Progress In Electromagnetics Research C, Vol. 145, 107-117, 2024

PIER C

(Received 6 May 2024, Accepted 11 July 2024, Scheduled 21 July 2024)

# Gap-Coupled Designs of Hexagonal Microstrip Antennas on Thinner Substrate Using Cavity-Backed Structure

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**ABSTRACT:** Multi-resonator gap-coupled design of coaxially fed half-hexagonal microstrip antennas is proposed in 900 MHz frequency range. It yields an impedance bandwidth of 32 MHz (3.28%) on a thinner FR4 substrate ($\sim 0.01\lambda_g$). Reduction in patch area in the gap-coupled design is achieved by employing the ground plane slots. Slots reduce the fundamental mode resonance frequency on each patch, thereby realizing wideband response in a lower frequency region. With impedance bandwidth of 26 MHz (3.4%), slot cut ground plane design provides patch area reduction by 38.13% and frequency reduction by 21.8%. Enhancement in the broadside gain on a thinner lossy substrate in the gap-coupled designs is achieved by integrating a cavity-back structure which provides gain increment by nearly 2.5–3 dBi. Thus, the proposed work outlines a technique that enhances the bandwidth and reduces the patch size with an increment in the gain, on a thinner lossy substrate. An experimental verification for the obtained results is carried out that shows a close agreement.

## 1. INTRODUCTION

Microstrip antenna (MSA) finds maximum usage in wireless application owing to its numerous advantages like low profile and planar configuration [1]. The radiating patch in MSA can take any shape, but regular shapes are preferred due to their fabrication simplicity [1]. Circular MSA offers harmonic rejection for the input radio frequency (RF) signal as its fundamental and higher order resonant modes do not appear in a harmonic progression [1]. Against circular shape, hexagonal MSA (HMSA) is preferred since it has a wider gap-coupling area. In the initial days, MSAs were regarded as a lower bandwidth (BW) configuration, but over the last three–four decades, many techniques are evolved to enhance BW. BW enhancement is possible with the presence of multiple resonant modes in the patch. This is achieved by employing techniques like multi-resonator gap-coupled and stacked configurations [2–8], use of modified shape of the radiating patch [9], resonant slots cut MSAs [10–12], and modified ground plane structures [13–19]. The modified ground plane designs that offer reduction in the patch resonance frequency do not add to the BW. Of the many techniques reported for BW enhancement, gap-coupling method is the simplest one. These multi-resonator designs provide a gain larger than 10 dBi [3–8], but they require larger patch size. While considering a smaller size solution in the gap-coupled antenna, a thinner substrate is used to provide a cost effective solution, and a cheaper but lossy substrate is selected. However, the gain in these designs is poor. In this regard, there exists a research gap to achieve a cost effective solution for a wideband gap-coupled antenna that offers moderately large antenna gain on a thinner substrate but with a reduction in total patch size. The work presented in this paper attempts to address this gap with an innovative technique, employing gap-coupled design and cavity backed slot cut ground plane.

Gap-coupled variations of half hexagonal MSA (H-HMSA) with HMSA on a thinner FR4 substrate ($\varepsilon_r = 4.3$, $\tan\delta = 0.02$, $h = 0.16$ cm) backed by conventional and rectangular slots cut ground plane are proposed in this study. Initially, the design with conventional ground plane is discussed. An optimum response in terms of BW and less increment in the overall patch size is achieved in the gap-coupled design of fed HMSA with parasitic H-HMSAs. It yields simulated and measured BWs of 3.28% on a thinner FR4 substrate. Reduction in patch size in the gap-coupled design is achieved by embedding rectangular slots on the ground plane, which lie below the fed and parasitic patches. The slots on the ground yield reduction in the fundamental mode frequency on fed and parasitic patches thereby yielding wider BW in the lower frequency region. On a thinner FR4 substrate it offers simulated and measured BW of 3.4%. Against the conventional ground plane design, a gap-coupled antenna employing slot cut ground plane achieves patch area reduction by 38.13%. Since a thinner FR4 substrate is employed in the gap-coupled designs, broadside antenna gain is lower. The gain increment is achieved by using the cavity-backed configuration. Aperture of the gap-coupled antenna is increased gradually using the ground plane dimension flaring, and through the parametric study, the optimum configuration was obtained. In the two designs, by employing cavity-backed designs, increment in the broadside gain by 2.5–3 dBi is achieved. This value is notable since the same is achieved on a low-cost lossy thinner substrate.

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When a cost-effective solution for a lower thickness antenna is needed, an FR4 substrate is the designer's choice. The primary drawback of the simplified gap-coupled technique is a larger patch size, and the reported literature provides no solutions to reduce it on a thinner lossy substrate. To bridge this research gap, current study offers an easy approach for minimizing the patch size in gap-coupled antennas, by first selecting the compact half wavelength resonators in the form of H-HMSA, and further by employing a slot cut ground plane. Further, on a thinner substrate, gain enhancement is achieved by using a simple cavitybacked structure. These are the technical contributions made in the proposed study. The proposed configurations are simulated using IE3D antenna simulation software [21]. An SMA connector with an inner probe radius of 0.6 cm is used to feed the MSA. Measurements are carried out using high-frequency instruments, specifically ZVH-8, FSC-6, and SMB 100A. A good match is achieved between the measured and simulated data.

