A Truly S-shaped Slot-loaded Broadband Microstrip Antenna for 5G Communication

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ABSTRACT In this paper, a compact, microstrip-fed, wide-band patch antenna with an S-shaped slot is proposed for 5G communication systems. Initially, a basic rectangular patch antenna with the modified ground plane is designed at the resonating frequency of 3.13 GHz, exhibiting a bandwidth of 830 MHz. Then, in the middle of the patch, a truly circular arch-based S-shaped slot is introduced to achieve wideband operation from 2.7 – 5.6 GHz, covering a part of the sub-6 5G communication band. With the introduction of the slot, the resultant antenna provides two resonating frequencies at 3.21 GHz and 5.45 GHz, corresponding to TM_{10} and $TM_{\delta 0}$ modes with a wide operating bandwidth of 2.9 GHz having an overall gain of approximately 2 dB at both the resonating frequencies. Afterward, to compare the performances of the proposed antenna with the truly S-shaped slot, another antenna with a conventionally used abrupt 90^0 bending S-shaped slot is also designed. Using fabricated prototypes, the simulated results of the antenna performances have been validated with experimental results. The comparative result illustrates that the proposed simple curved based compact design provides better or equivalent performances.

INDEX TERMS Broadband, microstrip patch antenna, slot in patch, impedance bandwidth, gain.

I. INTRODUCTION

Microstrip antenna (MSA) plays a vital role in present communication systems by virtue of its advantages, such as low profile and planar configuration. However, it exhibits lower bandwidth and larger patch size in the lower UHF band. The size of the antenna can be reduced through several miniaturization techniques such as, use of substrate with higher dielectric constant, placement of shorting post, cutting slots at appropriate positions and defected ground structure [1].

Over the years, MSA with various slot structures have been reported for wideband, ultra-wide band (UWB) and multiband communication for transmitting signals with high data rate. In [2], an antenna with U-slot embedded on an E-shaped patch is proposed for WLAN, Wi-Max, Wi-Fi 6E, and sub-6 GHz applications. In [3], a wide band circularly polarized S-shaped slot antenna with T-shaped feeding line for ISM band applications is reported. In [4], a printed wide slot circularly polarized (CP) antenna having inverted T shaped patch with a small notch is investigated for digital cellular system (DCS). A wideband dual CP compact antenna with L-shaped slot is proposed in [5]. Another compact CP antenna with square slot fed by a G-shaped feedline is proposed in [6]. An A-shaped coax fed broadband antenna is demonstrated for WLAN/ WiMAX/ UWB lower-band [7]. A monopole patch antenna with a V-shaped slot is designed for the car-to-car and WLAN communications [8]. Monopole antenna with circular slot [9] and M-shaped slot [10] are presented for ultra-wide band applications. In [11], a high gain wide band U-shaped patch antenna with two equal arms on poly tetra fluoro-ethylene substrate and with modified ground plane is presented for wireless communication systems. Circularly polarized, wide band, reconfigurable E-shaped patch antenna consisting of single-layer single-feed E-shaped slot with two RF switches is reported in [12-13]. A small printed antenna by reducing the effect of ground-plane [14] and a miniaturized wide-band half E-shaped patch antenna with half U-shaped slot [15] are reported for UWB applications.

Recently, S-shaped structure in MSA is also being used for 5G and THz communication systems. In [16], an S-shaped meta surface based wide band CP patch antenna has been proposed for C-Band applications. An inverted S-shaped microstrip antenna for 5G millimeter-wave applications was designed with a great performance that can effectively support the high data rate requirements of the 5G systems [17]. In [18] an S-shaped simple CP on-chip microstrip antenna is developed for THz communication. Another mid-band CP S-shaped slot antenna for 5G application was proposed in [19]. In [20], a simple structure having an S-shaped patch with a dual-band circular polarization is proposed to operate at 3.5 GHz and 5.8 GHz frequency range respectively. In another study [21], a linear array of S-shaped microstrip patch antennas is designed for use in wireless systems. A miniaturized S-shaped multi-slotted inset-fed hexagonal patch antenna was proposed for wireless applications in [22].

In [23], a dual-band microstrip printed quad port MIMO antenna with S and inverted C-shaped radiators was presented for multiband applications such as WLAN, LTE, etc. In [24], a compact S-shape microstrip patch antenna with rectangular slots loaded with open circuit stubs is presented for dual-polarized multiband and wide band response suitable for personal communication applications.

