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RESEARCH PAPER

Compact modified 'T' slot circular patch quad band antenna for MIMO applications

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Compact modified T-slot circular patch antenna for multiple input multiple output (MIMO) applications, which has good response for four operating frequency bands is developed. Here the design consists of a circular patch with a new slot loaded T- shape on one side of the substrate and a feeder line on the other side of the substrate. A shorting pin is located between the patch and the feeder line. This proposed antenna resonates at the frequencies of 2, 4.8, 5.4, and 6.2 GHz covering the S-band, C-band, and LTE applications. The independent tuning of frequency bands is achieved by varying the length of the slots. By independent tuning of frequency bands, the selection of interested frequency band is achieved. The single element with miniaturized size of 1.945λ × 1.945 λ (30 × 30 mm²) is achieved including the feed line. The antenna has been tested for MIMO applications. The measured envelope correlation coefficient between the two elements, which are spaced 0.139 λ is <0.1(low correlation) and mutual coupling is found to be in the range of −20 dB to −80 dB. The simulation and measurement results of reflection coefficient, mutual coupling, and radiation pattern are presented.

Keywords: Modified T-slot, Circular patch, Frequency tuning, Multiple input multiple output (MIMO), Envelope correlation coefficient (ECC), Mutual coupling

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I. INTRODUCTION

The development of wireless technology in recent years has catapulted the demand for handheld devices for communication. The requirement is to cover more than one frequency band to support many wireless applications in commercial area. An ideal possibility is to integrate multiple bands in a single antenna device that can handle several usable frequency bands of various applications. As a matter of fact, the antenna design for handheld devices must be miniaturized in terms of space and design complexity for the fabrication of antenna to be cost effective.

Micro strip printable antenna has been more attracted for it satisfies the basic requirements of an antenna design such as low profile, simple to manufacture, and low cost [1]. Recently many good performance multiband and wideband antennas are reported for several applications including global system for mobile communication (GSM), global positioning system (GPS), digital cellular radio systems (DCRS), personnel communications service (PCS), wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMAX). Several techniques have been employed to achieve multiband and miniaturized antennas like multi-layer stacked patches, slot loading techniques, shorting pins and posts, planar patch antennas, etc. Multiband antenna design using stacked patches providing wide bandwidth with good return loss and performance is acceptable in mobile environment [2]. But the multi-layer patch antenna complicates the fabrication as well as height of the patch antenna gets increased, which will generate surface wave. Various types of slot loading multi-band antennas were reported. In [3], Tao Ni *et al.* states that multiple operating bands, stable antenna gain, and almost an omni-directional radiation pattern can be achieved by loading T-shaped slots in the terminals of a T-shaped antenna with good impedance matching. Antenna performance is independent of feed methods. In [4] C-shape slot loaded in disk shape patch to achieve quad band features for the applications of S-, C-, and X-bands is designed. However, frequency tuning is not attained in it. A miniaturized quad band antenna using slots with modified ground structure is reported in [5] in which bandwidth enhancement has been achieved. In [6], dual and tri operating frequency bands is achieved by using meandered strip and protruding stubs. Also various shaped planar patch antenna like H shape and U shape, has been used as tuning element for achieving multiband was reported [7–8].

The multiple input multiple output (MIMO) technology offers high data rate, large coverage, and spectral efficiency with multiple antennas at transmitter and receiver side. The important features to be taken care of while designing MIMO antenna systems are isolation, mutual coupling, and correlation [9]. Several printed antennas for MIMO applications have been proposed over the years [10–12]. MIMO antenna has been designed for the applications of Bluetooth,

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Wi-Fi, WiMAX, and UWB using two orthogonally separated semi-circular monopole antennas [9]. The MIMO antenna for WLAN and WiMAX applications have been proposed with four slot antenna elements in which quad frequency bands with correlation of <0.05 was achieved [10]. In [11] an E-shaped monopole antenna is proposed for MIMO systems to cover tri bands of 2.4, 5.4, and 5.8 GHz.

In this paper, a modified T slot on a circular patch compact quad band antenna for MIMO applications is proposed. Work on this paper is towards the achievement of a compact size multi band microstrip antenna with simple structure and also cost effective. The results of slot loading technique in patch antennas provide multiple bands and also the size gets reduced. Likewise, the proposed design of T-slot on patch provides four frequency bands of 2 GHz (2–2.2 GHz), 4.8 GHz (4.6–4.9 GHz), 5.4 GHz (5.28–5.44 GHz), and 6.6 GHZ (6.15–6.5 GHz) covering the applications of S-band (2–4 GHz), C-band (4–8 GHz), and LTE and compact size antenna. Also the proposed design is arranged in two elements configuration for MIMO applications, which has good response in envelope correlation coefficient (ECC) and diversity gain. However slot loading is not a new technique, the proposed design has the following advantages over papers reported in [1–11].

