

A Typical Slotted SIW Cavity-backed Antenna for Dual frequency operations in U-NII Bands

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ABSTRACT A low profile circular shaped cavity-backed substrate integrated waveguide (SIW) antenna with two-typical intersecting rectangular slots on the ground plane is designed to operate in the dominant TM_{010} mode at a frequency of 5.19 GHz in U-NII-1 band for wireless applications. The initially designed antenna produces a gain of 4 dBi with a narrow impedance bandwidth extending from 5.17 – 5.22 GHz. The antenna design is further modified by insertion of another shifted two-typical intersecting rectangular slots to finally resemble that of Hash shape; resulting in dual band antenna operation at 4.9 and 5.93 GHz. The gains obtained are 3.7 dBi and 1.4 dBi for 4.9 and 5.93 GHz respectively with an impedance bandwidth covering 4.88 - 4.92 GHz and 5.92 – 5.94 GHz respectively. The antenna prototype is fabricated using Arlon AD270 substrate material. Parametric studies are performed in terms of return loss and gain of the antenna. All simulations are carried out using HFSS v19.0 and show similar behavior to their experimentally measured counterparts.

INDEX TERMS Circular Cavity-Backed Antenna, Dual Band, Gain, Substrate Integrated Waveguide (SIW), Slot Antenna.

I. INTRODUCTION

With the advancement of wireless communication, the demand for low profile antenna has increased enormously in recent years. Antennas can be designed on the basis of microstrip or waveguide technologies. To overcome the issues of low power handling and electrical shielding, the concept of substrate integrated waveguide (SIW) technology [1]-[4] is used. It consists of posts with periodic gaps placed along the sidewalls of the structure and hence, provide low leakage loss [5]. Cavity backed antennas are evident choices among the designers for low profile antennas as they provide high gain, high power handling capabilities and unidirectional radiation pattern due to suppression of surface waves as compared to the conventional slot antenna [6] - [9]. Different SIW structures [10] and single band antennas [11]-[13] are reported in literature. Bandwidth and gain of antenna can be improved using Dielectric resonators [14] or, by using frequency selective surface as superstrate as discussed in [15, 16]. Antennas with dual bands of operation are attracting researchers worldwide owing to increase in demand for wireless systems such as global positioning system (GPS), wireless local area network (WLAN) and satellite communication.

Generation of two narrowband resonance through insertion of a combination of traverse slots along with longitudinal slots for excitation of two different modes of operation is reported in [17]. Dual band resonance is achieved in SIW

cavity-backed antenna with triangular-ring slot [18]. Longitudinal slot array SIW antenna exhibiting good radiation pattern with dual-frequency response within X band is proposed in [19]. A cross shaped slot of different lengths operating at 9.5 GHz and 10.5 GHz is proposed in [20]. A bow-tie shaped slot on the ground plane is inserted in SIW cavities of different sizes connected by coupling windows on their common wall. The cavities are used to excite the four hybrid modes in X band to obtain dual band resonance [21]. Three layered compact dual band antenna is proposed in [22], where the top layer consists of SIW cavity backed slot antenna and the middle layer is a quarter mode SIW antenna operating at 2.6 GHz and 5.9 GHz. The concept of bilateral slots [23] on top plane and ground plane is used to achieve dual frequency of operation for the SIW based cavity -backed antenna on single substrate at 9.85 GHz and 14 GHz. Body wearable textile antenna is proposed in [24] to perform dual frequency operations in the ISM and 4G LTE band. It can be integrated with solar harvesting system, consisting of a flexible solar cell, a power management system, and energy storage. Frequency reconfigurable antenna consisting of PIN diode as switching element can be designed with narrowband of less than 1% as discussed in [25]. Dual band frequency at 9.5 GHz and 13.85 GHz can also be obtained by inserting dumbbell shaped slot on the ground plane of a thin SIW cavity backed antenna as presented in [26]. However owing to high Q-factor of SIW structures, the bands generated in all these dual-band

antennas are in general narrow and the bandwidths do not exceed 2.1% in any cases.