An S-shaped, efficient meander monopole antenna for WLAN/WiMAX/UWB applications was designed [25] to operate in S/C/X bands with a wide bandwidth of 12.55 GHz. In [26], the application of a novel S-shaped structure in a peach-like UWB antenna with dual band-notched characteristics is depicted. The S-shaped structure is composed of a square patch and two L-shaped slots with center symmetry. In another proposed design [27], four different stage-by-stage developments of an S-shaped meander line antenna generate three different bands of frequency, which can be used for the application of IoT and ISM band applications. The proposed antenna gives rise to the triple band resonant at the frequency of 1.9 GHz, 4.3 GHz, and 6.68 GHz, respectively. In [28], an array of novel S-shaped DRAs is proposed for 5G mobile networks.

In all the reported S-shaped slotted antennas [16 - 28], the intended structure is realized with the help of rectangular slots. Despite the curved gradual bending of S, the corresponding structure has abrupt 90^0 bending. Thus, the resultant shape is not an exact replica of S. In this paper, a basic rectangular patch antenna with FR4 dielectric substrate and modified ground plane is designed at the resonating frequency of 3.13 GHz. Then, an S-shaped slot, resembling the actual shape of the alphabet 'S' is introduced at the middle of the patch to achieve wide band operation from 2.7 – 5.6 GHz covering a part of the sub-6 5G communication band. Ansys make HFSS v19.0 is used to simulate the antenna parameters and the same have been compared with experimentally measured ones.

II. BROADBAND ANTENNA DESIGN AND CONFIGURATION

A. ANTENNA DESIGN

The geometrical configuration of the proposed truly S-shaped slot-loaded and the conventionally used abrupt bending S-shaped microstrip rectangular patch antennas are illustrated in Figure 1(a-d) while their typical design dimensions are enlisted in Table-1. The antennas are modeled with FR4 dielectric substrate with dielectric constant $\in_r = 4.4$, loss tangent $\tan \delta = 0.02$ and thickness h = 1.6 mm. The substrate for both the antenna is of dimension 38 mm (L) × 30 mm (W). The radiating patch in the form of a rectangular strip is of length L_p = 20 mm and width W_p = 18 mm. A microstrip feed line is placed on the same side as the radiating element to excite the latter centrally from the bottom edge. The feeding strip length, L_f and width, W_f are adjusted in a manner to achieve 50 Ω impedance matching with the antenna. The ground plane on the other side is modified, as shown in Figure 1(b, d), with dimensions L_g (= 9 mm)×W_g (= 30 mm). The designed antenna is made compact by introducing an S-shaped slot into the radiating patch. The antenna is developed by employing a truly S-shaped slot for Antenna – I and a conventional S-shaped slot for Antenna – II.

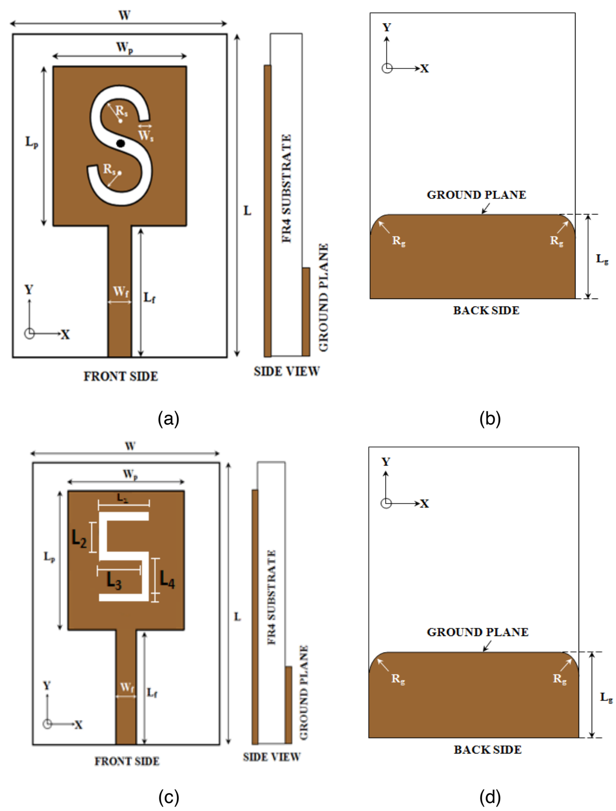


FIGURE 1. Analytical dimensions of two proposed S-shaped slotted patch antenna (Antenna – I and Antenna – II)

