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Compact Four-Element MIMO Antenna System Based on Substrate-Integrated-Waveguide Cavities

Bing-Jian Niu* and Jie-Hong Tan

Abstract—A compact four-element multiple-input-and-multiple-output (MIMO) antenna system is proposed based on substrate-integrated-waveguide (SIW) cavities. By bisecting a square SIW cavity, two rectangle half-mode cavities with opened edges are formed. They are arranged side by side sharing a row of metallic vias. Then two narrow T-shaped slots are etched along symmetry planes to divide these two cavities into four quarter-mode sub-cavities. Excited by feeding ports, four antenna elements with compact size are constructed, which radiate incident wave through opened cavity edges and etched slots. Moreover, antenna isolation can be easily improved by adjusting slot length though these elements interconnect. A prototype with the cavity size of $0.22\lambda_0 \times 0.86\lambda_0 \times 0.04\lambda_0$ has been fabricated. The fabricated MIMO antenna system exhibits the center frequency of 3.51 GHz, port isolation of 14 dB, envelope correlation coefficient of 0.03, peak gain of 4.9 dBi, and high efficiency of 77.4%. The compact size and effective isolation improvement make the proposed design attractive for practical applications.

1. INTRODUCTION

With further requirements of high data rate and reliable link quality, multiple-input-and-multiple-output (MIMO) technology has been greatly introduced in modern wireless communication. As an important part, massive antenna elements are utilized to exploit multipath environments and provide multiplexing/diversity channel gain [1–3]. However, this generally leads to large overall size and poor isolation. Therefore, multiple-element MIMO antenna systems with compact size and high isolation are mostly required.

In recent years, substrate-integrated-waveguide (SIW) cavities have been widely studied for antenna designs, due to attractive advantages such as low profile, low-cost fabrication, and seamlessly planar integration [4–6]. However, these antennas have a drawback of large cavity size. Half-mode (HM) and quarter-mode (QM) cavity antennas are investigated in [7–10]. Though compact size is obtained, only an antenna element can be formed in these SIW cavities. A two-element MIMO antenna system based on SIW technology has been developed in [11], in which high isolation is achieved by increasing antenna distance and optimizing system configuration. Recently, four-element MIMO systems have been reported in [12, 13] where isolating elements are utilized to reduce the coupling among antenna elements. However, these designs suffer from complex structures and low radiation efficiency which limit their practical applications.

In this letter, a compact four-element MIMO antenna system based on SIW cavities is proposed. In order to achieve compact size, antenna elements are constructed in QM sub-cavities which are connected with each other. The isolation among them can be effectively improved by adjusting the length of two etched T-shaped slots. The design evolution, parametric study, field distribution, and 3-D radiation pattern are given. Experimental results of a fabricated prototype demonstrate a decent agreement with the simulation ones.

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2. GEOMETRY AND DESIGN

The geometrical evolution of the proposed design is shown in Figure 1. Enclosed by metallic vias with diameter r and center-to-center spacing s, a square SIW cavity is printed on a single layer substrate with the permittivity $\varepsilon_r = 2.5$ and thickness $h = 3\,\mathrm{mm}$. By bisecting it along the symmetry plane A-A', two rectangle HM cavities are formed. Compared to the former with a closed structure, the latter possesses opened edges which can effectively radiate cavity energy into free space. Then they are arranged side by side to obtain radiation diversity, and a row of vias are shared to achieve compact size. Excited by coaxial ports, a two-element MIMO antenna system is realized. Note that the inner probes and outer conductors of ports are connected with the top and bottom planes of SIW cavities, respectively. Proper antenna matching can be obtained by optimizing port positions (F_v and F_h).

