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Design of Broadband Compact Canonical Tetra Sleeve Cage Antenna Covering UHF Band

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Abstract—In this paper, design of a novel broadband Canonical Tetra Sleeve Cage Antenna is presented. This antenna is designed using distributed antenna matching techniques. It has canonical shaped antenna elements and coaxial sleeves. The designed antenna operates over a wide frequency range in UHF band with omnidirectional characteristics. The proposed antenna is simulated in CST Microwave Studio, fabricated, evaluated, and the results are presented. The simulated and measurement results are in agreement. It has VSWR $< 1.9 : 1$ in frequency bands 270–330 MHz and 930–1670 MHz. The maximum value of VSWR in 250–1850 MHz is $3.3 : 1$. The measured gain of the antenna varies from 0.6 to 5.5 dBi in the frequency range of 250 MHz to 1850 MHz. The implementation of distributed matching techniques by using canonical shaped antenna elements and tetra sleeves results in reduction of the length of the antenna by 59.86% compared to the length of a half wave dipole antenna designed at the lowest frequency. The proposed antenna finds applications in defence and wireless communication systems as a transceiver antenna.

1. INTRODUCTION

Rapidly emerging wireless communication systems require compact broadband omnidirectional antennas, especially in VHF and UHF bands. Dipole and monopole antennas are the simplest omnidirectional antennas. However, their usage is limited for narrowband applications due to their resonant behaviour. Biconical and Conical unipole antennas have broad bandwidth [1]. The largest dimensions of these antennas are of the order of quarter wavelength at the lowest frequency. Hence, the size of these antennas becomes large when being realised in VHF/UHF bands. Shukla and Upadhyay presented the design of a broadband biconical antenna in [2]. Several papers are reported in literature for designing broadband omnidirectional antennas with compact structures. Ali et al. presented a dual meander sleeve antenna for Personal Communication Network bands in 850–2050 MHz using open sleeve configuration [3]. The antenna used a square ground plane of 900 mm $\times$ 900 mm. Radiation patterns and gain of the antenna were not reported. George Thomas et al. presented a dual sleeve top loaded monopole antenna with substantially small ground plane [4]. Ravipati and Reddy designed a sleeve monopole antenna with cylindrical element having disc loading and shorting posts operating in frequency range of 350–1300 MHz for VSWR $< 3 : 1$. This antenna required a ground plane for its operation [5]. Gain of the antenna was not reported. Design techniques using shorting pins were also reported for accomplishing broad bandwidth and size reduction of antennas. Wang et al. presented a dual sleeve antenna with a shorting load in the frequency range of 400–900 MHz [6]. The antenna achieved return loss better than 10 dB. Gain of the antenna is not indicated. Zhou et al. designed a low profile broadband conical monopole antenna covering 470–6000 MHz [7]. The antenna used a capacitive ring, three oblique shorting lines and required a ground plane of 800 mm diameter. Omnidirectional antennas with multi-octave bandwidth were also designed by incorporating impedance

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matching networks. Wu et al. presented a broadband resistively loaded sleeve monopole antenna with top loading and matching network [8]. The antenna covered frequency range of 170–520 MHz with efficiency of 23.85% at 200 MHz. Broad bandwidth was achieved in this antenna at the expense of efficiency. This is the compromise in achieving broad bandwidth using resistive loading. Mazhar et al. designed an antenna using distributed and lumped matching techniques [9]. A broadband sleeve monopole antenna with capacitive loads, matching network, and impedance transformer was used to accomplish broadband performance in the frequency range of 84–890 MHz. The E-plane patterns of the antenna exhibit nulls of the order of 5 dB near horizon, which is not desirable. Gain of the antenna was not reported. Zhang et al. demonstrated a sleeve monopole with cylindrical element and disc loaded conical sleeve with shorting pins in the frequency range of 446–732 MHz [10]. The antenna required a ground plane of 400 mm diameter. Khumanthem et al. designed a broadband rectangular sleeve dipole in the 850–2500 MHz range, giving a bandwidth ratio of 2.91 : 1 [11]. The antenna used a rectangular sleeve on a dipole to enhance impedance bandwidth of dipole antenna. Jiang et al. presented a sleeve dipole with three sleeves to cover 800–2500 MHz with VSWR $\leq 2:1$ giving a bandwidth ratio of 3.125 : 1 [12]. A broadband sleeve dipole was designed covering frequency range of 1000–3000 MHz [13]. Sairam et al. presented a compact broadband omnidirectional antenna using canonical structures and single sleeve configuration in 500–3000 MHz range [14].

