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Compact 'q'-Shaped Connected Ground 4-Element MIMO Antenna for X-Band Applications

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Abstract—This work introduces a novel compact 4-element MIMO antenna in the form of a q for use in the X-band. The proposed antenna has a footprint of $25 \times 25\,\mathrm{mm}^2$ and can be easily produced using an FR-4 epoxy substrate. The antenna consists of a 50-ohm microstrip line connected to ground and four q-shaped radiators. The antenna's impedance matching characteristics were analysed by performing a parametric study on its several parameters. The antenna has excellent impedance matching capabilities and operates between 7.2 GHz and 12.6 GHz. By utilising the connected ground technique and placing radiating elements in an orthogonal orientation, we can achieve the isolation of greater than 15 dB. The measured and simulated results demonstrate the antenna's high peak gain of > 4 dBi and high radiation efficiency of $> 90\%$, as well as its good impedance bandwidth ($S_{11} \leq 10$ dB) and isolation ($S_{21}/S_{31}/S_{41}$ of ≥ 15 dB). The presented antenna is a good option for X-band applications because its envelope correlation coefficient (ECC) is less than 0.00001, its total active reflection coefficient (TARC) less than -10 dB, channel capacity loss (CCL) less than 0.03 bits/sec/Hz, and mean effective gain (MEG) less than -3 dB.

1. INTRODUCTION

Current and next-generation wireless communications require high-speed data transmission, quality, and low bit error rates. Multiple-input multiple-output (MIMO) technique reduces bit error rate, increases transmission data rate, eliminates multiple fading, and increases channel capacity, improving transmission reliability. MIMO uses multiple antennas at both ends of the communication channel. MIMO antennas for 5G, WiMax, WLAN, C-band, X-band, Ku-band, K-band, and ultra-wideband (UWB) have been created for portable devices. MIMO system design must maximise port isolation, which affects diversity performance and channel capacity [1, 2]. Portable devices have limited space, making mutual connection between antennas challenging. Numerous MIMO antennas with different designs and isolation methods have been published [3–14].

In [3], a dumbbell-shaped slot is added between element centres for optimal isolation. In MIMO antennas, a defected ground structure (DGS) reduces mutual coupling [4]. T-shaped and narrow slots in the ground plane reduce mutual coupling [5]. [6] reduces radiating element mutual interaction with a T-shaped stub from the ground plane. Parasitic reflectors and ground strips improve isolation [7]. T-shaped stubs and rectangular strips improve isolation [8]. A U-shaped slot DGS in the ground plane promotes isolation [9]. In [10], symmetrical inverted L-monopole antennas (ILA) with interconnected ground planes improve isolation. In [11], a rectangular hole under each microstrip feed-line reduces mutual coupling. [12] proposed a new un-protruded multi-slot (UPMS) isolating element between two

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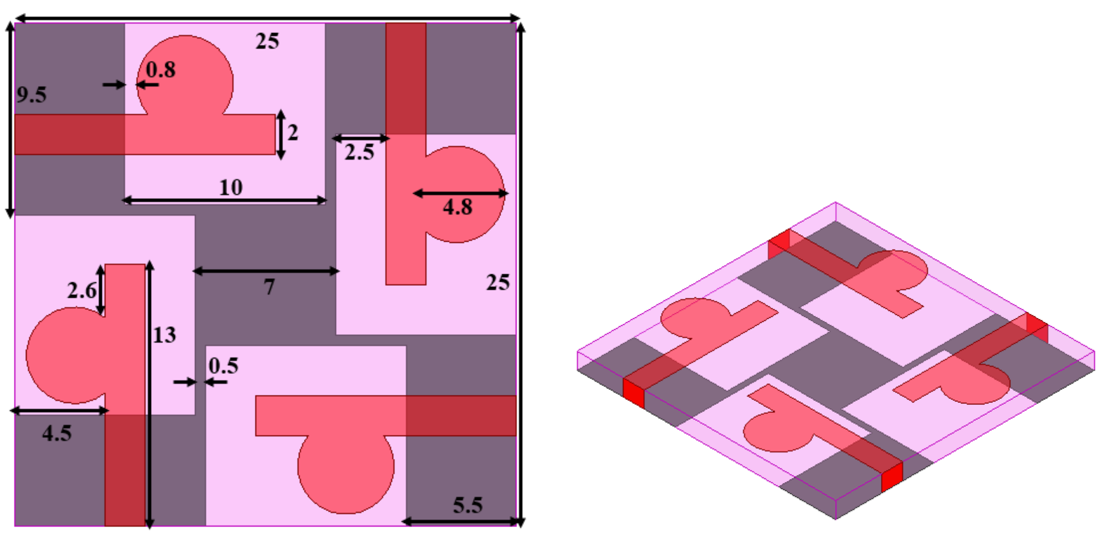
closely spaced antenna components to achieve excellent port isolation. In [13], orthogonal feed lines and decoupling crossed-slot and crossed-strip promote isolation. [14] isolates ports with four orthogonal pieces.