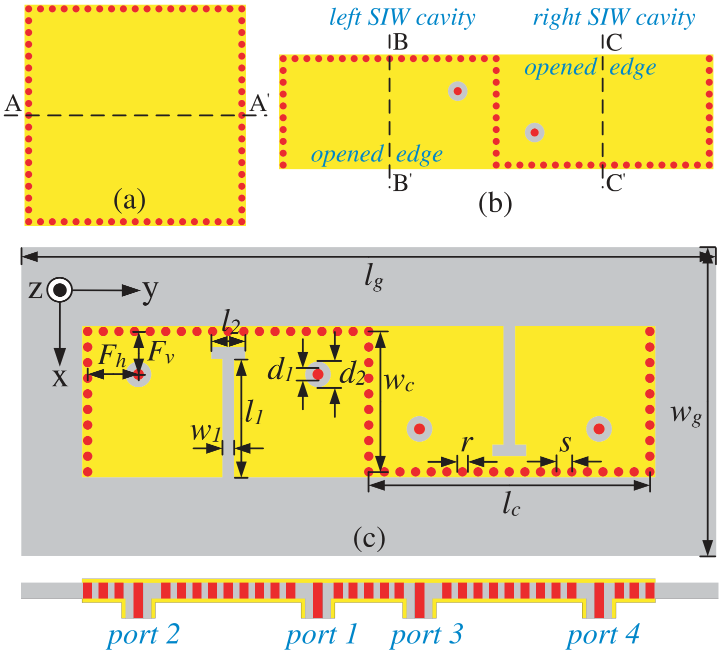


Figure 1. Geometrical evolution: (a) square SIW cavity; (b) two-element MIMO antenna system; and (c) four-element MIMO antenna system.

In order to further increase the quantity of antenna elements, a narrow T-shaped slot is etched along B-B' and C-C', respectively. As shown in Figure 1(c), it consists of a long slot stub l_1 and a short stub l_2 with the same width w_1. It should be noted that etched slots can not only divide these HM cavities into four QM sub-cavities and but also reduce the energy coupling among them. The effects of these slots on port isolation are shown in Figure 2. When slots are removed, S_{21} is as high as $-3.1\,\mathrm{dB}$. As slot length l_1 gradually increases, port isolation between elements 1 and 2 is greatly improved within the frequency of interest while S_{31} keeps high isolation almost unchanged. This simple and effective isolation improvement makes the proposed design attractive for practical applications. Moreover, as shown in Figure 3, the reflection coefficient S_{11} is hardly affected by the ground plane. This is because cavity resonances are utilized in the proposed design, which are primarily determined by cavity size (l_c and w_c). Therefore, a four-element MIMO antenna system with compact size and high isolation is proposed.

To understand the operating principle, the electric-field magnitude distribution of the proposed design is plotted in Figure 4. It can be found that electric field exhibits the same distributions when different ports are excited. Compared with the distribution presented in [10], QM resonances are verified. It is also observed that though these four antenna elements interconnect, incident wave of one element is mainly radiated through opened cavity edges and etched slots into the air and negligible leaked to other

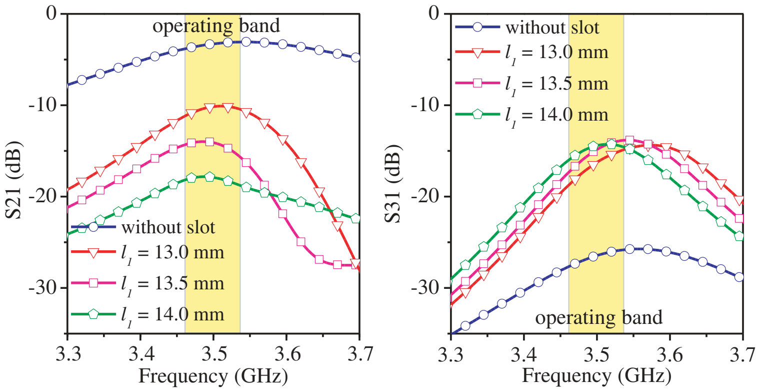


Figure 2. Effects of slot length on port isolation.