- Simple structure of loading T slot on the circular patch
- Miniaturized size of antenna
- Independent tuning of frequency bands
- Simple to fabricate and cost effective
- Low correlation <0.1 and reduced mutual coupling.

Section II of this paper describes the antenna geometry and design. In Section III, the details of simulation, measured results of single element and performance parameters of the antenna are provided. Section IV covers the two element MIMO antenna design and its performance.

II. ANTENNA GEOMETRY AND DESIGN

Figure 1 shows the configuration of the proposed compact quad band modified T-slot in a circular patch antenna, which is fed by 50 Ω micro strip feed line. The design uses the substrate as low cost FR4 epoxy with a relative permittivity of $\varepsilon_r = 4.4$ at a height of 1.5748 mm. The proposed antenna is designed for the frequency of 2.45 GHz, which has a conventional circular patch of radius of 15.4 mm. The inclusion of modified T-slot with various wavelengths in the conventional circular patch causes a quad band performance. The total size of the miniaturized proposed antenna is 30 × 30 mm^2. In Fig. 2, the photograph of the proposed T-slot antenna is shown.

The step by step process of compact modified T-slot antenna to achieve the quad band performance is shown in Fig. 3. The design starts with a conventional circular patch antenna for the operating frequency of 2.45 GHz [13]. A modified T-slot is loaded in circular patch on one side of the substrate. A feeder line of dimension L_f X W_f is provided on the other side of the substrate. The shorting pin of radius 0.7 mm is linked between feeder line and the radiating circular patch. The shorting pin between feeder line and the patch through substrate acts as a ground for the proposed design. A modified T-slot is achieved by introducing various wavelength slots on the patch in order to obtain quad band operation. Introduction of quarter wavelength slot, $\lambda_g/4$ ~22 mm, where $\lambda_g = c/f\sqrt{\varepsilon_{eff}}$ is the guided wavelength at the operating frequency band of 5.4 GHz as shown in Fig. 3(a). The resonant frequency (f_{r1}) and slot parameters can be related as shown in equations (1) and (2)

$$f_{r1} = \frac{c}{4l_e\sqrt{\varepsilon_{eff}}}, \tag{1}$$

$$l_e = \frac{L_1}{W_1} - (2l + 0.4) + \frac{4l}{\sqrt{\varepsilon_{eff}}}, \tag{2}$$

where l_e is the effective length of the slot, ε_{eff} is the effective dielectric constant, l is the correction coefficient and is predicted as *1.4535*. Introducing another one-eighth of a wavelength L-slot ($\lambda_g/8$ ~10 mm) with the existing one as shown in Fig. 3(b), provides a center frequency of 2 GHz. In this case the resonant frequency (f_{r2}) and slot parameters can be related as shown in equations (3) and (4).

$$f_{r2} = \frac{c}{8l_e\sqrt{\varepsilon_{eff}}}, \tag{3}$$

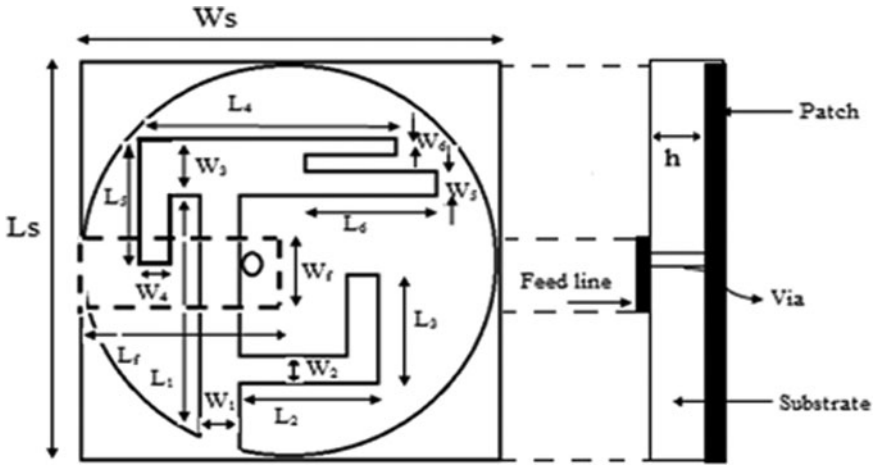


Fig. 1. Proposed compact modified T slot quad band antenna with dimensions $L_s = 40$ mm, $L_f = 18$ mm, $L_1 = 22$ mm, $L_2 = 10$ mm, $L_3 = 6.5$ mm, $L_4 = 13$ mm, $L_5 = 8$ mm, $L_6 = 9$ mm, $W_s = 40$ mm, $W_f = 5.4$ mm, $W_1 = 3$ mm, $W_2 = 2$ mm, $W_3 = 3.5$ mm, $W_4 = 2$ mm, $W_5 = 1.5$ mm, and $W_6 = 1$ mm.