For Antenna 1, the truly S-shape is obtained by vertically making two three quarter circular ring slots and orienting them in opposite direction. For convenience, the middle point is indicated with a dot in Fig. 1(a). With inner radius R_e and width W_s, the equivalent mean radius of the circular slot becomes $R_e = R_s + \frac{W_s}{2}$ and the overall length of the slot can be calculated as $L_s = 2 \times \frac{3}{4} \times 2\pi R_e$. Through parametric study the optimum values of R_s and W_s are obtained as 3 mm and 1.5 mm respectively. Hence, the optimum length is calculated as 35.34 mm. The slot-loaded antenna (Antenna – I) is found to resonate at two frequencies, 3.21 GHz and 5.45 GHz, with an impedance bandwidth extending from 2.7 to 5.6 GHz covering the sub-6 5G communication band.

For Antenna – II, lengths of the different sections of the conventionally used S-shaped slot, as indicated in Fig. 1(c), are L1 = L3 = 8 mm, L2 = L4 = 6 mm, and width, W = 1.5 mm. The dimensions of the slot are optimized to achieve the best performance. Finally, Antenna – II operates at 3.11 GHz and 5.24 GHz with 2.53 – 5.53 GHz impedance bandwidth.

TABLE 1. Typical dimensions of various parameters of the proposed antennas (in mm)

Antenna – I (Truly S-shaped slot)		Antenna – II (Conventional S-shaped Slot)	
Parameter	Value (mm)	Parameter	Value (mm)
L	38	L	38
W	30	W	30
L_p	20	L_p	20
W_p	18	W_p	18
L_f	15	L_f	15
W_f	3	W_f	3
L_g	9	L_1	8
R_g	5	L_2	6
R_s	3	L_3	8
W_s	1.5	L_4	6
		W_s	1.5

B. DESIGN EQUATIONS

The resonating frequency of the rectangular patch antenna for the dominant mode TM_{10}, with dimensions $L_p \times W_p$, is given by the expression [29].

$$(f_r)_{010} = \frac{1}{(2L\sqrt{\varepsilon_r}\sqrt{\mu_0\epsilon_0})} = \frac{c_0}{(2L\sqrt{\varepsilon_r})} \quad (1)$$

Now, considering fringing effects, the above expression is modified as

$$(f_{rc})_{010} = \frac{1}{(2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\epsilon_0})} \quad (2)$$

where $L_{eff} = L + 2\Delta L$ with ΔL being the change in length due to fringing effect and is given as

$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad (3)$$

$$\varepsilon_{reff} = \frac{1}{2}\left[(\varepsilon_r + 1) + (\varepsilon_r - 1)\left(1 + \frac{12h}{W_f}\right)^{-\frac{1}{2}}\right] \quad (4)$$

After simulation of the patch antenna, the simulated value for the resonant frequency is obtained as 3.13 GHz. The slot-loading technique is very obvious for broadband operation in the case of microstrip antennas with thin dielectric substrates and to achieve an overall 2 – 3 times impedance bandwidth as compared to its counterpart without a slot.

III. RESULTS AND DISCUSSIONS

A truly S-shaped slot is incorporated in the patch to obtain broadband antenna performance. The dimensions of both the slots are optimized to excite the patch surface current densities of the TM_{10} and $TM_{\delta 0}$ modes and to obtain better performance of the antenna with respect to bandwidth, return loss and gain. Upon optimization, through slot length and width variation, the excited surface current densities for TM_{10} and $TM_{\delta 0}$ modes can be suitably perturbed such that these two modes are excited at adjacent frequencies with the ratio of the two resonant frequencies less than about 1.68, which results in a wide operating bandwidth.

