# Mutual Coupling Reduction of Compact Four-element MIMO Slot Antennas Using Metamaterial Mushroom Structures

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***Abstract*—In this paper, the mutual coupling reduction of four-element substrate integrated cavity-backed slot (SICBS) antenna system based on two types of metamaterial mushroom structures are studied. In the first case, a double-layer mushroom wall is vertically positioned in between the SICBS antenna elements. In the second design, five double-layer mushroom cells are horizontally positioned above the SICBS antenna elements for mutual coupling suppression. The mushroom structure-loaded four-element SICBS antenna systems achieve ultra-low inter-element mutual coupling of -40 dB over the bandwidth of 2.39–2.45 GHz and 2.386–2.43 GHz (|$S_{11}$|<- 10 dB), respectively.**

***Keywords*—Mutual coupling, metamaterial, mushroom, MIMO, substrate integrated cavity-backed slot (SICBS) antenna***

## I. INTRODUCTION

With the further requirements of larger channel capacity in wireless communication systems, multiple-input multiple-output (MIMO) technology has been integrated into new wireless local area network (WLAN) standard to overcome the shadowing and fading phenomena in multipath environments [1]. The larger mutual coupling degrades the diversity performance, diminishes the radiation efficiency, and lowers the channel capacity [2]. The system capacity can be enhanced by using more antenna elements [3]. WLAN 802.11n and WLAN 802.11ac standards are expected to realize the maximum stream data rate of 600 Mbps and 6.93 Gbps by adopting 4×4 and 8×8 MIMO system, respectively [1]. However, the limited size of the antenna system will result in greater mutual coupling between the closely positioned antenna elements and degrade the performance of the antenna system. Therefore, the reduction of the inter-element coupling is one of the key issues for MIMO antenna systems.

With the promotion of WLAN 802.11n, the four-element antenna system has been greatly focused on; the reported mutual coupling reduction techniques of the four-element antenna system include the adoption of reactive/passive circuits [4], optimization of antenna configurations [5], introduction of metamaterial structures including split ring resonators (SRRs) [6] and planar mushroom [7]. However, with the strong industrial requirement of larger channel capacity for wireless communication system, an ultra high isolation, for example larger than 40 dB, simultaneously for all four antenna elements in a MIMO antenna system becomes a challenge.

Substrate integrated cavity-backed slot (SICBS) antenna has the merits of stable far-filed patterns, low profile, light weight, and easy integration with modern printed wireless communication system [8]. In particularly, the SICBS antenna is with less surface wave excitation and thus suitable to be the antenna element for a MIMO antenna system with ultra-low inter-element coupling.

Owing to the ban-gap characteristics, the mushroom structures can be applied for mutual coupling suppression in two- or four-element antenna systems, [7], [9], in particular, for reduction of the surface-wave coupling. However, such configurations are difficult to achieve ultra-low mutual-coupling when the coupling is mainly attributed to radiated-field instead of the surface-wave.

In this paper, the four-element SICBS antenna systems with two types of mushroom structures are proposed to achieve ultra-low mutual coupling of -40 dB at 2.4 GHz band. First, double-layer mushroom walls are vertically positioned in between the SICBS antenna elements. Second case, the double-layer mushroom structures are horizontally positioned above the four-element SICBS antenna system. For both cases, the isolation of 40 dB can be achieved within the operating band.

## II. FOUR-ELEMENT SICBS ANTENNA SYSTEM

As shown in Fig. 1, a symmetrically distributed SICBS antenna system with the same edge-to-edge distance of $g_1$ between each adjacent element is adopted, wherein each elements is fed by a coaxial probe. The mutual coupling between the adjacent elements along both vertical and horizontal directions is identical, namely |$S_{21}$|=|$S_{32}$|=|$S_{43}$|= |$S_{41}$|. In addition, the mutual coupling between the adjacent elements along the diagonal line is the same as well, namely |$S_{31}$|=|$S_{42}$|. For brevity, only |$S_{11}$|, |$S_{21}$| and |$S_{31}$| are presented in the following section.

