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Research Article

Design and Implementation of Novel *H*-Shaped Self-Diplexing SIW Rectangular Cavity-Backed Antenna with Harmonic Suppression for Terrestrial Communications

Ravindiran Asaithambi and Rajkishor Kumar

School of Electronics Engineering, Vellore Institute of Technology, Vellore 632014, India

Correspondence should be addressed to Rajkishor Kumar; rajkishorkumar88@gmail.com

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A novel and low profile, planar, rectangular cavity-backed self-diplexing substrate integrated waveguide (SIW) antenna with *H*-shaped slot for dual-band wireless services was designed and demonstrated. The proposed antenna structure radiates from *H*-shaped slot, which is etched on top of the SIW rectangular cavity, and is excited by two separate 50 Ω microstrip feed lines. The *H*-shaped slot is a combination of two vertical slots and one horizontal slot; because of that the presented antenna radiates at two distinct frequency bands around 8.95 GHz and 10 GHz, simultaneously. The design methodology results show that the *H*-shaped slot is significantly more effective than various other slots in the proposed geometry to suppress the unwanted harmonics, attaining good impedance matching and bandwidths and achieving better isolation between these two ports. Hence, the complete design mechanism helped to achieve self-diplexing characteristics. Furthermore, a self-diplexing *H*-shaped SIW rectangular cavity-backed antenna was fabricated and characterized for the complete demonstration purpose and found good covenants between the simulated one. Measured results show that the presented designed has impedance bandwidths for the lower and upper frequency bands of around 2.0% (8.89–9.03 GHz) and 3.1% (10.01–10.32 GHz), respectively, and obtained maximum measured gain of 5.11 dBi and 5.41 dBi at 8.95 GHz and 10.15 GHz, respectively. The proposed self-diplexing SIW rectangular cavity-backed structure shows that front-to-back ratios (FTBRs) are more than 21 dB, and on the other side, it provides good isolation between the two ports, which is more than 20 dB.

1. Introduction

In the current scenarios, the demands for wireless communication services are increasing day by day; therefore, to meet these requirements, a low-profile, planar, high-gain, and multifunctionality antenna radiators are required [1, 2]. A multiband or multifrequency operation in a single radiator is very essential to drastically reduce the physical size of the antenna so that it can be easily mounted on the same platform for different applications at the same time [3, 4]. In this perspective, self-multiplexing antennas based on cavity-backed substrate integrated waveguide (SIW) are more prominent candidates, which offer more attractive features such as compact size, high gain, less back-lobe radiations, low mutual coupling amongst ports, and ease of iteration in the circuits [5, 6]. Hence, several research groups have developed self-duplex/self-diplexing/self-triplexing/self-quadruplexing and self-hexaplexing antennas based on SIW cavity-backed technologies for different multiband operations such as dual-, triple-, quad-, and hexaband operations, respectively [7–19].

On the top of the SIW, a rectangular slit is cut that divides the cavity into two unequal sections, which are excited with the appropriate feed, so that each component acts as a half-mode SIW resonator that radiates via an additional longitudinal slot that supports open-end of half-mode SIW which was reported in [8]. Khan et al. proposed a dual-mode dual-excitation self-diplexing SIW antenna, whereas radiation was carried out in a single square cavity with a rectangular ring slot and reported in [10]. A combination of bowtie-shaped slots and SIW cavity was used by the authors to excite two different feed lines and resonate at two different frequencies in the X-band (8–12 GHz) reported in [11]. The authors presented two quarter-mode SIW resonators that are arranged near and together, which were exited via two coaxial probes. All the resonators were closed ends, and two more rectangular slots were inserted into them to produce more capacitances. Because both resonators were operating below their fundamental frequencies, hence down-scaling was possible as reported in [14]. The authors designed a self-diplexing shielded quarter-mode SIW which has closely spaced bands for achieving excellent isolation, which was reported in [15]. In the same configuration, a *Y*-shaped groove was etched on top of the metal for achieving extra capacitance of the quarter-mode SIW cavity resonator. Also, *Y*-shaped groove helps for reduction of size and obtained dual-band characteristics. The design was excited by two orthogonal feed lines for obtaining two different bands of operations.

In addition to that, very few techniques were found in the literature to suppress the harmonics such as defected ground structure, photonic bandgap structures, loaded slot ring, and shorting pins, respectively [20–23].

Hence, as per the above brief, for the first time, harmonic suppression is obtained in a self-diplexing SIW rectangular cavity-backed single layer antenna by introducing *H*-shaped slot on top of the surface. The presented design was employed by two planar top side feed ports, which operate at two distinct frequency bands such as 8.95 GHz and 10.15 GHz, respectively. Furthermore, a better level of isolation around 20.1 dB and 29.9 dB was achieved between these two input ports.