A. ANTENNA – I: PARAMETRIC STUDY

The parametric study involving variation of the inner radius R_e such that length L_s changes from 35 – 37 mm and variation in width W_s from 1 – 2.25 mm of the S-shaped slot are depicted in Figures 2(a) and 2(b) respectively. From the figures it is quite evident that for L_s = 36 mm and W_s =

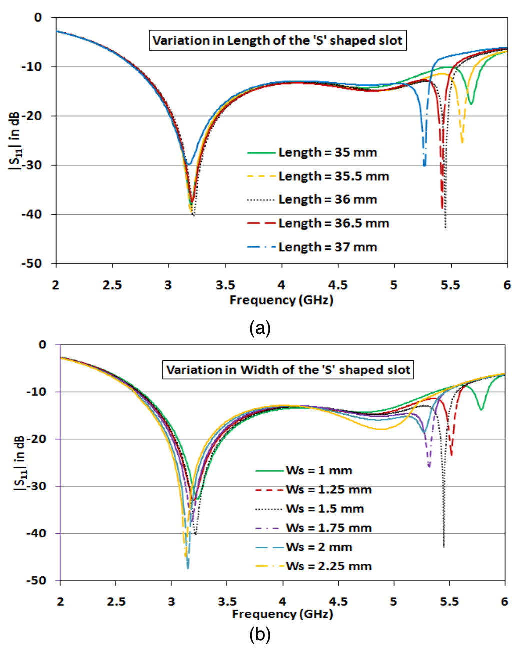


FIGURE 2. Parametric study of the proposed antenna by variation of (a) length and (b) width of the slot

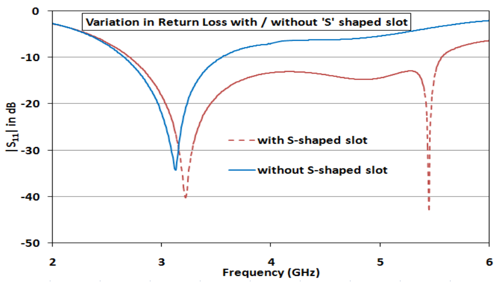


FIGURE 3. Plot of return loss characteristics of the antenna with and without slot

1.5 mm, the antenna performance is better in terms of return loss and operating bandwidth which extends from 2.7 to 5.6 GHz covering a part of the sub-6 5G communication band. Hence the antenna resonating at the two frequencies of 3.21 GHz and 5.45 GHz depicts a wide operating bandwidth of 2.9 GHz. A plot of optimized reflection coefficient characteristics of the antenna with and without slot is depicted in Figure 3.

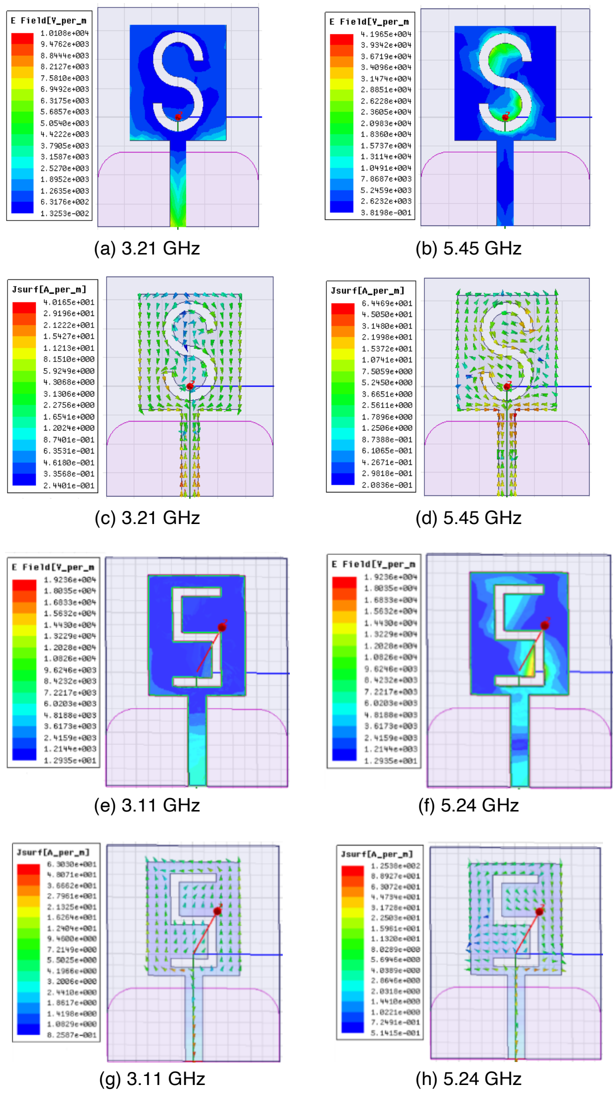


FIGURE 4. Electric field and Surface current distributions at the respective resonant frequencies of Antenna – I (a – d) and Antenna – II (e – h).