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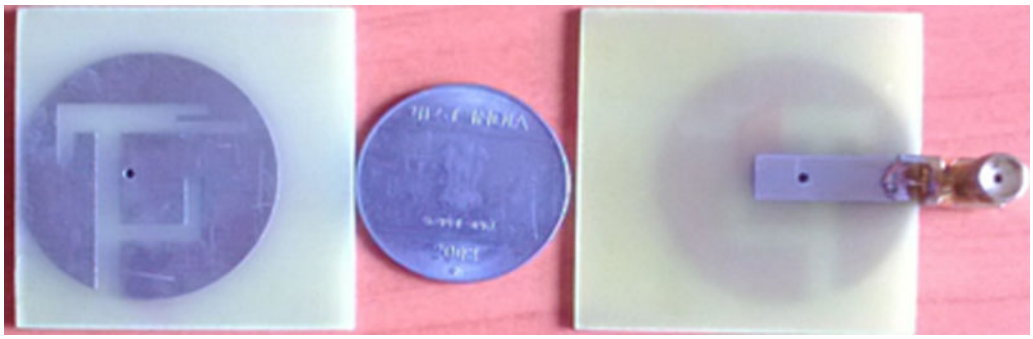


Fig. 2. Photography of proposed fabricated 'T' slot quad band antenna.

$$l_e = \frac{L_2}{L_3} + W_2 + \frac{8l}{\sqrt{\varepsilon_{eff}}}. \quad (4)$$

By introducing half wavelength ($\lambda_g/2 \sim 13$ mm) slot in addition to existing slots at upper part as shown in Fig. 3(c), offered the additional frequency response at 4.8 GHz. In this case the resonant frequency (f_{r3}) and slot parameters can be related as shown in equations (5) and (6).

$$f_{r3} = \frac{c}{2l_e\sqrt{\varepsilon_{eff}}}, \quad (5)$$

$$l_e = L_4 + L_5 - (W_4 + W_3 + W_6) + \frac{2l}{\sqrt{\varepsilon_{eff}}}. \quad (6)$$

Finally, introducing another one-half wavelength ($\lambda_g/2 \sim 18$ mm) slot as shown in Fig. 3(d) by slightly modifying the previous case give the frequency response at 6.2 GHz. In this case the resonant frequency (f_{r4}) and slot parameters can be related as shown in equations (7) and (8).

$$f_{r4} = \frac{c}{4l_e\sqrt{\varepsilon_{eff}}}, \quad (7)$$

$$l_e = \frac{L_6}{W_5} - 2l + \frac{4l}{\sqrt{\varepsilon_{eff}}}. \quad (8)$$

Based on the appropriate slot dimensions, Quad band frequency of interest can be achieved. Thus the combined modified T-slot offers four bands at the frequencies of 2, 4.8, 5.4, and 6.2 GHz. In order to get the desired frequency bands optimized lengths of the slots are considered for designing.

III. RESULTS AND DISCUSSION

The simulated *S*-parameter characteristics of the proposed Modified T-slot antenna from a single band to a quad band are shown in Fig. 4. Antenna 1 has an open ended quarter wavelength slot in the circular patch and gives the response at 5.4 GHz band, which covers LTE application bands. Antenna 2, after introducing the slot of one-eighth wavelength of L-slot in addition to the previous one, provides responses at 2 and 5.4 GHz. Antenna 3, which is developed by introducing another half wavelength slot in addition to the existing slots give the responses at 2, 5.4, and 4.8 GHz. Antenna 4 in which a half wavelength slot introduced along with the previous half wavelength slot offers a band at 6.2 GHz in addition to the center frequencies of 2, 4.8, and 5.4 GHz.

The surface current distribution of the proposed design at each frequency band of operation is shown in Fig. 5. The maximum current flow in a slot represents its corresponding resonant frequency of operation. That is to say the maximum intensity of surface current flow in L slot, which is responsible for 2 GHz band of operation. Moreover the maximum surface current flow in other slots is also responsible for its corresponding specific band of frequency.

The parametric study of proposed design is done by varying the length of each slot while keeping the other slot lengths constant and also the analysis of frequency tuning is performed. By varying the length of a specific slot, the interested frequency band can be tuned accordingly. The

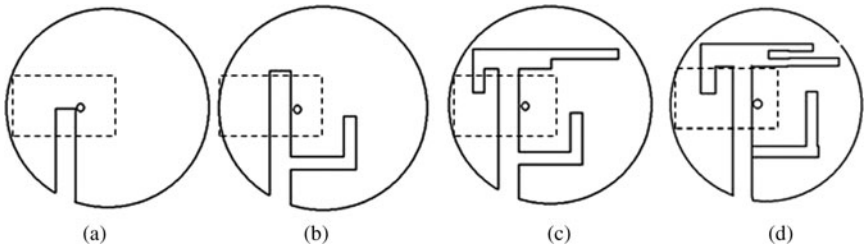


Fig. 3. Design steps of proposed quad band antenna. (a) Circular patch with single slot (Antenna 1 with resonant frequency f_{r1}). (b) Circular patch with dual slot (Antenna 2 with resonant frequency f_{r2}). (c) Circular patch with triple slots (Antenna 3 with resonant frequency f_{r3}). (d) Circular patch with quad slot (Antenna 2 with resonant frequency f_{r4}).

