Compact Tri-Band Antenna With Double Winding Structures for 3G/4G/5G Base Station Applications

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Abstract –

This paper introduces a compact triband antenna fed by a coplanar waveguide (CPW) for 3G/4G/5G base station applications with an ability to attain reversibility of transformer operation. The newly presented design provides Step-up and step-down transformer operation with double winding structures on either side of the central resonator. The antenna design is attained through methodical design procedures accompanied by thorough analysis for the development of prototypes rapidly. The proposed compact triband antenna performance is evaluated for both with and without windings in the antenna structure. The proposed design without the winding structure achieves a dual band of operation whereas the design with a winding structure achieves tri-band operation with improved S_{11} performance and very less VSWR. Two prototypes of triband UWB antenna with double winding structures of high design specifications are fabricated and tested to validate the proposed design principle. The effectiveness of the projected design is evident from the excellent association between simulated and measured results. It is shown that the proposed design is very effective with low cost and the fabricated prototypes of the antenna with double winding structures are very compact with the dimensions of 18.6 X 15.6 mm^2 achieving three frequency bands of operations at 2.9 GHz, 6.5 GHz, and 11.3 GHz with improved return loss < -10db and VSWR < 1.8.

Keywords—MIMO, Transformer, Tri-Band, Microstrip Antenna, coplanar waveguide.

I. INTRODUCTION

Wireless Communication has gained more interest in the last few decades due to communication devices capable of operating simultaneously with various standards at the frequency bands assigned to them such as Bluetooth (2402–2480 MHz), GSM850/900 (824–894/890–960 MHz), wireless local area network (WLAN) (2412–2482 MHz, 5150–5825 MHz), and

DCS/PCS/ UMTS (1710–1880/1850–1990/1920–2170 MHz). Systems that operates in 5G technology and devices that operates in multiple bands has been developed hastily to satisfy the raising demand for wireless data services. Multiband antenna are an evitable requirement for communication devices that operate with different standards since it helps in simplifying the device structure, eliminating unwanted coupling between antennas, and more importantly reducing the cost of the device by size reduction. The integrated circuits with improved features find a variety of applications as transceivers in the natural resources monitoring and the defense industry. Wider bandwidth is a very important requirement for a wide range of applications without compromising the size, integration capability, and more importantly power consumption. The miniaturized compact antennas are preferred mostly for the increasing demand for compactness and functionality for military and commercial applications. The implementation of dual-band antennas is achieved by combining orthogonal polarization antennas which provide appropriate isolation between different frequency bands. However, the radiation characteristics are the important parameters that limits the choice of antenna combination. Coupling between the antennas may cause interference with the operating frequency bands. Multiband antennas can be achieved by various design principles which include incorporating stubs, loop strips, or slots [1] – [3]. The insertion of these structures with the antenna design redistributes current distribution and resonates with the increase in efficiency of radiation at extra mode. Multiband antennas frequency band of operation can be varied by incorporating slots, stubs, or strips to the antenna design. Generally, operating frequency bands will be affected due to modifications in the antenna design hence optimization is preferred compromising the performance of the antenna at different frequency bands. Impedance transformers are also used to achieve multiple frequency bands of operation in antennas. The greatest benefit of this approach is redesigning of original antenna structure is not required and the performance of the antenna can be optimized through impedance transformer design.