The electric field and the surface current distributions of the proposed broadband antenna at the two resonating frequencies of 3.21 and 5.45 GHz are depicted in Fig. 4 (a – d). It shows that, at 5.45 GHz, the current is mostly surrounded in the two circular ring having length closed to the corresponding guided wavelength. These results show that the proposed antenna provides good impedance matching within the sub-6 5G communication band and finds its suitability to be used for wireless communication systems in case of 5G communication.

B. ANTENNA – II: PARAMETRIC STUDY

The lengths (L_1, L_2, L_3 and L_4) and widths (W) of the antenna are optimised to obtain the desired result in terms of bandwidth with two resonant frequencies, gain and return loss. Best optimised results are obtained for $L_1 = L_3 = 8$ mm, $L_2 = L_4 = 6$ mm and $W = 1.5$ mm. The electric field distribution and the surface current distributions of the corresponding antenna at the two resonating frequencies of 3.11 and 5.24 GHz are depicted in Figure 4 (e – h).

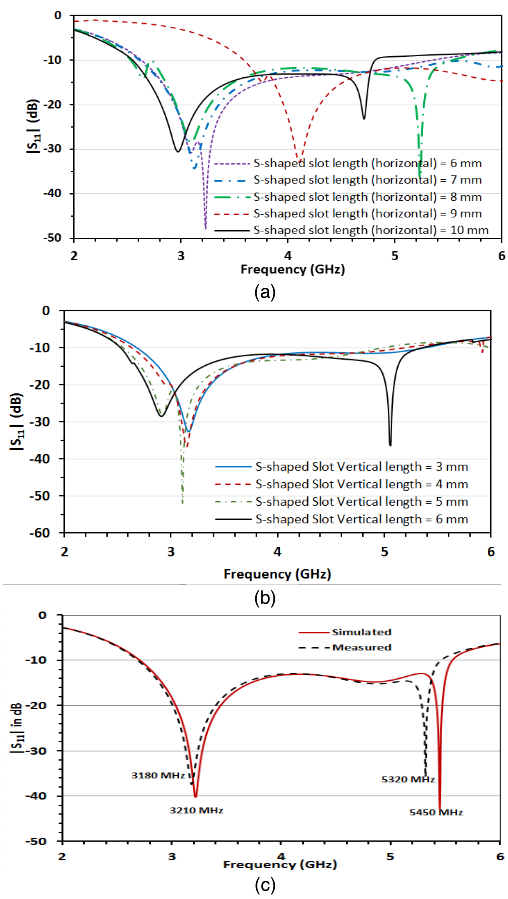
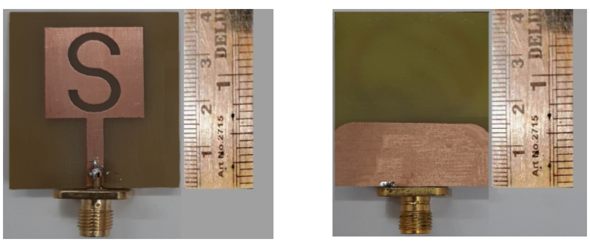


FIGURE 5. Parametric study of Reflection coefficient by variation of (a) horizontal length, (b) vertical length and (c) width of Conventional S-shaped Slot

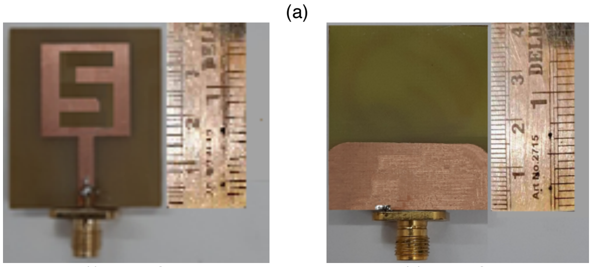
The horizontal lengths (L_1, L_3) of the conventional S-shaped slot are changed from 6 mm to 10 mm while the vertical lengths (L_2, L_4) are changed from 3 mm to 6 mm as shown in Figure 5 (a, b). It is evident from the figure that, both the resonance frequencies are affected with changes in the slot length. Due to increase in slot width, the S_{11} characteristics in Fig. 5(c) are not so varied at lower frequencies while the prominent variations at higher resonance. The antenna impedance bandwidth is observed about 3 GHz ranging between 2.53 – 5.53 GHz.

