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A High Gain, Wide Bandwidth and Low Cross-Polarization Compact Horn Antenna Fed by a Cavity-Backed Stacked Microstrip Antenna

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Abstract—A conical horn antenna fed by a cavity-backed two-layered suspended microstrip antenna has been proposed. The overall compact antenna with a length of $2.3\lambda_0$ yields a wide impedance bandwidth of 57% centred around 2.8 GHz with a very high gain of 19.9 dBi, an average gain of 17.5 dBi, and a radiation efficiency of above 88%. In effect, the gain of the basic two-layered suspended microstrip antenna is enhanced by 8.4 dB when it is backed by the cavity and the conical horn. A good radiation characteristic is obtained throughout the impedance bandwidth with main beam stability, high isolation between two such antennas, and low cross-polarization. Over the entire operating bandwidth cross-polarization lower than −30 dB with co-cross polarization isolation better than 50 dB is obtained in 45° plane. In comparison to conventional conical horn antennas yielding the same gain, the proposed antenna is more efficient with only 45% length. The prime contribution of the work is the concurrent yield of high 19.9 dBi gain, wide bandwidth, high efficiency, and good radiation characteristics including unidirectional stable radiation patterns, low cross pol., and high isolation between antennas which has not been reported so far. The proposed antenna is designed for various S-band FMCW Radars.

1. INTRODUCTION

Horn antennas are characterized by high gain. However, these antennas do not concurrently yield high gain over a wide bandwidth, high efficiency, main beam stability, low cross-pol. and compact electrical length in low frequencies [1, 2]. Particularly, smooth-walled horn antennas suffer from high cross-pol. especially in 45° plane which limits its application [3]. Multi-resonator stacked microstrip antennas have moderate gain, wide bandwidth (BW), and high efficiency and are relatively compact [4, 5]. When these stacked configurations are cavity-backed, BW increases with a moderate increase in gain and improvement in radiation characteristics including lowering of cross-pol. level [6]. This work attempts to design a novel antenna configuration, which combines desirable attributes of horn and cavity-backed stacked microstrip antennas yielding a high gain over a wide operating BW, low-cross pol., and high efficiency concurrently with a relatively compact antenna at the lower end of microwave frequency.

The improvement of performance of horn antenna by hybrid configurations has been reported. In these reported hybrid configurations, horn antenna has been fed by microstrip antenna [7–11], dielectric resonator [12, 13], dipole array [14], Vivaldi array [15, 16], and magneto-electric dipole antenna [17]. These methods have not yielded high gain, wide BW, and low cross pol. concurrently. The overall BW yielded by the hybrid-horn antenna is almost the same as the BW of the feed antenna configuration. However, the overall gain of the hybrid antenna is enhanced by the horn backing the fed antenna. For a given horn size, this gain enhancement is more if the antenna configuration used to feed the horn has a higher gain. Thus, a wider BW and higher overall gain hybrid-horn antenna can be configured by feeding the horn with a wider BW and higher gain feed antenna configuration. A configuration in [18] reports a very wide BW and high gain double cavity-backed two-layered suspended stacked one

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bottom four top (1B4T) rectangular microstrip antennas. This paper proposes to feed a conical horn with a cavity-backed stacked 1B4T like [18]. The use of a cavity-backed stacked suspended microstrip antenna to feed a compact conical horn for very high gain is novel. The proposed configuration yields the impedance BW of 57% centred at 2.8 GHz with a high gain of 19.9 dBi and a radiation efficiency above 88% throughout the band. The electrical length of the proposed antenna is only $2.3\lambda_0$ (25 cm), where λ_0 denotes the wavelength corresponding to centre frequency within the operating bandwidth of the proposed antenna. The length of the proposed antenna is 65% smaller than the conventional horn antenna yielding the same gain [1, 19]. The antenna also yields good radiation characteristics with main beam direction stability, low cross-pol., and high isolation better than 56 dB between two such proposed antennas. Obtaining a low cross-pol. of −30 dB with co-cross isolation better than 50 dB over the entire wide operating BW in 45° plane is also an important contribution of the proposed antenna because most of the reported smooth-wall horn antennas suffer from high cross pol. in 45° plane which limits their utilization [3]. The concurrent yield of these vital desirable attributes as mentioned above enhances the overall performance of the proposed antennas in comparison to other relevant reported antennas demonstrating the novelty of the proposal. The enhanced performance of the proposed antenna at a relatively compact volume makes it suitable for various S-band radar applications such as ground penetrating radar (GPR) and through wall imaging radar (TWIR).