2. Antenna Design Analysis and Methodology

This section explained how a self-diplexing SIW rectangular cavity-backed antenna was developed using the *H*-shaped slot on the rectangular cavity. The mathematical equations were also incorporated in the section.

2.1. Antenna Configuration and Analysis. Figure 1 exhibits the proposed self-diplexing SIW rectangular cavity-backed antenna having *H*-shaped slot for the suppression of harmonics, whose length and width are presented by l_{cav} and w_{cav}. A self-diplexing SIW rectangular cavity-backed *H*-shaped slot antenna operating at two distinct bands is designed using the RT/duroid 5880 substrate (dielectric constant of 2.33 and loss tangent of 0.0009) with thickness of h_s for application of terrestrial communication.

The given mathematical formulas can be applied to find out the modes of the SIW rectangular resonator and its resonant frequency of TE_{mnp} mode [24–26].

$$f_{\text{mnp}}^{\text{SIW}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{l_{\text{caveff}}}\right)^2 + \left(\frac{n\pi}{w_{\text{cave1ff}}}\right)^2 + \left(\frac{p\pi}{h_{\text{eff}}}\right)^2}, \quad (1)$$

$$l_{\text{caveff}}^{\text{SIW}} = l_{\text{cav}} - 1.08\frac{d_v^2}{p_v} + 0.1\frac{d_v^2}{l_{\text{cav}}}, \quad (2)$$

$$w_{\text{cav1eff}}^{\text{SIW}} = w_{\text{cav}} - 1.08\frac{d_v^2}{p_v} + 0.1\frac{d_v^2}{w_{\text{cav1}}}, \quad (3)$$

where m (=1, 2, ...), n (=1, 2, ...), and p (=1, 2, ...) are the half-cycle variations of electric field over the x dimension, y dimension, and z dimension, $\varepsilon = \varepsilon_0\varepsilon_r$, $\mu = \mu_0\mu_r$, l_{caveff} and w_{cav1eff} are equivalent length and width of cavity, and d_v and p_v are the diameter of via and the spacing between adjacent vias. To avoid excess energy leakage, the diameter and the pitch of the vias were chosen as per the given conditions, for example, d_v/λ_0 is less than or equal to 0.1 and d_v/p_v ratio must be greater than or equal to 0.5, respectively.

The presented designed self-diplexing SIW rectangular cavity-backed supported half-mode SIW (HMSIW) i.e., TE_{mn0} mode, where there is no variation in z-direction, hence it can be calculated from the following equation:

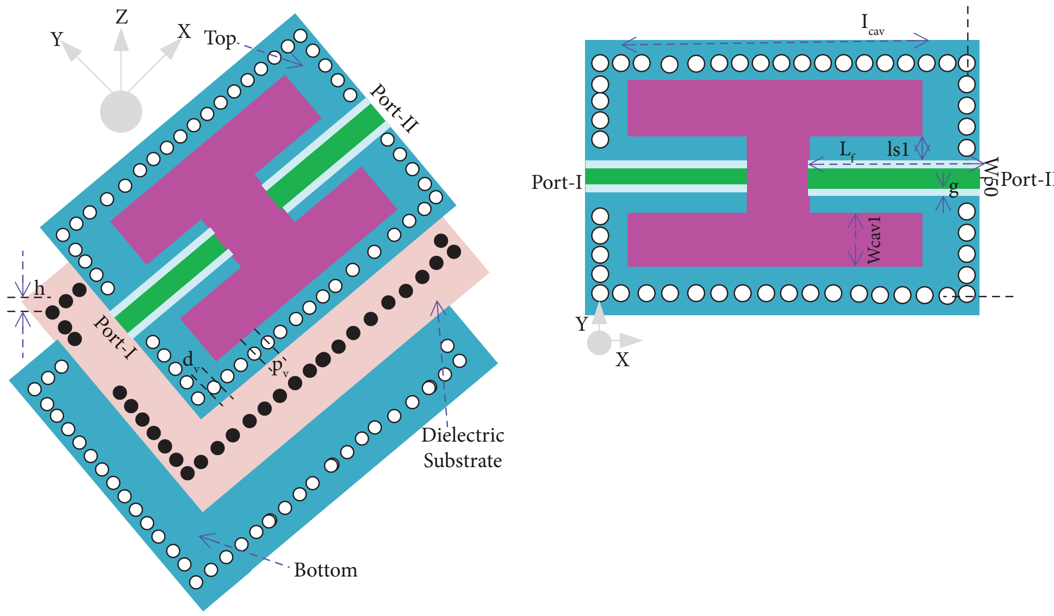
$$f_{\text{mn0}}^{\text{SIW}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{l_{\text{caveff}}}\right)^2 + \left(\frac{n\pi}{w_{\text{cav1eff}}}\right)^2}. \quad (4)$$

After selecting the operating frequency using approximation equations (1)–(4), the initial dimensions of the presented self-diplexing SIW rectangular cavity-backed antenna layout are developed and designed. The complete dimension of the presented self-diplexing SIW rectangular cavity-backed antenna has been given in the caption of Figure 1. A series and chains of metallic vias have been used for the development of the rectangular-shaped lateral side wall, which behaves as a magnetic wall. The presented design supported full-mode SIW but after being divided into two equal subsections using an H-shaped slot and obtained half-mode SIW resonators.