In this paper, a novel compact broadband omnidirectional antenna operating in the UHF band is presented. Novel concepts of distributed matching techniques using canonical shaped antenna elements along with three closed sleeves and one open sleeve are employed to design the antenna. The design techniques employed in this antenna overcome several limitations of designs reported earlier. The antenna has compact form factor, does not require a ground plane, and has good broadband omnidirectional characteristics.

2. DESIGN AND IMPLEMENTATION OF TETRA SLEEVE CAGE ANTENNA

Cylindrical dipole is a narrowband resonant antenna. To increase bandwidth of dipole antenna, sleeve concepts are applied. The number of sleeves is increased to further enhance its bandwidth. Sleeves modify the current distribution along the antenna, thus increasing radiation resistance and reducing the reactance variation in antenna impedance. The bandwidth of the dipole antenna can also be increased by increasing the diameter of the dipole, which increases the resistive part of impedance and reduces the variation of reactive part of the impedance, thus achieving more bandwidth than a thin dipole antenna. To study the effect of the bandwidth enhancement, other canonical shapes like hemisphere and conical shapes are explored in the paper for the first time instead of conventional cylindrical dipole.

The dipole structure is designed as a combination of hemisphere, cone, and cylinder, respectively, starting from the feed gap. The antenna is designed for the center frequency of $f_o = 925$ MHz, and the corresponding wavelength is $\lambda_o = 324.32$ mm.

Design of the antenna can be divided into:

1) Design of Canonical sections:
   a) Design of hemisphere section: The diameter of the hemisphere is obtained as $0.17\lambda_o$.
   b) The diameters of the conical section are selected to match the hemispherical section, which is $0.17\lambda_o$, and the diameter of the other side of the cone is obtained as $0.34\lambda_o$.
   c) The conical section is further extended with a cylindrical section of diameter $0.38\lambda_o$ and height of $0.05\lambda_o$.
2) Design of Sleeves:
   Dipole antenna is designed with a central sleeve and two sleeves symmetrical around it.
   a) The diameter and length of the first (central) sleeve are obtained as $0.1\lambda_o$ and $0.35\lambda_o$, respectively.
   b) The diameter and length of the second and third sleeves are obtained as $0.13\lambda_o$ and $0.48\lambda_o$, respectively.
   c) The bandwidth of the antenna is further extended by designing a fourth sleeve as an open sleeve with top loading. The length of the fourth sleeve is $0.58\lambda_o$, and its diameter is $0.6\lambda_o$. The inner and outer diameters of the loading plate are $0.48\lambda_o$ and $0.82\lambda_o$, respectively.

Antenna design is carried out by using genetic algorithm optimization in CST Microwave studio. The design parameters of the antenna are varied around their nominal design values. The optimised values of the parameters of the antenna are given in Table 1. The front view of simulation models of Canonical Antenna, Single Sleeve Antenna, Dual Sleeve Antenna, Triple Sleeve Antenna, and Tetra

Table 1. Tetra Sleeve Cage Antenna parameters.

Sl. No.	Parameter of Antenna	Value (mm)
1	a, Diameter of cylindrical section	125.7
2	f, Diameter of hemispherical section	55.1
3	h, Height of conical section	73.08
4	g, Feed gap	3.94
5	d, Length of first sleeve	34.67
6	b, Diameter of first sleeve	115.74
7	e, Length of second sleeve	45.2
8	j, Diameter of second sleeve	156.64
9	c, Distance of second and third sleeve from first sleeve	17.62
10	k, Diameter of rod of fourth (open) sleeve	8.4
11	i, Diameter of top conical section	111.5
12	l, Length of cylindrical extension	17.85
13	m, Inner diameter of loading plate of fourth sleeve	156.64
14	n, Outer diameter of loading plate of fourth sleeve	268.47
15	Length of fourth sleeve	190.54
16	Diameter of fourth sleeve	197.03
17	Overall dimensions: Height × Diameter	240.8 mm × 268.47 mm