## 2. GAP-COUPLED VARIATIONS OF HMSA AND H-HMSAS

Gap-coupled designs of a circular MSA (CMSA) and rectangular MSA (RMSA) have been reported in the literature [1]. Since the fundamental and higher order resonant modes in CMSA do not appear in a harmonic progression, the circular patch offers the rejection for harmonic frequencies as supplied by the RF source [1]. Gap-coupled designs of CMSA have been reported [1]. However, the gap-coupling is poor between the fed and parasitic patches, as it takes place through a tangential point that exists between the two circular patches. The HMSA has similar resonant field and frequency distributions as that of the circular patch [1]. In addition, HMSA has wider edges through which the gap-coupling can take place when being used in a multi-resonator configuration [1]. For these reasons, HMSA is selected in a gap-coupled design ahead of CMSA in this study. Fig. 1(a) depicts the design of gap-coupled HMSAs employed with a conventional ground plane. The conventional one refers to the rectangular shape of the ground plane. The paper refers to the patch dimensions and frequencies in 'cm' and 'MHz', respectively. Initially, the designs are analyzed using infinite ground plane in IE3D simulations. An infinite ground plane is selected to reduce the computation time in simulations and to get quick estimate of the BW in each gap-coupled designs. Later, the optimum of the gap-coupled design is studied using finite ground plane of length $L_g$ and width $W_g$ cm. The central coaxially fed HMSA denoted as '$M$' in Fig. 1(a), with radius '$R$' on a single-layer FR4 substrate, is intended to resonate at the fundamental $TM_{11}$ mode frequency of 900 MHz. The coupling of electromagnetic energy through the fringing fields from the patch edges excites the parasitic patches [1]. For the given coaxial feed position and $TM_{11}$ mode of excitation on the fed HMSA, parasitic patches when being placed along the $x$- or $y$-axis of the fed HMSA will result in a poor gap-coupling. Hence, the combination of parasitic patch placements along the horizontal and vertical axes together around the fed HMSA is chosen. This results in two symmetrical gap-coupled variations, the first one with patches $P_1$, $P_2$, and $P_3$ of radius $R_1$ around the fed patch $M$ and the second one with patches $P_4$, $P_5$, and $P_6$ with radius $R_2$ around the coaxially fed HMSA. Gap-coupled designs are optimized for the wideband response using the parametric optimization in the '$R_1$', '$R_2$', and '$g$' values [1]. As the BW optimization process for gap-coupled design is well described in the literature [1], it is not discussed here. The '$g$' refers to the air gap between the fed and parasitic patches. Various antenna dimensions in the optimized gap-coupled HMSAs designs, as provided in Fig. 1(a), are '$R$' $=$ '$R_1$' $= 5.1$, '$R_2$' $= 4.9$, '$g$' $= 0.4$, '$x_f$' $= 3.3$ cm. As compared to a 15 MHz (145%) of reflection coefficient ($S_{11}$) BW obtained in a single HMSA, the gap-coupled antenna considering patches $P_1$, $P_2$, and $P_3$ or the patches $P_4$, $P_5$, and $P_6$, yield simulated BW of 29 MHz as mentioned in Fig. 1(c). With all the six patches present, i.e., $P_1$–$P_6$, the gap-coupled antenna offers simulated BW of 39 MHz, as shown in Fig. 1(c). However, the placement of six patches around the fed patch increases the total patch area. At the fundamental mode, when there exists a symmetry of the resonant fields across the feed point axis, a compact variation can be realized by using half of the patch [1]. Using this concept, combinations of parasitic H-HMSAs and coaxially fed HMSA have been employed to realize compact gap-coupled designs as shown in Fig. 1(b). On an FR4 substrate, a coaxially fed HMSA, denoted as '$M$', is gap-coupled with the parasitic H-HMSAs '$P_7$', '$P_8$', and '$P_9$' with radius $R_3$, and '$P_{10}$', '$P_{11}$', and '$P_{12}$' with radius $R_4$, respectively. Parametric optimization for the BW is carried out by varying the parasitic patch radius with respect to the fed patch, air gap between the patches, and the position of the parasitic patches. The $S_{11}$ BW plots for different combinations of parasitic patches are given in Fig. 1(c). The obtained BW is governed by the amount of gap-coupling between the fed and parasitic patches in each configuration; hence it varies amongst the various designs. Designs that employ H-HMSAs as the parasitic elements yield wider impedance BW than the HMSA as the parasitic patches. Due to half of the patch geometry in H-HMSA, impedance of the radiating slots across the perimeter of hexagonal patch increases, which increases the magnitude of impedance variation across the H-HMSA resonant dimension [1]. This results in stronger mutual coupling between the fed HMSA and parasitic H-HMSAs, which results in larger loop size in the Smith chart to yield wider $S_{11}$ BW [1].

With patches $P_7$–$P_9$, gap-coupled design offers simulated BW of 39 MHz whereas with patches $P_{10}$–$P_{12}$, gap-coupled antenna provides simulated BW of 38 MHz. The design of fed HMSA with gap-coupled H-HMSAs ($P_7$–$P_{12}$) yields optimum results in terms of BW. Its antenna parameters are '$R$' $= 5.05$, '$R_3$' $= 4.3$, '$R_4$' $= 4.4$, '$g$' $= 0.1$, '$x_f$' $= 3.3$ cm. On an infinite ground plane, the antenna offers simulated BW of 48 MHz as mentioned in Fig. 1(c). Against the single patch, this BW is three times larger in s gap-coupled compact antenna employing parasitic H-HMSAs. In terms of $S_{11}$ BW, since this is the optimum configuration amongst all the HMSA and H-HMSA variations, the response of this gap-coupled antenna was verified using finite ground plane of dimension, width '$W_g$' $= 22$, length '$L_g$' $= 30$ cm. The results for gap-coupled design of H-HMSAs ($P_7$–$P_{12}$) with HMSA backed by finite ground plane are shown in Fig. 1(d). The simulated and measured BWs are