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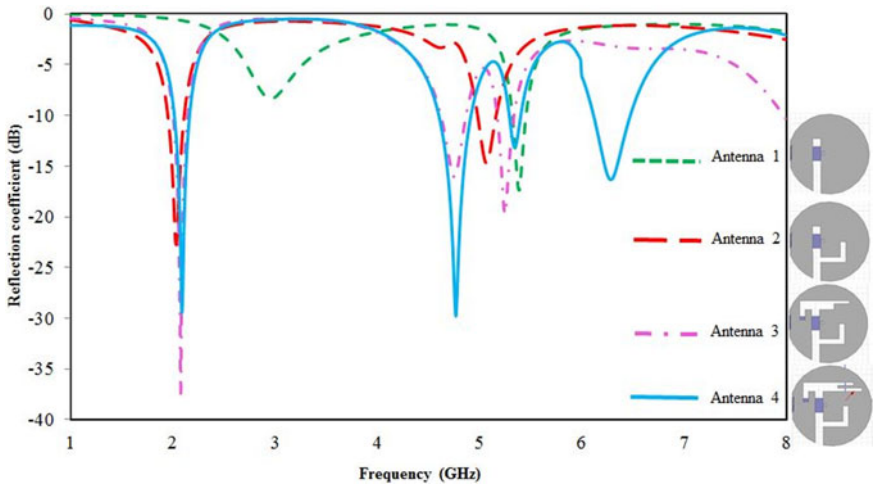


Fig. 4. Simulation *S*-parameter characteristics of the proposed antenna from single band to quad band.

parametric study shows that the proposed design offers an independent frequency tuning between each frequency bands. Figure 6 shows the frequency tuning of 5.4 GHz band by varying the length of the quarter wavelength slot while keeping the other slot lengths constant. When increasing the length of the slot L_1 and keeping other slot lengths constant causes the tuning of 5.4 GHz band move towards high frequency with slight tuning of 4.8 GHz band. Furthermore by decreasing the length of the one-eighth of a wavelength of the L-slot while keeping all other parameters of the design is constant, the tuned 2GHz frequency band move towards higher frequency and 4.8 GHz band move from 4.4 GHz to towards it (Fig. 7).

As shown in Fig. 8, by decreasing the length of the half wavelength upper slot and keeping all other bands constant the tuning of 6.6 GHz band move towards higher frequency. It is important to say that from this analysis the independent tuning of frequency bands can be achieved with the proposed design.

The comparison between the simulated and measured reflection co-efficient characteristics of the proposed antenna can be obtained by HFSS and Agilent's vector network analyzer is shown in Fig. 9, which shows a reasonable performance between simulated and measured results at particular bands of operation except with some amount of loss occur during fabrication and measurements.