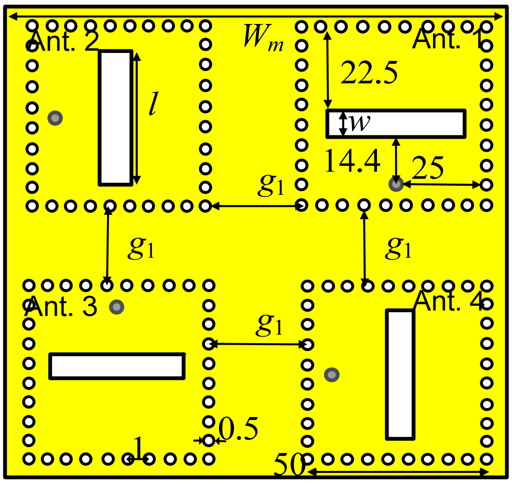


Fig. 1 The geometry of the four-element SICBS antenna system ($w$=6.7, $l$=45.5, $W_m$=150, Unit: mm).

The four-element SICBS antenna system is designed using a piece of the single-layer Rogers 4003C substrate with a thickness of 1.524 mm, $\varepsilon_r$ =3.55 and tanδ = 0.027. The effect of the distance, $g_1$, on the $S$-parameters of the four-element antenna system is illustrated in Fig. 2. When $g_1$=3 mm, $|S_{21}|$<–37 and $|S_{31}|$<-23 dB within the operating band of 2.4–2.45 GHz. Meanwhile, both $|S_{21}|$ and $|S_{31}|$ are increased by about 3 dB as $g_1$ increases from 3 mm to 18 mm.

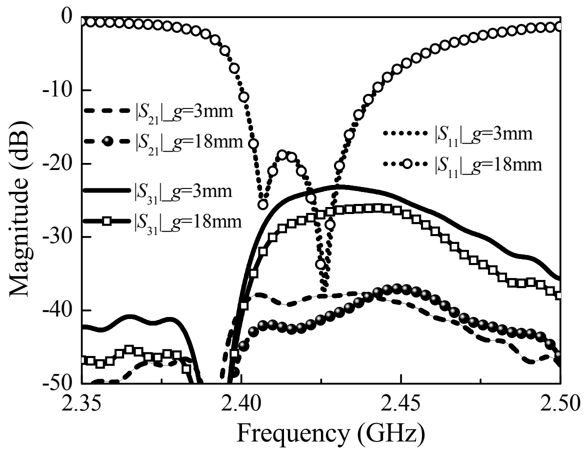


Fig.2. Simulated S-parameters of the antenna system with the variation of $g_1$

## III. FOUR-ELEMENT ANTENNA SYSTEM WITH MUSHROOM WALL

The configuration of the four-element SIW CBS antenna system with mushroom walls is shown in Fig. 3, wherein the two pieces of mushroom walls are symmetrically crossed in between the four CBS antenna elements. The adjacent SIW CBS elements are orthogonally positioned and fed by four coaxial probes, respectively.