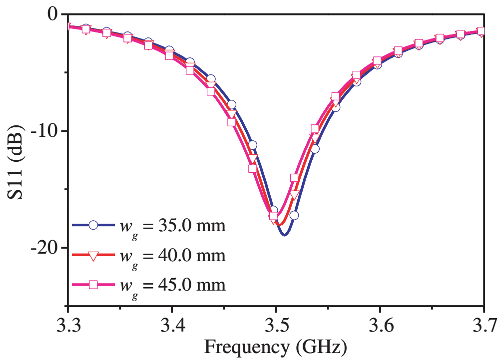


Figure 3. Effects of ground plane on reflection coefficient.

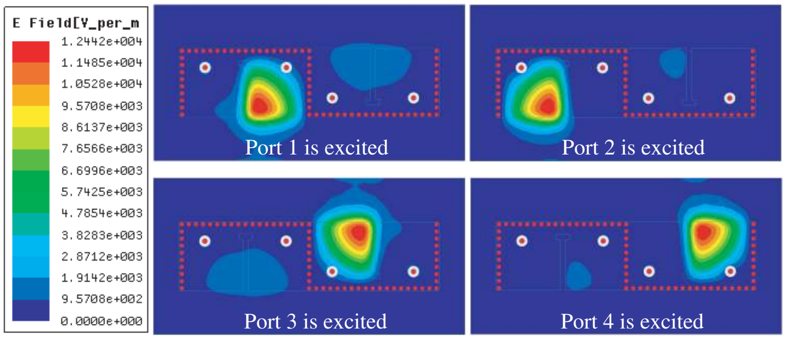


Figure 4. Simulated electric-field magnitude distribution.

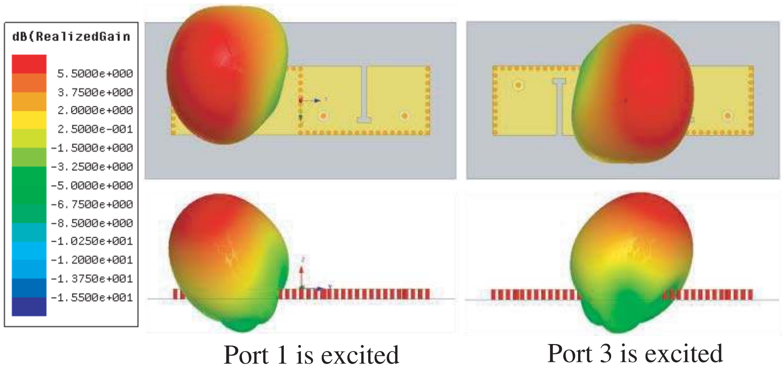


Figure 5. Top and side views of simulated 3-D radiation patterns.

elements. This indicates that high isolation has been achieved. The 3-D radiation patterns of elements 1 and 3 are shown in Figure 5. It can be seen that tilted and unidirectional radiation is obtained owing to the reflection effect of metallic vias. Therefore, angle diversity is confirmed in the proposed design. Detailed geometrical parameters optimized by CST Microwave Studio are $l_g = 90.0\,\mathrm{mm}$, $w_g = 45.0\,\mathrm{mm}$, $l_c = 37.0\,\mathrm{mm}$, $w_c = 18.5\,\mathrm{mm}$, $l_1 = 14.5\,\mathrm{mm}$, $l_2 = 4.3\,\mathrm{mm}$, $w_1 = 1.5\,\mathrm{mm}$, $F_v = 4.5\,\mathrm{mm}$, $F_h = 7.0\,\mathrm{mm}$, $d_1 = 1.4\,\mathrm{mm}$, $d_2 = 3.3\,\mathrm{mm}$, $r = 0.6\,\mathrm{mm}$, and $s = 1.0\,\mathrm{mm}$.

3. EXPERIMENTAL RESULTS

To verify the proposed design, a prototype is fabricated, and 50 Ω SMA connectors are soldered. Figure 6 shows a photo of the fabricated prototype with the cavity size of $0.22\lambda_0 \times 0.86\lambda_0 \times 0.04\lambda_0$. The S-parameters and radiation performance have been experimented by an Agilent vector network analyzer and a Satimo microwave chamber, respectively.

Figure 6. Photo of the fabricated prototype.