In this paper, a SIW based circular-shaped cavity-backed two-typical intersecting rectangular slots antenna is designed to operate at 5.19 GHz in the U-NII-1 band (5.15 – 5.25 GHz) used for indoor wireless devices. The antenna radiates backwards with a gain of 4 dBi. The initially designed antenna is further modified with the inclusion of shifted two-typical intersecting rectangular slots resembling that of Hash (#)-shaped slot resulting in dual narrowband frequency operation at 4.9 GHz and 5.93 GHz for wireless applications. The antenna is fed with power at the upper metal surface and produces backward radiation with gains of 3.7 and 1.4 dBi at that two frequencies respectively. The proposed antenna is designed using Arlon AD270 substrate and simulated using ANSYS make HFSS v19.0.

The following sections of the paper deals with designing of single and dual band antennas in Section II along with its results discussed in Section III; followed by conclusion in Section IV.

II. SIW Based Circular Cavity-backed slot antenna for Wireless Applications

The circular cavity-backed antenna with slot is designed at an operating frequency of 5.19 GHz for U-NII-1 band to be used for indoor wireless applications. Further, the designed is modified by inclusion of another shifted slot so as to operate at dual frequencies of 4.9 GHz and 5.93 GHz for public safety and U-NII-5 band respectively for Wireless applications.

Theoretical Background: The cavity resonator that confines the electromagnetic energy is basically a metallic enclosure and the stored electric and magnetic energies determine the equivalent inductances and capacitances of the cavity. The equivalent resistance is calculated by the energy dissipated by the finite conducting walls. Typically, a circular cavity finds its applications in microwave frequency meter where the power is absorbed by the cavity when it is tuned to the operating frequency. The resonant frequency for a circular cavity of radius ‘a’ is given by [27]:

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (1)$$

where n, m, and l are the half-guide wavelength in x, y and z directions respectively, and p_{nm} is the m th root of $J_n(x)$.

The circular cavity, thus designed, is modified with inclusion of array of metallic vias placed along the circumference of the circular patch thereby resulting in a SIW structure. The vias are filled with copper paste on the inner surface leading to shorting of upper and lower metal surfaces, thereby acting as perfect electrical conducting walls and confining the electromagnetic energy within it. Each via placed along the circumference has a diameter of 1 mm and centre-to-centre distance of 1.5 mm satisfying the necessary conditions of $s/p < 2$ and $p/w < 1/5$ [5], where p is the diameter of the via and s is the centre-to-centre distance. The trapped energy

is released out of cavity through a slot inserted on the ground plane making the circular cavity structure resemble that of a cavity-backed SIW antenna.

Antenna Configuration: The circular cavity-backed slot antenna is designed in the dominant TM_{010} mode and fabricated on Arlon AD 270 substrate material with a thickness (h) of 0.79 mm, dielectric constant (ϵ_r) = 2.7 and loss tangent (δ) = 0.002. The overall dimension of the antenna is 60 mm (L) × 60 mm (W) × 0.79 mm (h) with a circular patch of radius (R) = 16 mm. Since, the vias are placed along the circumference, the effective radius extending upto the PEC walls of cavity is $16 - (1.6 + 1) = 13.4$ mm as shown in Fig. 1(a).

a. Single frequency Antenna with two-typical intersecting rectangular slots: Two-typical intersecting rectangular slots of length (l_{slot}) and width (w_{slot}) is introduced at a position where the maximum field perturbation exists on the ground plane for the purpose of radiation. The highest radiation efficiency can be achieved with the help of resonant slot operating at the desired frequency. The length of each arm of two typical intersecting rectangular slot can be calculated as:

$$l_{slot} = \frac{1}{2f_{nml}\sqrt{\mu_r\epsilon_{eff}}} \quad (2)$$

where, l_{slot} is the length of slot and ϵ_{eff} is the effective permittivity given by $\epsilon_{eff} = (\epsilon_r + 1)/2$. Apart from serving as the radiating element, the two typical intersecting rectangular slots and Hash-shaped slot also excites the fundamental mode in circular cavity i.e. TM_{010} ($n = 0, m = 1$ and $l = 0$). Thus, equation (1) is modified as:

$$f_{010} = \frac{2.405c}{2\pi a\sqrt{\mu_r\epsilon_r}} \quad (3)$$

Using equation (3), the theoretically calculated value of frequency obtained is 5.22 GHz which shows close juxtaposition to the simulated frequency of 5.19 GHz. The cavity is excited with an inset feed with depth (d) = 11.85 mm placed along the centre line top operating at 5.19 GHz in the dominant TM_{010} mode. Though the power is fed on the top surface but since the slot is inscribed on the ground plane, hence, the antenna radiates in the backward direction. Dimensions of the initially designed antenna are enlisted in Table I along with its analytical dimension shown in Fig. 1.

