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Design of half-mode substrate integrated cavity inspired dual-band antenna

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Abstract

A novel and compact design of dual-band antenna, based on substrate integrated cavity is developed. The antenna comprises a half-mode cavity, an open-ended longitudinal slot, and a printed inset-feed mechanism. Finally, the proposed design is fabricated and its results are validated. It shows the measured impedance bandwidths of 3.51% and 1.40% at 8.8 and 11.2 GHz, respectively. Their corresponding peak gain values of 5.04 and 5.01 dBi. The results of the fabricated antenna in terms of bandwidth, gain, and radiation patterns are in close agreement with their simulated counterparts. On the account cavity-backed design, the antenna exhibits unidirectional and stable radiation patterns in both bands. Moreover, the uniplanar design gives additional flexibility of easy integration with other active/passive circuits. The proposed antenna can be a suitable candidate for dual-frequency operation in X-band (8-12 GHz), especially where small frequency-ratio is stringent.

1 | INTRODUCTION

The concept, substrate integrated waveguide (SIW) has emerged as a substitute to the prevailing convention version of metallic waveguides. The SIW has the proficiency to integrate the topographies of existing printed-circuit-boards (PCBs) and 3D metallic waveguide technologies.[1,2] The SIW-based structure can be fabricated by using uniplanar circuit printing technology. In the last decade, SIW has been established as a promising candidate for designing microwave and millimeter-wave antennas that uphold the conflicting properties: reduction in installation space, high gain, low-insertion loss, and ease of planar integration. The SIW-based antennas are presented in References 3-6, offer single-band frequency property. To attain dual-frequency operation into the SIW slot antenna, many efficient types of research have been performed.[7-10] In these designs, dual-frequency property has realized by using complicated slots or active components. Furthermore, SIW-based dual-frequency cavity-backed slot antennas have been suggested.[11-13] Dual-frequency operation has realized using different cavity modes and their distinct frequency band tuning is interdependent. Moreover, large footprints of full-mode SIW cavity-based antennas limit their potential applications in critical areas. Modern mobile communication or radar systems need more compact dual-frequency antennas. Size-reduced SIW cavity antennas have been presented in References 14-16 using half-mode (HM) and quarter-mode (QM) counterpart of the full SIW cavity, where the total size of the cavity reduced around 50% and 75%, respectively. To the best of authors' knowledge, very limited efforts have been made so far to implement HM SIW cavity-backed multifrequency antennas. Multiband HMSIW cavity with loaded U-shaped strips has been introduced in Reference 17. Due to these strips, the overall size of these antennas has been enlarged by 50%. It is very thought provoking to realize high and stable radiation performance in both frequency bands with a common radiator, especially when the small frequency-

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ratio is stringent. Moreover, it is very challenging to design miniaturized antennas, as the gain and bandwidth of the antenna is frequency and size-dependent.

To this end, a study of an HM substrate integrated cavity inspired dual-frequency antenna is presented for dual-band applications. The antenna uses an open-ended longitudinal slot as a radiator and a couple of metallic vias around it. These vias play a critical role in impedance matching and independent frequency band tuning. Owing to HM cavity topology, the antenna possesses compact size with a simple inset-feed mechanism. Finally, the design is fabricated using the PCB technique. Simulated results are confirmed with the measured ones. Moreover, the overall performance of the antenna is comparable to the conventional full-mode SIW-based designs.

2 | ANTENNA CONFIGURATION AND DESIGN PROCESS

SIW structure has a dielectric substrate with copper laminates on top and bottom, which forms the broad walls while the rows of embedded metallic vias act as lateral/side-walls of the equivalent conventional waveguide. To avoid the energy leakage-loss from the gaps between the vias, the condition given in Reference 18 must be satisfied. The electric field distributions of full SIW and HMSIW cavity resonators, operating in the fundamental TE_{110} mode are shown in Figure 1A and it can be estimated by Equation (1).[19]

$$f_r = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1}{W_{\text{eff}}}\right)^2 + \left(\frac{1}{L_{\text{eff}}}\right)^2}, \tag{1}$$

where,

$$L_{\text{eff}}\, or\, W_{\text{eff}} = W\, or\, L - 1.08\frac{d^2}{p}, \tag{2}$$

L and W are the physical dimensions of SIW cavity, d is diameter and p the pitch distance of the vias. The resonant frequency would depend on the different combinations of the dimension W and L.