In this work, a novel compact 4-element MIMO antenna is suggested for X-band applications. The antenna of size $25 \times 25\,\text{mm}^2$ consists of four q-shaped radiators powered by a 50-ohm microstrip feed. Isolation of more than 15 dB is achieved by positioning radiating elements orthogonally and using the connected ground technique. The antenna working in the frequency range from 7.2 GHz to 12.6 GHz with good impedance matching properties demonstrates that the presented antenna is more suitable for X-band communication.

2. ANTENNA DESIGN & EVOLUTION

Figures 1(a) and 1(b) show the optimum design and isometric view of the suggested structure. FR-4 epoxy substrate material is used to mimic and build the antenna. The substrate has relative permittivity 4.4, height 1.6 mm, and loss tangent 0.02. The antenna has four q-shaped radiating elements on a $25 \times 25\,\text{mm}^2$ substrate. The bottom layer of the substrate has connected ground generated by combining all of the ground parts ($9.5 \times 2\,\text{mm}^2$) of individual antennas with a thin strip of $4 \times 0.5\,\text{mm}^2$ and a square component of $7 \times 7\,\text{mm}^2$. A 50-ohm microstrip line feed excites the $13 \times 2\,\text{mm}^2$ antenna. Radiating elements are orthogonally positioned to produce antenna port isolation above 15 dB. Connected grounds between antenna elements increase isolation and impedance matching. Ansoft HFSS was used to design, optimise, and simulate the proposed antenna. Figures 2(a)–2(c) and 3 show antenna evolution and S_{11} plots. Antenna #C operates from 7.2 GHz to 12.6 GHz with better impedance matching than Antennas #A and #B. The antenna parameters were tuned using parametric analysis: feed width (2 mm), ground width (5.5 mm), patch length (13 mm), gap between ground and patch (0.8 mm), and location of circular component attached to rectangular patch (8.5 mm). Figures 4(a)–4(e) show that the improved antenna has strong impedance matching characteristics and is used in this design.



(a) (b)

Figure 1. Proposed antenna; (a) Design with dimensional values and (b) isometric view.

The surface current distributions (SCDs) of the proposed MIMO antenna at 8.5 GHz, 9.5 GHz, 10.5 GHz, and 11.5 GHz when port 1 is excited are depicted in Figures 5(a)–5(d). The SCD illustrates how the surface current of one element in the MIMO architecture influences another. It can be identified that the connected ground provides more isolation between the ports of remaining elements. The surface currents are blocked by the connected ground, and hence no radiation enters the other ports.