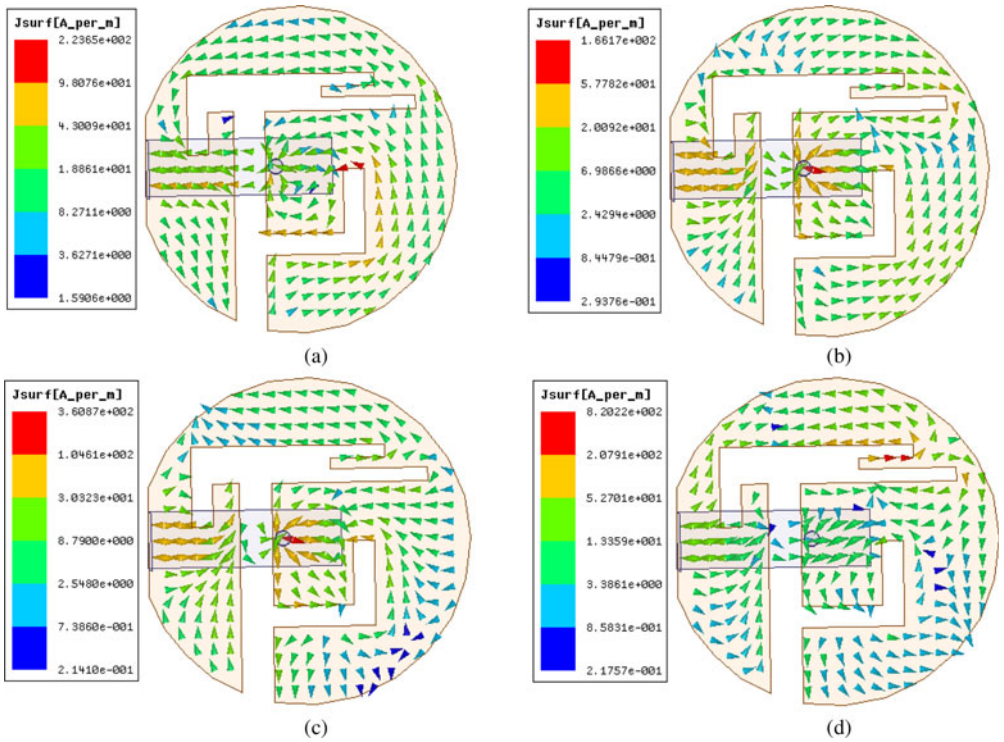


Fig. 5. Surface current distribution of proposed quad band antenna. (a) Surface current distribution at 2 GHz, (b) surface current distribution at 4.8 GHz, (c) surface current distribution at 5.4 GHz, and (d) surface current distribution at 6.2 GHz.

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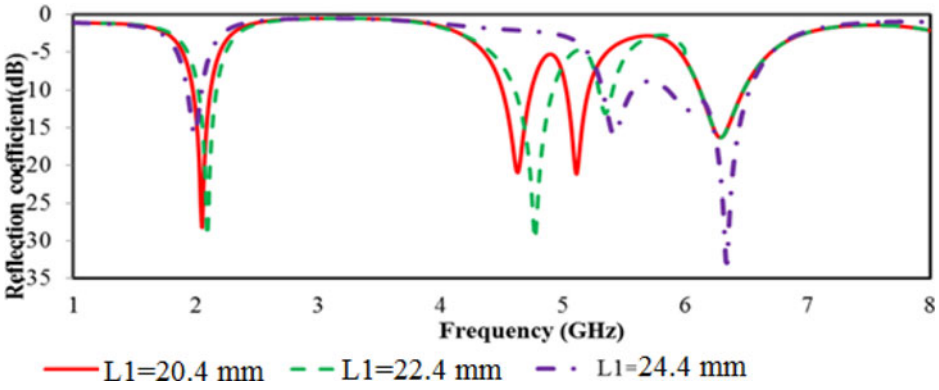


Fig. 6. S_{11} (dB) versus frequency in different value of L_1 provide tuning 5.4 GHz with 4.8 GHz.

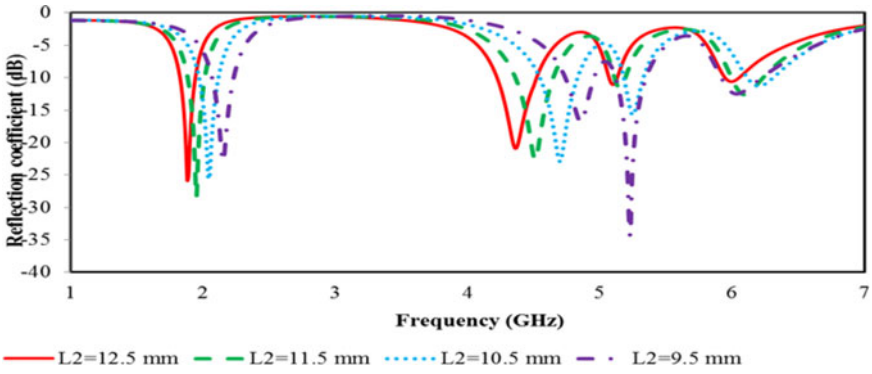


Fig. 7. S_{11} (dB) versus frequency in different value of L_2 provide tuning 2 GHz with 4.8 GHz.

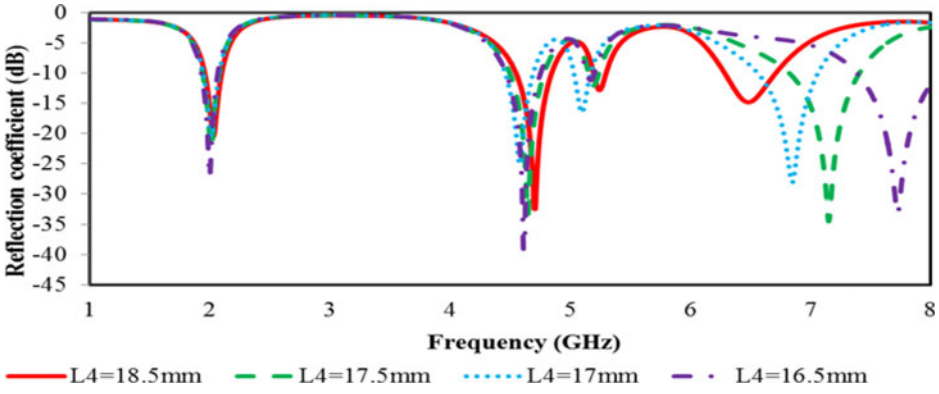


Fig. 8. S_{11} (dB) versus frequency in different value of L_4 provide tuning 6.2 GHz.