Essentially, HMSIW counterpart was obtained by cutting the SIW along the magnetic-wall,[20] as denoted by $o - o'$. HMSIW upholds a similar field distribution with half in magnitude or size. The geometry of the proposed single-layered HMSIW antenna is shown in Figure 1B. It consists of an HMSIW cavity resonator with an open-ended slot and a pair vias are loaded in the vicinity of the broadside of the slot. The antenna radiates into the air through the slot and opened aperture of the HM cavity when it is excited by a simple inset-feed mechanism of the characteristic impedance of 50 Ω. The initial dimensions of the SIW cavity resonator have been determined from the center frequency of X-band (8-12 GHz) and the cutoff frequency 6.3 GHz of the TE_{10} mode.[14]

Conventionally, the HMSIW cavity introduces a single resonant frequency. To extend the antenna capability to dual-band, the proposed longitudinal slot is carved on the top of the cavity. This slot divides HMSIW into two halves (QMSIW-like resonators) and introduces the hybrid modes in the vicinity of the primary resonant frequency. Furthermore, these resonant frequencies are tuned with the help of the loaded vias, namely, v_1 and v_2 as shown in Figure 1. The design process of the antenna begins with an HMSIW resonator (case_A), followed by an open-ended longitudinal slot-loaded HMSIW (case_B).

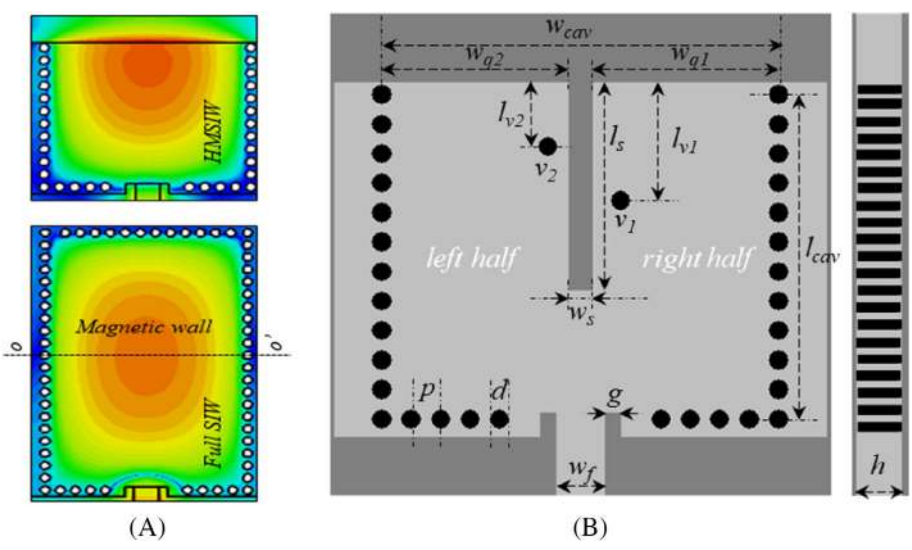

FIGURE 1 The design concept. A, The electric field of full SIW and HMSIW cavity resonator at dominant TE_{110} mode and. B, Design's front and lateral view. ([in mm]: $l_{cav} = 19.27$, $w_{cav} = 20.2$, $w_{q1} = w_{q2} = 9.45$, $P = 1.5$, $d = 1.0$, $w_s = 1.3$, $l_s = 10.6$, $l_{v1} = 6.0$, $l_{v2} = 3.25$, $w_f = 2.4$, $g = 0.9$, $h = 0.787$). HM, half-mode; SIW, substrate integrated waveguide