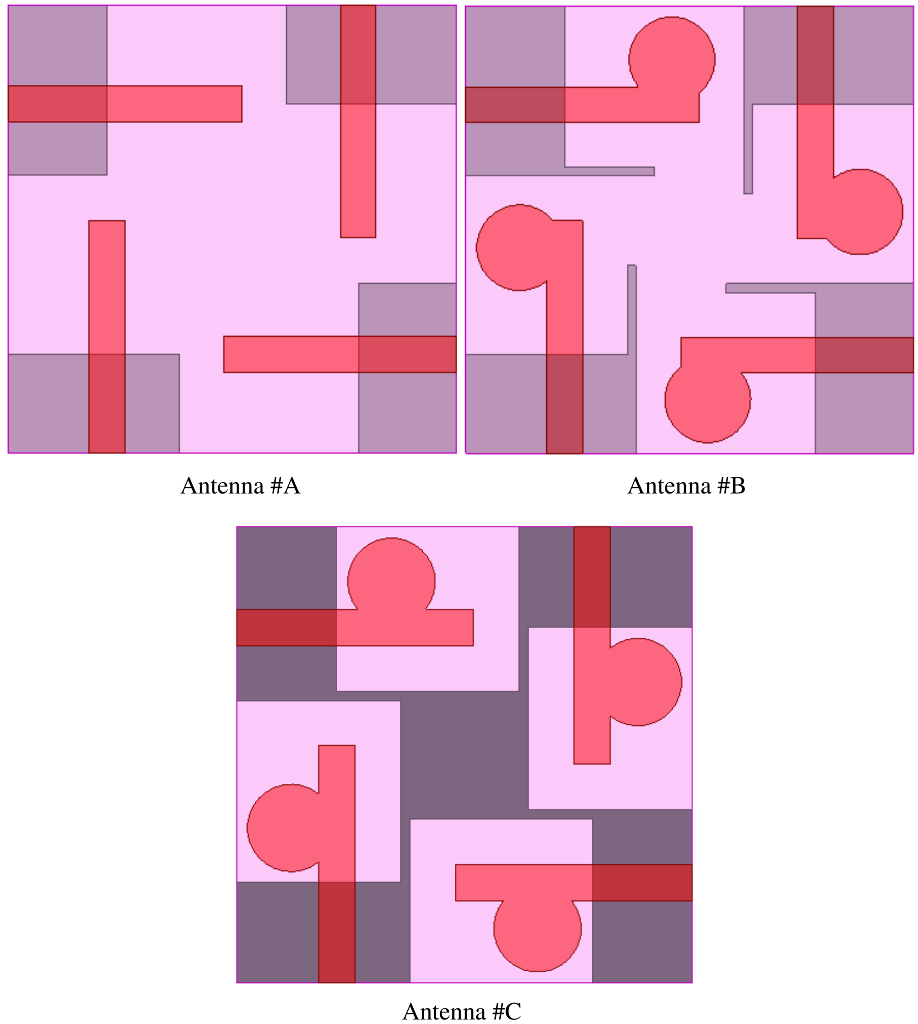


Figure 2. Proposed antenna evolution.

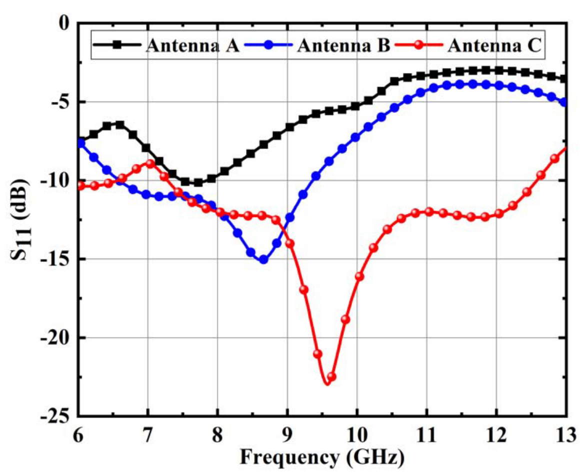


Figure 3. Proposed antenna evolution S_{11} results.