The 3G (1.6 GHz – 2 GHz) and 4G (2 GHz - 8GHz) wireless communication systems will coexist with 5G (3 GHz -30 GHz) communication system in single base station for extended period of time. Therefore, single base station antennas will have high theoretical and practical value if it operates at multiple frequency bands suitable for 3G/4G/5G applications. Triband dual polarized square loop antenna for baseband applications with high port isolation is proposed [4]. Triband E- shaped antenna for WLAN and multiple input and multiple output (MIMO) applications is proposed [5]. A Compact bow-Tie antenna achieves triband operation by introducing couple of metal strips without increasing the area of the antenna structure [6]. Monopole antenna with dual inverted L slots in the compact radiator achieves triband operation for WLAN/WiMAX applications [7]. A Compact patch antenna incorporated with composite transmission line structures achieves triband operations [8]. The offset-fed inverted F-shaped vehicular antenna achieves triband operation without the need for an external matching network [9]. A compact monopole antenna fed by a coplanar strip achieves triband operation and omnidirectional radiation pattern using open-ended slots [10]. Compact monopole antenna implemented with metal pattern and matching stub operates in tri frequency bands for USB dongle applications [11]. Multiband circularly polarized antenna with compact structure achieves triband operations using metallic strips and split ring resonators (SRR) [12]. A Circularly polarized single feed single patch antenna achieves triband operation using stubs and slots [13]. A Triband antenna for radio frequency identification (RFID) application with fractal geometry is proposed [14]. Square slot antenna designed for WLAN/WiMAX applications achieves triband of operation using L-shaped strips [15]. A Tri-band reconfigurable UWB antenna with improved performance and reduced harmonics is achieved using single a winding structure [16].

In this paper, a triband antenna with compact dimensions and simple architecture to achieve reversibility of transformer operation is proposed. The proposed antenna structures can be configured for step-up and step-down transformer operations by changing the double winding structures. The new design procedure and deliberation on design parameters for achieving triband band operation and improved bandwidth with design flexibility are discussed. Furthermore, both the configurations of the proposed compact tri-band antenna with double winding structures are designed, fabricated and tested. The measurement results of the fabricated antennas finds close correlation with the simulated results and it is a real testament to the effectiveness of the proposed design.

II. DESIGN AND FABRICATION

A. *Design*

The proposed design for the novel compact triband antenna achieves reversibility of transformer operation by using three resonators (A, B1, and B2). The central resonator (A) is the key resonator in the design which is supported by two supplementary resonators (B1 and 2) and the proposed design resembles a balanced loop with feedback connection. The feedback connection in the proposed design is incorporated for the principle of zero reverse transmission characteristics. Providing perfect balance and wide bandwidth are a very important features of the balun and it can be realized and modified in different ways. In the proposed design the balun structure is realized by creating windings next to the central resonator (A). The proposed design principle achieves reversibility of transformer operation by varying the position of the winding structure at either sides of the central resonator (A). The step-up transformer has more windings on the primary side than on the secondary side resulting in an increase in voltage thereby decreasing the current. However, the step-down transformer has more windings on the secondary side and inverses the step-up transformer operation by decreasing the voltage and increasing the current. In the proposed design the right side of the central resonator (A) is considered as the primary side and step-up transformer operation is accomplished by creating a double winding structure to the right side of the central resonator (A). Furthermore, the step-down transformer operation is attained by creating a double winding structure to the left side (secondary side) of the central resonator (A). The winding is the very essential part of the transformer. Winding is the internal circuit of the transformer and it is referred to as heart of the transformer since it has a direct connection with the power grid. The change in winding reflects the change in voltage and the reversibility of transformer operation can be achieved by interchanging the winding structure from primary to secondary. The structure of the proposed compact antenna with and without double winding structures is shown in fig 1. The dielectric constant and the guided wavelength for the proposed design are calculated from equations (1) and (2)

$$\lambda_g = \frac{c}{[f\sqrt{\varepsilon_{eff}}]} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2}\right)\left[\frac{1}{\sqrt{\left(1 + 12\frac{h}{w}\right)}}\right] \tag{2}$$

Where, λ_g is the guided wavelength, C is the velocity of light, f is the fundamental mode resonant frequency, ε_{eff} and ε_r respectively denotes effective dielectric constant and relative dielectric constant, w and h denotes substrate's Width, and substrate's thickness. The characteristic impedance of the microstrip line is calculated from equation (3). The length and width of the feed are determined using equations (4) and (5). Table 1 depicts the dimensions of the proposed compact triband antenna with and without windings.