As this slot divides the cavity and perturbs the field distribution of TE_{10} mode, which generates hybrid modes the vicinity of its primary resonant frequency. The resonances due to the hybrid modes tuned with the help of vias v_1 and v_2 at the lower frequency (f_L) and higher frequency (f_H) bands, respectively (case_C). A detailed study about such hybrid mode generation is investigated in Reference 11. The antenna performance at the design evolution stages is shown in Figure 2. Finally, the proposed dual-frequency antenna operates in bands of f_L of 8.67 to 8.98 GHz and f_H of 11.15 to 11.32 GHz. The radiation mechanism of the antenna has been explained with the help of absolute electric field distributions the resonant frequencies. As Figure 3A shows the field distribution at the f_L. It can be observed that the right half of HMSIW cavity is predominant in contributing radiation through an open aperture. The two resonances are appearing in lower frequency band is due to two nearby degenerate modes and are differing in the magnitude and phase. Similarly, at f_H only the left half of the cavity contributes to the radiation (Figure 3B). Thus, the antenna independently radiates into the free space via dedicated aperture of the cavity when operates in the lower and higher-frequency band, respectively. Moreover, the radiating aperture's length is around the half-wavelength at the corresponding resonant frequency and can be controlled by changing the locations of the v_1 and v_2. The antenna design has been optimized by using a CST electromagnetic simulator. Finally, optimized antenna parameters are denoted in Figure 1.

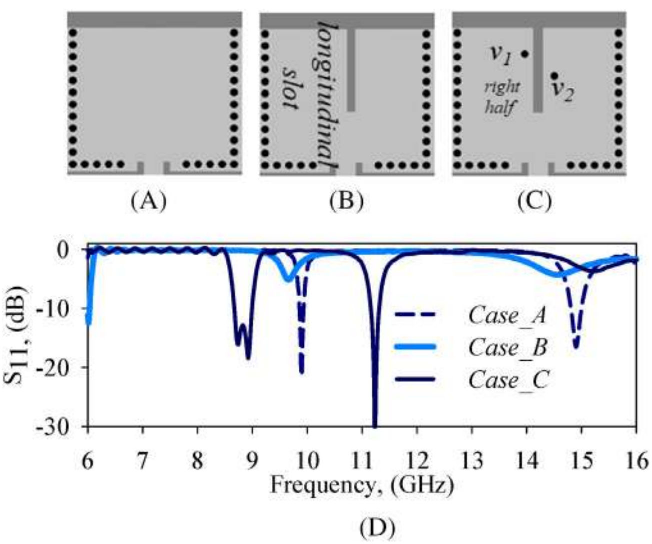

FIGURE 2 A, HMSIW cavity (case_A). B, HMSIW with a longitudinal slot (case_B). C, Proposed design with loaded vias (case_C). D, Performance at antenna evolution stages. HM, half-mode; SIW, substrate integrated waveguide

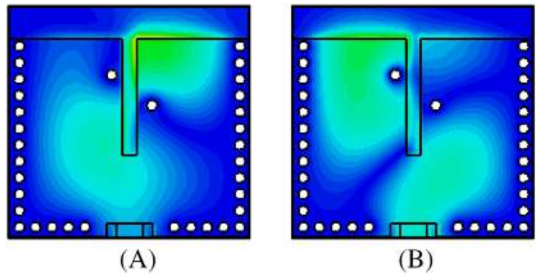

FIGURE 3 Absolute electric field on the top metallic layer at the frequencies. A, 8.92 GHz and B, 11.24 GHz

The characteristic impedance of the HMSIW antenna is very sensitive to these loaded-vias. The locations of the vias have optimized to excite the antenna for dual-frequency operation. For better understanding, a parametric study of locations of v_1 and v_2 is shown in Figure 4. The impedance matching at the f_L and f_H can be achieved by tuning the parameters l_{v1} and l_{v2}, respectively. Furthermore, resonant frequencies f_L and f_H of the antenna can be shifted by changing the parameters w_{q1} and w_{q2} respectively as shown in Figure 5. Thus, antenna gives a degree of freedom to tune the resonant frequency without affecting the other band, except a slight impedance mismatch. Moreover, this design topology reduces the size of antenna overall significantly while maintaining reliable performance.