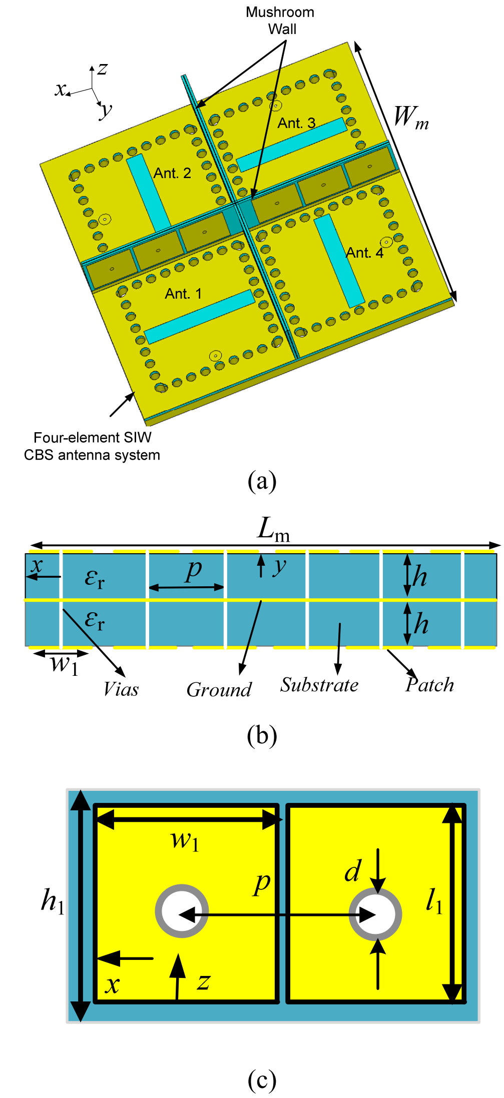


Fig.3. Configuration of the four-element SIW CBS antenna system with mushroom walls; (a) overall view, (b) cross-sectional view of the mushroom wall, and (c) top view of the mushroom wall

TABLE I
DIMENSIONS OF THE FOUR-ELEMENT SIW CBS ANTENNA WITH MUSHROOM WALL (MM)

| | | | | | |
|---|---|---|---|---|---|
| $w_1$ | 17.3 | $l_1$ | 17.4 | $d$ | 1.52 |
| $p$ | 18.06 | $h_1$ | 21 | $h$ | 0.813 |
| $W_m$ | 120 | $L_m$ | 122 | $g$ | 2.8 |
| $w$ | 6.1 | $l$ | 49 | | |

The dimensions of the mushroom wall, comprising 1 × 6 mushroom cells, are listed in Table I. The mushroom wall is fabricated using two piece of Rogers 4003C substrates with a thickness of 0.813 mm each.

The simulated and measured *S*-parameters of the four-element SIW CBS antenna system with mushroom walls is shown in Fig. 4. Because the four identical SIW CBS antenna elements are symmetrically distributed, the reflection coefficient of each element is identical. Thus, only the reflection coefficient of the Antenna Element 1 is presented. It can be seen that the frequency band for the −10-dB reflection coefficient is 2.395–2.45 GHz. In addition, the measured mutual couplings between all the adjacent antenna elements are less than −42 dB over the impedance bandwidth.

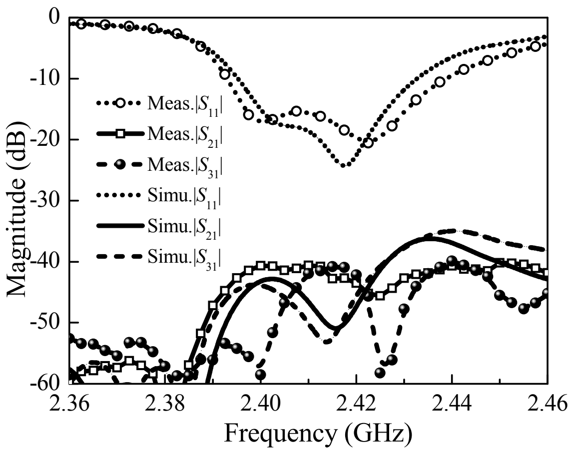


Fig.4. Measure and simulated S-parameters of the four-element SIW CBS antenna system with mushroom walls

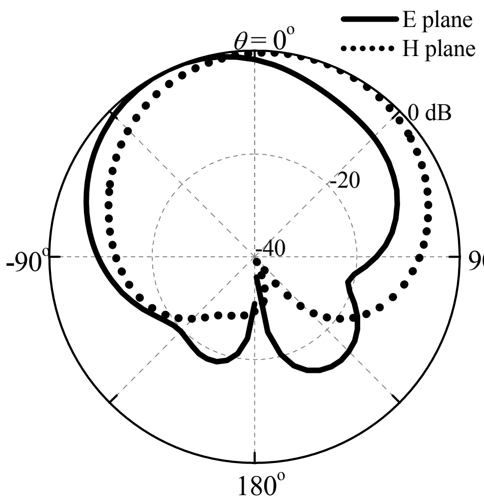


Fig. 5. Simulated radiation patterns of the four-element SIW CBS antenna system with mushroom walls; (Antenna 1@2.42 GHz).