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}\left\{\frac{w}{h} + 1.39 + 0.68 \times \ln\left(\frac{w}{h} + 1.44\right)\right\}}} \tag{3}$$

$$L_f = \frac{\lambda_g}{4} \tag{4}$$

$$W_f = \frac{2h}{\pi}\{(B-1-\ln(2B-1)+(\frac{\varepsilon_r-1}{2\varepsilon_r})\}\,x\,\{\ln(B-1)+0.39-(\frac{0.61}{\varepsilon_r})\} \tag{5}$$

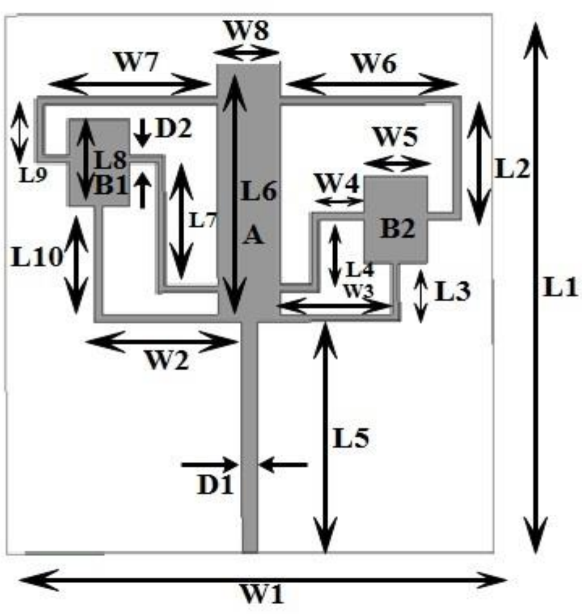
Where, $h = \frac{0.0606\lambda}{\sqrt{\varepsilon_r}}$ and $B = \frac{60\pi^2}{z_0\sqrt{\varepsilon_r}}$

The effective length (L_{eff}) is determined through equation (6)

$$L_{eff} = \frac{\lambda}{2\sqrt{\varepsilon_{reff}}} \tag{6}$$

Table 1: Dimensions of the proposed compact triband antenna

Antenna Structure	Parameters	Dimensions (mm)										
Basic antenna without Winding structure	**Length(L)**	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	
		18.6	4	2.5	2.75	9	9	4.75	3	2	4	
	Width(W)	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**D1**	**D2**	
		15.6	4	3.6	2	2	5.8	5.8	2	0.5	0.25	
Step down Transformer - Double Winding	**Length(L)**	**L22**	**L23**	**L24**	**L25**	**L26**	**L27**	**L28**	**L29**	**L30**	**L31**	**L32**
		8	5	4	3	2.5	2.75	9	4.25	4.75	2	8
	Width(W)	**W17**	**W18**	**W19**	**W20**	**W21**	**W22**	**W23**	**W24**	**D5**	**D6**	
		2	2	2	5.8	2	5.8	4.4	1.2	0.5	0.25	
Step up Transformer – Double Winding	**Length(L)**	**L44**	**L45**	**L46**	**L47**	**L48**	**L49**	**L50**	**L51**	**L52**	**L53**	**L54**
		8	4.25	7	4	2.75	2.75	4.75	3	2	7	2.5
	Width(W)	**W32**	**W33**	**W34**	**W35**	**W36**	**W37**	**W38**	**W39**	**D9**	**D10**	
		1.2	2	2	5.8	2	5.8	3.8	2	0.5	0.25	



a)

