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Bandwidth Enhancement of Low-Profile SIW Cavity Antenna with Bilateral Slots

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Abstract—A novel design to enhance the bandwidth of a low-profile substrate integrated waveguide (SIW) cavity antenna is presented. Distinct from traditional antennas with unilateral slots, bilateral slots are utilized as radiating elements in the proposed design. By etching an additional slot at the bottom plane, a new resonant mode is introduced, and quality factors of two original modes are significantly reduced. Antenna's bandwidth can be dramatically enhanced by merging these three modes within a single operating band. A prototype is fabricated and measured. With the height of $0.018\lambda_0$, the measured 10-dB bandwidth is 410 MHz (3.24–3.65 GHz), corresponding to 11.9% fractional bandwidth. The measured gain is higher than 4.3 dBi, and the measured efficiency is around 75% within the operation band. Those attractive features, e.g., low profile, enhanced bandwidth and moderate radiation performance, make the proposed antenna suitable for future 5G systems.

1. INTRODUCTION

Low-profile antennas with wide bandwidth and good radiation are in great demand for modern wireless communications [1, 2]. Cavity antennas based on the substrate integrated waveguide (SIW) technique have attracted increasing attention, which exhibit some outstanding advantages, such as low cost, convenient integration, and surface wave suppression [3]. However, due to low profile and high quality factor (Q-factor), conventional SIW cavity antennas usually suffer from narrow bandwidth, restricting their practical applications [4].

Recently, some solutions aimed at enhancing the bandwidth of cavity antennas have been investigated [5–16]. In [5], a SIW cavity antenna with a unilateral slot was reported, in which one cavity mode was excited by a probe feeding and energy was radiated from the etched slot. However, the fractional bandwidth (FBW) was only 1.45%. A compact cavity antenna with unilateral ramp-shaped slots was also designed in [6]. In [7], a method of substrate removal under the radiating slot was proposed, where antenna's bandwidth was enhanced to 2.16%. However, the bandwidth enhancement is limited due to single mode excitation.

Increasing the substrate thickness is a simple and effective solution to improve the impedance bandwidth [8–11]. Two-layer stacked SIW patch antenna fabricated by using printed circuit board (PCB) process was discussed in [8]. According to the similar technique, a cavity E-shape patch antenna was investigated in [9], whose bandwidth was up to 10.9%. However, multi-layer and thick substrates undoubtedly increase the fabrication cost.

The other method to enhance antenna's bandwidth is to merge multiple resonant modes in a single passband [12–16]. In [12], a unilateral non-resonant slot was utilized as the radiating element, which effectively excited two hybrid cavity modes. By adjusting these two resonating modes close to each other, the impedance bandwidth was enhanced to 6.3%. A cavity antenna with a bow-tie slot is also

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proposed in [13]. A probe-fed cavity antenna with two unilateral radiating slots was investigated in [14]. Though the bandwidth was extended, circularly polarized radiations were achieved.

In this letter, two bilateral slots are utilized to enhance the bandwidth of low-profile SIW cavity antenna. A short slot and long slot are etched on the top and bottom plane of the cavity, respectively. Q-factors of two original modes are significantly reduced and a new mode is introduced in the proposed design. By merging these three modes within an operating band, the operating bandwidth of the proposed antenna is dramatically enhanced. With the height of $0.018\lambda_0$, a fabricated prototype achieves a 10-dB bandwidth of 410 MHz (3.24–3.65 GHz, 11.9% FBW). The measured radiation pattern, antenna gain, and efficiency verify good radiation characteristics of the proposed design.

2. ANTENNA DESIGN

2.1. Antenna Configuration

The geometry of the proposed antenna is shown in Figure 1. A SIW cavity ($L \times W$) is formed by using metalized vias at a F4B-2 substrate with a permittivity of 2.5 and thickness of 1.57 mm. Served as radiating elements, a short slot ($ls_1 \times ws_1$) is etched on the top plane with a distance ds_1 from the lower sidewall of the cavity and a long slot ($ls_2 \times ws_1$) is etched on the bottom plane with a distance ds_2 from the upper sidewall of the cavity. It is noteworthy that there is an overlap between these two slots to obtain good radiation patterns. The antenna is fed by a SMA connector, where its outer conductor (r_2) and center pin (r_3) are connected to the top and bottom of the cavity, respectively.