The feed line positions have been placed in such a way that it can achieve adequate impedance matching at the desired resonance frequency. Here, an H-shaped slot, which is a combination of vertical slots and horizontal slot, was inserted on the top of the metal layer, and it acts as a radiator. The *H*-shaped slot is able to divide the main cavity into two subcavities for realization of HMSIW modes as shown in Figure 2. The slot's width is kept fairly large to prevent mutual coupling of the incident power with nearby ports.

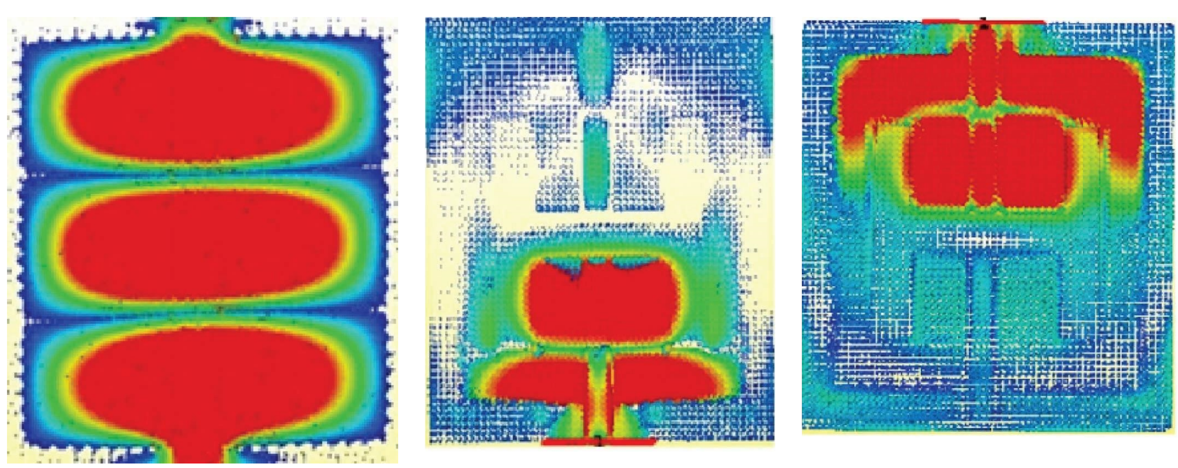
2.2. Design Methodology and Operational Mechanism. The self-diplexing design evolution process has been discussed in this section, with the starting point being a SIW rectangular cavity-backed resonator. To prevent unintended power leakage or radiation losses, SIW characteristics were carefully selected in terms of its size. Here four different major stages are discussed to obtain the final design, which are given below:

Stage 1: In this stage, development of SIW rectangular cavity resonator has been done by employing the standard equations to calculate the initial length and width of the rectangular cavity as indicated in Figure 3(a). The related reflection coefficients and their isolation are shown in Figure 4(a). It is clearly observed from Figure 3 that the presented rectangular SIW cavity antenna has multiple harmonics along with the fundamental frequency. It is important to note that these harmonics are undesired and could cause problems for



(a) (b)

Figure 1: Proposed self-diplexing SIW rectangular cavity-backed H-shaped slot antenna. (a) 3D view and (b) top view ($L_t = 45$, $W_t = 39$, $h_s = 0.787$, $l_{cav} = 25$, $W_{cav1} = 5$, $W_{50} = 2$, $W_f = 2$, $L_f = 21$, $l_{s1} = 5.75$, $g = 0.75$, $t = 0.035$, $d_v = 1$, $p_v = 1.5$, unit: millimeter).



(a) (b) (c)

Figure 2: E-field distributions: (a) SIW rectangular cavity offers TE_{130} mode, (b) H-shaped slot loaded on SIW when port 1 is ON, and (c) H-shaped slot loaded on SIW when port 2 is ON.

other wireless communication systems. Hence, suppressing such harmonics is always preferred. It is also found from Figure 4(a) that stage-1 is showing very poor isolation due to spreading of electromagnetic wave inside the cavity.