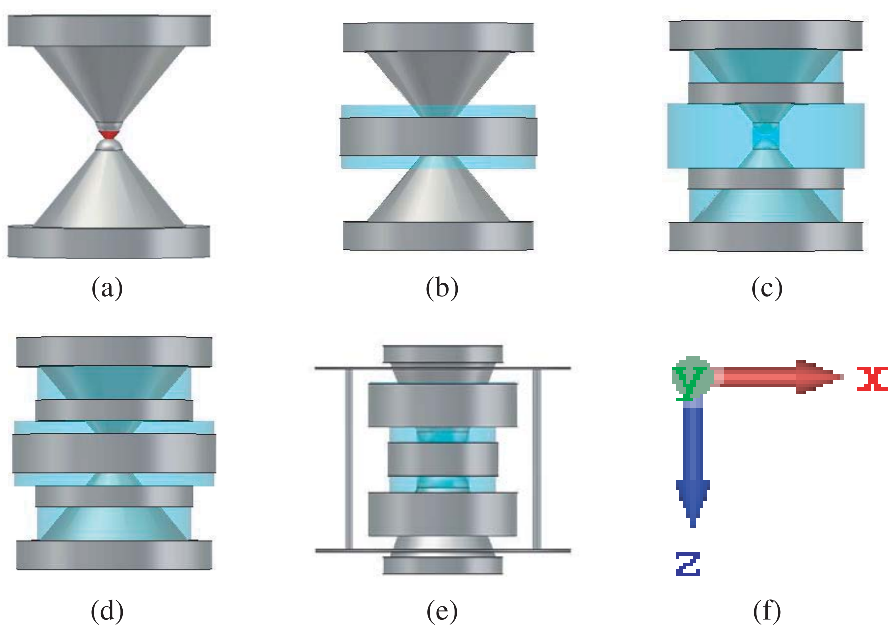


Figure 1. Simulation models of (a) Canonical Antenna, (B) Single Sleeve Antenna, (c) Dual Sleeve Antenna, (D) Triple Sleeve Antenna and (e) Tetra Sleeve Cage Antenna, (f) coordinate system.

Sleeve Cage Antenna along with reference coordinate system are shown in Fig. 1.

The VSWR plots of these antenna configurations are shown in Fig. 2. It can be observed that all the antennas have initially high values of VSWR and are improved as frequency increases. Triple Sleeve Antenna has the highest value of 40 : 1 at 250 MHz and has good matching characteristics from 390 MHz to 1850 MHz. The Single Sleeve and Dual Sleeve Antenna configurations have VSWR below 3 : 1 in the frequency band 350–1850 MHz. Tetra Sleeve Cage Antenna has the best VSWR characteristics in the entire frequency range of design. It is well matched at low frequency end of 250 MHz also and has maximum VSWR of 3 : 1 in the frequency band of 250–1850 MHz.

The simulated gain plots at horizon (in X-Y plane, at 90° from Z axis, see Fig. 1(f) for reference coordinate system) for these antenna configurations are shown in Fig. 3. Gain is of the order of −2 dBi at 250 MHz, for all antennas except Tetra Sleeve Cage Antenna. This is because Tetra Sleeve Cage Antenna is better matched than other configurations at 250 MHz. The gain of the antennas increases as the frequency increases. The gain of Dual Sleeve Antenna is reduced above 1500 MHz. This is because

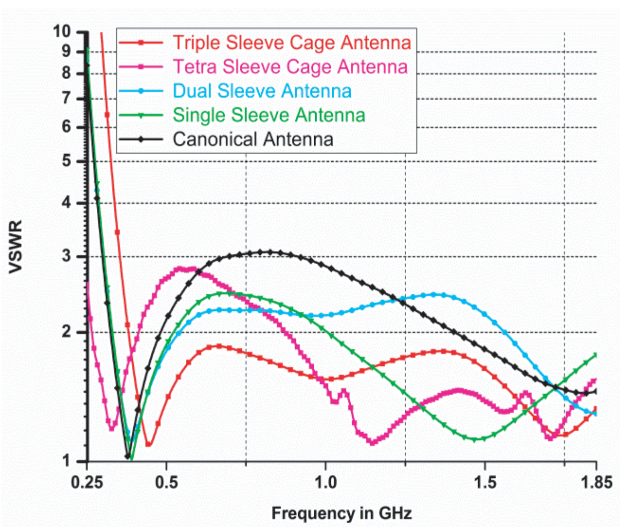


Figure 2. Simulated VSWR of various antenna configurations.

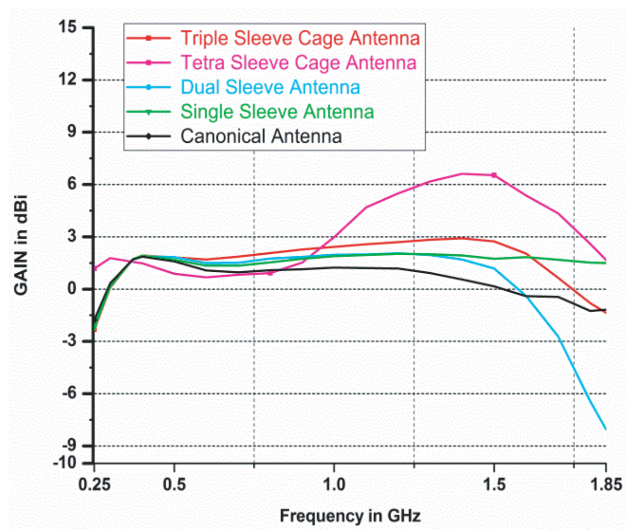


Figure 3. Simulated gain of various antenna configurations.