2. DESIGN OF THE PROPOSED ANTENNA

The basic radiating structure used has a co-ax fed rectangular microstrip patch at the bottom layer and four rectangular microstrip patches (1B4T) at the top layer suspended in the air as shown in Fig. 1. Its design parameters have been optimised to maximise BW and gain at a centre frequency of 2.8 GHz using the same parameters given in [5, 18]. [18] uses double cavity to further enhance the BW and gain. However, to keep the overall structure compact, this work uses only one cavity-backing. The cavity-backing is kept at a distance of $Cgap$ from the centre of the antenna structure such that the structure yields maximum BW. With increasing or decreasing $Cgap$ the BW decreases. After fixing the $Cgap$, the height of the cavity is varied. It is noted that the gain increases after the cavity height becomes more than the total suspended height of the 1B4T configuration, and maximum gain is yielded when the cavity height becomes Ch.

After optimising BW and gain of the single cavity-backed 1B4T microstrip antenna configuration, a conical horn-type structure is mounted on the ground surface as shown in Fig. 1. The base of the conical horn structure has a hollow cylinder with a diameter of $Dcyl$ such that it just encircles the

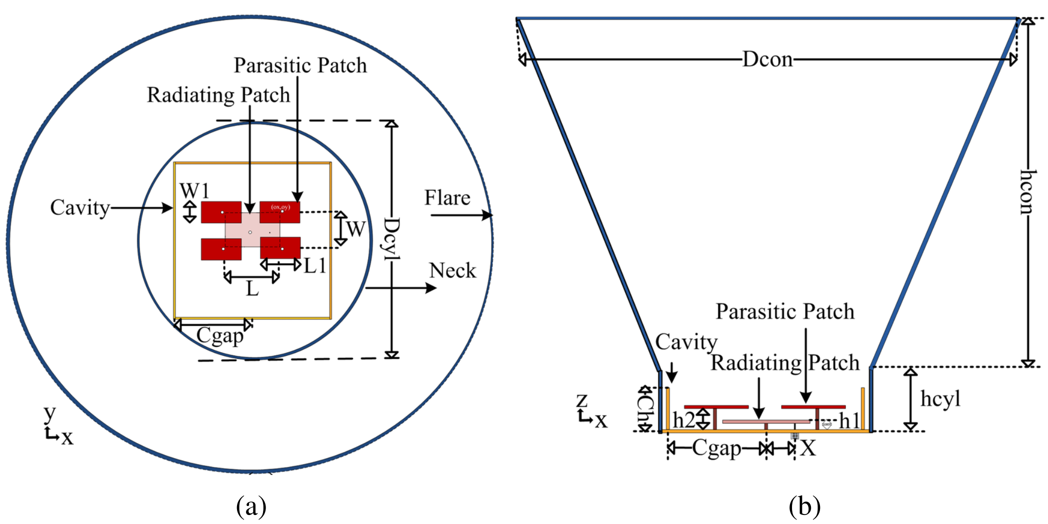


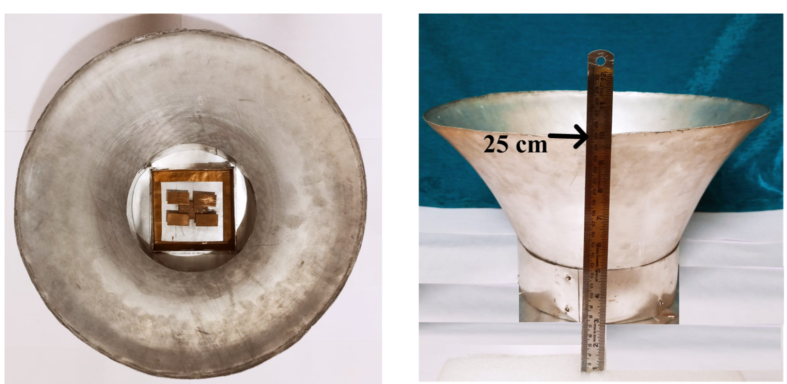
Figure 1. Schematic diagram of the proposed compact conical horn antenna fed by a cavity-backed two-layered 1B4T rectangular microstrip antenna; (a) Top view and (b) cross-sectional side view.