IV. TWO ELEMENT MIMO ANTENNA

The compact modified T slot circular patch quad band antenna elements discussed in detail in Section II can be used for MIMO applications when arranged in arrays. The photograph of the fabricated two element array antenna is shown in Fig. 10. In order to achieve the polarization diversity, each element of MIMO antenna is arranged in 180° or orthogonal fashion. In these arrangements the spacing between the elements is 0.139 λ, where λ is the wavelength of the lowest resonant frequency. In general for the good MIMO antenna system, which has low correlation and high isolation and also the mutual coupling between the elements, must be low. The closeness of simulations and measurements results can decide the channel capacity of MIMO system [14]. In fact in MIMO antenna, the effect of sharing a common ground causes severe mutual coupling problem due to surface current. But in the proposed design the rejection of sharing the common ground plane offers low mutual coupling.

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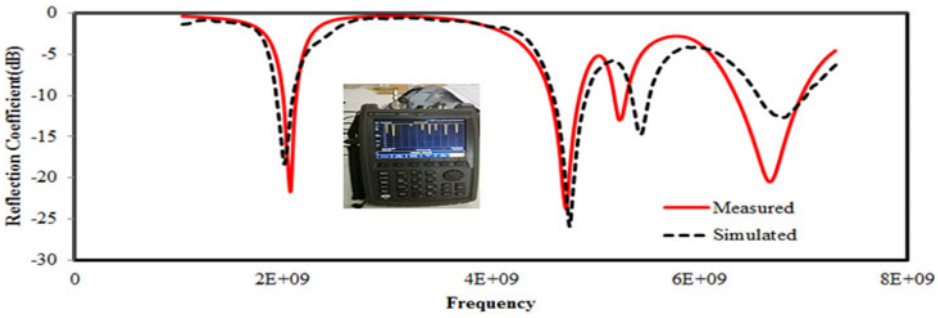


Fig. 9. Simulated and measured *S*-parameter ($|S_{11}|$) of proposed 'T' slot quad band antenna.

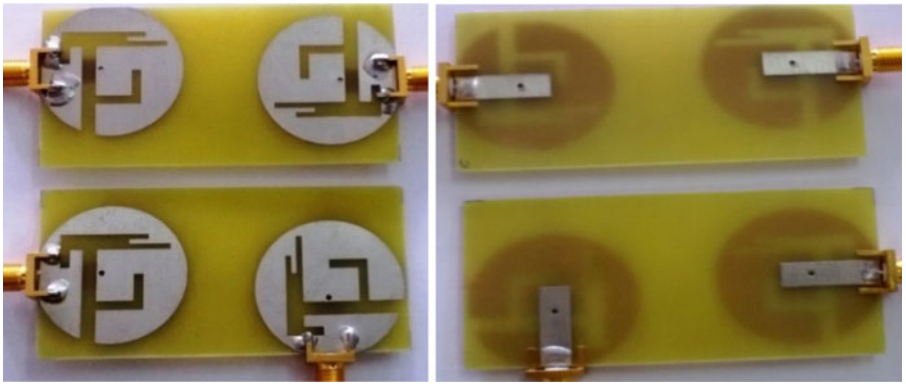


Fig. 10. Photograph of fabricated two elements MIMO antenna, placed 90° and 180° to each other.