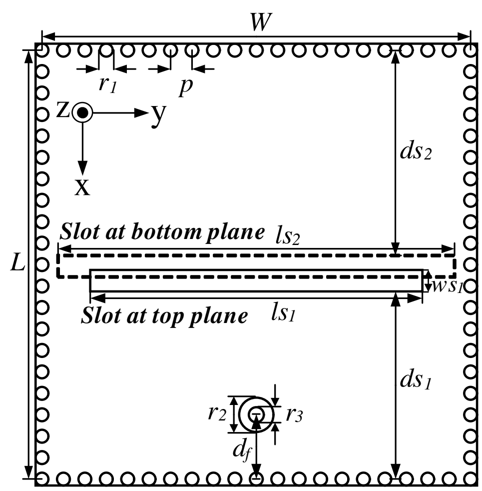

Figure 1. Geometry of the proposed SIW cavity antenna with bilateral slots.

2.2. Working Mechanism

Distinct from a reference antenna with a single unilateral slot as shown in Figure 2, bilateral slots are utilized in the proposed design. Simulated $|S_{11}|$s are carried out by using Ansys HFSS. By observing the blue triangle curve, the reference antenna has two narrow passbands with about 0.98% FBW. These limited bandwidths are mainly due to the antenna's low profile ($0.018\lambda_0$), which generally results in high Q-factors of cavity modes. This is the inherent drawback of low-profile SIW cavity antennas [4]. In order to enhance the bandwidth, an additional slot is introduced on the bottom plane of the cavity. As can be seen, Q-factors of the two original modes are significantly reduced and a new mode is also excited in the SIW cavity. The operation bandwidth of the proposed antenna is dramatically enhanced, which is 450 MHz bandwidth (3.24–3.69 GHz, 12.98% FBW). Under the condition of the same cavity's height, an about 12 times wider bandwidth is achieved by the proposed technique.

Within the matched frequency range, there are three modes in the SIW cavity. To investigate the working mechanism of the proposed antenna, the field distributions are shown in Figure 3. From

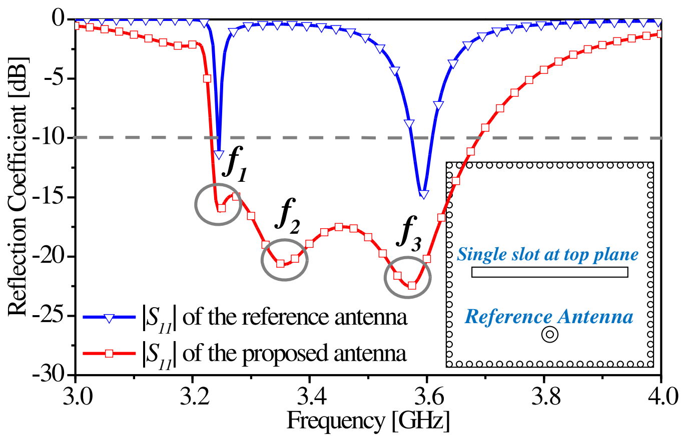

Figure 2. Simulated $|S_{11}|$s of the reference antenna and proposed antenna. ($L = W = 41.8$, $ds_1 = 18.6$, $ds_2 = 20.3$, $ls_1 = 33$, $ls_2 = 39$, $ws_1 = 1.5$, $df = 8.4$, $r_1 = 0.6$, $r_2 = 3.2$, $r_3 = 1.4$, $p = 1$, all in the unit of millimeters).