TABLE I. Sizes of various parameters of the initially designed SIW based cavity-backed slot antenna (in mm)

L	R	w	W	H	D	L
60	16	1.065	2.13	0.79	11.85	14.15

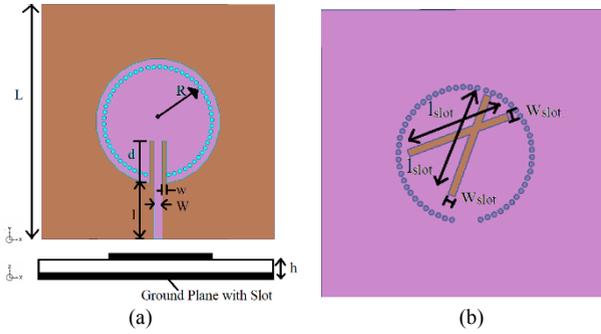


FIGURE 1. Analytical dimensions of SIW based Circular cavity-backed two-typical intersecting rectangular slots antenna

b. Dual Band Antenna with Hash-Shaped Slot: The initial antenna design is slightly modified by the introduction of shifted two-typical intersecting rectangular slots resulting in a shape similar to that of ‘Hash’ with same dimensions of length (l_{slot}) and width (w_{slot}) as depicted in Fig. 2. The fabricated prototype of the modified antenna is as shown in Fig. 3. The Hash-shaped slotted antenna so formed operates at dual frequencies of 4.9 GHz and 5.93 GHz.

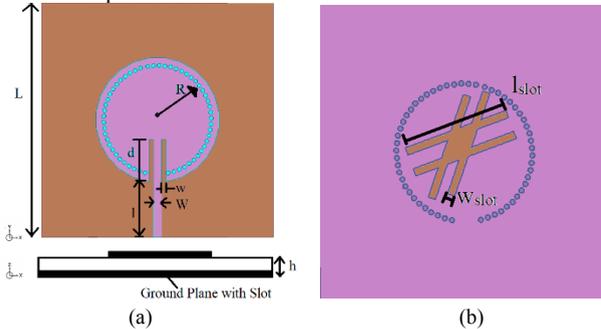


FIGURE 2. Analytical dimensions of SIW based Circular cavity-backed Hash-shaped slot antenna



FIGURE 3. Fabricated SIW based Circular cavity-backed Hash-shaped slot antenna

III. Results and Discussions

Parametric studies using optimetrics are performed on the initially designed antenna and modified dual band antenna in terms of variation in length and width for better performance of antenna with respect to gain and return loss using ANSYS make HFSS v19.0.

a. Single frequency antenna with two-typical intersecting rectangular slots: Parametric studies with variations in length (l_{slot}) and width (w_{slot}) of the initially designed antenna are plotted in Fig. 4. Fig. 4(a) shows the variation in length (l_{slot}) of the two-typical intersecting

rectangular slots keeping its width fixed while Fig. 4(b) unveils the variation in width (w_{slot}) keeping the length of the slot fixed.

From Fig. 4(a), it is evident that upon variation in slot length (l_{slot}) from 14 mm to 22 mm, keeping other dimensions constant, the antenna performance degrades in terms of resonating frequency of antenna. For slot lengths $l_{slot} = 14$ mm, 16 mm and 18 mm, the resonating frequency moves far away from the theoretically calculated value of 5.22 GHz obtained from eq. (2) while for slot length $l_{slot} = 20$ mm and 22 mm, a better response of reflection coefficient is obtained at frequencies close to theoretically calculated frequency.