A brief design guideline for the proposed antenna is suggested as: (i) Design HMSIW cavity resonator with a resonant frequency is average required f_L and f_H; (ii) Insert an proposed slot in the middle of the cavity; (iii) Load the vias v_1 and v_2 and adjust their locations for impedance matching; (iv) Vary the length (w_{q1}, w_{q2}, l_s) for desired f_L and f_H; (v) Retune the location of v_1 and v_2 to attain better impedance matching.

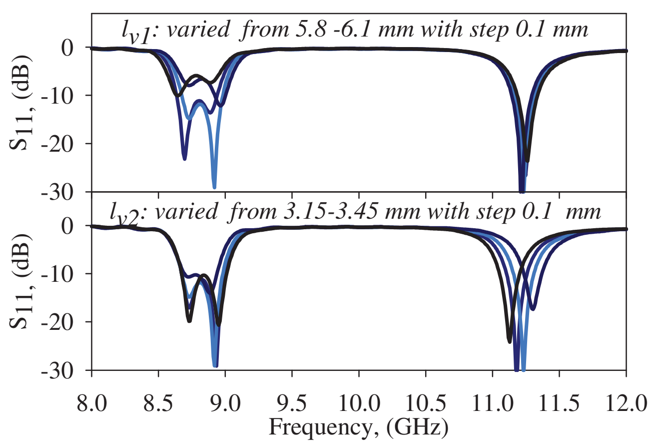

FIGURE 4 The antenna performance with change in parameters l_{v1} and l_{v2}

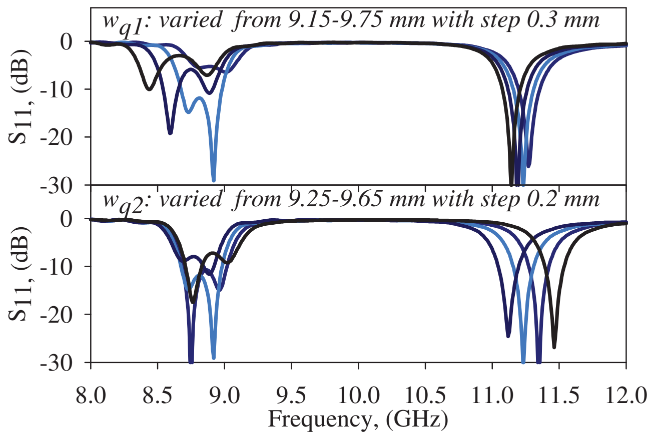

FIGURE 5 The antenna performance with change in parameters w_{q1} and w_{q2}

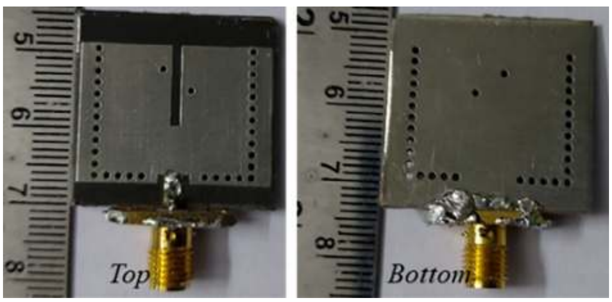

FIGURE 6 The fabricated sample

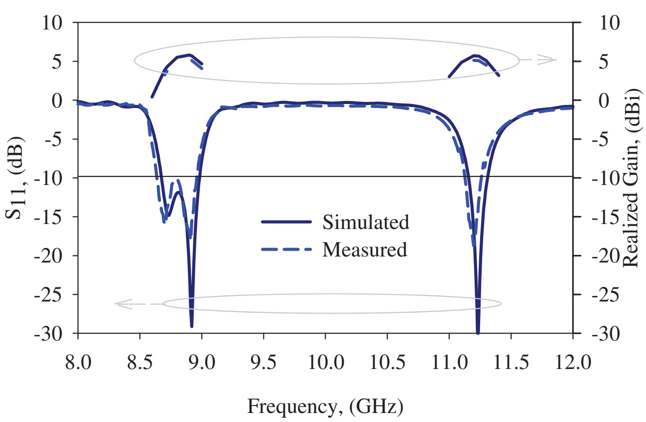

FIGURE 7 The dual-band antenna performance: S_{11} and realized gains