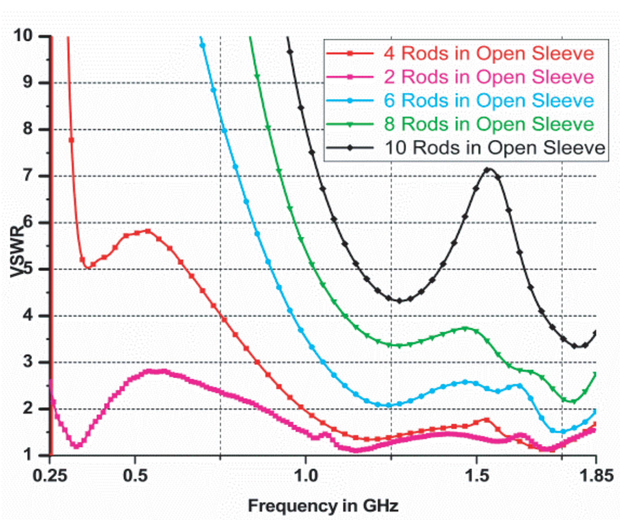


Figure 4. Simulated VSWR of Tetra Sleeve Cage Antenna with open fourth sleeve.

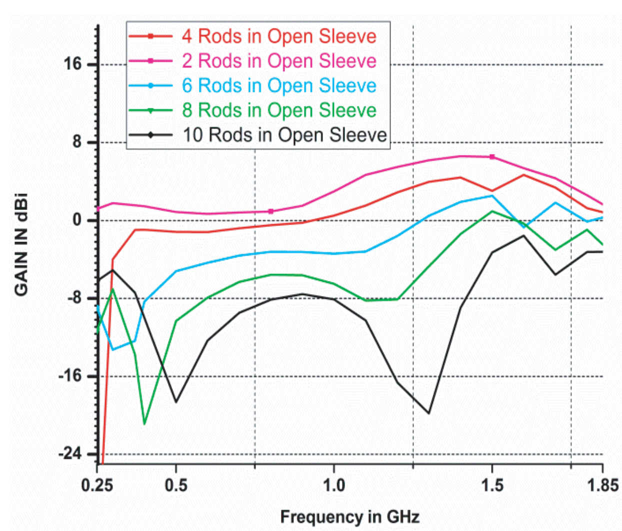


Figure 5. Simulated gain of Tetra Sleeve Cage Antenna with open fourth sleeve.

its radiation patterns are tilted, leading to decrease in gain at horizon. Tetra Sleeve Cage Antenna has better gain characteristics than other antenna configurations.

Optimisation of rods in open sleeve configuration of Tetra Sleeve Cage Antenna: Tetra Sleeve Cage Antenna shown in Fig. 1(e) has the fourth sleeve implemented as an open sleeve with two Al alloy rods. Simulation studies are carried out for different numbers of rods in the fourth sleeve. Study is carried out for even number of rods as it would have symmetrical configuration and gives better omnidirectional characteristics. The comparison of simulated VSWR for Tetra Sleeve Cage Antenna with two, four, six, eight, and ten rods in the fourth sleeve is shown in Fig. 4. It is found that for the number of rods greater than two, VSWR increases at low frequency and decreases as frequency increases. The impedance matching is reduced, as the number of rods in the fourth sleeve is increased above two. Hence, the fourth sleeve with two rods is selected for the design.

The comparison of simulated gain at horizon for Tetra Sleeve Cage Antenna with two, four, six, eight, and ten rods in the fourth sleeve is shown in Fig. 5. Tetra Sleeve Cage Antenna with more sleeves has negative gain values over most portion of frequency range (250–1850 MHz). Tetra Sleeve Cage Antenna with 2 rods has more gain than the other configurations and is greater than 0 dBi over the entire frequency range of 250–1850 MHz.