The simulated far-field patterns of the Antenna Element 1 at 2.42 GHz are shown in Figs. 5. The maximum gain of 4 dBi is achieved at 2.42 GHz. The beam squinting is caused by the reflection from the mushroom walls. A beam squinting of 20° from the bore-sight in both *E*- and *H*-planes is observed. It can be seen that within the impedance bandwidth of 2.395–2.45 GHz, the front-to-back ratio is larger than 25 dB.

## IV. FOUR-ELEMENT ANTENNA SYSTEM WITH MUSHROOM CELLS

The configuration of the four-element SICBS antenna system with double-layer mushroom cells is shown in Fig. 6. The adjacent SIW CBS elements are orthogonally positioned and fed by four coaxial probes respectively. The double layered mushroom cells comprises two metallic discs and a post. The post connects the discs and connected to the ground plane. Five double layer mushroom cells are positioned in between the antenna elements wherein one is positioned in the centre and the other four are placed at the left/right and upper/lower sides symmetrically.

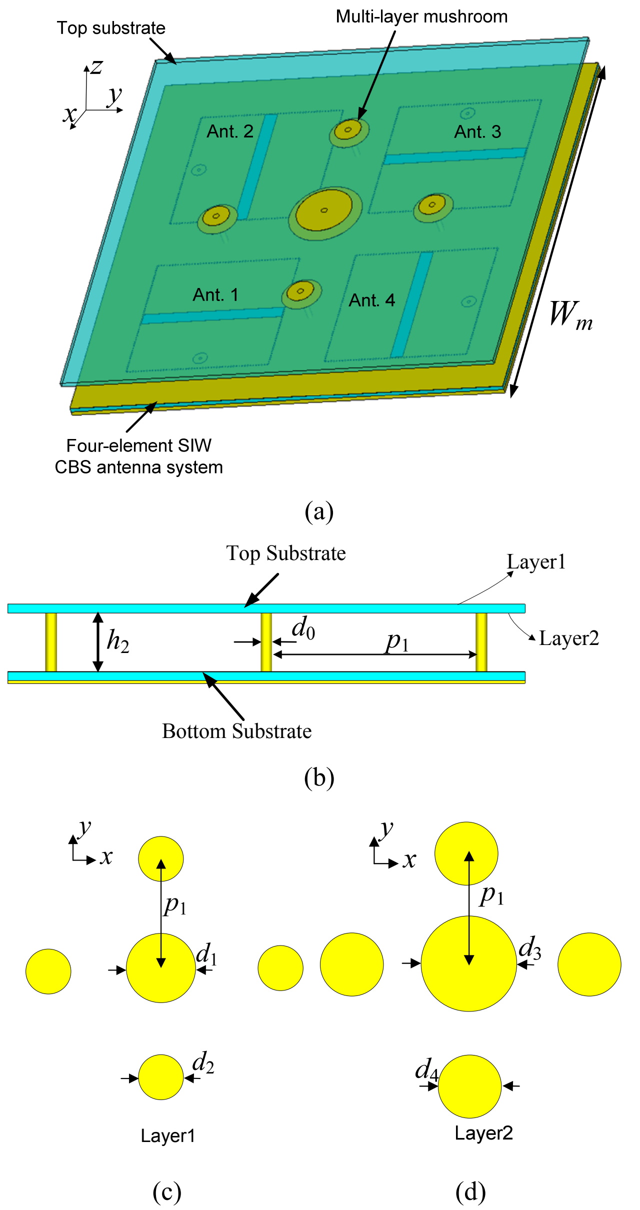


Fig.6. Configuration of the four-element SIW CBS antenna system with double-layer mushroom cells; (a) overall view, (b) cross-sectional view of the antenna system, (c) layer 1 and (d) layer 2.