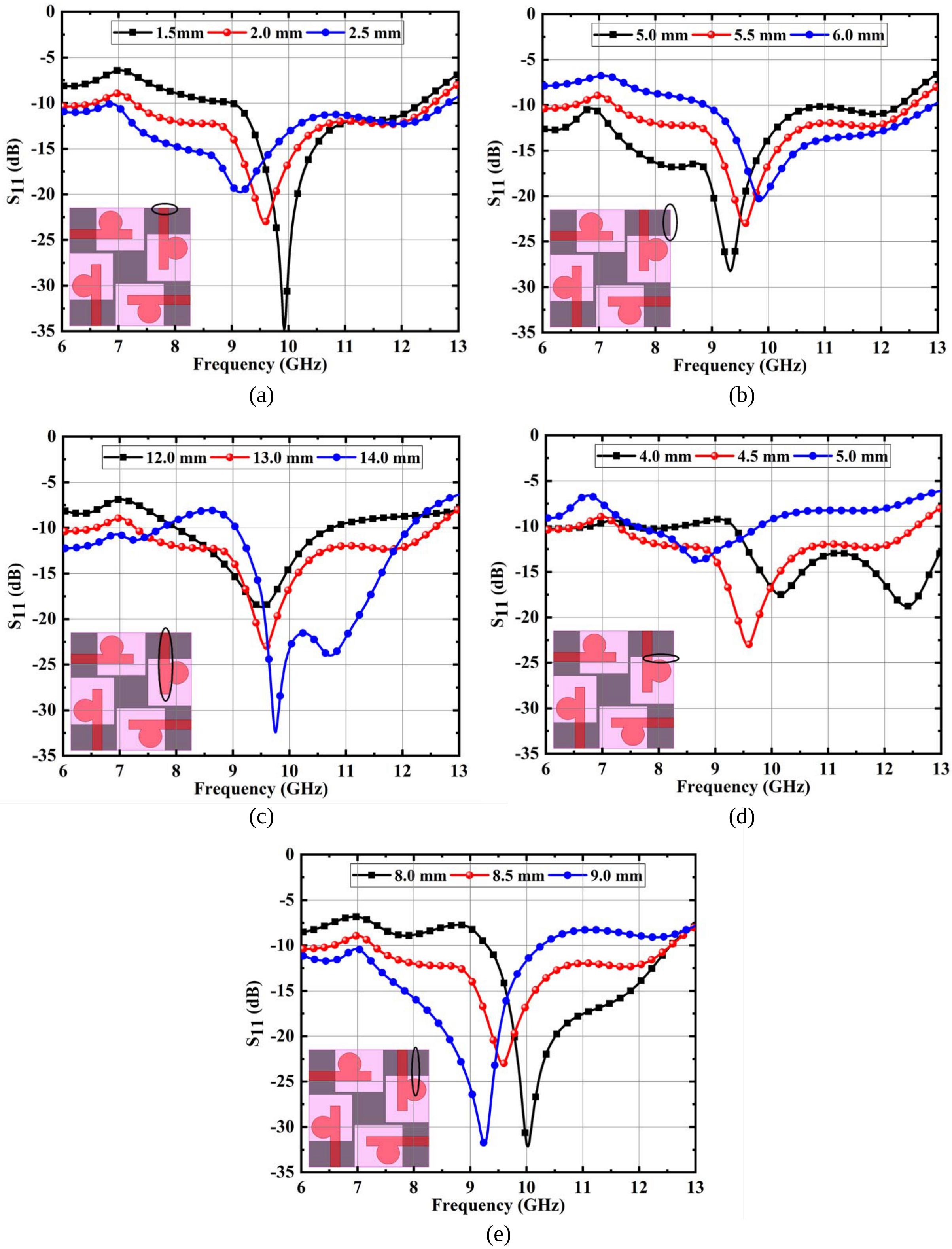


Figure 4. (a)–(e) Proposed antenna parametric analysis on various values.