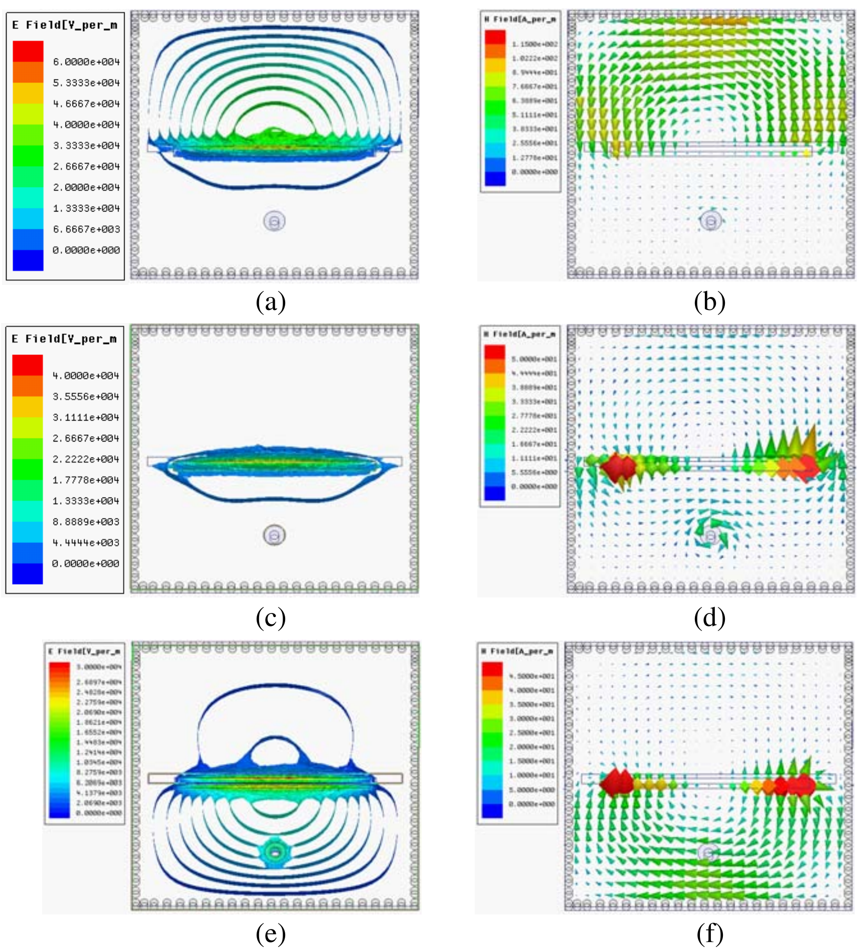

Figure 3. Field distributions in the SIW cavity. (a) E-field scalar and (b) H-field vector distributions at $f_1 = 3.25$ GHz; (c) E-field scalar and (d) H-field vector distributions at $f_2 = 3.35$ GHz; (e) E-field scalar and (f) H-field vector distributions at $f_3 = 3.57$ GHz.

Figures 3(a) and (b), it can be found that dominant E- and H-fields are distributing in the upper half cavity part with very weak field density in the lower half cavity part. Thus, a half mode is excited in the SIW cavity at $f_1 = 3.25\,\text{GHz}$. As also can be seen in Figures 3(e) and (f), the dominant E- and H-fields are located only in the lower half cavity part. Thus, another half mode is excited in the SIW cavity at $f_3 = 3.57\,\text{GHz}$. By observing the field distributions plotted in Figures 3(e) and (f), the E-field is concentrating in the overlap region of the two slots and the dominant H-field is distributing in their ends. Because of the difference in magnitude and phase of the field at the opposite sides of these two slots, electromagnetic wave can be radiated into free space at $f_2 = 3.35\,\text{GHz}$.

2.3. Parameter Study

The ds_1 and ds_2 characterize the lengths of the lower and upper half cavities, and their effects on the frequency response of the proposed antenna are shown in Figures 4 and 5. As the ds_1 increases, the resonating size of the lower half cavity mode is enlarged. The resonant frequencies f_3 are decreasing evidently and the frequencies of the other two modes are almost constant. Thus, the upper frequency boundary of operating bandwidth is correspondingly reduced while the lower frequency boundary remains unchanged. Similarly, the resonant frequencies f_1 is decreased gradually and the lower frequency boundary of operating bandwidth is correspondingly reduced when the ds_2 increases from 20.1 to 20.3 mm, as shown in Figure 5. From these parametric studies, we can conclude that these two half modes inside the SIW cavity can be independently adjusted, which offers high design freedom on the operating frequency range of the proposed antenna.