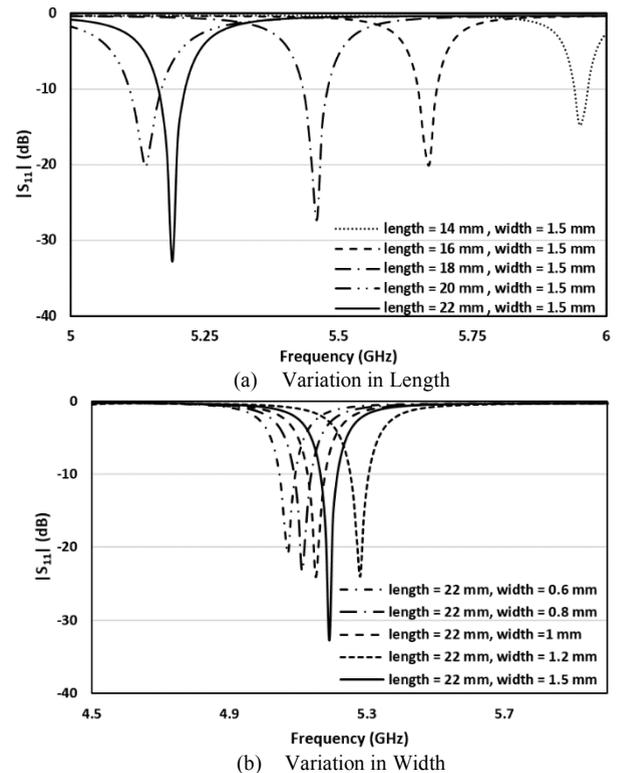


FIGURE 4. Parametric study of variation of reflection coefficient with change in (a). length (width fixed at 1.5 mm) and (b). width (length fixed at 22 mm) of the two-typical intersecting rectangular slots of the initially designed antenna

Hence, slot length $l_{slot} = 22$ mm can be considered as an optimum length of the slot as the antenna resonates closely to the theoretically calculated value and has a better reflection coefficient of -32.78 dB.

Similarly, variation in width of the slot (w_{slot}) from 0.6 mm to 1.5 mm results in a slight shift in the resonating frequency; however, the overall reflection coefficient characteristics are not much altered. The optimum slot width can be considered as 1.5 mm for better reflection coefficient characteristics. Hence, from the parametric studies, the optimized length and width of the slot is considered to be 22 mm and 1.5 mm respectively.

The simulated reflection coefficient obtained is -32.78 dB for 5.19 GHz frequency in the dominant TM_{010} mode as shown in Fig. 5 with an impedance bandwidth of 5.17 - 5.22 GHz.

Electric field and surface current distributions for the initially designed antenna are displayed in Fig. 6(a) and Fig. 6(b) respectively. The electric field co-polarised simulated gain obtained is 4 dBi while the simulated H-field co-polarised gain is 3.8 dBi as shown in Fig. 7. The cross-pol gains are over 30 dBi less than their co-pol counterparts.

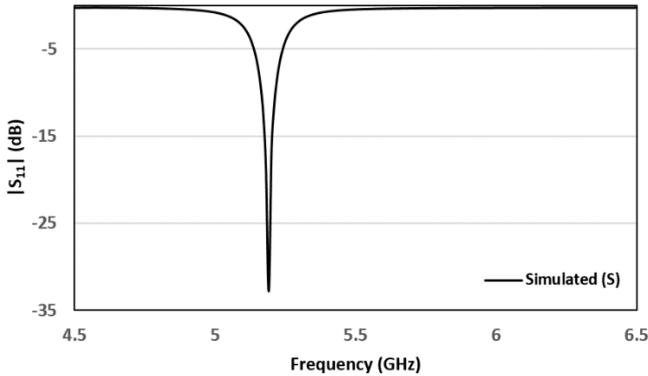


FIGURE 5. Simulated Reflection Coefficient of the initially designed antenna

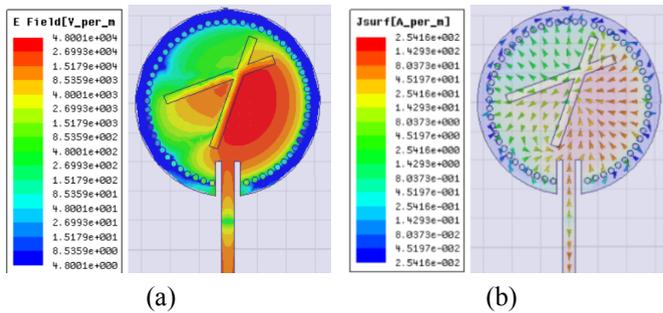


FIGURE 6. (a). Electric Field distribution and (b). Surface current distribution of the initially designed SIW based Circular cavity-backed two-typical intersecting rectangular slots antenna at 5.14 GHz