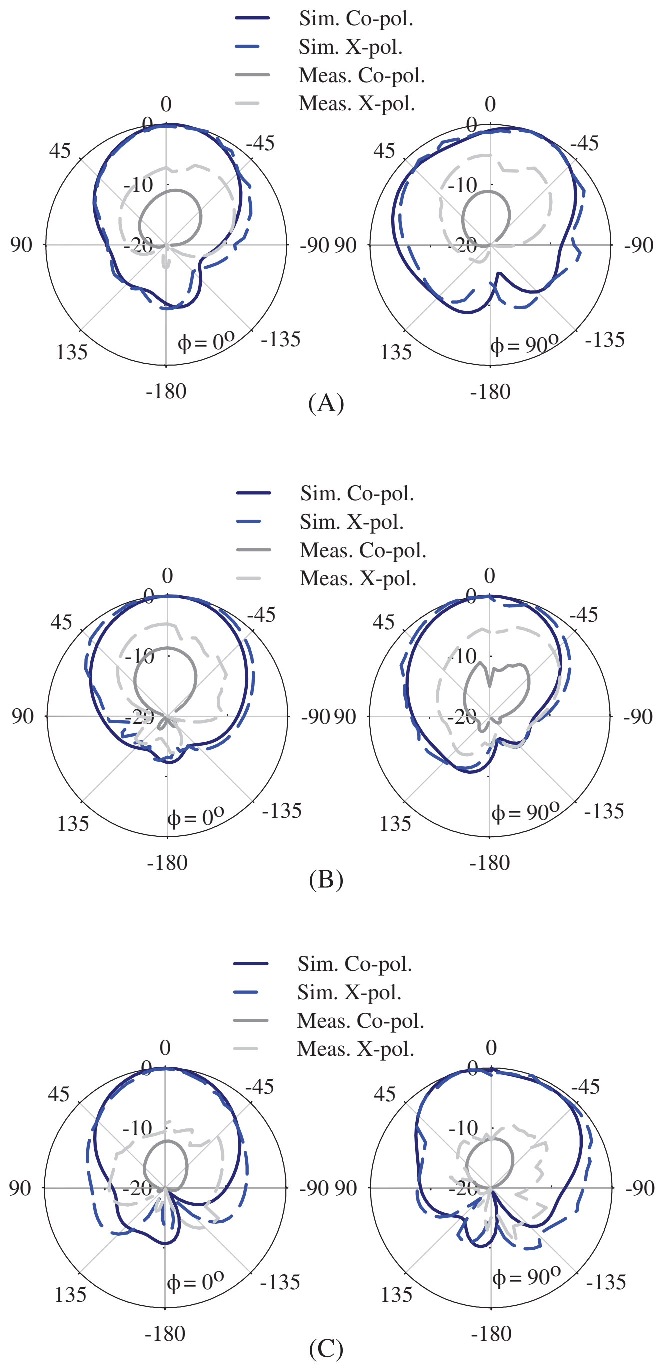

FIGURE 8 The radiation patterns at frequencies of A, 8.72, B, 8.92 and C, 11.25 GHz in two principle cut planes

3 | RESULTS AND DISCUSSIONS

Figure 6 shows the fabricated antenna structure. The antenna structure has been fabricated by using cost-efficient single-layered Rogers RT/Duroid – 5880 ($DK = 2.20 + - 0.02$) with electro-deposited copper circuitry of thickness of 0.035 mm. The antenna is excited by SMA connector and its performance is examined with the help of Anritsu (Shock-Line MS46122B series) vector network analyzers (VNA). Simulated and measured $|S_{11}|$ of the antenna is plotted in Figure 7. It reveals that the antenna shows two distinct frequency bands, a lower frequency band around 8.8 GHz and a higher frequency band around 11.2 GHz. The measured impedance