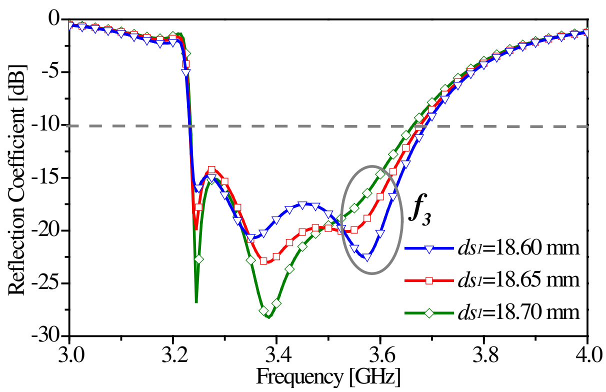

Figure 4. $|S_{11}|$ with different ds_1.

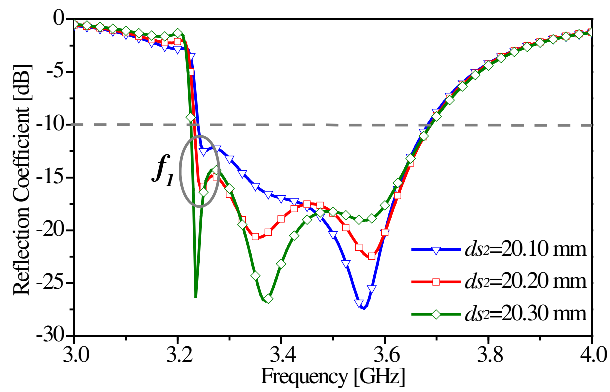

Figure 5. $|S_{11}|$ with different ds_2.

Since the bottom slot excites an additional mode at f_2, its length ls_2 has notable effects on this frequency. From Figure 6, it can be observed that the f_2 is in inverse proportion to the ls_2. As the ls_2 increases from 38 to 39 mm, the f_2 decreases from 3.43 to 3.35 GHz while the other two frequencies are almost unchanged. Moreover, the improvement of impedance matching at f_1 is noticed with the decrease of f_2. In fact, by properly adjusting the frequency interval of multiple modes, the tri-resonant wideband antennas can be achieved.

After the frequencies of the three resonance modes are determined, the input impedance of the antenna can be matched to $50\,\Omega$ by moving the feeding location d_f. As can be observed in Figure 7, the operating frequency of the proposed antenna is hardly changed by variation of the d_f, but its impedance matching is evidently affected. When $d_f = 8.4\,\text{mm}$, good impedance matching is obtained and the reflection coefficients are better than $-14\,\text{dB}$. The optimized parameters are shown in the inset of Figure 1.

3. RESULTS AND DISCUSSION

To verify the proposed design, a prototype of the antenna was fabricated. Photographs of its top and bottom views are shown in Figure 8. In terms of the free-space wavelength of 3.45 GHz, the total size

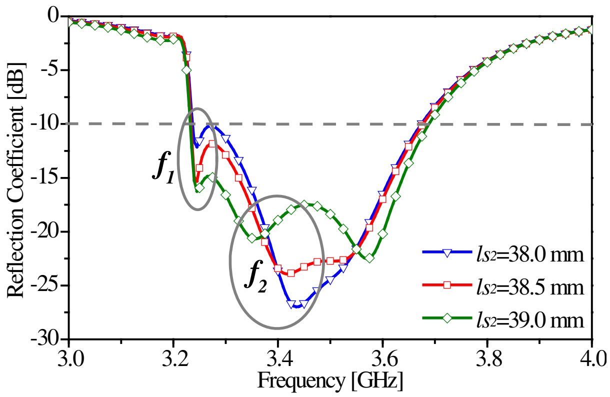

Figure 6. $|S_{11}|$ with different ls_2.