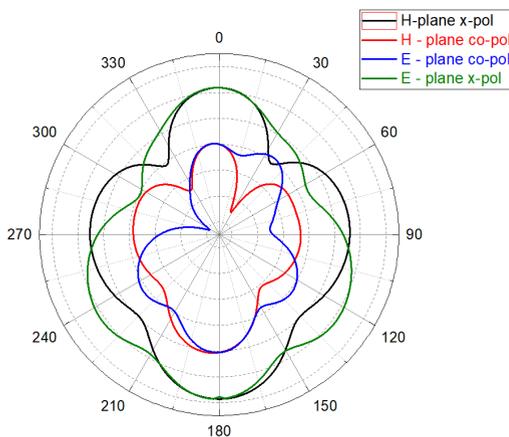


FIGURE 7. Radiation pattern of the initially designed SIW based Circular cavity-backed slot antenna

b. Dual band Antenna with Hash-shaped slot: Parametric studies with variations in length (l_{slot}) and width (w_{slot}) of the hash-shaped slot in the modified antenna are carried out to obtain the best antenna performance as shown in Fig. 8. Fig. 8(a) deals with the variation in length (l_{slot}) of the hash-shaped slot keeping its width fixed while Fig. 8(b) shows the variation in width (w_{slot}) keeping the length of the

slot fixed. From the parametric studies shown in Fig. 8(a), it is seen that the variation in length of slot (l_{slot}) from 14 mm to 22 mm, keeping other parameters constant, results in deterioration of antenna performance in terms of reflection coefficient and resonating frequency. For lengths $l_{slot} = 14$ mm, 16 mm, 18 mm and 20 mm, the reflection coefficient of antenna is poor in the first frequency band, but it improves in the second frequency band while for slot length $l_{slot} = 22$ mm, the reflection coefficient is better in both the bands operating at resonating frequencies. There is a slight change in the impedance bandwidth at higher frequencies for all variations in slot length. Hence, the optimum length of Hash-shaped slot is chosen to be 22 mm. Upon variation in width of the Hash-shaped slot (w_{slot}) as shown in Fig. 8(b), there is a slight shift around the resonating frequencies in both the bands. At smaller width of slot ($w_{slot} = 0.6$ mm and $w_{slot} = 0.8$ mm), the reflection coefficient is greater than -10dB, but the results improve for larger slot widths of 1 mm, 1.2 mm and 1.5 mm in the first frequency band. In the second frequency band, there are infinitesimal increase in the reflection coefficients for smaller slot widths but for $w_{slot} = 1.5$ mm, it is seen that the reflection coefficient is around 20 dB for both the bands. Thus, from the parametric studies, the best antenna performance can be perceived from the graph are for the slot dimensions of 22 mm and 1.5 mm respectively. The simulated reflection coefficient for the designed antenna obtained are -21.13 dB and -21.54 dB for 4.9 GHz and 5.93 GHz frequency in the dominant TM_{010} mode. The measured reflection coefficient using Anritsu make VNA model MS205B for the fabricated antenna is -24.38 dB at 5.06 GHz and -26.54 dB at 6.1 GHz. A comparative plot of simulated and measured reflection coefficient is shown in Fig. 9 with an impedance bandwidth of 4.88 - 4.92 GHz and 5.92 - 5.94 GHz. A modest variation manifests due to mismatch in SMA connector or intolerance of material resulting from manufacturing anomalies. Electric field and surface current distributions for the modified antenna are shown in Fig. 10(a) and Fig. 10(b) respectively at the fundamental frequency of 4.9 GHz and 5.93 GHz for the dominant TM_{010} mode. The antenna's radiation pattern is measured using Hittite HMC-T2100 microwave signal generator (10 MHz -20 GHz) and a Krytar 9000B power meter. A plot of the simulated and measured electric field radiation pattern is shown in Fig. 11(a). For the fundamental TM_{010} mode, the electric field co-polarized simulated gain obtained is 3.7 dBi, while its measured value is 3.4 dBi at $\theta = 180^\circ$ for 4.9 GHz while for 5.93 GHz, the electric field co-polarized value is 1.4 dBi with a measured value of 1.6 dBi. Likewise, the simulated and measured H-field co-polarized gains are 3.5 dBi and 3.2 dBi, respectively for 4.9 GHz and 1.4 dBi and 1.2 dBi for 5.93 GHz as shown in Fig. 11 (b). The cross field values are 20-30 dB lower than their corresponding co-pol values in both cases. A comparison between the circular SIW antenna without slot (say Antenna-I), circular cavity-backed SIW antenna with two typical intersecting rectangular slots (say Antenna-II) and circular cavity-backed SIW antenna with Hash-shaped slot (say Antenna-III) is performed on the

basis of frequency of operation, reflection coefficient, gain and impedance bandwidth and is shown in Table – II.