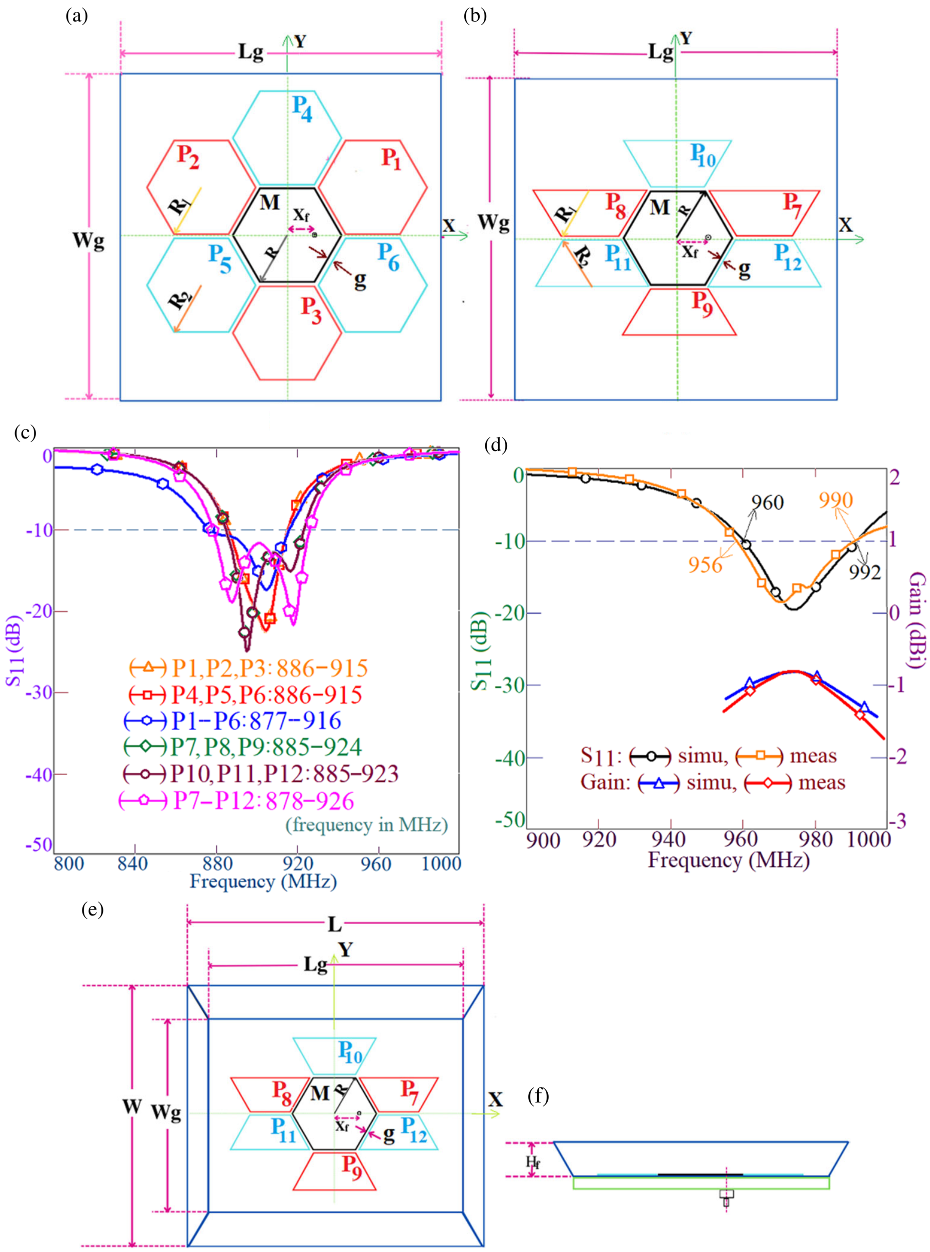


**FIGURE 1**. Gap-coupled configuration of (a) HMSAs and (b) H-HMSAs, and (c) simulated $S_{11}$ BW plots for gap-coupled combinations of fed and parasitic HMSA and H-HMSAs, (d) $S_{11}$ BW and gain plots for optimum design of gap-coupled H-HMSAs on finite ground plane, (e) top and (f) side view of gap-coupled H-HMSAs employing cavity-backed structure.

32 MHz (3.28%) and 34 MHz (3.49%), respectively. Against the infinite nature of the ground plane and substrate, finite ground plane is not a lossy cavity, due to which $S_{11}$ BW is smaller. Gap-coupled antenna exhibits broadside radiation pattern over the BW with $E$-plane directed along $\Phi = 0°$. Owing to a thinner lossy substrate, broadside antenna gain is lower than 0 dBi.

For the gain enhancement, different techniques like the use of thicker substrates, implementation of slots, and use of metamaterial, EBG, and FSS structures are discussed in the literature. These methods increase the design complexity and cost of the configuration. As the proposed configuration employs a thinner substrate, modifications are realized in the antenna geometry in the form of cavity-backed structure as shown in Figs. 1(e), (f) [6–8, 20]. With reference to the ground plane dimensions, cavity-backed dimensions are selected, and using the flaring, their dimensions are increased to create a large aperture [6–8, 20]. This helps in focusing the radiating energy in the broadside direction that achieves improvement in the gain. The cavity-backed design is used only for the gain improvement without affecting the %BW and polarization of the original gap-coupled antenna. Hence, a parametric study is carried out for the various parameters of cavity like '$W$' concerning '$W_g$' and '$L$' with respect to '$L_g$'. Based on this, optimized