Stage 2: To solve the harmonic problems, one vertical open-ended slot has been inserted on top of SIW rectangular cavity, having initial slot length of approximately $\lambda_g/2$, where λ_g is the guided wavelength at lowest first band resonating frequency as shown in Figure 3(b). The top side of vertical slot upsurges the shunt capacitance, and hence the overall capacitance increases with the increase of l_{s1}. This gives shifting of the resonant frequency to the lower frequency side (because of a change in the effective permittivity) as shown in Figure 4(b). The matching is also deteriorated, it could be possible for higher values of magnetic fields inside the cavity compared with electric fields. The insertion of single vertical capacitance slot is not very much capable for restriction of spreading of electromagnetic wave inside the cavity, and hence poor isolation can be observed as shown in Figure 4(b).

Stage 3: This stage involved loading of one more vertical open-ended slot on top of SIW rectangular cavity as

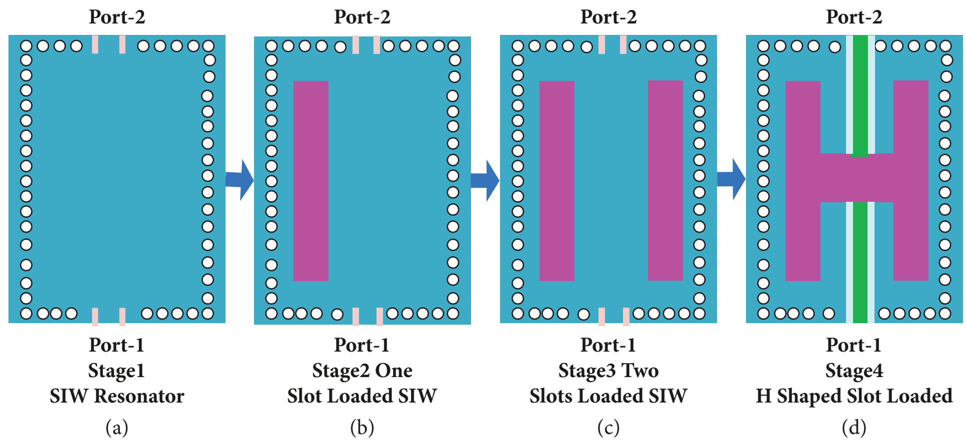


FIGURE 3: Evolution stages of self-diplexing SIW rectangular cavity-backed antenna with *H*-shaped slot: (a) rectangular cavity, (b) single (one vertical) slot loaded in SIW rectangular cavity, (c) dual (two vertical) slots loaded in SIW rectangular cavity, and (d) *H*-shaped slot loaded in SIW rectangular cavity.