TABLE I Proposed design versus reported SIW cavity antennas

Properties		Here, $f_L = 8.8\, f_H = 11.3$	[9] $f_L = 9.5\, f_H = 10.5$	[11] $f_L = 8.6\, f_H = 13.3$	[12] $f_L = 25.3\, f_H = 30.7$	[17] $f_L = 4.6\, f_H = 5.5$
Thickness (h) (mm)		0.787 0.031λ_o	0.50 0.023λ_o	1.57 0.031λ_o	0.245 0.030λ_o	1.575 0.035λ_o
Permittivity		2.2	2.2	2.2	2.2	2.2
Gain (dBi)	f_L	5.3	5.5	5.1	6	5.1
	f_H	4.3	5.5	6.3	6	5.5
FTBR (dB)	f_L	14	20.8	<10	n.a.	15
	f_H	16	18.1	<10	n.a.	16
BW (%)	f_L	2.0	1.8	2.3	< 0.4	1.9
	f_H	1.4	2.1	6	< 0.4	0.3
[a]Size (λ_o^2) (including feeding network)		0.65 × 0.60	0.92 × 0.78	0.8 × 0.9	2.3 × 0.5	1.2 × 0.61 Approx
FR(f_H /f_L)		1.2	1.3	1.5	1.2	1.2
Feeding technique/ cavity-type		MSL/HMSIW	MSL/full SIW	MSL/full SIW	MSL/full SIW	MSL/HMSIW
Rad. patterns		Unidirectional				

Abbreviations: HM, half-mode; SIW, substrate integrated waveguide.
[a]λ_o: wavelength at the lowest resonant frequency; na: not available.

bandwidths (−10 dB) at lower and higher frequency bands are 315 MHz (3.5%) and 162 MHz (1.4%), respectively. It can be witnessed that the simulated and measured $|S_{11}|$ is in nearby. The bandwidth of the antenna can be further improved by increasing the thickness of the substrate. A comparative study of the simulated and measured gain of the antenna is also presented in Figure 7. The measured peak gain of the antenna at the resonant frequencies is 5.04 dBi and 5.01 respectively. As the antenna shows two passbands and it shows maximum gain at the corresponding resonant frequency (in-band). Also, it can be observed that the reflection coefficient does not show any glitches except the in-band, thus, negligible radiation in out-bands and the antenna gain fall down rapidly. The normalized far-field radiation patterns ($\lambda/2\pi$) at the frequencies of 8.72, 8.92, and 11.24 GHz are shown in Figure 8. It can be observed that the measured and simulated copolarization patterns are identically similar, and are in good mutual agreement in boresight direction. Besides, the measured and simulated cross-polarization level of the proposed antenna also shown in Figure 8.

The overall proposed circuitry-size, inclusive of inset-feed is 20.2 × 22.2 × 0.787 mm. The use of a single slot structure with dual-resonance miniaturizes the size of the antenna. This makes it a more feasible choice for dual-frequency operation, requiring compactness and high-radiation performance Thus, it has a bright future in antenna miniaturization in millimeter-wave applications. Moreover, the antenna possesses a simple and uniplanar design, which is very convenient to integrate with associated active or passive circuitry. The proposed antenna shows flexibility in adjusting the frequency ratio by varying the concerned parameters. The performance of the proposed antenna is studied concerning to the previously reported SIW-based works in Table I. It can be experienced that the proposed design owns relatively small-size with good in-band radiation performance. Also, there are enormous scopes of extending this work to corporate-fed array configurations.

4 | CONCLUSION

Here, a compact and novel dual-band cavity-backed slot antenna is designed and demonstrated. The size reduction around 50% is realized by using HM substrate integrated cavity. The antenna radiates energy into the air through the dedicated aperture for each band. The antenna shows dual-frequency property within X-band with peak gain better than 5 dBi according to the measured results. The design shows unidirectional radiation patterns with high gain and moderate bandwidth at both frequency bands, maintaining good in-band performance. Moreover, the resonant frequencies of the antenna can be shifted to a certain extent by changing the corresponding parameters.

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