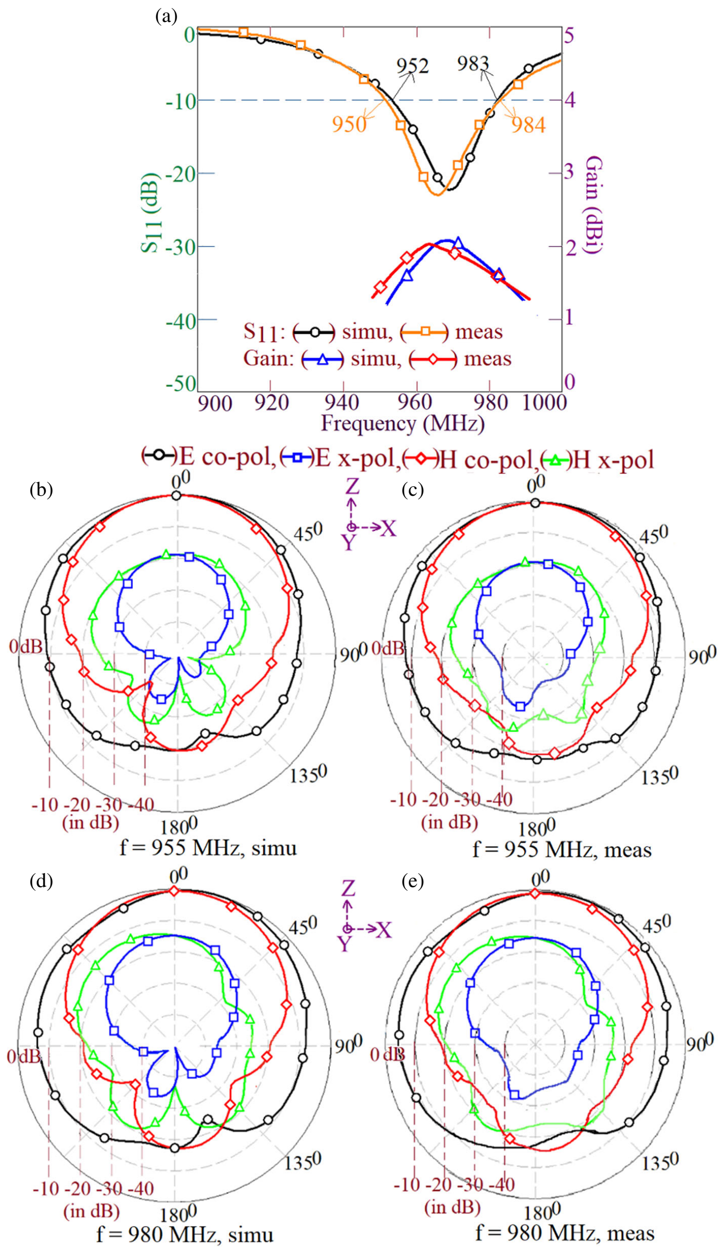


**FIGURE 2**. (a) $S_{11}$ BW and broadside gain plots and (b)–(e) radiation pattern nearer to band start and stop frequencies of BW for gap-coupled HMSA with H-HMSAs employing cavity-backed structure.

dimensions of the cavity integrated with the gap-coupled H-HMSAs are '$L$' $= 36$, '$W$' $= 28$, '$H_f$' $= 10$ cm, and the corresponding results are displayed in Fig. 2(a). The simulated and measured BWs are 31 MHz (32%) and 34 MHz (352%), respectively. The antenna offers simulated and measured broadside gains of 2.1 dBi and 2.0 dBi, respectively. As per Figs. 2(b)–(e), radiation patterns observed near the band start and stop frequencies of $S_{11}$ BW are along the broadside directions with $E$- and $H$-planes aligned along $\Phi = 0°$ and $\Phi = 90°$, respectively, with a cross-polar level less than 15 dB compared to co-polar level. Thus, by employing a cavity-backed structure in the gap-coupled design, improvement in the broadside gain by nearly 3 dBi is achieved.

To understand the increment in gain due to the cavity-backed design, average and vector surface current distributions for the gap-coupled HMSA with and without cavity-backed configuration are studied, as provided in Figs. 3(a) and (b). As noted with the cavity-backed structure, surface currents distributions are directed along the horizontal direction on the patch and ground plane that helps in focusing radiated energy in the broadside direction. This helps in achieving the gain increment. The fabricated prototype along with the impedance and pattern, gain measurement setup for the gap-coupled H-HMSA with cavity-backed structure is provided in Figs. 3(c) and (d). The impedance measurement was performed using a vector network analyzer (ZVH-8), and pattern and broadside gain were measured using a spectrum analyzer (FSC-6) and an RF source

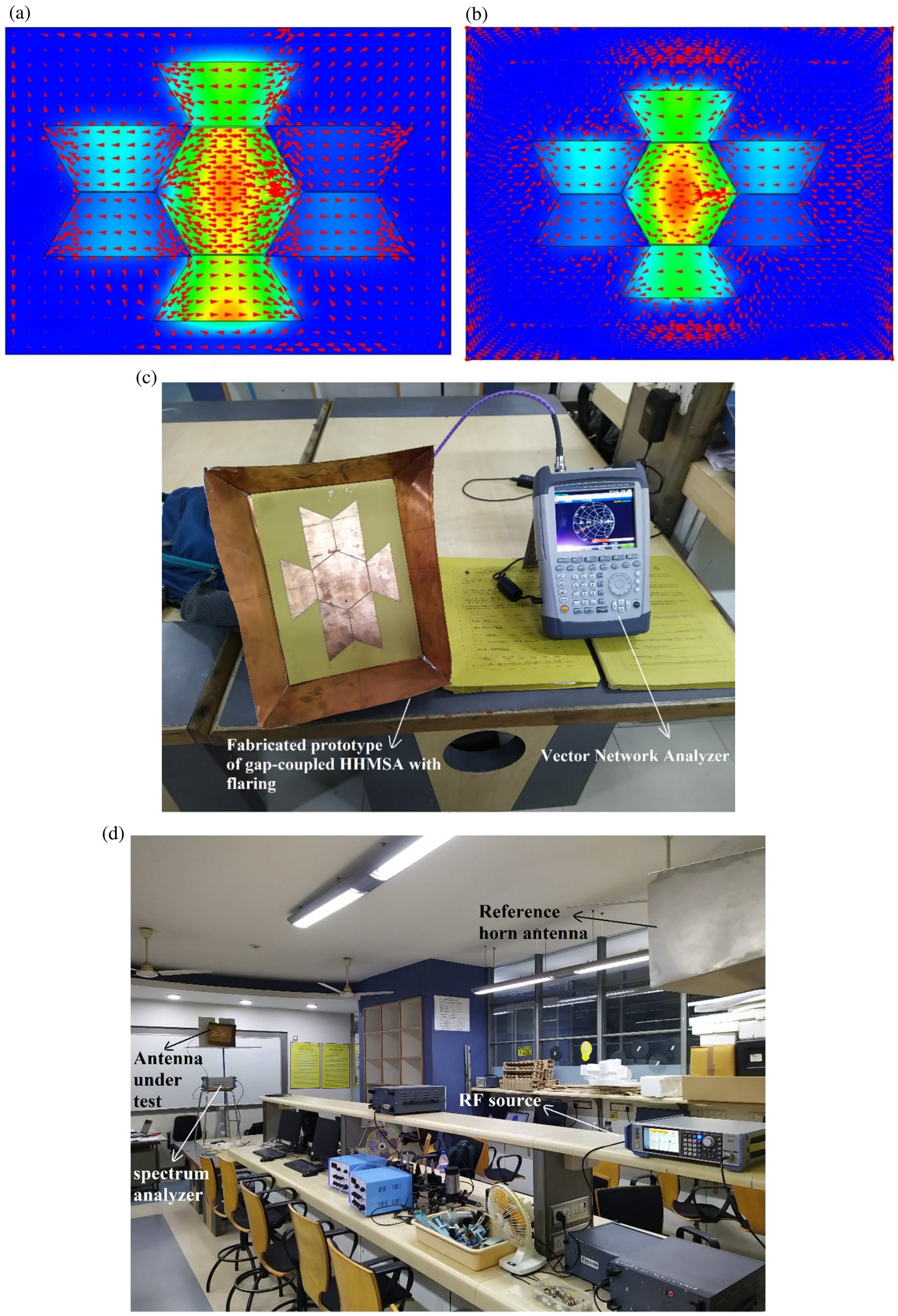


**FIGURE 3**. Average and vector surface current distribution for (a) gap-coupled design and (b) cavity-backed gap-coupled design, (c) impedance and (d) radiation pattern, gain measurement setup.