TABLE II. Proposed antenna analysis for types of slots

Antenna	Type of Slot	Operating Freq.(GHz)	Reflection Coefficient (dB)	Impedance Bandwidth (GHz)	Co-polarized Gain (dBi)	
					E field	H field
I	No slot	5.20	-0.77	-	-	-
II	Two Typical Intersecting Rectangular Slots	5.19	-32.78	5.17 - 5.22	4	3.8
III	Hash-shaped Slot	4.9/ 5.93	- 21.13/ -21.54	4.88 - 4.92/ 5.92 - 5.94	3.7/ 1.4	3.5/ 1.4

Antenna - I does not show any resonance below -10 dB because the electromagnetic wave energy is trapped inside the cavity. On the introduction of two typical intersecting rectangular slots (Antenna –II), the antenna operates at a single band frequency of 5.19 GHz with -32.78 reflection coefficient. Further, as the slot is modified to Hash-shaped slot, the modified Hash-shaped slotted antenna (Antenna – III) now resonates in dual band frequencies of 4.9 GHz and 5.93 GHz. Antenna – II is seen to exhibit a E field co-pol gain of 4 dBi and H field co-pol gain of 3.8 dBi at 5.19 GHz. The corresponding impedance bandwidth ranges from 5.17 – 5.22 GHz. Dual-band Antenna –III, on the other hand, exhibits E field and H field co-pol gains of 3.7 and 3.5 dBi at 4.9 GHz while the same are 1.4 dBi at 5.93 GHz frequency. The corresponding impedance bandwidth ranges from 4.88 – 4.92 GHz and 5.92-5.94 GHz respectively. It is thus seen that both Antenna –II and Antenna –III exhibits similar gain values at the corresponding resonating frequencies. The antenna can be independently controlled at its different resonant frequencies by varying either of the antenna parameters i.e. length of the slots or width of the slots. In case of Hash-shaped slotted SIW antenna, the variations in lengths of the horizontal slots or variations in lengths of the vertical slots are performed in order to achieve variation in either of the dual frequencies of the antenna. Thus, the dual frequencies of 4.9 and 5.93 GHz can be independently controlled. Studies on parametric variations in either the length of the horizontal or vertical slot is carried out and is depicted in Fig. 13. (a) and (b) respectively. From the graphs, it can be inferred that on varying the length of the horizontal slot between 16 mm to 20 mm, changes in the lower resonance frequency is observed between 4.8 GHz to 5.17 GHz while the higher resonance frequency remains unaffected at 5.93 GHz. On the other hand, while varying the vertical slot of Hash-shaped Slot between 15 mm to 24 mm, it is clearly evident that there is almost no change observed

in lower resonance frequency while the higher resonance frequency changes between 5.22 GHz to 5.93 GHz. Thus, the dual frequencies can be independently controlled by varying either the length of horizontal slot or vertical slot of the proposed antenna.

A comparative study has been performed on the proposed dual band antenna with the reported literature as shown in Table III.

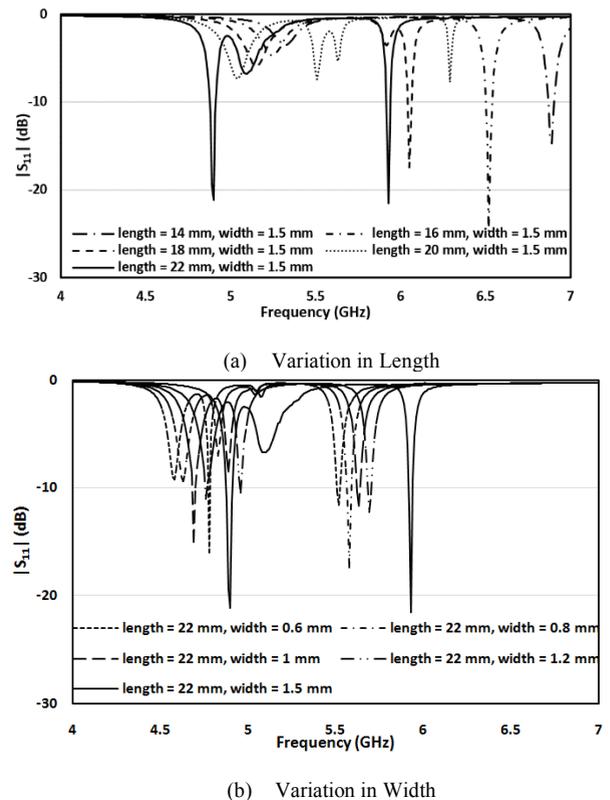


FIGURE 8. Parametric study of variation of reflection coefficient with change in (a). length (width fixed at 1.5 mm) and (b). width (length fixed at 22 mm) of the Hash-shaped slot antenna