The measured S-parameters (color curves) are shown in Figure 7, compared with the simulated ones (grey curves). They are in a decent agreement. Since the reflection coefficients (S_{11}, S_{22}, S_{33}, and S_{44}) differ marginally, only S_{11} is given. The fabricated antenna operates at 3.51 GHz with impedance matching of −15.4 dB. The measured 10-dB bandwidth is 65 MHz, which is slightly less than the simulated value of 75 MHz. Moreover, both the simulated and measured port isolations including S_{21}, S_{31}, and S_{41} are below 14.0 dB, which is suitable for MIMO operations.

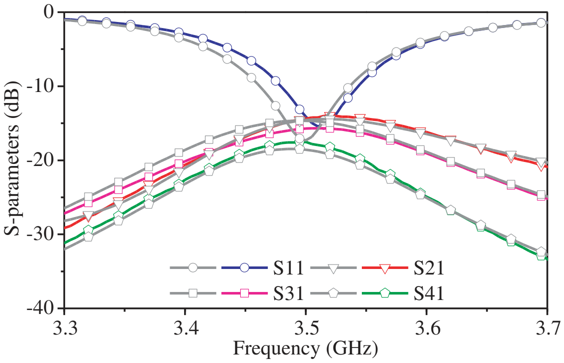


Figure 7. Measured S-parameters compared with simulated results.

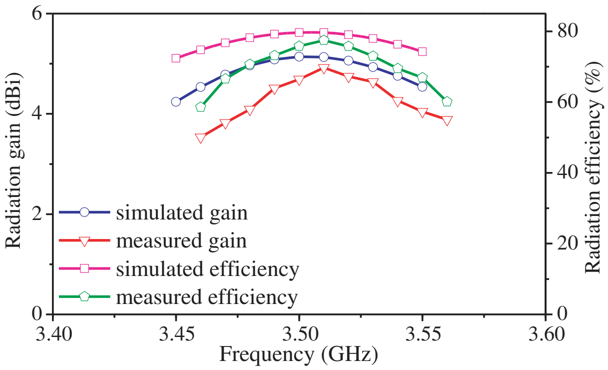
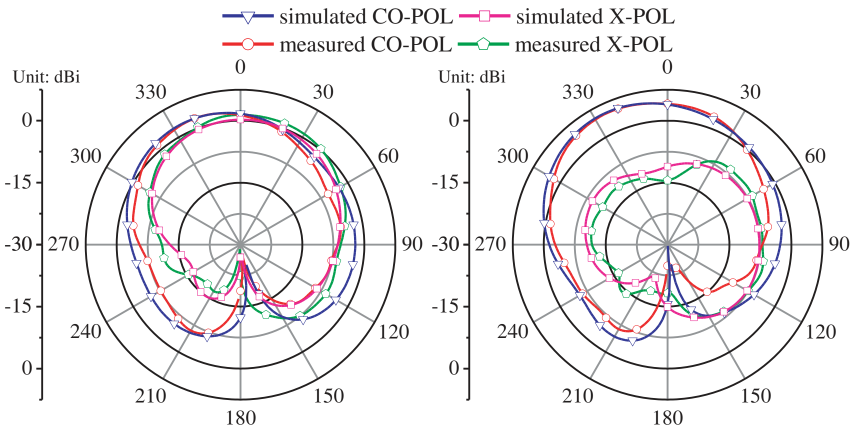


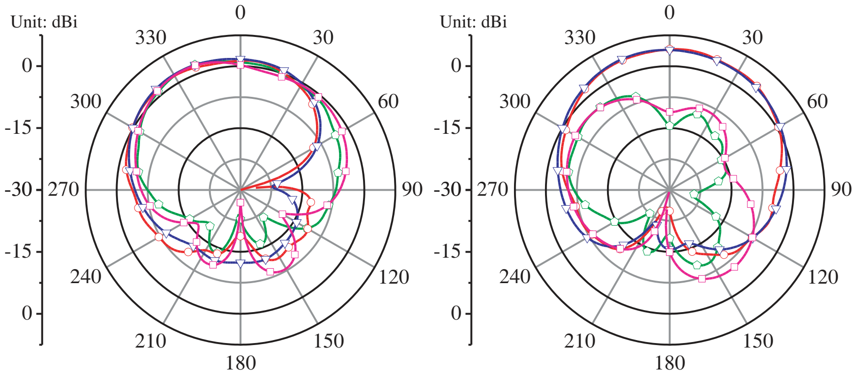
Figure 8. Measured radiation gain and efficiency compared with simulated results.