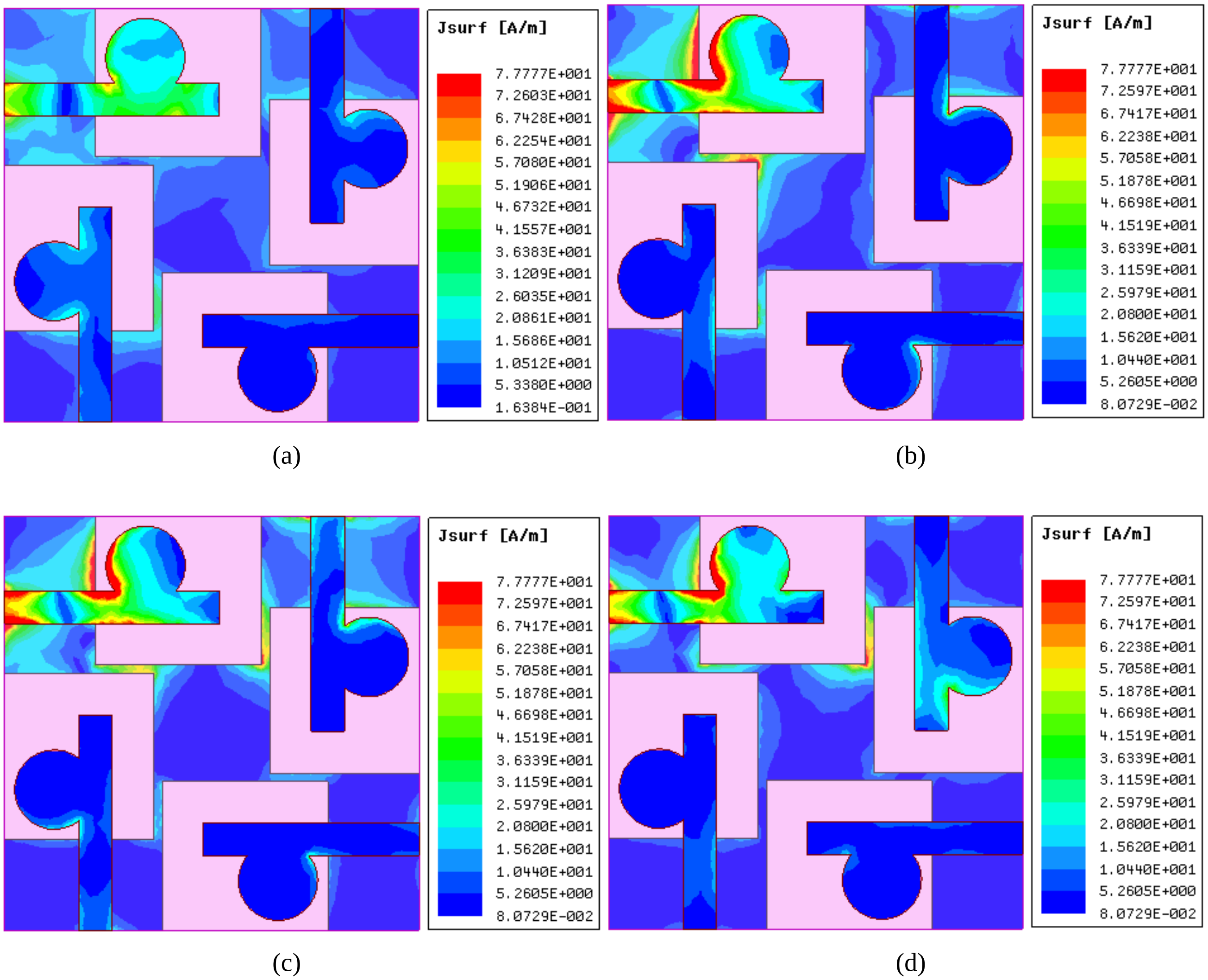


Figure 5. Proposed antenna SCD responses; (a) 8.5 GHz, (b) 9.5 GHz, (c) 10.5 GHz and (d) 11.5 GHz.

3. RESULTS AND DISCUSSIONS

The simulated antenna is fabricated, and its results are validated using vector network analyser (Anritsu MS2037C/2) and an anechoic chamber. The measured impedance (S_{11}) and isolation (S_{21}) characteristics along with simulated results are presented in Figures 6(a)–6(b). The results show a good agreement except with some minor differences due to fabrication tolerance, SMA soldering procedure, measuring environment, and tools employed. The antenna works from 7.2 GHz to 12.6 GHz with acceptable isolation.

Figures 7(a)–7(d) show the proposed antenna's simulated and measured E and H field patterns at 8.5 GHz, 9.5 GHz, 10.5 GHz, and 11.5 GHz, respectively. It can be observed that the antenna offers bidirectional E-plane pattern and omnidirectional H-plane pattern. The radiated E- and H-field patterns are perturbed at 11.5 GHz due to higher-order modes at higher frequencies and disturbances in the field distribution.

The peak gain and radiation efficiency plots of the proposed design are shown in Figure 8. The antenna offers the peak gain of more than 3 dBi and radiation efficiency of greater than 90% in the whole X-band from 7.2 GHz to 12.6 GHz.

Figures 9(a)–9(d) provide measurements of the envelope correlation coefficient (ECC), total active

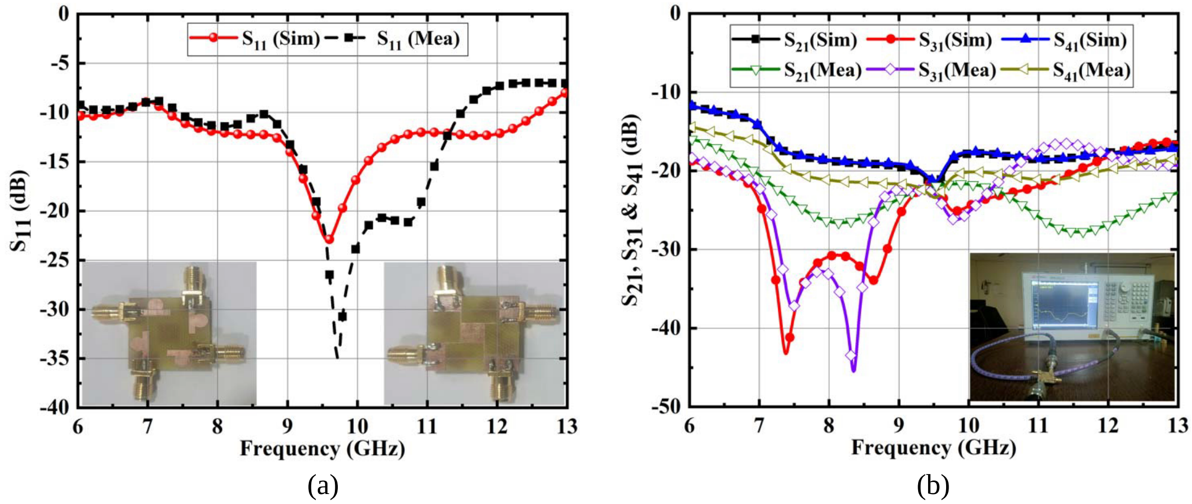


Figure 6. Proposed antenna simulation and measured results comparison; (a) S_{11} and (b) S_{21}, S_{31} & S_{41}.