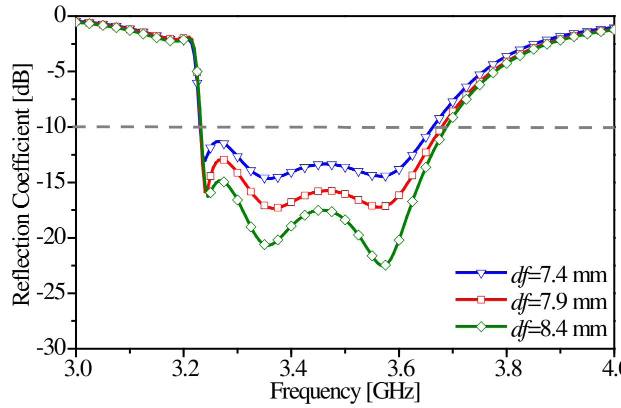

Figure 7. $|S_{11}|$ with different d_f.

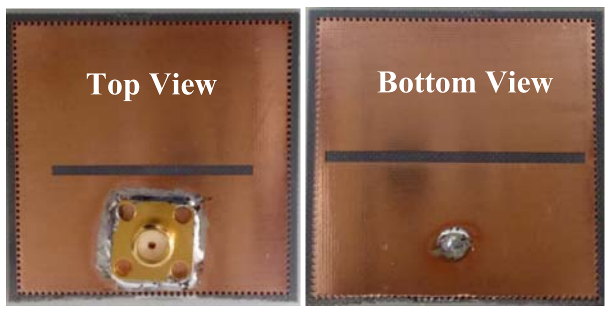

Figure 8. Photograph of the top and bottom views of the fabricated antenna.

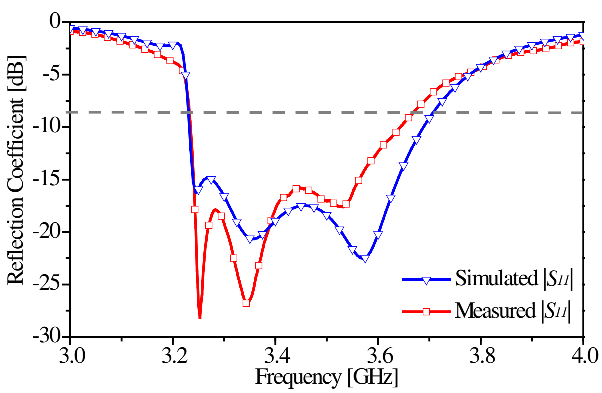

Figure 9. Measured $|S_{11}|$.

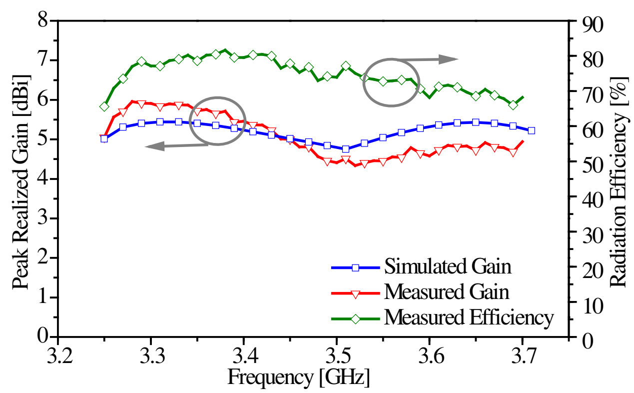

Figure 10. Measured gain and efficiency.

of the antenna is $0.48\lambda_0 \times 0.48\lambda_0 \times 0.018\lambda_0$.

The reflection coefficient of the fabricated antenna has been measured by an Agilent E5071C network analyzer. As shown in Figure 9, the simulated and measured $|S_{11}|$s are in a good agreement and the slight difference between these results is mainly contributed from the soldered SMA connector. It can be observed that three modes are clearly excited, which are merged into a wide operating band. The measured 10-dB bandwidth of the fabricated antenna is 410 MHz (3.24–3.65 GHz, 11.9% FBW), which is close to the simulated bandwidth of 450 MHz.