Hence, it can be concluded that Tetra Sleeve Cage Antenna with 2 rods in the fourth open sleeve

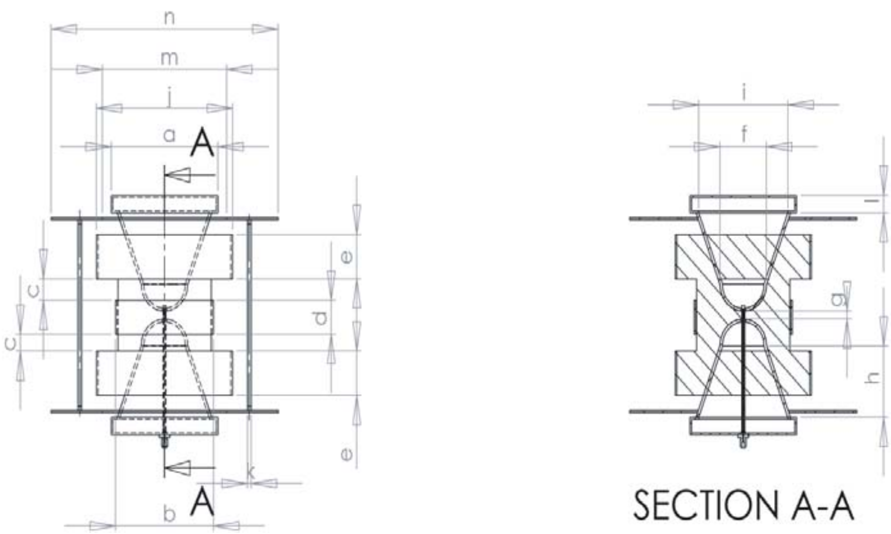
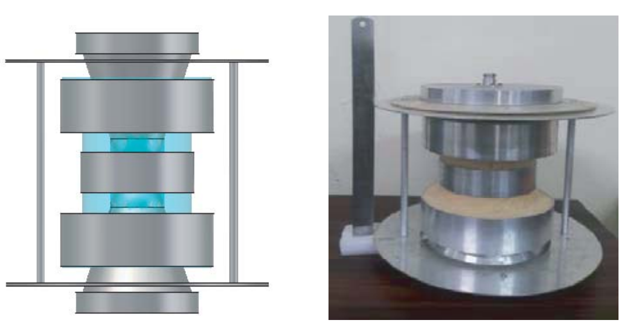


Figure 6. Structure of the proposed Tetra Sleeve Cage Antenna.



(a) (b)

Figure 7. (a) Simulation model, (b) realised model of the proposed antenna.

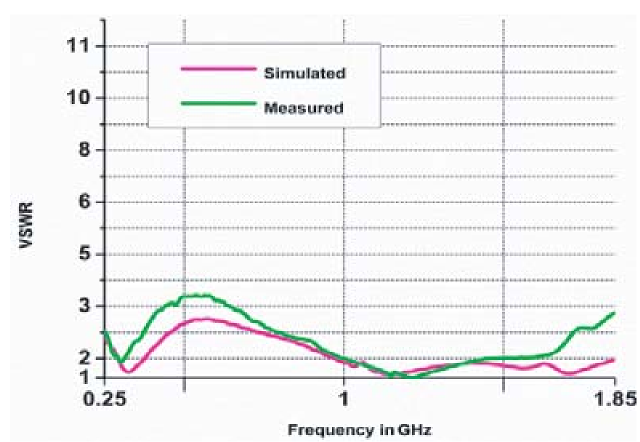
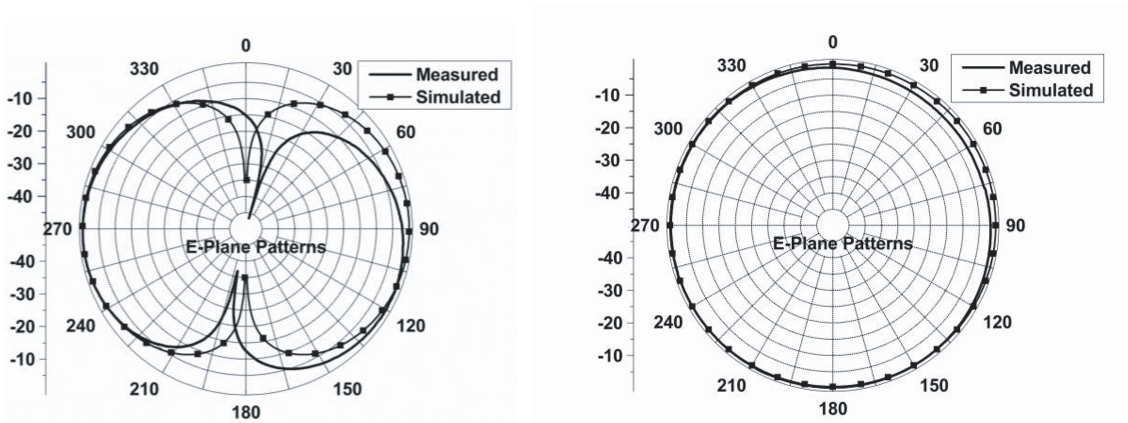