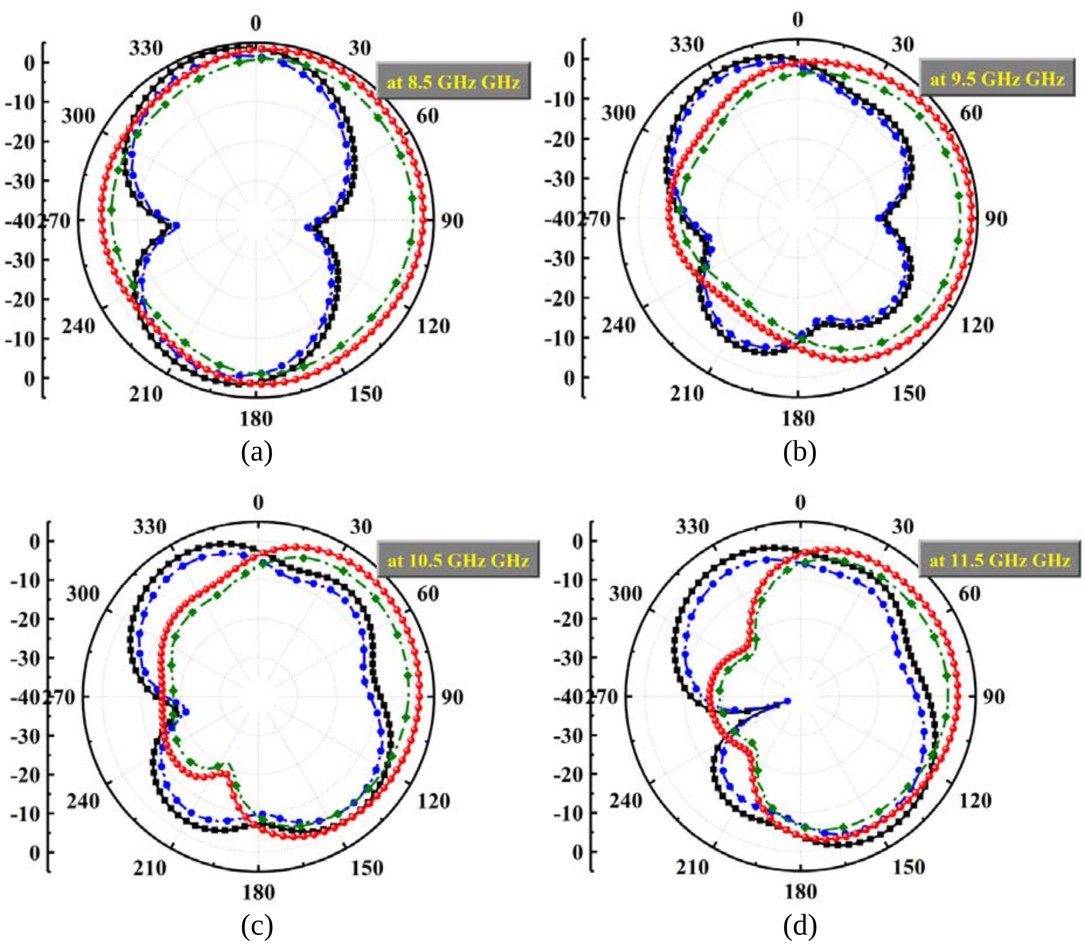


Figure 7. Proposed antenna E & H field patterns; (a) 8.5 GHz, (b) 9.5 GHz, (c) 10.5 GHz and (d) 11.5 GHz.

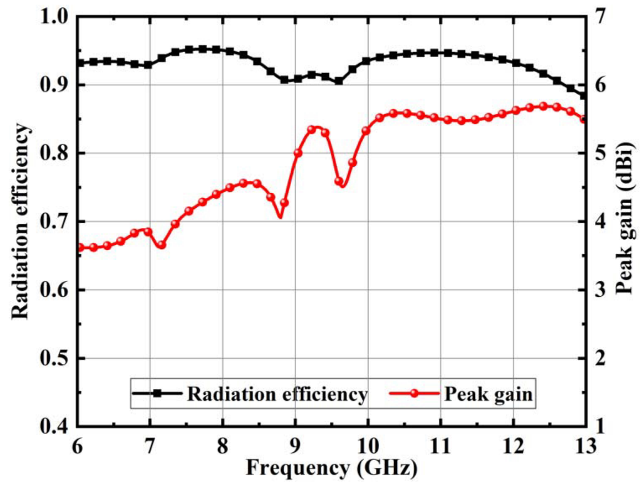


Figure 8. Proposed antenna radiation efficiency and peak gain results.