(SMB 100A). Reference wideband and high gain horn antennas are selected in the measurement. Three-antenna method is used to measure the antenna gain because it is an accurate procedure that can be used inside the laboratory.

## 3. GAP-COUPLED VARIATIONS OF H-HMSAS EMPLOYING GROUND PLANE SLOTS

A limitation of the gap-coupled design is the increase in antenna size. In MSA, patch size reduction is achieved by cutting the slot [1]. To reduce the patch size in MSA, a slot on the ground plane or on the patch is considered. The slot on the ground plane yields better control of input impedance with an equivalent reduction in the resonance frequency against the slot on the patch [22]. Hence, a slot on the ground plane is considered in this study. A thin rectangular slot of dimensions '$L_s$' and '$W_s$' is placed below the center of each of the fed and parasitic patches as shown in Fig. 4(a). This slot position is orthogonal to the $TM_{11}$ mode surface currents. The effects of modifications in the ground plane surface currents with the slot are linked to

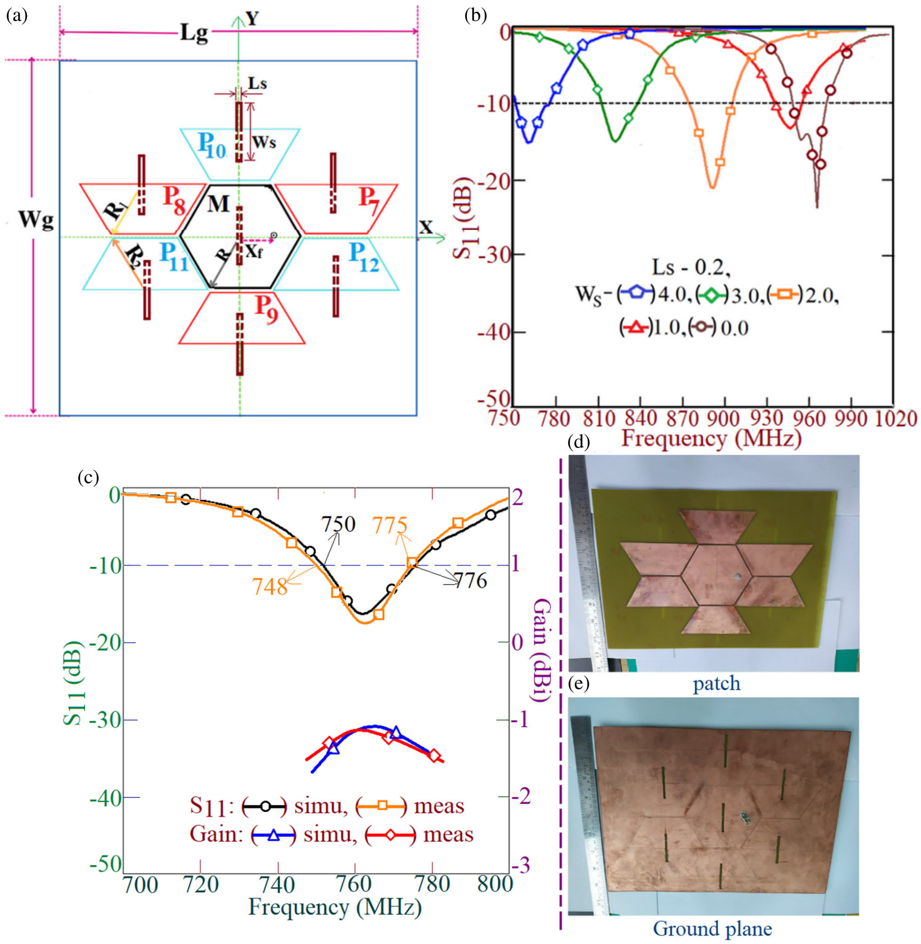


**FIGURE 4**. (a) Gap-coupled H-HMSAs backed by slot cut ground plane, its (b) $S_{11}$ plots for varying ground plane slot width $W_s$, (c) $S_{11}$ BW and gain plots for optimum design, fabricated prototype showing (d) patch and (e) slot cut ground plane.

the current variation on the patch through the fringing fields between the patch and ground plane. This assists in $TM_{11}$ mode frequency reduction. With an increase in the slot width '$W_s$', BW in the gap-coupled design is formed in a lower frequency region as shown in Fig. 4(b).

With an increment in the slot dimension, %BW should also be reduced owing to a smaller value of '$h/\lambda_g$'. Against this, %BW in the gap-coupled design employing slot on the ground is found to be increasing. This is attributed to the cavity becoming lossy with the positioning of the rectangular slot. Since a narrow slot is cut, variation in the loss factor of the antenna cavity beyond certain slot width is not significant. Hence, the BW increment is not observed. With an increase in slot dimensions, frequency reduction is achieved, but antenna gain also decreases because of the back-lobe radiation. Hence, while deciding the optimum design, a trade-off exists between the frequency and gain reduction. On this point, for peak gain not less than $-1$ dBi, the optimum design is selected for $W_s = 4.0$ cm.