The circular metallic patches of the mushroom cells are etched on the opposite sides of the top substrate, which is a single-layer Rogers 4003C substrate with a thickness of 1.524 mm, $\varepsilon_r$ =3.55, tanδ = 0.027. The dimensions of the antenna system are tabulated in Table II. The size of the antenna ground is 160 × 160 mm$^2$.

TABLE II
DIMENSIONS OF THE FOUR-ELEMENT SIW CBS ANTENNA WITH FLAT DOUBLE-LAYER MUSHROOM (MM)

| | | | | | |
|---|---|---|---|---|---|
| *w* | 4 | *l* | 48.6 | $d_0$ | 1.8 |
| $p_1$ | 37.4 | *g* | 19 | $d_1$ | 17.2 |
| $d_2$ | 9.2 | $d_3$ | 13.2 | $d_4$ | 14 |

The simulated and measured *S*-parameters of the four-element SICBS antenna system with double-layer mushroom cells are shown in Fig. 7. Similar to the case of the antenna system with a mushroom wall, only the reflection coefficient of the Antenna Element 1 is presented. It can be seen that the frequency band for the -10-dB reflection coefficient is 2.386–2.43 GHz. The mutual couplings between each antenna element are less than -40 dB over the impedance bandwidth.

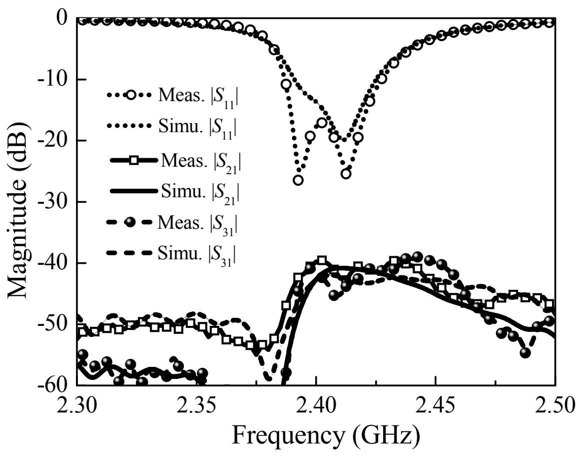


Fig.7. Measure and simulated S-parameters of the antenna system

The simulated far-field patterns of the Antenna Element 1 at 2.4 GHz are shown in Figs. 8. The maximum realized gain of 6.5 dBi is achieved at 2.415 GHz. The front-to-back ratio is larger than 20 dB within the operating bandwidth.

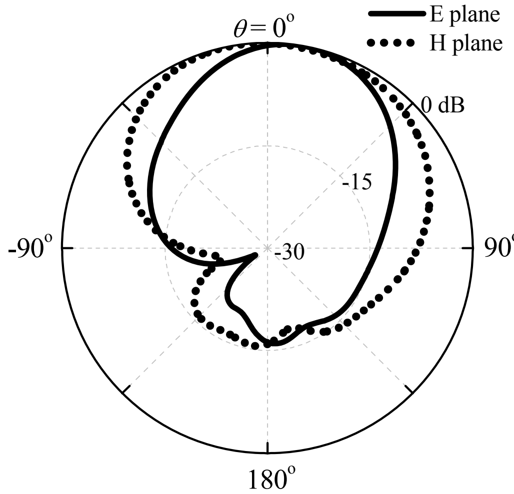


Fig. 8. Simulated radiation patterns of the four-element antenna system (Antenna 1@2.4 GHz).

## V. CONCLUSION

Two types of mushroom structures have been proposed to suppress the mutual coupling of the four-element SICBS antenna system. The mutual couplings of less than –40 dB between each antenna element have been achieved. This technology is promising for antenna design for higher data rate MIMO antenna system.

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