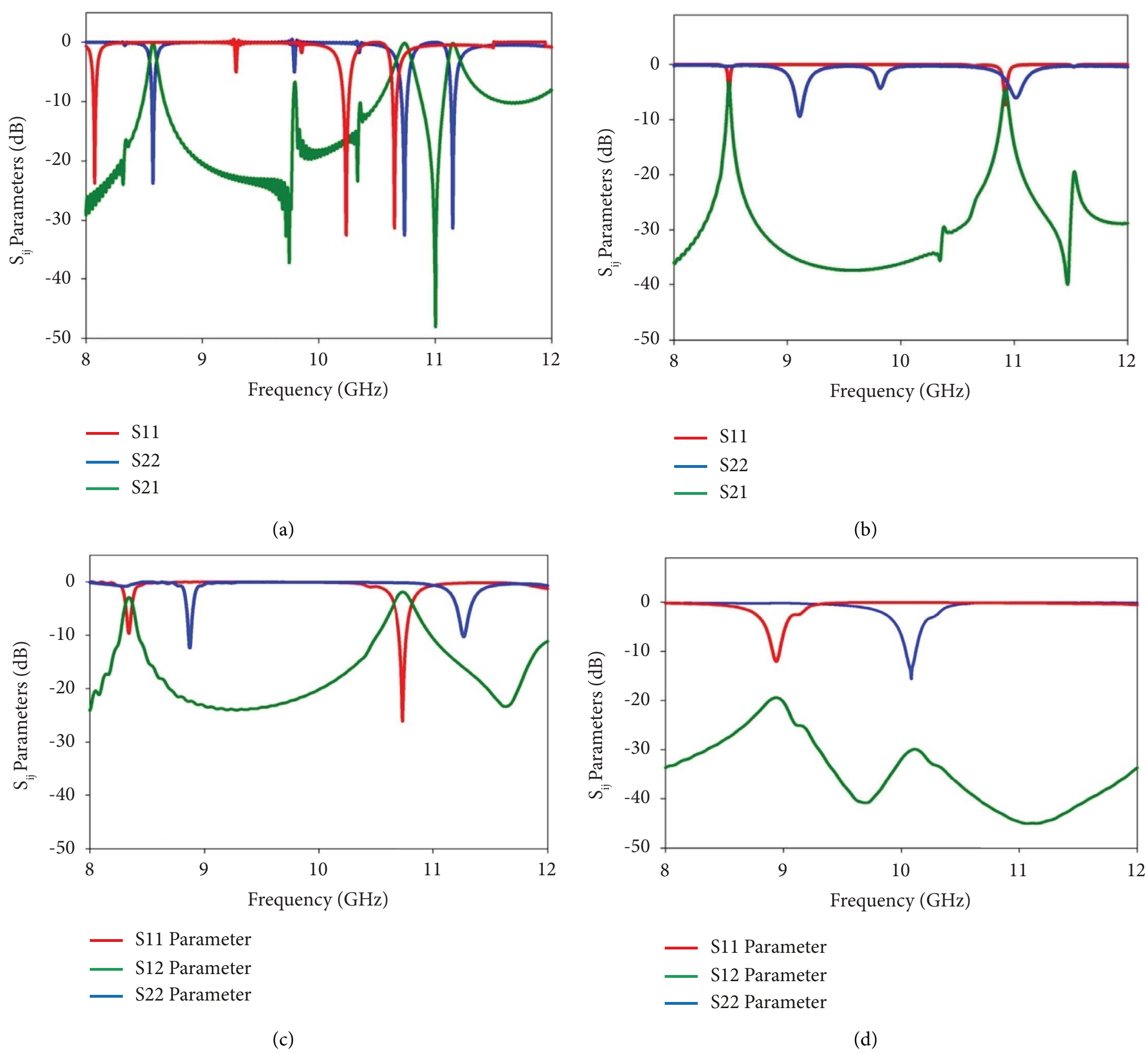


FIGURE 4: Evolution stage and performance of the proposed self-diplexing SIW rectangular cavity-backed antenna: (a) stage-1, (b) stage-2, (c) stage-3, and (d) stage-4 (proposed design).

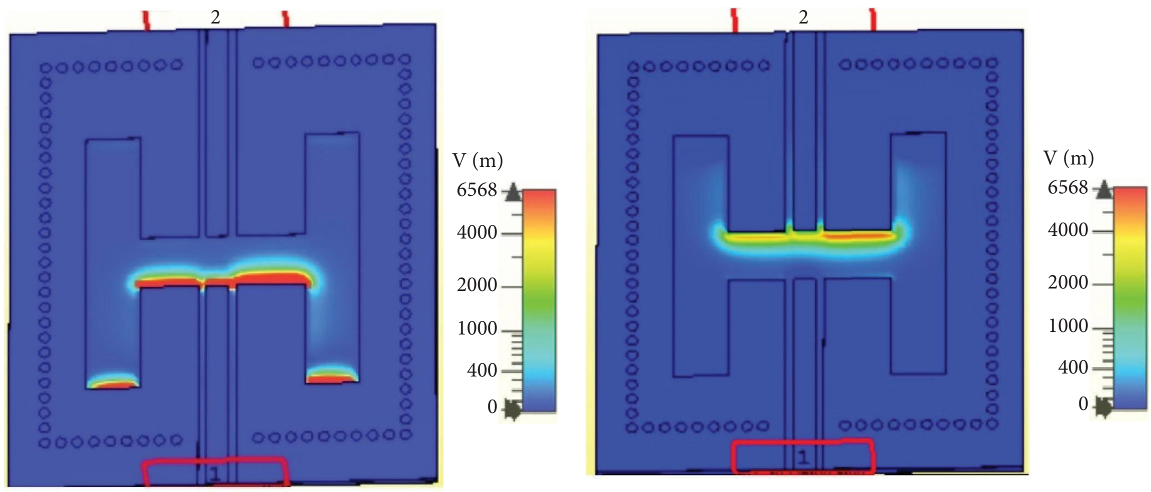


Figure 5: Electric field magnitude distributions at each resonant frequency: (a) port 1 ON and (b) port 2 ON.

shown in Figure 3(c), having the same initial slot lengths, i.e., roughly $\lambda_g/2$. The insertion of another vertical slot again increases the shunt capacitance values while it decreases the area of top conducting layer, i.e., inductive effects. The combined effect of two vertical slots helps to maximize the impedance matching and improves the −10 dB impedance matching as shown in Figure 4(c). But it also enables to improve the isolation because these two vertical slots, i.e., more shunt capacitance, are unable to curtail the electromagnetic wave inside the cavity.