cavity-backed 1B4T structure without making physical contact with the cavity. To keep the overall structure compact, the diameter of this cylinder is not optimised to enhance BW with a cavity-backing. The ground of the whole structure is also made circular with a diameter of $Dcyl$. When the height of the cylinder is increased more than Ch, there is slight increase in gain which is maximum when the cylinder height reaches $hcyl$. To enhance the gain further, a hollow conical structure is placed over the hollow cylinder to make a conical horn structure. The height of the conical structure is chosen to be $hcon$ and the diameter of the flare is increased. $Hcon$ is chosen such that the total length of the overall structure is limited to 25 cm ensuring compactness for practical applications. It is observed that as the diameter of the flare increases the gain increases until the gain is maximum at the flare diameter $Dcon$. On increasing the flare diameter more than $Dcon$, the gain decreases. The thickness of the microstrip patches, cavity wall, and conical horn structure is kept at t. CST Microwave Studio software has been used for the optimisation of parameters. Key design parameters are summarised in Table 1.

Utilising these optimised dimensions, a single cavity-backed 1B4T microstrip antenna is fabricated. On this cavity-backed structure a conical horn antenna is added on common backing ground plane with the optimised parameters as given in Table 1. Fig. 2(a) and Fig. 2(b) show the top view and side view, respectively, of the final prototype fabricated. Microstrip patches are fabricated using a copper plate while the cavity wall and conical horn structure have been fabricated on the ground plane using a thin aluminum plate.

Table 1. Optimised dimension of the compact conical horn antenna fed by a cavity-backed two-layered 1B4T microstrip antenna.

Parameters	Val. (mm)	Parameters	Val. (mm)
$Dcyl$	220	$h1$	5
L	51	$h2$	12
W	31	Ch	30
$L1$	39	$Cgap$	72
$W1$	21	$hcyl$	45
x	21	$hcon$	205
(ox, oy)	(30, 18)	$Dcon$	465
-	-	t	1



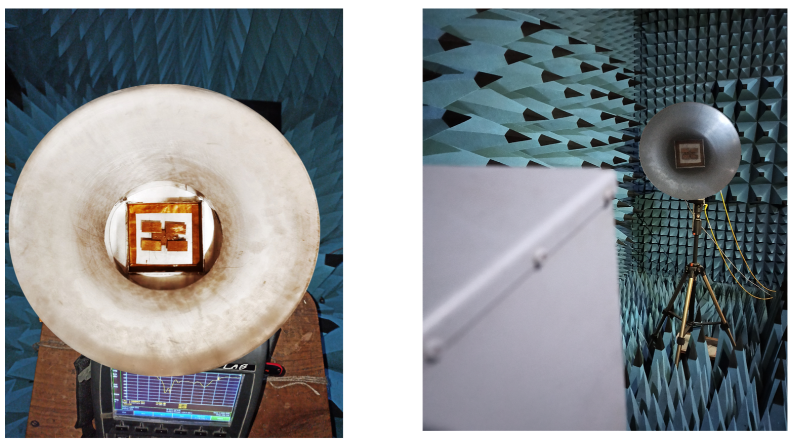
(a) (b)

Figure 2. Photograph of the fabricated prototype of the proposed compact conical horn antenna fed by a cavity-backed two-layered 1B4T rectangular microstrip antenna; (a) Top view and (b) side view.