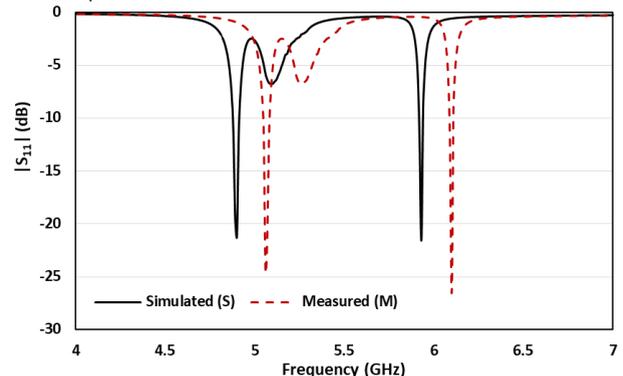


FIGURE 9. Simulated and Measured Reflection Coefficient of the proposed Hash-shaped slot SIW cavity backed antenna

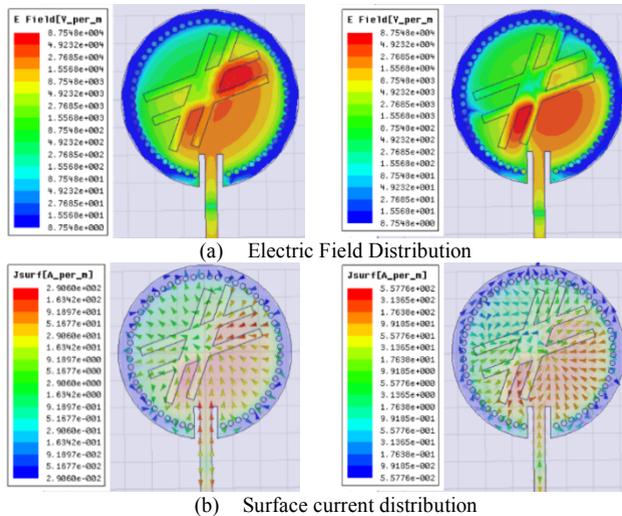


FIGURE 10. (a). Electric Field distribution and (b). Surface current distribution of the modified SIW based Circular cavity-backed hash-shaped slot antenna at 4.9 GHz and 5.93 GHz.

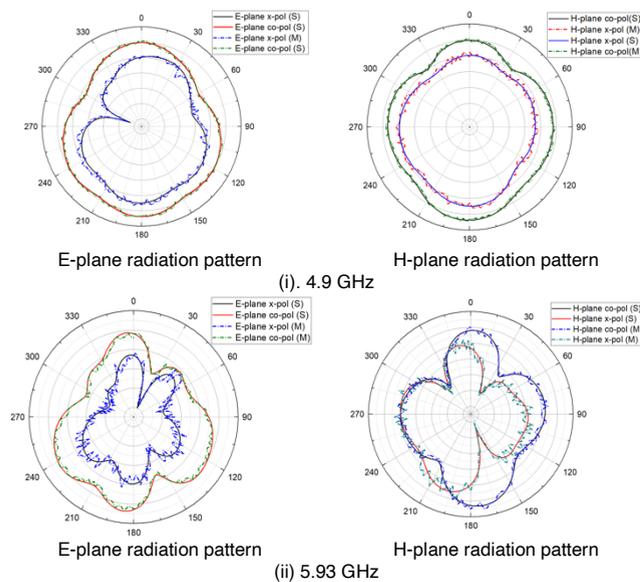


FIGURE 11. Simulated and measured radiation pattern of the SIW based Circular cavity-backed Hash-shaped slot antenna at (i). 4.9 GHz and (ii). 5.93 GHz