Stage 4 (proposed design): The final stage mainly depends on the improvement of isolation, impedance bandwidth, and its matching. Therefore, a horizontal slot is inserted on top of SIW rectangular cavity, which is connected to two vertical slots to make H-shaped slot, and this configurations help to maximize the shunt capacitance as shown in Figure 3(d). Actually, the cavity works as a parallel RLC network whose resonant frequency can be determined by equation (5), so adding the capacitance slots on top of SIW works as parallel capacitance, and hence it brings down the resonance frequency [27].

$$f_{\text{res}} = \frac{1}{\sqrt{L_{\text{eqv}} C_{\text{eqv}}}}. \quad (5)$$

In addition to that, the H-shaped slot generates more shunt capacitance to counter the inductance present in the configuration, hence the presented design shows an incredibly good −10 dB impedance bandwidth and impedance matching as shown in Figure 4(d). It is also found from Figure 4(b) that *H*-shaped slot is very much effective for restricting the spreading of electromagnetic wave inside the cavity, and hence it shows high isolation between the ports. This happened due to mainly horizontal slot restricting the fields from passing the next level of the HMSIW resonator as shown in Figure 5.

It is worth mentioning that the entire antenna configuration helps to achieve self-diplexing properties which can be observed from Figure 4(d).

2.3. Parametric Analysis. This section is based on the selection of width (W_{cav1}) of the slot and its effect on the input reflection coefficient and isolation. It is clearly observed from Figure 6 that the slot width affects the impedance bandwidth and its matching, resonant frequency, and isolation between the ports of both the HMSIW cavity resonators. It is found that the initial calculated width of slot dimension using equation (3) is not sufficient to get the optimal values of capacitance, and hence, optimized values of width are required. In this context, the width of the slots varies from 5 mm to 3 mm to observe the effects on the input reflection coefficient and its isolation. As the widths of presented slots are changed, all key values of antenna parameters are changed; it happens due to not obtaining optimal values of capacitance in the proposed self-diplexing design. From the above observations and Figure 6, it is worth communicating that the optimal values of capacitance are required to achieve the desired performance.

3. Experimental Verifications

A prototype self-diplexing SIW rectangular cavity-backed antenna with H-shaped slot has been fabricated and characterized for validation of simulated results. The photograph of the prototype antenna is shown in Figure 7 with top view, backside view, and measurement setup of anechoic chamber. During the measurements process, one port has been fed by 50 Ω, while another port is terminated by its matched load i.e., by 50 Ω load. Figure 8 depicts the measured S-parameters of the proposed self-diplexing SIW rectangular cavity-backed antenna with H-shaped slot in relation with each input port.

It is found that the presented design resonates at 8.95 GHz when port 1 is ON having measured −10 dB impedance bandwidths of around 2.0% (8.89–9.03 GHz) while it resonates

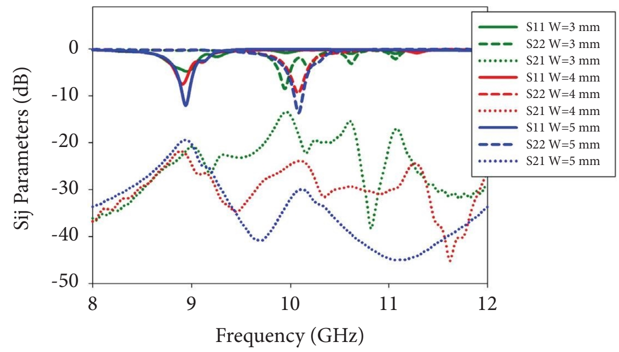
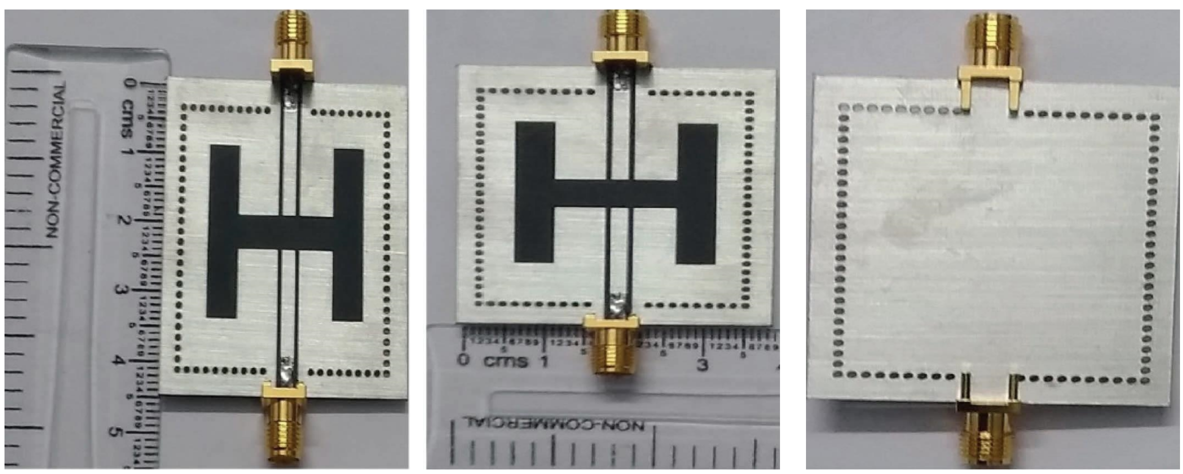


Figure 6: Reflection coefficients and isolation with variation of width of presented self-diplexing SIW rectangular cavity-backed antenna.