3. RESULTS

The performance of the proposed antenna was demonstrated first by simulations using Microwave CST software followed by fabrication and experimental measurements. All the experiments have been performed inside an anechoic chamber. FieldFox N9916A Network Analyser (Keysight), placed inside an anechoic chamber, has been used to measure antenna performances including S_{11}, gain, cross-pol., and S_{21}. Experimental setups for the measurement of S_{11} and radiation pattern are as shown in Fig. 3(a) and Fig. 3(b), respectively. For the measurement of S_{21}, two identical antennas of each type were fabricated, and measurements were carried out to determine the isolation (S_{21}) between these antennas by keeping these antennas at a flare/mouth separation of $0.5\lambda_0$. Performances in terms of impedance BW and gain of the basic 1B4T rectangular microstrip antenna, cavity-backed 1B4T rectangular microstrip antenna, and conical horn antenna fed by the cavity-backed 1B4T rectangular microstrip antenna are given in Fig. 4(a) and Fig. 4(b), respectively. As evident from the figures, experimental results are in close agreement with the simulations.

The $|S_{11}| < -10\,\text{dB}$ impedance BW for the configuration without cavity-backed 1B4T is from



(a) (b)

Figure 3. Experimental setup inside anechoic chamber; (a) Measurement of S_{11} and (b) measurement of radiation pattern.

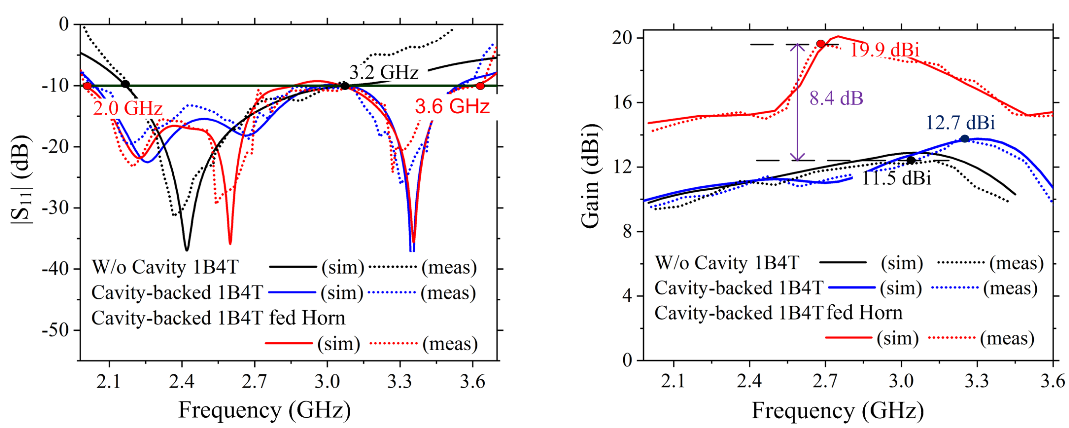


Figure 4. Comparison of simulated and measured performance of configurations of without cavity, cavity-backed and conical horn antenna fed by cavity-backed 1B4T rectangular microstrip antenna; (a) Reflection co-efficient ($|S_{11}|$) and (b) gain.

2.2 GHz to 3.2 GHz, which is extended from 2 GHz to 3.6 GHz by the cavity-backing as evident from Fig. 4(a). Horn structure excited by cavity-backed configuration has marginal effect on the $|S_{11}|$ plot without altering the BW, which remains unaltered at 57%. From Fig. 4(b), it is evident that the basic 1B4T microstrip configuration without cavity yields a maximum gain of 11.5 dBi with an average value of 10.5 dBi which is improved to 12.7 dBi and 11.3 dBi, respectively, with including the cavity. The gain is further drastically increased to a maximum of 19.9 dBi with an average value of 17.5 dBi when the cavity-backed configuration is used to feed the conical horn antenna. This improvement in gain is 8.4 dB in maximum value and 7 dB in average value in comparison to basic 1B4T rectangular microstrip configuration.