To experimentally validate the simulation results, prototype of both the proposed antennas are fabricated, as shown in Figure. 6. The S_{11} characteristics of both the fabricated prototype are measured using Anritsu make VNA Model MS2025B and the same along with the simulated results are plotted in Figure 7. For Antenna – I, the simulated values of S_{11} at two resonant frequencies, 3.21 GHz and 5.45 GHz are obtained as -40 dB and -43 dB. The experimental result shows two resonances at 3.18 GHz and 5.32 GHz with S_{11} values of -37 dB and -36 dB, respectively. For Antenna –II, the simulated value of S_{11} is obtained as -28.13 dB and -36.35 dB at 3.11 GHz and 5.24 GHz while its measured value is -32.51 dB and -38.06 dB at 3.04 GHz and 5.16 GHz, respectively. The measured impedance bandwidth is approximately 3 GHz for both the antennas extending from 2.7 to 5.6 GHz for Antenna – I and 2.49 – 5.46 GHz for Antenna – II. From the plot it can be observed that the measured result shows broadband characteristics in close proximity with the simulated ones. The slight deviation between simulated and measured return loss characteristics is observed due to connector mismatch and the antenna fabrication error.



(i) Front Side (ii) Back Side

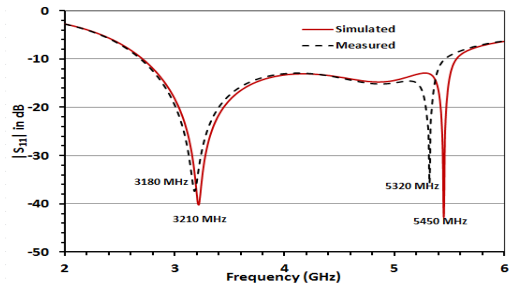
(a)



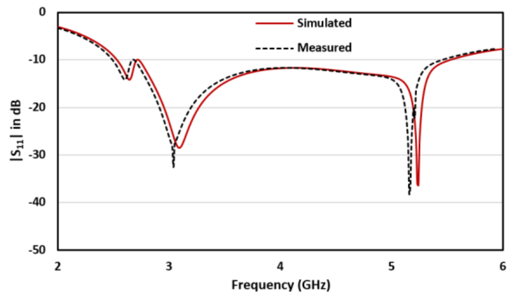
(i) Front Side (ii) Back Side

(b)

FIGURE 6. Fabricated prototype of the proposed (a) Truly S-shaped slotted patch antenna (b) Conventional S-shaped slotted patch antenna



(a)



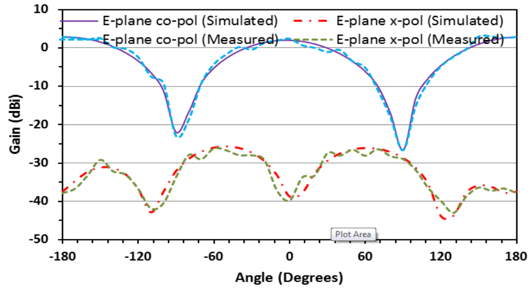
(b)

FIGURE 7. Plot of simulated and measured reflection coefficient characteristics. (a) Antenna – I, (b) Antenna – II.

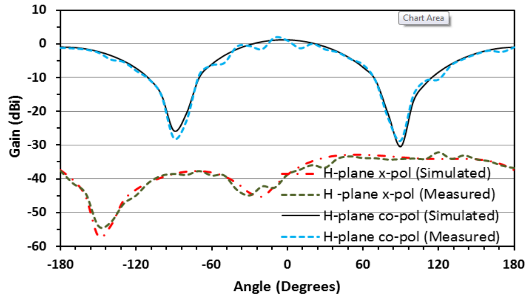
The radiation pattern characteristics are measured using gain transfer method for both the antennas (Antenna-I and Antenna-II). The measurement system consists of a Hittite HMC-T2100 Microwave Signal Generator (10 - 20 GHz), a Krytar 9000B Power Meter and a Horn antenna as shown in Fig. 8. At the two resonant frequencies, the simulated and measured co-pol and cross-pol characteristics of Antenna –I and Antenna - II at E- plane and H-plane are compared in