Measured and simulated $S_{11}$ BW and gain plots are shown in Fig. 4(c). Simulated and measured BWs for '$W_s$' $= 4.0$ cm are 26 MHz (34%) and 27 MHz (354%), respectively. With reference to the simulated results, center frequency of the BW in slot cut ground plane design is 763 MHz against the center frequency of BW of 976 MHz, observed in the conventional ground plane antenna. Thus, slot cut ground plane antenna offers 213 MHz (21.8%) reduction in the BW's center frequency. The total patch area in the gap-coupled H-HMSAs backed by slots cut ground plane at frequency of around 763 MHz is 25.44 cm$^2$. A similar gap-coupled antenna was designed using a conventional ground plane at the center frequency of 763 MHz. This antenna requires the total patch area of 41.134 cm$^2$. By comparing the two, a reduction in the area as noted in the gap-coupled design using slots cut ground plane is 38.13%. The fabricated antenna showing the patch and ground plane is given in Figs. 4(d) and (e).

Since the gap-coupled antenna is realized on a lossy thinner substrate, broadside gain is lower than 0 dBi as mentioned in Fig. 4(c). Hence, for the broadside gain improvement, a similar cavity-backed technique is used as mentioned in Fig. 5(a). A parametric study is carried out for various parameters of the cavity-backed aperture like '$W$' for '$W_g$' and '$L$' for '$L_g$', by which cavity-backed design is realized, and the dimensions are '$L$' $= 41$, '$W$' $= 44$, and '$H_f$' $= 10$ cm. As compared with a cavity-backed structure realized in the gap-coupled design using conventional ground plane, aperture dimensions are wider in slot cut ground plane antenna. The ground plane slot cut antenna is compact in size since it operates at a lower reso-

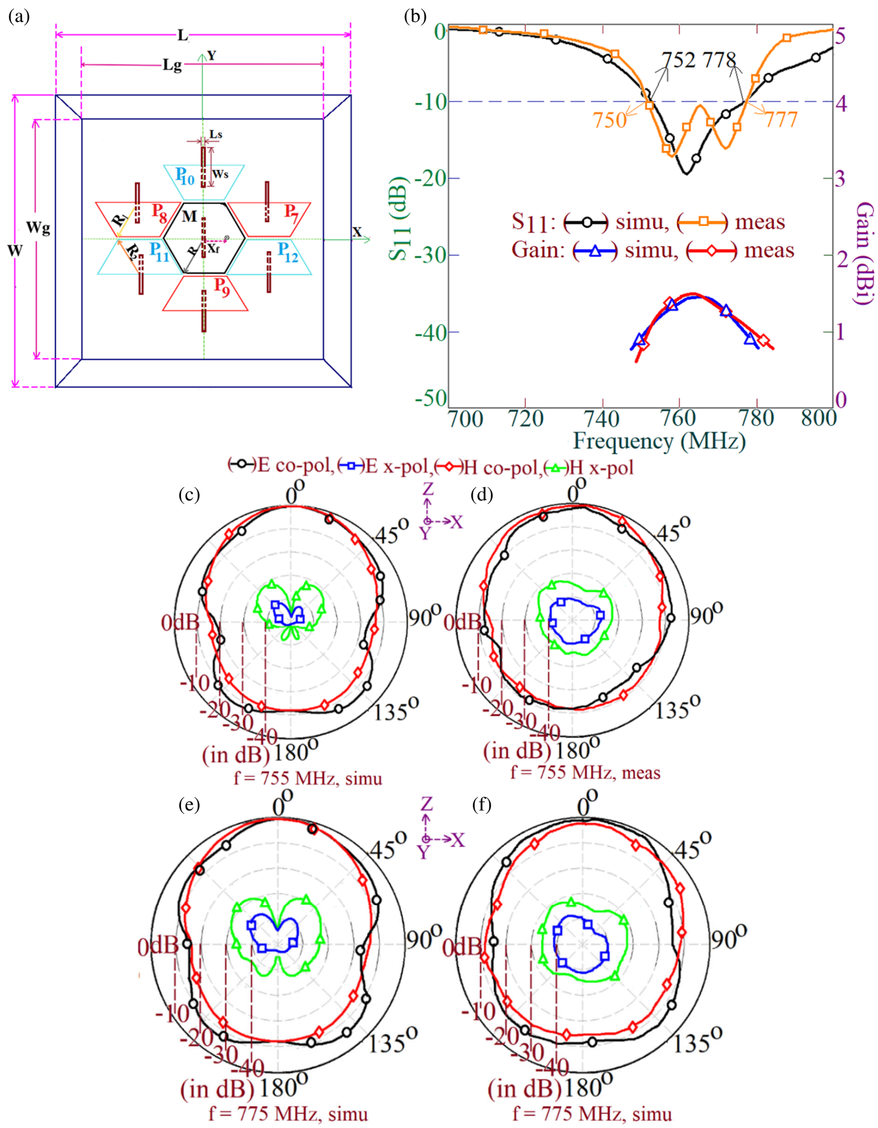

**FIGURE 5**. (a) Gap-coupled H-HMSAs backed by slot cut cavity-backed design, its (b) $S_{11}$ BW and gain plots and its (c)–(f) radiation pattern nearer to band start and stop frequencies of the BW.

nance frequency. Thus, it has a smaller value of $h/\lambda_g$, and the initial antenna gain without the cavity-backed ground plane is smaller. Thus, to achieve an equivalent gain improvement as compared with the previous design, a wider aperture is considered. The corresponding $S_{11}$ BW and gain results are displayed in Fig. 5(b). In this design, simulated and measured $S_{11}$ BWs are 26 MHz (3.34%) and 27 MHz (3.54%), respectively. The antenna offers simulated and measured broadside gains around 1.4 dBi. Against the slot cut ground plane antenna, cavity-backed structure provides broadside gain improvement by around 2.5 dBi.

As per Figs. 5(c)–(f), radiation patterns observed near the band start and stop frequencies of the $S_{11}$ BW are along the broadside directions with $E$-plane aligned along $\Phi = 0°$. The cross-polar level is less than 15 dB as compared to the co-polar level. Thus, the proposed gap-coupled antenna with ground plane slots and cavity-backed design provides the patch area reduction and gain improvement using a thinner and lossy FR4 substrate. When the modifications in ground plane are selected, unwanted radiation, causing higher degree of back-lobe radiation, arises. To assess the back-lobe radiation for various modifications in the proposed configurations, simulated radiation pattern plots at the center frequency of respective $S_{11}$ BW are provided in Figs. 6(a)–(d). As noted, going from the conventional ground plane antenna to slots cut ground plane, back lobe radiation increases. However, the employment of cavity-backed structure reduces the same and improves the broadside antenna gain.