Radiation performance of the proposed antenna has been measured in a Satimo microwave chamber. The radiation efficiency is calculated by the total radiation power over the input power [17]. The measured antenna gain and radiation efficiency are shown in Figure 10. Although these are some

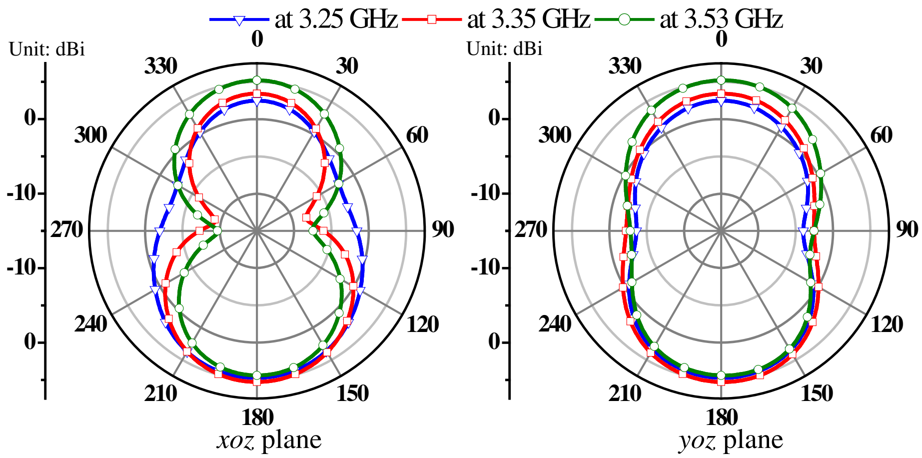

Figure 11. Total-gain radiation patterns at three frequencies.

differences between the measured and the simulated results, the proposed antenna has a gain of higher than 4.3 dBi and keeps efficiency around 75% within the operating band. Total-gain radiation patterns at the *xoz* plane and *yoz* plane are shown in Figure 11. Bi-directional radiation patterns are observed at these three frequencies. Owing to bilateral slots etched on the SIW cavity, the proposed antenna exhibits good bidirectional radiations.

A comparison among the proposed antenna and the reported antennas is listed in Table 1. Our proposed antenna has the widest fractional bandwidth among those reported works. Besides enhanced bandwidth, the proposed antenna has advantages of low profile, compact size, and moderate gain. Therefore, it is a promising candidate for the fifth generation (5G) wireless communication systems [18, 19].

Table 1. Performance comparisons of the proposed and reference antennas.

Reference	This work	[5]	[7]	[12]	[13]	[14]
Frequency (GHz)	3.45	2.42	2.45	10	10	10
Cavity size (λ_0)	$0.48 \times 0.48 \times 0.018$	$0.41 \times 0.41 \times 0.012$	$0.37 \times 0.45 \times 0.016$	$0.41 \times 0.59 \times 0.017$	$0.53 \times 0.59 \times 0.026$	$0.53 \times 0.53 \times 0.052$
Slot's characteristic	Two, bilateral	One, unilateral	One, unilateral	One, unilateral	One, unilateral	Two, unilateral
No. of resonance	Three	One	One	Two	Two	Three
FBW (%)	11.9	1.45	2.16	6.3	9.43	10.8
Gain (dBi)	4.3	5.1	-	6.0	3.7	4.4

4. CONCLUSION

A method for enhancing the bandwidth of the SIW cavity antenna is demonstrated. The design with bilateral slots is adopted, where a short slot is etched on the top plane of the cavity, and a long slot is etched on the bottom plane. Merging with the original two half cavity modes and new generated mode, the operation bandwidth of the proposed antenna is dramatically enhanced. A fabricated prototype centered at 3.45 GHz is measured. The proposed antenna with bilateral slots has more than 12 times of impedance bandwidth than the conventional antenna with a single unilateral slot. With low profile, enhanced bandwidth, and good radiation, the proposed antenna has potential applications in modern wireless systems.

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