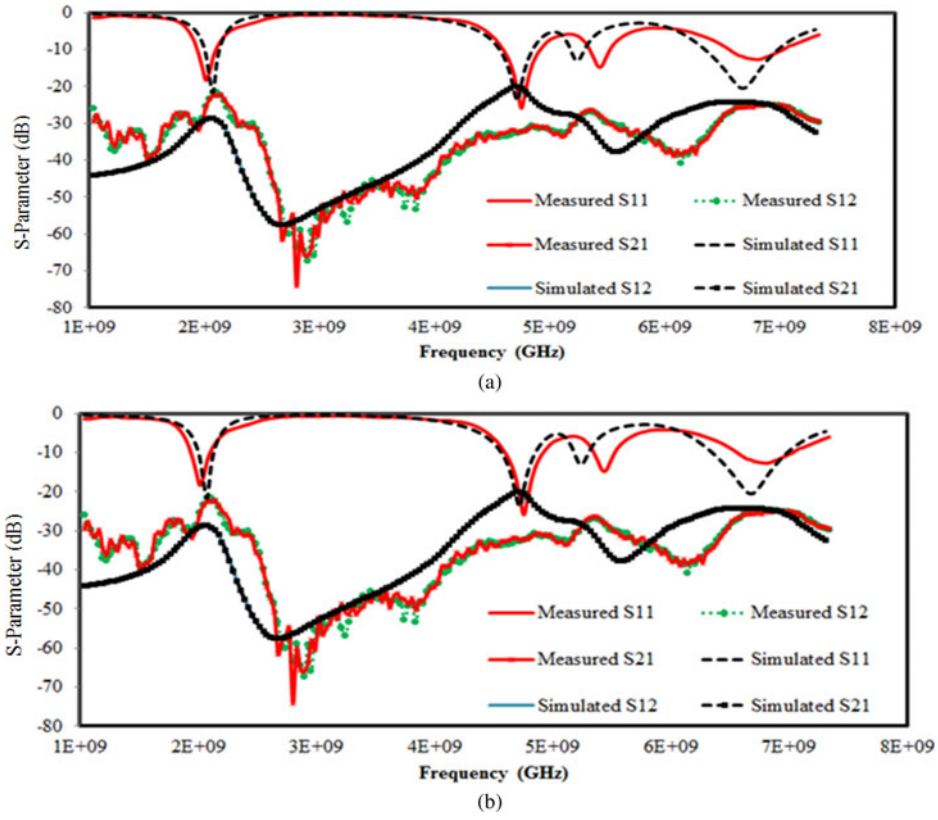


Fig. 11. Measured and simulated *S* parameters of two element 90° and 180° placed MIMO antenna. (a) Comparison of measured and simulated two element orthogonally (90°) placed MIMO antenna. (b) Comparison of measured and simulated two element 180° placed MIMO antenna.

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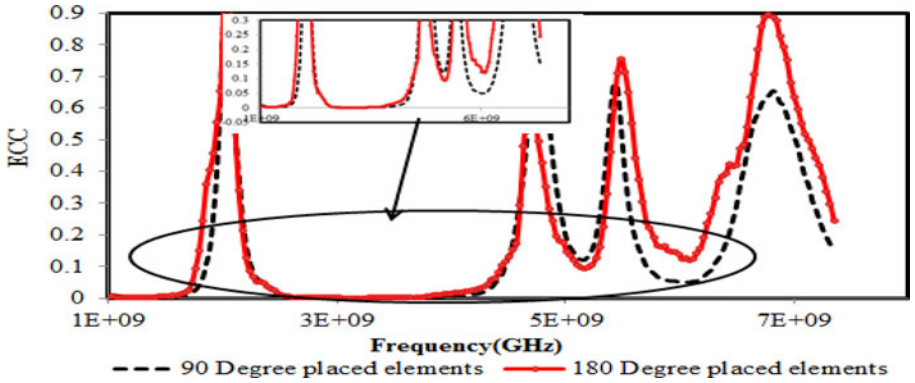


Fig. 12. Measured ECC of two element MIMO antenna.

The measured and simulated *S* parameters of both MIMO antenna arrangements are shown in Fig. 11(a) and (b). The measured reflection coefficient S_{11} of both cases shows the same result as that of individual element, which are matched with the simulation result. The mutual coupling S_{12} of orthogonally placed MIMO antenna shows a reduced mutual coupling of nearly <-20 dB to -80 dB compared with 180° placed MIMO antenna, which have only <-10 dB to -50 dB. Since the orthogonally placed elements do not affect each others performance it leads to low antenna correlation and the individual elements are in compact size.

A) Diversity performance of two element MIMO antenna

The ECC is calculated through *S*-parameters in a uniform environment, which is given as [15],

$$\rho_{eij} = \frac{\left|s_{ii}^{*}s_{ij} + s_{ji}^{*}s_{jj}\right|^{2}}{\left(1-\left(|s_{ii}|^{2}+|s_{ji}|^{2}\right)\right)\left(1-\left(|s_{jj}|^{2}+|s_{ij}|^{2}\right)\right)}. \quad (9)$$