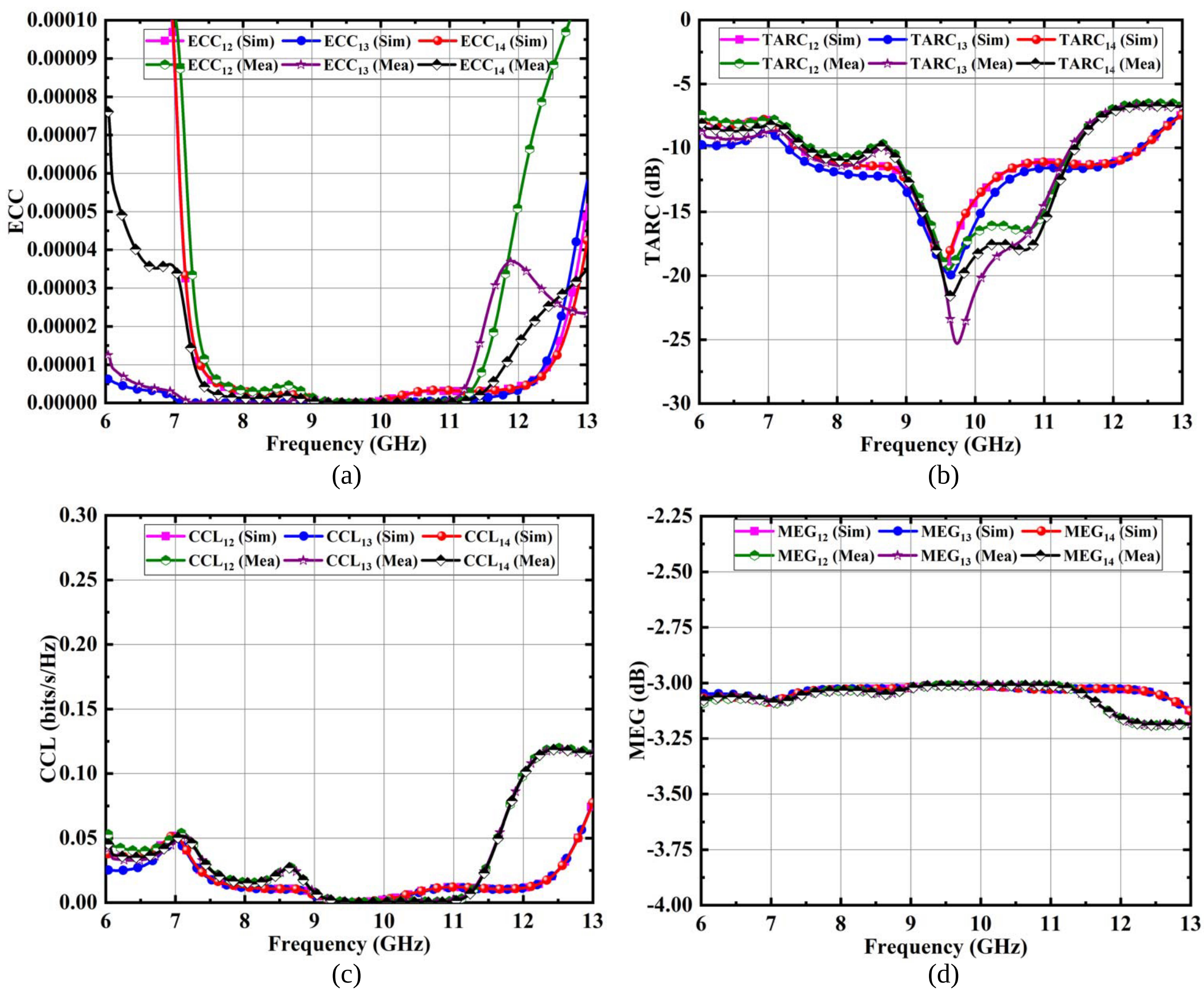


Figure 9. Proposed antenna MIMO diversity results; (a) ECC, (b) TARC, (c) CCL and (d) MEG.

reflection coefficient (TARC), channel capacity losses (CCLs), and mean effective gain (MEG) for the proposed antenna's MIMO diversity performance. These parameters are computed using Equations (1) to (4) given below [15–22].