Next, the radiation patterns of the proposed configuration are presented. Radiation patterns at four representative frequencies within the BW are given in Fig. 5. The half-power beam-width (HPBW) in the E plane varies from 31.6° corresponding to the lowest gain at 2.1 GHz to 14.5° corresponding to the highest gain at 2.75 GHz, while in the H plane it varies from 28.5° to 21.3°, respectively. The radiation patterns depict main beam stability, low cross-pol. in both E and H planes within the HPBW as depicted by the shaded portion in Fig. 5, and acceptable radiation pattern symmetry. Simulated and measured cross-pol. at 45° plane are depicted in Fig. 6(a). The cross-pol. obtained at 45° plane is less than −30 dB with co-cross pol. isolation better than 50 dB over the entire operating BW. The radiation patterns also indicate that there is no major splitting of the main beam and relatively low sidelobe levels. The sidelobes are also located away from the narrow HPBW and thus can be filtered out using signal processing. Simulated and measured isolations between two proposed antennas placed at $0.5\lambda_0$ separation between the flares/mouth of the horn structure and simulated efficiency plot of the proposed

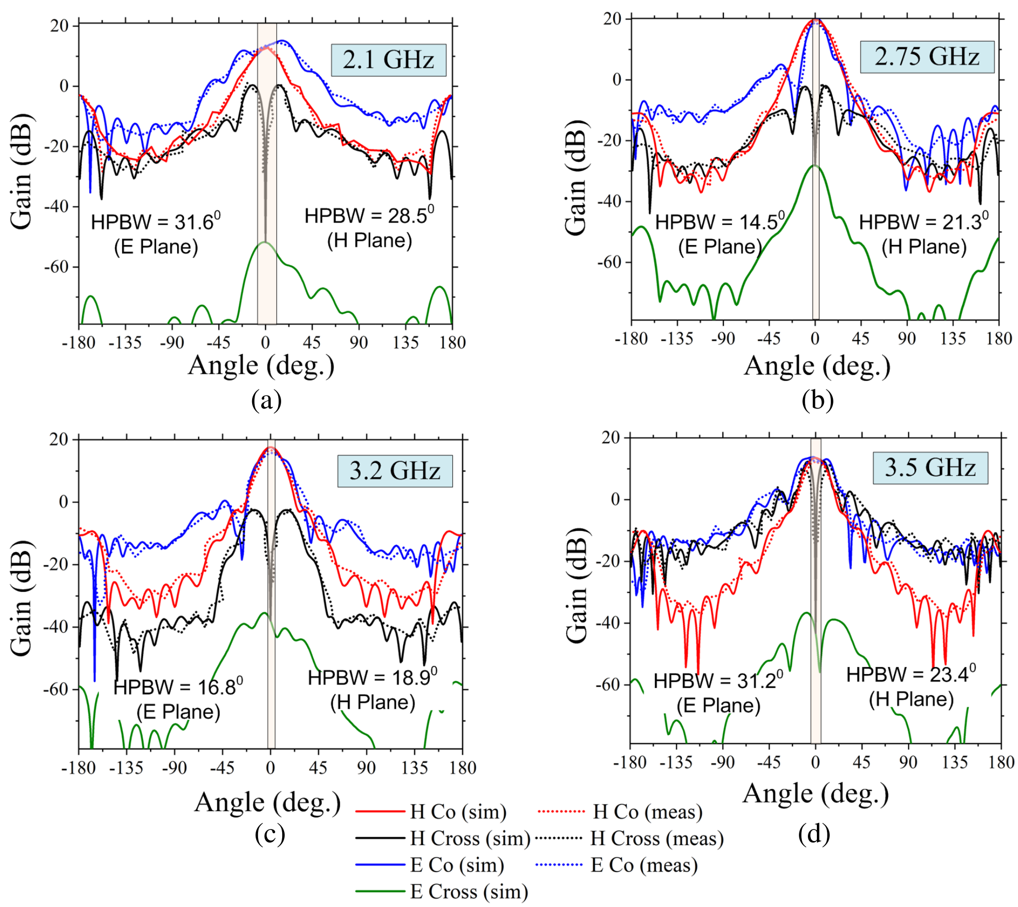


Figure 5. Simulated and measured radiation patterns of the proposed conical horn antenna fed by a cavity-backed 1B4T rectangular microstrip antenna; (a) 2.1 GHz, (b) 2.75 GHz, (c) 3.2 GHz and (d) 3.5 GHz.