The simulated and measured antenna gains are shown in Figure 8. Because of the symmetry of the MIMO antenna system, only the result of element 1 is given. The measured peak gain is 4.9 dBi, which is slightly lower than the simulated value about 0.2 dBi. Radiation efficiency has been calculated by measuring total radiation power with the angular sampling interval of 2 deg. Measured maximum efficiency is 77.4%.

The simulated and measured radiation patterns of element 1 at the center frequency of 3.51 GHz are plotted in Figure 9. This antenna element demonstrates tilted and unidirectional patterns in four cut planes. It is also found that cross polarization is quite high in all these planes. Since practical communication channels are generally multipath in indoor scenarios, the proposed antenna system can exploit angle and polarization diversity to achieve good MIMO performance. In order to quantitatively characterize the MIMO performance, the envelope correlation coefficient (ECC) between antenna elements is calculated from radiation patterns [14]. As shown in Figure 10, all simulated (grey



In 0^0-plane In 45^0-plane



In 90^0-plan In 135^0-plane

Figure 9. Measured radiation patterns compared with simulated results.

curves) and measured (color curves) ECCs of the proposed design are below 0.03, which is fairly good for MIMO applications.

The performance of the proposed design is summarized in Table 1. Compared with reported works, the proposed four-element MIMO antenna system has advantages of compact size, low profile, high radiation gain, and low ECCs. Therefore, it is a good candidate for 3.5 GHz-band fifth-generation communication [15].

Table 1. Comparison of the proposed design with reported works.

	Size (λ_0)	Antenna quantity	Frequency (GHz)	Isolation (dB)	Gain (dBi)	ECC
[1]	0.58 × 0.72 × 0.01	2	2.4	20	-	0.005
[4]	0.81 × 1.45 × 0.02	1	5.8	-	3.12	-
[11]	0.34 × 0.61 × 0.02	2	2.4	18	2.9	0.5
			5.5	35	5.0	
[12]	1.20 × 1.20 × 0.11	4	2.4	36	7.1	0.005
[13]	0.41 × 0.41 × 0.04	4	3.5	18.4	2.7	0.08
			5.7	22.7	2.85	
This work	0.22 × 0.86 × 0.04	4	3.51	14.0	4.9	0.03

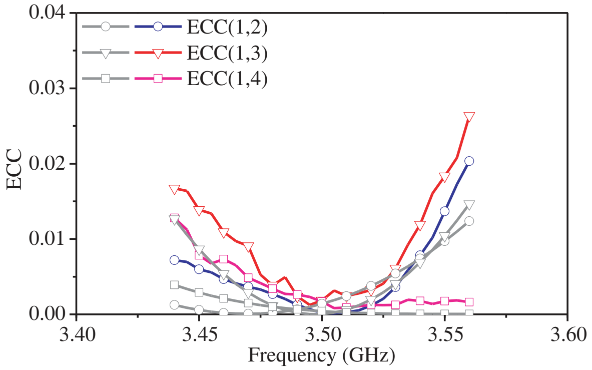


Figure 10. Measured ECCs compared with simulated results.

4. CONCLUSION

A compact four-element MIMO antenna system is presented. It consists of SIW cavities, etched T-shaped slots, and feeding ports. In order to realize compact antenna elements, four QM sub-cavities are constructed. Moreover, the isolation among them is improved by optimizing slot length. The simulated results of the proposed design including S-parameters, radiation performance, and MIMO performance are in a decent agreement with the measured results of a fabricated prototype.

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