The measured ECC for two element MIMO antennas is shown

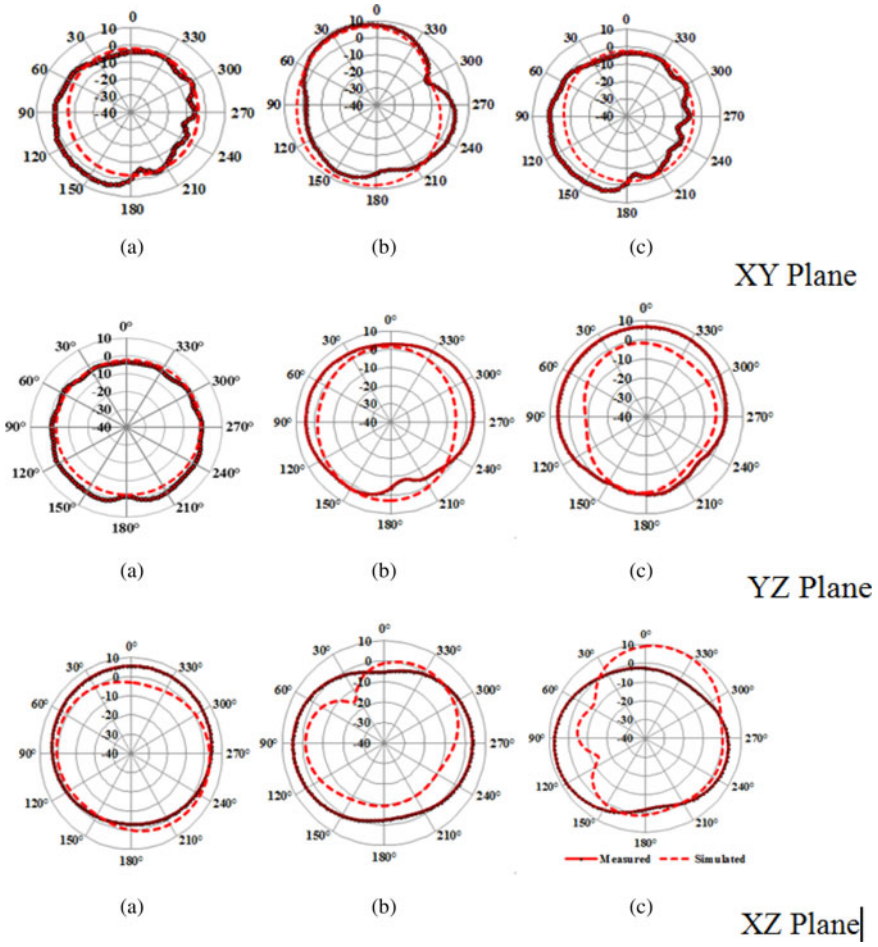


Fig. 13. Measured and simulated radiation pattern in three planes for the frequencies (a) 2 GHz, (b) 4.8 GHz, and (c) 5.4 GHz.

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Table 1. Measured performance of fabricated quad band antenna.

Methods	Achieved bands (GHz)	−10 dB bandwidth impedance (%)	Radiation efficiency (%)	Peak gain (dB)
Proposed method	Band I – 2.1 (2.02–2.2)	8.53	82.8	4.63
	Band II – 4.8 (4.6–4.92)	6.72	92.9	6.47
	Band III – 5.4 (5.3–5.4)	1.86	93.1	6.99
	Band IV – 6.2 (6.12–6.48)	5.71	91.3	6.2586
[2]	2.1	1.87	–	–
	2.42	1.035	–	–
[3]	2.41–2.51	–	–	1.5
	5.4–5.8	–	–	5
[5]	2.4	10		Peak gain 2.34
	3.3	4.8		
	6.4	53.9		
[6]	1.8	47.2		2.5
	5.2	14.6		3.7
	5.75	9.6		3.7
[8]	2.4	–	–	4.249
	5.8	–	–	5.36
[10]	2.6	–	88	3
	5.5	–	97	5.2
[11]	2.4	–	98	5.12
	5.2	–	97	3.99
	5.8	–	95	4.93
[12]	2.45	–	99	0.5
	5.4	–	96	3.6
	5.8	–	90	2.9
[15]	2.6	19.6	88	3
	3.5	20.7	95	4.3
	5.5	14.5	97	5.2

in Fig. 12 by using equation (9) and measured *S*-parameters. In general for a typical MIMO antenna, the correlation should be <0.5. But for the proposed MIMO antenna ≤0.1 correlation can be achieved for all bands. The expanded form of graph shows the correlation for 90° and 180° placed element MIMO antenna. Both cases show a low correlation value since both cases have a reduced mutual coupling between two elements.

The simulated and measured radiation pattern of single antenna element in *XY*, *YZ*, and *XZ* plane is shown in Fig. 13. The measured radiation patterns of proposed antenna are nearly identical and mostly omnidirectional at 2 and 5.4 GHz and this may be due to similar current distribution at both operating frequencies. Due to the surface current distribution, the measured radiation pattern of proposed antenna shows a directional characteristic for 4.8 GHz.

Measured gain, radiation efficiency, and impedance bandwidth for a particular operating frequency is shown in Table 1.

Among the measured results, the proposed method achieves 6.99 dB peak gain, which is more than that of the method presented in [2–12] and the peak radiation efficiency is 93.1%. In addition, compared with the C-shaped and L-shaped slot antenna designs in [15], this proposed slot antenna design can improve the gain of frequency of interest.

V. CONCLUSION

The compact modified T-slot circular patch quad band antenna with the tuning of interested frequency band for S-band, C-band, and LTE applications is designed. The designed antenna has a compact size of 30 × 30 mm² with the feed line. The measured results show that the attained maximum return loss is 30 dB at its one of the resonant frequency and has below 15 dB return loss for all other bands. Parametric studies show that the length of the slots provides the frequency tuning of single band of interest. The measured results of 90° and 180° placed elements, which offer a reduced mutual coupling between the elements of nearly <−20 dB to −80 dB and low correlation of ≤0.1 and the antenna provides high gain and good radiation efficiency.

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