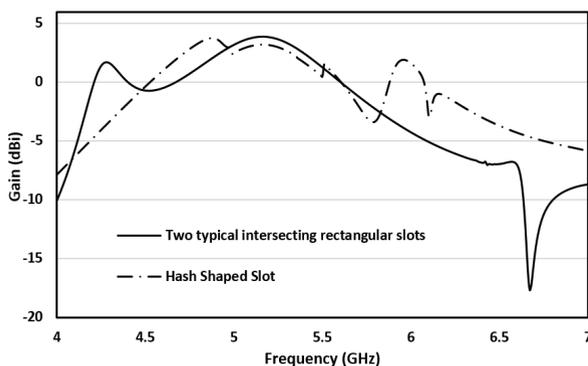
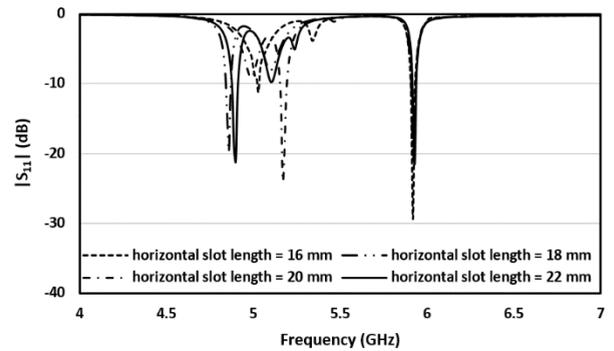
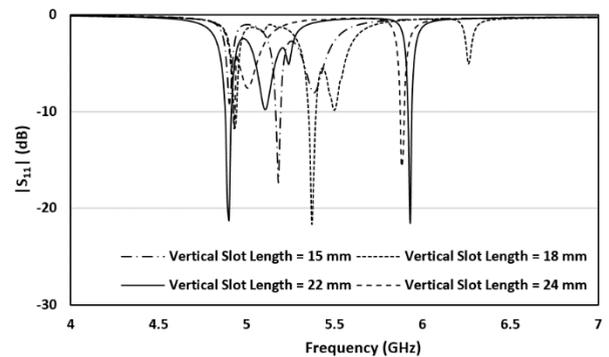


FIGURE 12. Effect of slots on gain of Antenna – II and Antenna - III



(a) Variation of Horizontal Slot of Hash-shaped slotted SIW antenna



(b) Variation of Vertical Slot of Hash-shaped slotted SIW antenna

FIGURE 13. Variation of length of (a) Horizontal slot for lower band frequencies and (b). Vertical Slot for higher resonance frequencies

IV. CONCLUSION

SIW based circular cavity-backed structure is initially designed and the cavity is excited with power fed through inset feed. Two-typical intersecting rectangular slots antenna are placed on the ground plane at a position with maximum field perturbation for radiation purpose. Thus the initially designed cavity-backed slot antenna so designed resonates at a centre frequency of 5.19 GHz in the IEEE 802.11a WLAN U-NII-1 band with a gain of 4 dBi. The antenna is modified to achieve dual-frequency operation through introduction of another shifted two-typical intersecting rectangular slots antenna giving it ultimate shape of a typical Hash. Now, the antenna resonates at dual band frequency of 4.9 GHz and 5.93 GHz with corresponding gain of 3.7 dBi and 1.4 dBi respectively. Thus, the dual-frequency antenna would be of immense help for public safety and U-NII-5 band and can also find wide application in the field of wireless technology under the IEEE 802.11a protocol.

TABLE III. Performance analysis of the proposed antenna with that of other similar type of antennas

Antenna	Frequency (GHz)	Substrate details	Reflection coefficient (dB)	Gain (dBi)	Impedance Bandwidth
Bow-tie shaped dual band SIW antenna [18]	8.28/ 10.16	Rogers RT Duroid 5880	~ -20/ ~ -22	5.3/ 4.4	600 MHz/ 888 MHz
Compact Dual-Band Antenna [19]	2.6/ 5.9	Rogers RO5880	< -10	3.11- 3.16 / 6.09 - 7.17	400 MHz/ 1600 MHz
Dual-Band Antenna Using Bilateral Slots [20]	9.85/ 14	RT/ duroid 5880	< -10	6.6/ 6.44	520 MHz/ 450 MHz
Integrated solar harvester using Textile antenna [21]	2.4/ 2.6	Textile	~-20 / ~ -30	4.7/ 5.1	409 MHz/-
Dumbbell Shaped SIW Slot Antenna [23]	9.5/ 13.85	Rogers RT Duroid 5880	~-23 / ~ -16	4.8/ 3.74	190 MHz/ 200 MHz
Proposed Work	4.9/ 5.93	Arlon AD270	- 21.13/ - 21.54	3.7/1.4	400 MHz/ 200 MHz

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