## 4. RESULTS DISCUSSION AND COMPARATIVE ANALYSIS

A thorough comparison is provided in Table 1 to highlight the novelties in the proposed work in contrast to the reported wideband configurations. Broadband designs, using resonant slot, parasitic resonators in a gap-coupled or stacked layer, and slot cut ground plane designs, have been considered in the comparison. For the comparison purpose, both H-HMSAs with and

**TABLE 1**. Comparison of wideband gap-coupled H-HMSAs variants against reported wideband MSAs.

| MSA shown in | Meas. BW (MHz, %) | Peak Gain (dBi) | patch area $A/\lambda_c$ | Substrate thickness $h/\lambda_c$ |
|---|---|---|---|---|
| **Figs. 1(e), (f)** | **34, 3.52** | **2.0** | **1.69** | **0.01** |
| **Fig. 5(a)** | 27, 3.54 | **1.4** | **1.35** | **0.008** |
| Ref. [2] | 42, 2.25 | $-3.9$ | 0.523 | 0.021 |
| Ref. [3] | 6300, 40 | 10 | 1.35 | 0.113 |
| Ref. [4] | 21, 1 | — | 3.104 | 0.018 |
| Ref. [5] | 160, 16 | 8.8 | 3.94 | 0.06 |
| Ref. [6] | 1114, 55.7 | 12.3 | 14.7 | 0.155 |
| Ref. [7] | 900, 42.2 | 10.8 | 5.37 | 0.233 |
| Ref. [8] | 1680, 64.12 | 12.45 | 4.087 | 0.105 |
| Ref. [9] | 600, 6.1 | 7.0 | 1.21 | 0.02 |
| Ref. [10] | 80, 9 | 7 | 5.4 | 0.04 |
| Ref. [11] | 2040, 68 | 10 | 2.224 | 0.023 |
| Ref. [12] | 3100, 12 | 6.8 | $> 5.9$ | 0.144 |
| Ref. [14] | 5760, 99 | 3.66 | 0.6 | 0.05 |
| Ref. [15] | 1960, 30.1 | 8.0 | 2.542 | 0.054 |
| Ref. [16] | 7700, 110 | 4.5 | 1.83 | 0.06 |
| Ref. [17] | 2100, 25.15 | 4.0 | 2.8 | 0.05 |
| Ref. [18] | 168, 12.88 | 1.8 | 5.315 | 0.013 |

without ground plane slots, integrated with cavity-backed structure, are considered. Table 1 considers a normalized total patch size and substrate thickness in terms of the guided wavelength ($\lambda_c$) at the $S_{11}$ BW center frequency. This normalization helps in comparing different configurations optimized in various frequency bands.

The gap-coupled antenna discussed in [2] requires low antenna volume and offers equivalent $S_{11}$ BW, but it offers lower gain. The gap-coupled antenna employing shorted patches in 15 GHz frequency range offers higher BW and gain [3], but antenna thickness is larger. The shorted microstrip-line fed design discussed in [4] requires larger patch size and offers lower BW, as against the proposed configurations.

The wideband stacked patch design offering filtering performance requires larger antenna volume [5]. The multi-resonator configurations employing cavity-backed design provide the gain of larger than 10 dBi [6–8]. However, all these designs fabricated on air or air suspended substrates, and they have large antenna volume. The modified 3D radiating patch geometry offers equivalent values of BW and antenna volume against the proposed configuration [9]. But the antenna is complex in fabrication, and it does not offer reduction in the patch resonance frequency. A novel technique to reduce the substrate thickness in slot cut antenna is discussed in [10]. However, the presented method is complex in design and implementation, and guidelines to realize similar thinner substrate slot cut wideband antennas at other frequencies are not discussed. A wideband antenna employing two U-slots discussed in [11] employs differential feeding and offers an end-fire radiation pattern, whereas the U-slots cut design presented in [12] requires large antenna size. By employing modified ground plane and radiating patch structures, wider BW configurations are reported [14–17]. Although these designs provide larger BW than the proposed gap-coupled configurations, the work presented in the same does not discuss the effects of modifications made in the patch and ground plane on resonant modes of the antenna cavity to yield such a wider BW. Further, none of these designs or other similar ones reported in the literature provide reduction in patch resonance frequency to offer patch size reduction. For the MSA discussed in [15, 17], a variation in the broadside gain is observed over the BW. The design reported in [18] employs a bow-tie slot that does not affect the surface current distribution to reduce the resonance frequency of fundamental mode. With bow-tie slot, it only offers 10% frequency reduction against 21.8% reduction achieved in proposed gap-coupled configuration. Further, bow-tie slot technique cannot be employed in gap-coupled antennas to reduce the overall antenna size. The gap-coupled compact antennas discussed in [19] have similar slot cut ground plane to reduce the patch size. However, designs discussed in [19] employ more efficient microwave substrate as against lossy but cheaper substrate employed in proposed work. Thus, as against the configuration in [19], the proposed work provides a cost effective solution. The design of a composite right/left-handed transmission line (CRLH-TL) with equilateral slots backing hexagonal patches is presented in [23], whereas the gap-coupled design of hexagonal patches backed by meshed triangular slot configuration is reported in [24, 25]. The designs present wideband response, but they do not offer patch size reduction, since the slots are not placed near and be-