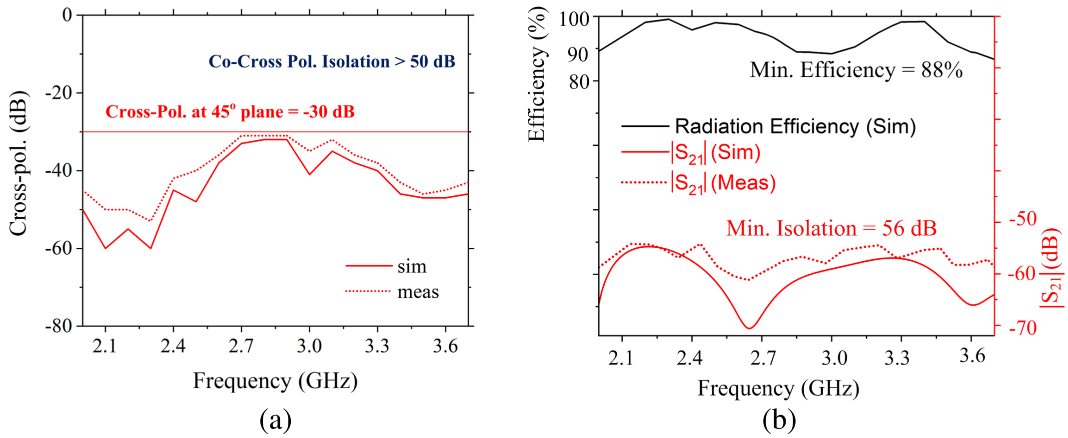


Figure 6. Performance parameters of the proposed conical horn antenna; (a) Cross-pol. at 45° plane and (b) $|S_{21}|$ plot for two identical proposed antennas placed at $0.5\lambda_0$ separation between the flares/mouth of the proposed conical horn structure and simulated Radiation efficiency plot.

hybrid horn antenna are given in Fig. 6(b). The proposed antenna is highly efficient with maximum radiation efficiency of 98% and minimum value of 88%, covering the wide operating band. Measured aperture efficiency at the centre frequency of operation is about 92%. The measured isolation obtained between the two proposed antennas varies from 56 dB to 62 dB as shown in Fig. 6(b). It is difficult to measure power level lower than −60 dB accurately, and thus the measured isolation is much lower than the simulated isolation obtained for simulated isolation better than 60 dB.

4. DISCUSSION

Cavity backing of a 1B4T rectangular microstrip antenna enhances the BW and gain due to the effective combination of TM_{10} mode of the rectangular microstrip patches and TM_{10} and TM_{30} modes of the loaded-cavity [18]. The Input impedance plot of the cavity-backed 1B4T microstrip antenna is shown in Fig. 7(a). Three resonance frequencies in the Input impedance plot correspond to the three minima in the S_{11} plot in Fig. 4(a). The impedance plot has four frequencies at which the real part of the impedance is high, and reactance is zero/near zero. At these frequencies, various TM modes get excited. Damping of these impedances widens the BW. Near 1.75 GHz the peak of the real part of the

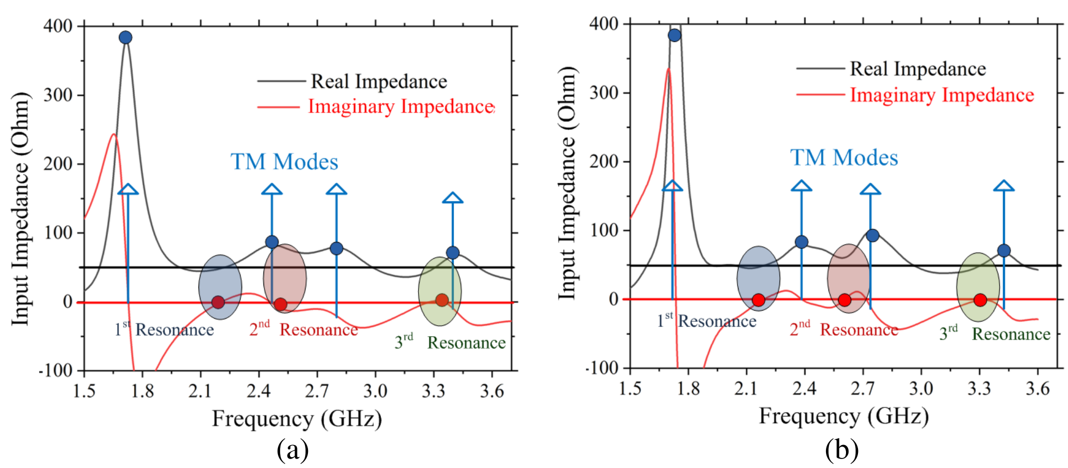


Figure 7. Input impedance plots; (a) Cavity-backed 1B4T microstrip antenna and (b) proposed conical horn fed by a cavity-backed 1B4T microstrip antenna.