(a) (b)

(c)

Figure 7: Photograph of the proposed self-diplexing SIW rectangular cavity-backed antenna with *H*-shaped slot: (a) top view, (b) backside view, and (c) anechoic chamber during the testing of the proposed antenna.

at 10 GHz when port 2 is ON having measured −10 dB impedance bandwidths of around 3.1% (10.01–10.32 GHz), respectively. It is also found from Figure 8 that the measured port isolation between the resonators is above 20 dB, which falls under the acceptable range, and is achieved without using any decoupling networks.

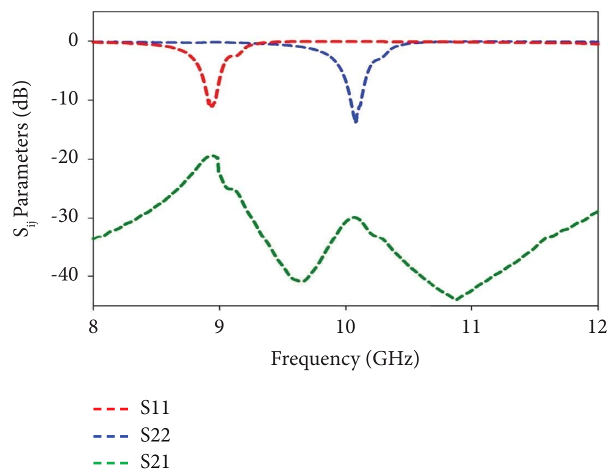
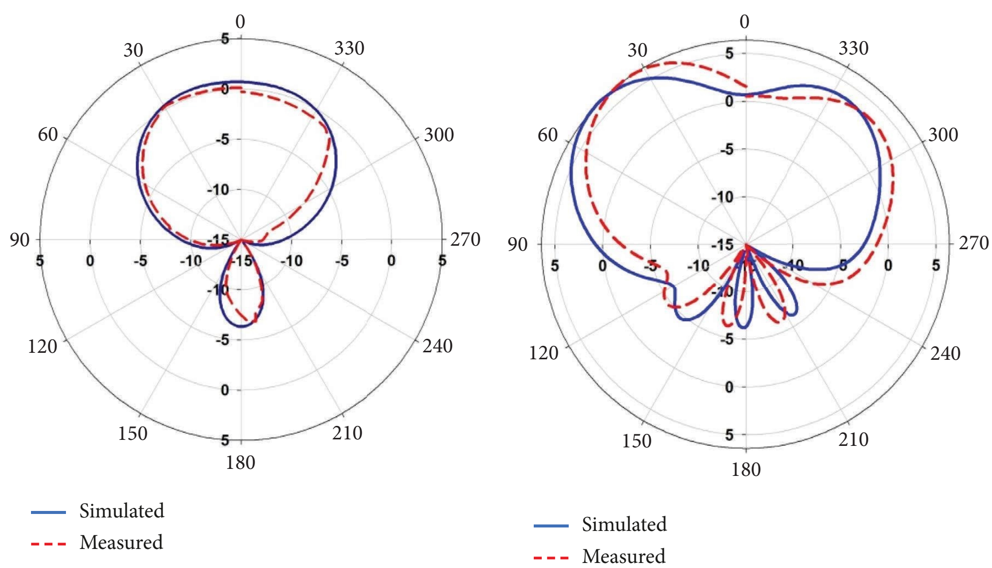


Figure 8: Measured S-parameters of the proposed self-diplexing SIW rectangular cavity-backed antenna with H-shaped slot.



(a)

(b)

Figure 9: Measured and simulated radiation patterns of the proposed H-shaped self-diplexing SIW antenna: (a) xz-plane at 8.95 GHz and (b) xz-plane at 10.15 GHz.

The far-field characteristics of radiation patterns were measured in the automatic anechoic chamber, and the normalized measured radiation patterns are observed in Figure 9 for port 1 and 2 excitations, respectively. In both E-(XZ) and H-(YZ) planes, the differences between co-polarization and cross-polarization for all frequencies are greater than 15 dB in broadside direction. The front-to-back ratio for the presented diplexing antenna is also found to be 21.01 dB and 25.62 dB at two distinct resonance (8.95 GHz and 10.15 GHz) frequencies.