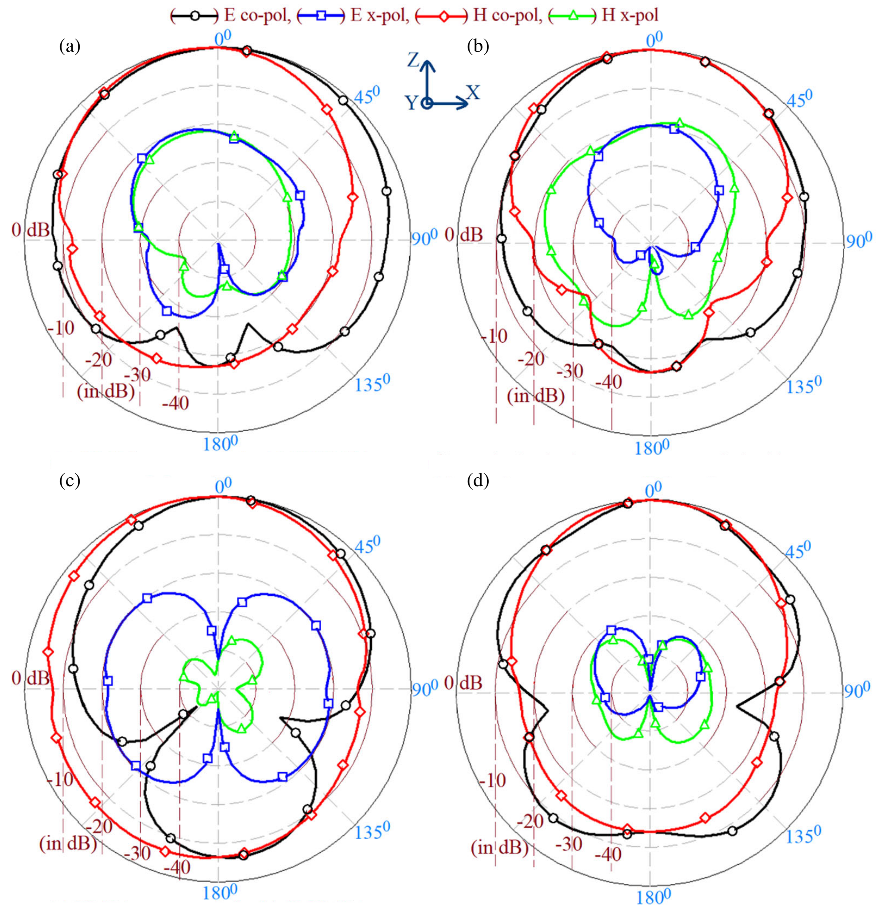


**FIGURE 6**. Simulated radiation pattern plots at the center frequency of $S_{11}$ BW for gap-coupled configurations of HMSA with H-HMSAs. (a) HMSA gap-coupled with H-HMSAs. (b) Cavity backed HMSA gap-coupled with H-HMSAs. (c) HMSA gap-coupled with H-HMSA backed by slot cut ground plane. (d) Cavity backed HMSA gap-coupled with H-HMSAs backed by slot cut ground plane.

low the maximum current location at the fundamental resonant modes on the hexagonal patches.

Numerous papers have been published using the gap-coupling technique for BW enhancement, specifically using thicker substrates, multi-layer configurations, and complex feeding techniques. However, antenna's overall dimensions are more than two-three times those of a single patch. In contrast to all these reported papers, the current study makes an effort to solve the size increment issue in the less complicated gap-coupling method, while using coaxially fed HMSA and H-HMSA variations on a thinner FR4 substrate ($\sim 0.01\lambda_g$). To decrease the overall patch size, ground plane rectangular slots are added beneath every patch, resulting in a defected ground plane structure (DGS). In a lower frequency range, and the rectangular slots produce BW by lowering the fundamental mode frequency on each patch. With a gap-coupled DGS design, reduction in the patch area by 38.14% is achieved for an impedance BW of 3.54%. The antenna with slot cut ground plane offers 21.8% reduction in the center frequency of $S_{11}$ BW as compared with the ground plane with no slots. Owing to the thinner substrate, gain enhancement is needed for the proposed configurations, which is achieved by employing a cavity-backed structure. Broadside gain in the range of 1.2 to 2.0 dBi is achieved with the proposed configurations. Against the MSAs without cavity-backed designs, this gain increment is by 2.5–3 dBi, which is notable as the same is achieved using a thinner low-cost lossy substrate. Further, the selection of low-cost substrate provides a cost-effective solution. These all are the technical novelties in the proposed work.

For the planar printed hexagonal patch fractal designs, the optimization of $S_{11}$ BW is obtained using techniques like Lightning Attachment Procedure Optimization [26, 27]. Unlike Lightning Attachment Procedure Optimization, optimization process for the gap-coupled antenna employing cavity-backed configuration in this work is based on the parametric study for the flared dimensions of the cavity. When similar flaring is to be optimized for realizing similar antenna in different frequency band, parametric optimization is needed as cavity-backed design is a function of frequency of operation and electrical substrate thickness of the antenna. Hence for the proposed optimum designs, design methodology is not put forward. Other substrates for the proposed design are not considered as main thrust of the paper is on providing the gain improvement while employing low cost, lossy thinner substrates. The patch size reduction aspect presented in this paper is with reference to the gap-coupled antenna without the cavity-backed structure. The cavity-backed design does increase the overall antenna thickness, but it is used for gain improvement. For the cavity-backed configurations [6–8] compared above in Table 1, the thickness of cavity-backed structure is not considered but the patch thickness. The reported cavity-backed structures also have cavity thickness that is greater than the patch substrate thickness.

## 5. CONCLUSIONS

The coaxially fed gap-coupled designs of compact H-HMSAs with HMSA are presented in 900 MHz frequency spectrum on a low cost lossy FR4 substrate. The optimum of gap-coupled variation provides $S_{11}$ BW of 3.52%. To achieve the patch area reduction, slot cut ground plane variation is considered. This modified ground plane gap-coupled antenna achieves 38.14% patch area reduction or 21.8% frequency reduction, while offering $S_{11}$ BW of 3.54%. The enhancement in the broadside gain is achieved by creating the cavity-backed structure. The cavity-backed design increases the aperture area, to achieve gain improvement by 2.5–3 dBi in the conventional and slots cut ground plane antenna. All these achieved improvements in antenna characteristics are notable since they are obtained on a low cost, lossy and thinner substrate. Thus, the proposed study presents a technique to reduce the patch size in gap-coupled antenna and improvement in broadside gain, while using lossy thinner substrates. With the obtained antenna characteristics, proposed antenna can find applications in personal communication and Wi-fi applications, where a short distance and cheap solution is needed.

## DECLARATION

The proposed compact gapcoupled design is published with application number 202421022000A, under the title "Compact Wideband gap-coupled variations of Hexagonal Microstrip Antennas on thinner substrate", in The Indian Patent Office Journal No. 16/2024 Dated 19/04/2024.

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