impedance corresponds to the TM_{10} mode of the single cavity-wall. At this resonance the real part is high, thus there is no proper input matching at this frequency. Peaks of the impedance near 2.5 GHz and 2.8 GHz correspond to the TM_{10} mode of the bottom patch and top four patches, respectively. The peak of the impedance observed near 3.4 GHz corresponds to the TM_{30} mode of the loaded single cavity. BW at the lower and upper edges of the frequency is enhanced by the effective combination of TM_{10} mode of bottom and top patches with the Cavity wall induced TM_{10} mode occurring at a lower frequency and Cavity wall induced TM_{30} mode occurring at relatively higher frequency yielding simulated BW from 2 GHz to 3.6 GHz as depicted in Fig. 4(a). It is noted that, though the TM_{10} mode excited due to the single-cavity is slightly outside the obtained operating BW, it gets combined with the mode of the fed patch yielding significant effect near 2.0 GHz. The higher gain obtained for the cavity-backed antenna is attributed to superposition of radiation from these in-phase modes. The input impedance of the proposed hybrid horn antenna excited by the cavity-backed 1B4T microstrip antenna is shown in Fig. 7(b). Comparing Fig. 7(b) with Fig. 7(a), it is evident that the introduction of the non-resonant conical horn structure on the cavity-backed 1B4T microstrip antenna does not excite any additional resonance to further improve the BW. Thus, the overall BW yielded by the proposed antenna is the same as that of a cavity-backed 1B4T microstrip antenna. As the input impedance plot remains almost unaltered after the introduction of the horn structure, the presence of the non-resonant horn structure retains good radiation characteristics of the cavity-backed 1B4T microstrip antenna of high efficiency, low cross-pol. even at 45° plane, acceptable E and H plane symmetry, and main lobe stability as obtained in [6, 18]. The linear tapering of the surface current distribution as obtained in cavity-backed 1B4T microstrip antenna as shown in our work [6, 18] is also not altered on the introduction of horn structure, and thus the sidelobes remain low for the proposed hybrid horn.

The gain yielded by a cavity-backed 1B4T rectangular microstrip antenna is moderately high with radiation pattern having a narrow beamwidth as compared to other microstrip antennas reported, to feed horn, as described in [7, 8, 10]. Comparing these feed microstrip antennas of a suspended circular patch, slot coupled two layered stacked rectangular patch, and aperture-coupled two layered stacked rectangular microstrip patch in [7, 8, 10], respectively, and the proposed work, it is analysed that the focusing of radiation from the feed by the horn is more effective if the feed is more directive, i.e., the gain enhancement by the horn structure is much higher if the gain of the feed microstrip antenna is higher, while maintaining the BW of the feed antenna. Very high gain obtained by the proposed antenna is also explained comparing it with conventional conical horn and quadratic aperture phase error therein. For the given gain of a conical horn antenna, length of the antenna is designed in conjunction with the flare angle which is translated to the diameter of the aperture. For the given antenna length, with increasing the flare angle (and hence the aperture diameter) further, the gain decreases because of the increase in quadratic phase error on the aperture [2]. To obtain a 20 dBi gain from the conventional conical horn antenna, the length required is $6\lambda_0$, and the corresponding aperture diameter works out to be $4.5\lambda_0$ [1, 19]. For the proposed antenna, the aperture diameter is $4.4\lambda_0$, which is comparable to the flare diameter of the conventional conical horn antenna as the gain is similar. However, the length of the proposed antenna is only $2.3\lambda_0$ as the feed element of a cavity-backed 1B4T stacked rectangular microstrip antenna has a rather high gain. Thus, with a comparatively less length the proposed antenna is compact leading to very small quadratic aperture phase error, which in turn also results in high efficiency.