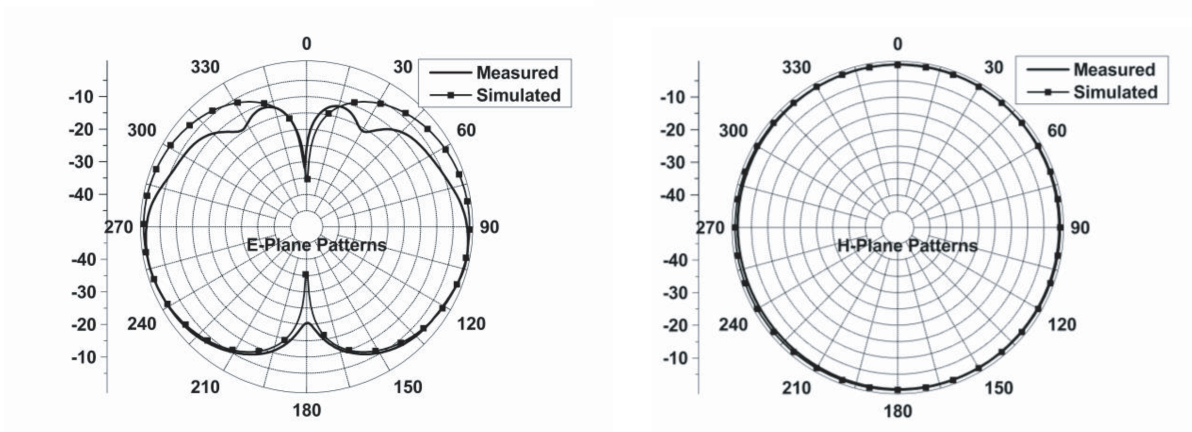
Figure 8. Simulated and measured VSWR of the proposed antenna.

is the optimum design. The structure of the proposed Tetra Sleeve Cage Antenna is shown in Fig. 6. The values of each parameter of Tetra Sleeve Cage Antenna are given in Table 1.

The height and diameter of the proposed Tetra Sleeve Cage Antenna are 240.8 mm and 268.47 mm, respectively. The size of a half wave dipole antenna at 250 MHz is 600 mm. Hence design of Tetra Sleeve Cage Antenna has resulted in size reduction of in 59.86% compared to a half wave dipole antenna at its lowest operation frequency. Tetra Sleeve Cage Antenna is fabricated as per design. The antenna is fed between edges of hemispheres using a 0.141” diameter, 50 ohm semi-rigid coaxial cable. The simulation model and a photograph of the realised Tetra Sleeve Cage Antenna are shown in Fig. 7.



(a)