$$\mathrm{ECC}_{S\text{-Parameters}} = \frac{\left|S_{ii}^{*}S_{ij}+S_{ji}^{*}S_{jj}\right|^{2}}{\left(1-\left(|S_{ii}|^{2}+|S_{ij}|^{2}\right)\right)\left(1-\left(|S_{jj}|^{2}+|S_{ij}|^{2}\right)\right)} \tag{1}$$

$$\mathrm{TARC}_{S\text{-Parameters}} = \sqrt{\frac{\left|(S_{11}+S_{12}e^{j\theta})^{2}\right|+\left|(S_{21}+S_{22}e^{j\theta})^{2}\right|}{2}} \tag{2}$$

$$\mathrm{CCL}_{S\text{-Parameters}} = -\log_{2}\det\left(\alpha^{R}\right) \tag{3}$$

where,

$$\alpha^{R} = \begin{bmatrix} \alpha_{ii} & \alpha_{ij} \\ \alpha_{ji} & \alpha_{jj} \end{bmatrix}$$

$$\alpha_{ii} = 1-\left(|S_{ii}|^{2}+|S_{ij}|^{2}\right); \quad \alpha_{ij} = -\left(S_{ii}^{*}S_{ij}+S_{ji}^{*}S_{jj}\right);$$

$$\alpha_{ji} = -\left(S_{jj}^{*}S_{ji}+S_{ij}^{*}S_{ii}\right); \quad \alpha_{ii} = 1-\left(|S_{jj}|^{2}+|S_{ji}|^{2}\right).$$

$$\mathrm{MEG}_{S\text{-Parameters}} = 0.5\eta_{i,\,\mathrm{rad}} = 0.5\left[1-\sum_{j=1}^{M}|S_{ij}|^{2}\right] \tag{4}$$

It can be found that the antenna achieves the ECC of < 0.00001, TARC of ≤ -10 dB, CCL of < 0.03 bits/sec/Hz, and MEG of ≤ -3 dB in the entire working band with good match between simulation and measurement results. Table 1 shows the comparison of proposed work with other present works listed in literature.

Table 1. Comparison of proposed work with others.

Ref.	**No. of elements**	**Size ($\mathbf{mm^2}$)**	**Bands (GHz)**	**Isolation (dB)**	**Gain (dBi)**	**R.E (%)**	**ECC**	**TARC (dB)**	**CCL (bits/ sec/Hz)**	**MEG (dB)**
[3]	2	35 × 40	8.4–26.7	> 22	-	-	0.0106	-	-	-
[4]	2	17 × 42	6.6–7.6, 8.3–10	> 13	> 1.7 dB	70	< 0.015	-	-	-
[5]	2	22 × 26	3.1–11.8	> 20	3.6–6	> 85	< 0.03	-	-	-
[6]	2	18 × 21	2.8–12.2	> 25	2–5	> 80	< 0.013	-	-	-
[7]	2	16 × 26	2.7–14.9	> 20	0.8–6.6	≥ 86	< 0.06	≤ −10	-	-
[8]	2	16 × 26	2.8–14.4	> 22	6.86	> 91	< 0.08	< −10	-	-
[9]	4	40 × 40	7.26–7.84	> 26	-	-	< 0.02	-	-	-
[10]	4	40 × 40	2.70–4.94	> 11	4		< 0.1	-	-	< −3
[11]	4	22 × 22	3.3–7.1	> 12	4.6–6.2	48–89	< 0.07	-	-	-
[12]	4	30 × 40	3.2–5.85	> 17.5	3.5	85	< 0.05	< −10	-	-
[13]	4	46.7 × 46.7	7.5–8.0, 9.2–10.7	> 20	3.5	70	< 0.03	-	-	-
[14]	4	25 × 25	7.8–16.5	> 15	1.02–5.5	92	< 0.14	< −4	-	-
P*	**4**	**25 × 25**	**7.2–12.6**	**> 15**	**> 4**	**> 93**	**< 0.00001**	**≤ −10**	**< 0.03**	**≤ −3**

4. CONCLUSIONS

This communication introduces a compact q-shaped 4-element MIMO antenna for X-band applications. The antenna has four q-shaped radiators activated by a 50-ohm microstrip feed. A parametric study of the antenna's characteristics was done to determine impedance matching. The antenna functions between 7.2 GHz and 12.6 GHz and matches impedance well. Isolation of > 15 dB is achieved by putting radiating elements orthogonally and using the linked ground technique. The antenna's peak gain is above 4 dBi, radiation efficiency over 90%, ECC less than 0.00001, TARC -10 dB, CCL below 0.03 bits/sec/Hz, and MEG -3 dB in the entire X-band from 7.2 GHz to 12.6 GHz. Simulate, build, and test the proposed antenna. The simulation and experimental findings match, confirming the antenna's suitability for X-band applications.

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