FIGURE 8. Experimental setup for the measurement of the radiation pattern

Figure 9 (a, b). For Antenna – I, the simulated and measured gain at E-plane (co-pol) are obtained as 1.9 dBi and 2.3 dBi at 3.21 GHz while the corresponding values at H-plane are 1.2 dBi and 1.0 dBi, respectively. At 5.45 GHz, the E-plane simulated and measured gains are found as 2.3 dBi and 1.8 dBi and the corresponding H-plane values are 2.1 dBi and 2.4 dBi, respectively. For Antenna-II, the simulation and measurement co-pol gains in E-plane are found as 1.9 dBi and 1.7 dBi at 3.11 GHz and 1.5 dBi and 1.3 dBi at 5.24 GHz, respectively. The corresponding H-plane co-pol gains at 3.11 GHz are obtained as 1.6 dBi and 1.2 dBi, and at 5.24 GHz their values are 1.4 dBi and 1.3 dBi, respectively. It can be seen that, the cross-pol gain for all the resonant frequencies is found to be 20 – 30 dBi below their co-pol gain. The performances of both Antenna–I and Antenna–II in terms of S_{11} characteristic and impedance bandwidth are compared in Table 2. It is quite evident that both the antennas do not show much deviation in their performances. Both antennas show fair radiation pattern and gain at the desired working band of wireless communication system in the 5G mid-band and sub-6 5G band.



(i)



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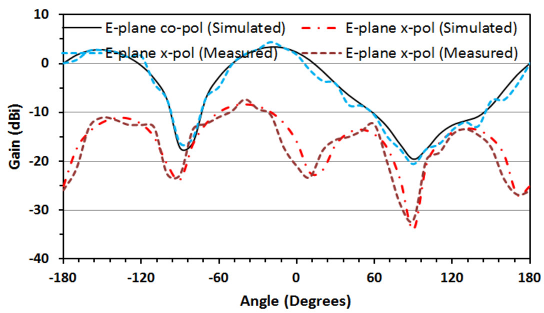

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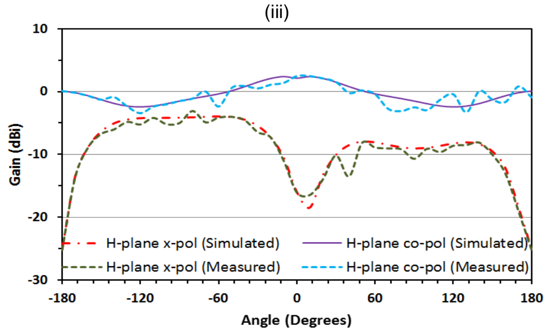
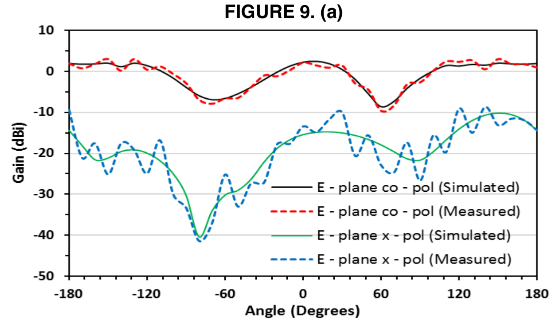


(iv)

FIGURE 9. (a)



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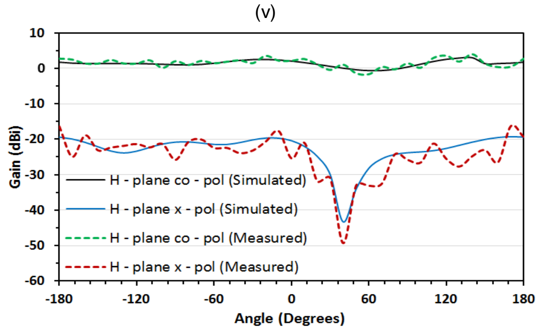