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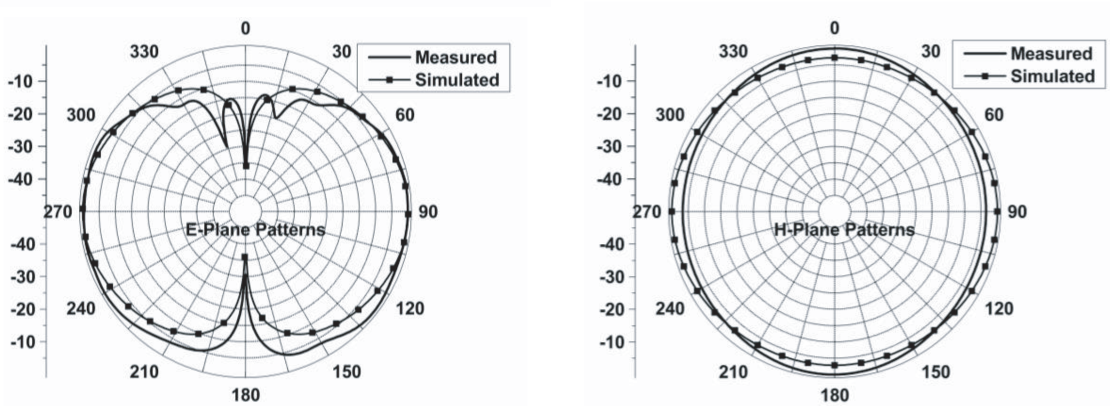
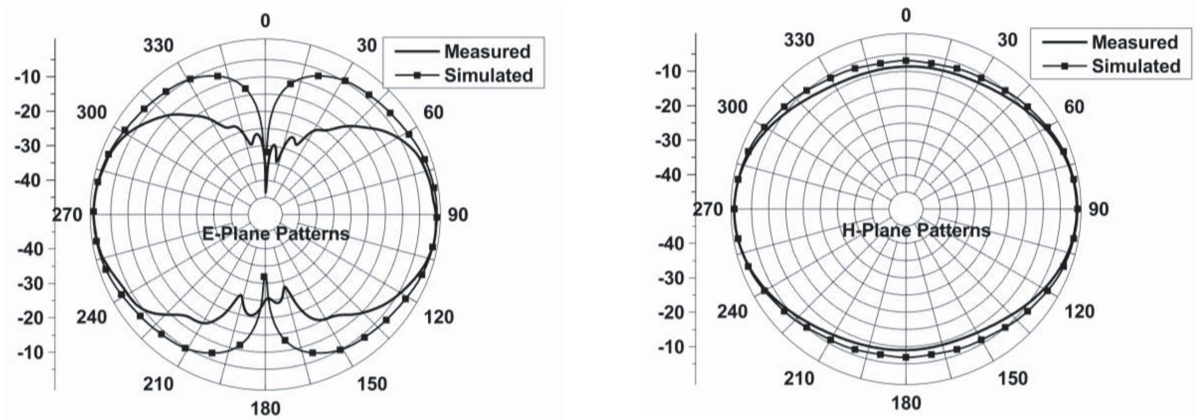
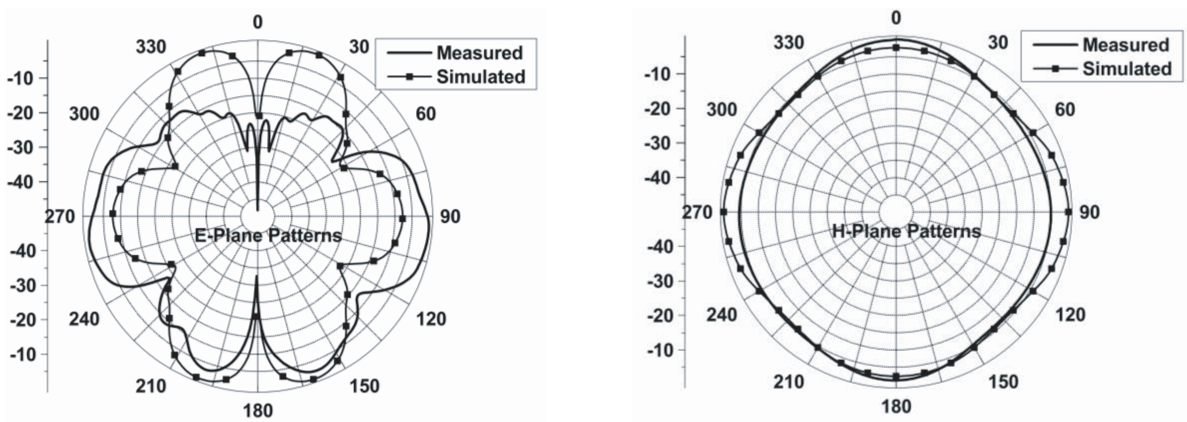


(c)



(d)



(e)

Figure 9. Simulated and measured radiation patterns of the proposed antenna, (a) 250 MHz, (b) 500 MHz, (c) 1000 MHz, (d) 1500 MHz, (e) 1850 MHz.

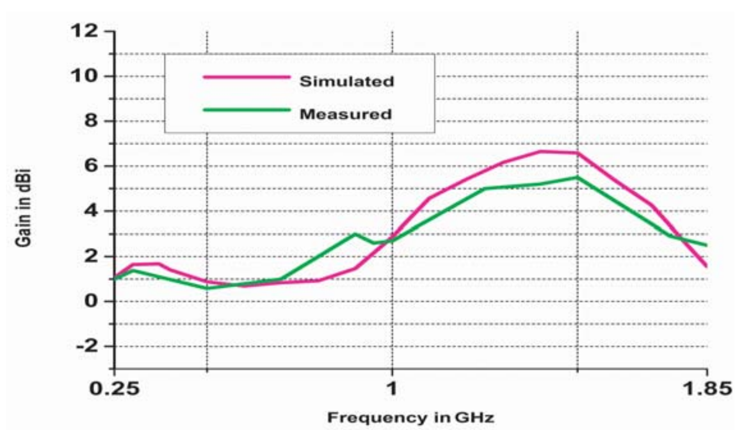


Figure 10. Simulated and measured gain plot of the proposed antenna.