The measured realized gains are found to be 5.11 dBi when Port 1 is excited at a resonance frequency of 8.95 GHz, while realized gains are found to be 5.41 dBi when Port 2 is excited at a resonance frequency of 10.15 GHz as shown in Figure 10. The presented antenna offers overall radiation efficiency of approximately 74.12% in the passband of broadside direction as depicted in Figure 11. Table 1 shows the complete features of the proposed design compared with previous work in terms of operating frequencies, fractional bandwidths, front-to-back ratio, gain, isolation, shape of the slot, multiplexing, and harmonic suppression. Compared with the other developed models, the presented design has huge advantages in terms of suppression of harmonics, achieving better isolation and better gain as well as obtaining good fractional bandwidths.

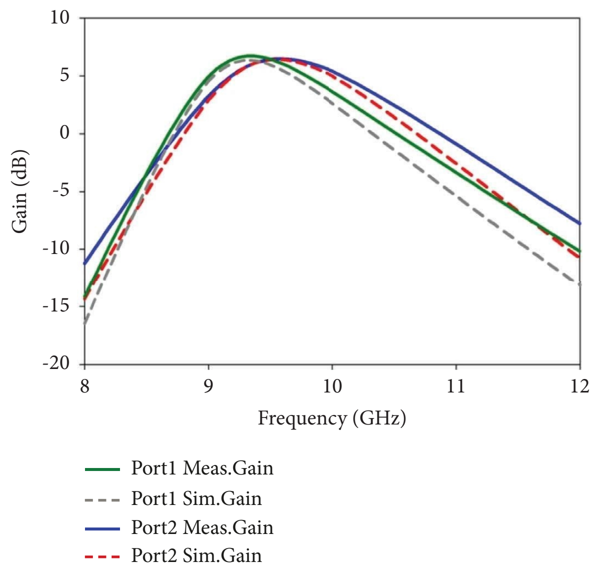


Figure 10: Simulated and measured gain of the presented self-diplexing SIW rectangular cavity-backed antenna with H-shaped slot.

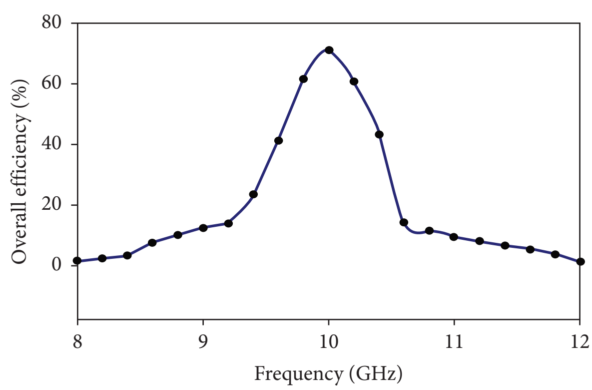


Figure 11: Simulated efficiency of the presented self-diplexing SIW rectangular cavity-backed antenna with H-shaped slot.

Table 1: Comparison of the proposed work with previously published self-diplexing SIW antennas.

References	Frequencies (GHz, f_1, f_2)	FWB (%, at f_1, f_2)	FTBR (dB, at f_1, f_2)	Gain (dBi, at f_1, f_2)	Isolation (dB)	Slot shape	Self-multiplexing	Harmonic suppression
[11]	9, 11.2	NA	21, 19	4.3, 4.3	25	Bowtie	Yes	No
[12]	8.26, 10.46	NA	23, 20	3.56, 5.24	27.9	Transverse	Yes	No
[13]	6.44, 7.09	2.1, 2.4	NA	3.2, 4.8	30	Rectangular	Yes	No
[23]	7.8, 9	<1, <1	NA	5.4, 5.1	22	Cross	Yes	Yes
This work	8.95, 10.15	2.0, 3.1	21.01, 25.62	5.11, 5.41	29.9	H	Yes	Yes

FWB = fractional bandwidths; FTBR = front-to-back ratio; NA = not available.

4. Conclusion

A HMSIW rectangular cavity-backed self-diplexing antenna with H-shaped slot has been implemented for dual-band wireless applications. The H-shaped slot has been obtained by carving on top of the rectangular metal surface of the presented antenna, which has been excited by two distinct ports from opposite sides to get two different frequencies of operations. Another feature of the presented design is that without using any decoupling network, only the insertion of two vertical slots and one horizontal slot, i.e., an H-shaped slot, is able to suppress the unwanted harmonics, hence showing good isolation. The outcome demonstrates that the measured fractional bandwidths of the dual band have been obtained at 2.0% and 3.1% whereas the measured gain of these dual bands is obtained at 5.11 dBi and 5.41 dBi, respectively. The favorable near- and far-field properties of the presented design make it more appropriate for wireless transceiver applications.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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