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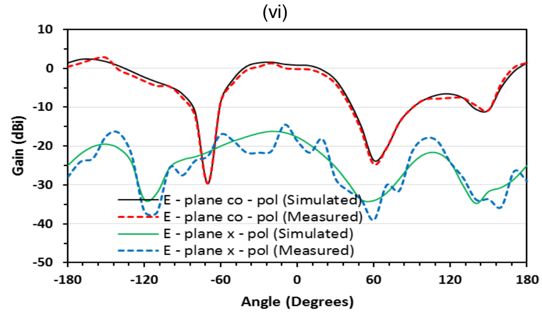

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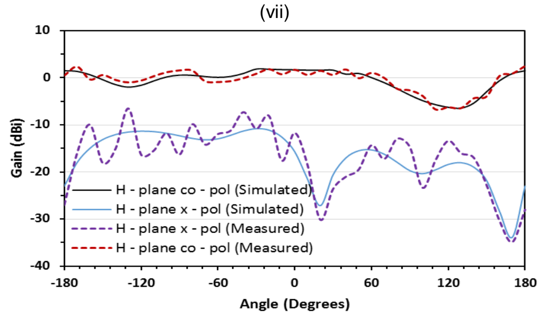

(viii)

FIGURE 9. (b)

FIGURE 9. Plot of simulated and measured radiation patterns. (a) Antenna – I at E-plane : (i) f = 3.21 GHz, (iii) f = 5.45 GHz; H-plane: (ii) f = 3.21 GHz, (iv) f = 5.45 GHz (b) Antenna – II at E-plane: (v) f = 3.11 GHz, (vii) f = 5.24 GHz. H-plane: (vi) f = 3.11 GHz, (viii) f = 5.24 GHz

TABLE 2. Comparison between parameters of Antenna –I and Antenna – II

Type of Slotted Antenna	Operation Frequency (GHz)	Reflection Coefficient (dB)	Gain (dBi)	
			E-plane (S)	H-plane (S)
Antenna – I	3.21/5.45	-39.9/42.7	1.9/2.3	1.2/2.1
Antenna – II	3.11/5.24	-28.13/-36.35	1.9/1.5	1.6/1.4

IV. PERFORMANCE ANALYSIS AND COMPARATIVE STUDY

The performances of the proposed compact S-shaped slot loaded wide band patch antenna with other similar types of antennas available in the literature are enlisted in Table 3. The proposed antenna is functional for sub-6, 5G and 5G mid band wireless communication applications at 3.11 to 5.45 GHz with compact architecture. It can be seen that as compared to the reported work, the proposed simple and compact antenna structure provides wide band characteristics with satisfactory gain.

TABLE 3. Performance of the proposed antenna with other similar types of reported antennas

Antenna	Frequency (GHz)	Gain (dBi)	Impedance Bandwidth	Overall Dimension
U-slot E-Shaped Broadband [2]	4.7-9.2	10.6	64.7%	$1.4\lambda_0\times1.4\lambda_0\times0.1\lambda_0$
S-shaped Wide band [3]	1.66-3.44	2.1-5.4	68.1%	$0.85\lambda_0\times0.85\lambda_0\times0.02\lambda_0$
Compact Broadband [7]	2.4/5.2/5.8	1.5-3.5	93.18%	$0.48\lambda_0\times0.38\lambda_0\times0.011\lambda_0$
U-Shaped Wide band [11]	4.5-11.4	4.1	86.79%	$0.85\lambda_0$ (diameter)
Metasurface-based Wide band [16]	4.05-6.6	6.16	43.22%	$0.6\lambda_0\times0.6\lambda_0$
Proposed Antenna	3.11-5.45	2.3	75.43%	$0.52\lambda_0\times0.41\lambda_0$

V. CONCLUSION

Two S-shaped slotted, compact, broadband rectangular patch antennas with modified ground plane have been proposed for sub-6 5G communication system. The basic rectangular patch antenna is modified with the inclusion of a truly and conventional S-shaped slot for compactness and wide-band operation. Both the broadband antennas depict an approximate 3 GHz wide bandwidth with approximately 2 dBi gain. In comparison to other available structures, the proposed antenna resonates at the center frequencies of 3.21 and 5.45 GHz with a bandwidth covering the sub-6 5G band. The measurement result shows that both the broadband antennas can achieve the desired radiation pattern with optimum gain that is useful for sub-6 5G and 5G mid-band wireless applications. Thus the designed antennas are effective for 5G applications and is expected to open up new vistas for research amongst the researcher community worldwide.

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