3. MEASURED RESULTS AND DISCUSSION

The VSWR measurement of Tetra Sleeve Cage Antenna is performed using a Vector Network Analyser. The comparison of simulated and measured VSWRs is given in Fig. 8. There is good agreement between them. The proposed antenna has VSWR $< 1.9 : 1$ in frequency bands 270–330 MHz and 930–10 MHz. It has VSWR $< 3 : 1$ in frequency bands 250–410 MHz and 680–1850 MHz. The maximum value of VSWR in 250–1850 MHz is 3.3 : 1. Though the reflected power is more for VSWR of 3.3 : 1, the antenna finds a place in special areas of applications, owing to its small form factor and good omnidirectional characteristics. These include communication, interception, monitoring applications of defence systems, spectrum monitoring systems in civil and commercial sectors. Radiation pattern and gain of Tetra Sleeve Cage Antenna are measured in open antenna test range in 250 MHz to 500 MHz and in an anechoic chamber in 500–1850 MHz. The measured and simulated E-plane and H-plane patterns of Tetra Sleeve Cage Antenna are shown in Figs. 9(a), 9(b), 9(c), 9(d), and 9(e). The measured E-plane and H-plane radiation patterns are in good agreement with the simulated radiation patterns. Tetra Sleeve Cage Antenna exhibits good omnidirectional characteristics. The measured omnivariation is less than ± 1 dB from 250 MHz to 1000 MHz. The omnivariation increases above 1000 MHz. The maximum measured omnivariation is less than ± 4.5 dB over the frequency band 250–1850 MHz. The measured E-plane 3 dB beamwidth of the antenna varies from 20° to 120° over 250–1850 MHz. The comparison of simulated and measured gains of the Tetra Sleeve Cage Antenna are shown in Fig. 10. The measured gain of the antenna varies from 0.6 dBi to 5.5 dBi. The comparison of performance of the proposed antenna with published literature is given in Table 2. It can be inferred that the proposed antenna has broad bandwidth in UHF band and overcomes the limitations of the earlier designs with small form factor.

Table 2. Comparison of results of Tetra Sleeve Cage Antenna with published literature.

Sl. No.	Type of Antenna & Dimensions	Results & Remarks
1	A Wideband Dual Meander Sleeve Antenna [3], 850–2050 MHz. Height: 66 mm and Width: 32.8 mm	VSWR $< 3 : 1$. It covers a bandwidth of 82.75% and requires a large ground Plane of 900 mm × 900 mm. Radiation patterns and Gain not reported.
2	Wide-Band Dual Sleeve Antenna [4], 500–2100 MHz. Height: 138 mm and Diameter: 50 mm	VSWR $< 1.9 : 1$. It covers a bandwidth of 123.07%. Gain of the antenna is not reported. Asymmetrical E-Plane pattern at 2000 MHz.
3	A low profile broadband Conical antenna [7], 470–6000 MHz. Height: 60 mm and Diameter: 300 mm	VSWR $\leq 2 : 1$. Antenna covers 170.94% bandwidth. The antenna requires a ground plane of 800 mm diameter. Gain of the antenna is not reported.
4	Rectangular Sleeve Dipole Antenna [11], 850–2500 MHz. Height: 132 mm and width: 95 mm	VSWR $\leq 3 : 1$. Antenna covers 98.50% bandwidth.
5	Multi-sleeve antenna for mobile communications applications [12], 800–2500 MHz. Height: 104 mm and Diameter: 60 mm	VSWR $\leq 2 : 1$. Antenna covers 103.03% bandwidth. Gain: better than 0 dBi.
6	Broadband sleeve dipole antenna [13], 1000–3000 MHz. Height: 106 mm and Width: 25 mm	VSWR $\leq 2 : 1$. Antenna covers 100% bandwidth. Gain of the antenna is not reported.
7	Canonical Sleeve Antenna, CSA [14], 500–3600 MHz. Height: 111.43 mm and Diameter: 116.66 mm	VSWR $\leq 2.7 : 1$, CSA has a bandwidth of 151.21% and does not require ground plane. Gain: 0 to 3.6 dBi. Antenna has good Gain and radiation patterns.
8	Tetra Sleeve Cage Antenna, (Proposed Antenna), 250–1850 MHz. Height: 240.8 mm and diameter of 268.47.	(a) For VSWR $< 1.9 : 1$, Tetra Sleeve Cage Antenna operates in frequency bands 270–330 MHz and 930–1670 MHz with bandwidths of 20% and 56.92% respectively. (b) For VSWR $< 3 : 1$, Tetra Sleeve Cage Antenna operates in operates in frequency bands 250–410 MHz and 680–1850 MHz with bandwidths of 48.486% and 92.49% respectively. It has Gain: 0.6 to 5.5 dBi. It requires no ground plane and has good omnidirectional radiation patterns.

4. CONCLUSION

A compact broadband Tetra Sleeve Cage Antenna is designed and realised, in UHF band. The antenna is designed using canonical shaped antenna elements, three closed sleeves, and a fourth open sleeve. The novel concept of Canonical antenna structure and tetra sleeves has resulted in broadband antenna with compact form factor and finds applications in wireless communication systems, spectrum monitoring, and defence systems.

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