities to achieve a MIMO antenna system. To improve the intrinsic isolation levels between any two radiating portions, parasitic metallic strips loaded with shorting vias are placed between two similar cavities. The diversity features are evaluated in terms of ECC and DG; both parameters satisfy the requirements of MIMO communication. The proposed MIMO antenna design is fabricated and practically validated. The measured and simulation show good mutual agreement with each other.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank the Rogers Corporation (USA) for providing sample substrates.

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