The high isolation of 56 dB obtained between two identical proposed antennas as shown in Fig. 6(a) is attributed to the very high gain with narrower main lobes as depicted in Fig. 4(b) and Fig. 5, which keeps the radiated power concentrated in the desired direction. In addition, sidelobes are reasonably suppressed leading to high isolation between two side by side kept antennas.

To demonstrate the novelty and effectiveness of the proposed design, it is compared with reported hybrid-horn and high gain improved horn antennas. The performance comparison is given in Table 2. Compared to all hybrid horn antennas and recently reported high gain horn antennas referred to in Table 2, the proposed novel antenna concurrently yields higher gain, much wider BW, higher efficiency, and relative compactness occupying smaller electrical length. Taking into consideration the reported hybrid antennas, the electrical lengths reported in configurations given in [7, 13] are smaller than the proposed antenna; however, the BW and gain obtained are much lower. Hybrid antennas [15, 16] yield higher BW because they use frequency independent Vivaldi antenna configuration to feed the horn;

Table 2. Comparison of the proposed antenna with hybrid-horn and high gain improved horn antennas.

Ref.	F_0 (GHz)	BW (%)	Max. G (dBi)	Avg. G (dBi)	Eff. (%)	Length (λ_0)
[7]	2.2	4.9	12.5	12	-	1.3
[10]	60	8.3	11.6	10	82	20
[11]	2.45	10	17	14	-	6.0
[12]	15.1	51.6	17.6	15	-	2.0
[13]	2.67	30	12.2	9	90	0.65
[15]	3.5	140	9.4	3	-	1.2
[16]	6	103	13	10.5	-	2.5
[20]	15.2	36	15.4	-	-	2.36
[21]	34	40	17.7	16.5	-	6.6
Prop.	2.8	54	19.9	17.5	88	2.25

however, the gain is low, in spite of [16] using array of two Vivaldi antennas. The proposed hybrid antenna outperforms recently reported high performing horn antennas [20, 21] in yielding more BW and gain and being more efficient. The proposed antenna yields 19.9 dBi gain for a length of only $2.3\lambda_0$ and flare diameter of $4.4\lambda_0$. Thus, in comparison to the conventional conical horn antenna [1, 19], the length of the proposed antenna is 65% smaller for approximately the same gain.

The non-resonant horn antenna preserves the low cross-pol. of the cavity-backed stacked microstrip antenna [6, 18] and yields a low cross-pol. of less than -30 dB covering the entire operating BW at 45° plane with co-cross pol. isolation better than 50 dB as shown in Fig. 6(a). Works reported to lower cross-pol. in horn antenna like in [22–25] are not optimised for 45° plane, which is vital for radar operation. [26, 27] report low cross-pol. of -30 dB in 45° plane. However, all these reported antennas yielding low cross-pol. do not concurrently yield compact size, high gain, wide BW, and high efficiency. Thus, the proposed antenna is superior in performance to these reported antennas

Due to the concurrent yield of the vital desirable attributes as illustrated above in the S-band, the proposed antenna is planned to be used in GPR. A strict space requirement is relaxed in GPR, and the proposed lightweight and compact antenna will not hinder portability of the radar. The base of our portable GPR prototype presented in [28] has been easily modified to accommodate the proposed 25 cm length hybrid horn antenna for it.

5. CONCLUSION

This paper presents a novel antenna configuration to achieve a very high gain in a wide operating BW of the S-band by feeding a compact conical horn antenna with a cavity-backed stacked 1B4T rectangular microstrip antenna. The proposed configuration yields a high gain of 19.9 dBi and an average gain of 17.5 dBi which is 8.4 dB and 7 dB higher than the gain of the stacked patch configuration, respectively. In the proposed hybrid configuration, the horn structure ensures that wide impedance BW and good radiation characteristics of the cavity-backed stacked patch configuration are maintained, yielding 57% BW, over 88% radiation efficiency, main beam stability, cross-pol. lower than -30 dB at 45° plane, and isolation better than 56 dB between antennas. In comparison to the conventional conical horn antenna yielding the same gain, the proposed novel antenna is more efficient with a 65% smaller length. The proposed antenna is planned to be used in GPR applications.

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