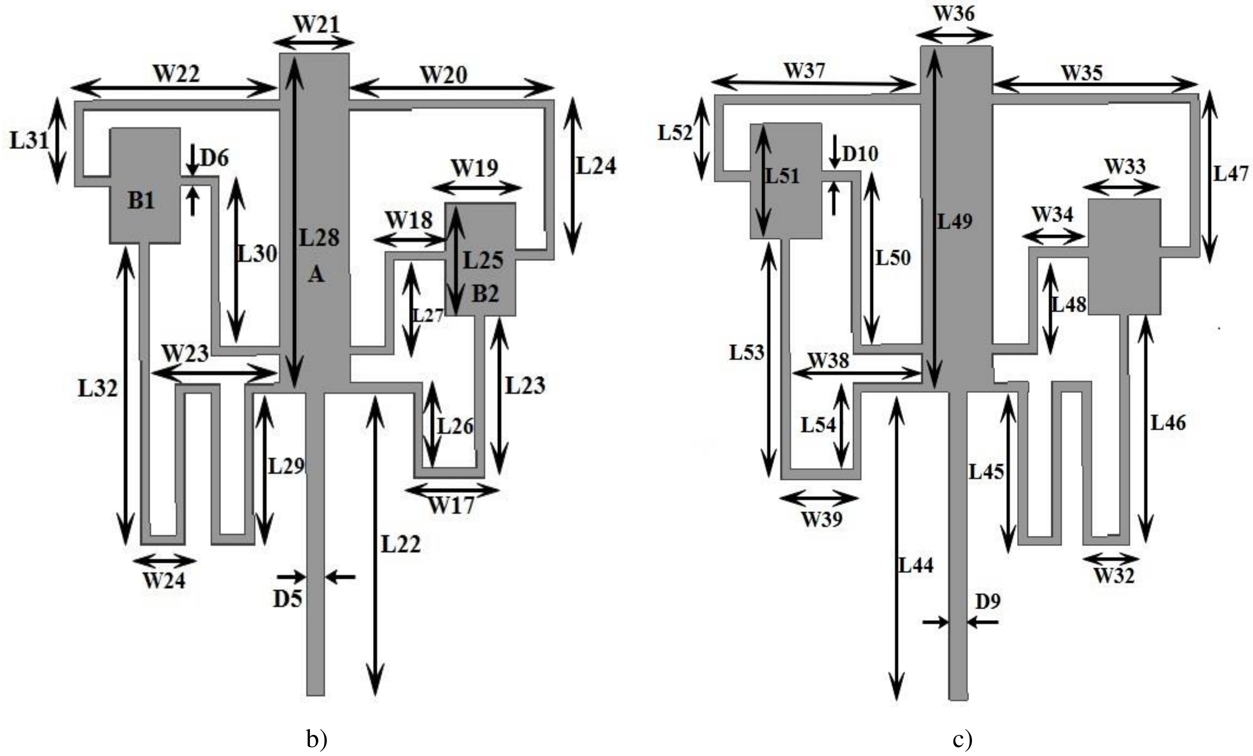
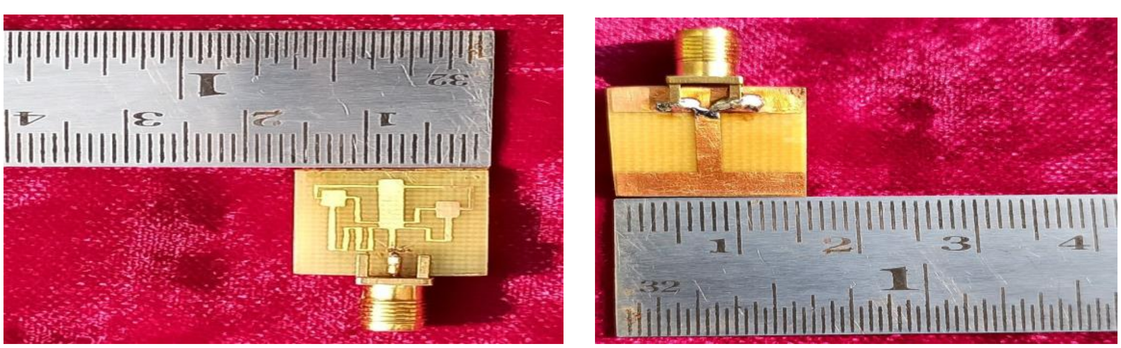


Fig 1 Structure of the proposed antenna a) without Windings b) With Windings - Step down transformer configuration

C) With Windings – Step up transformer configuration

B. Fabrication

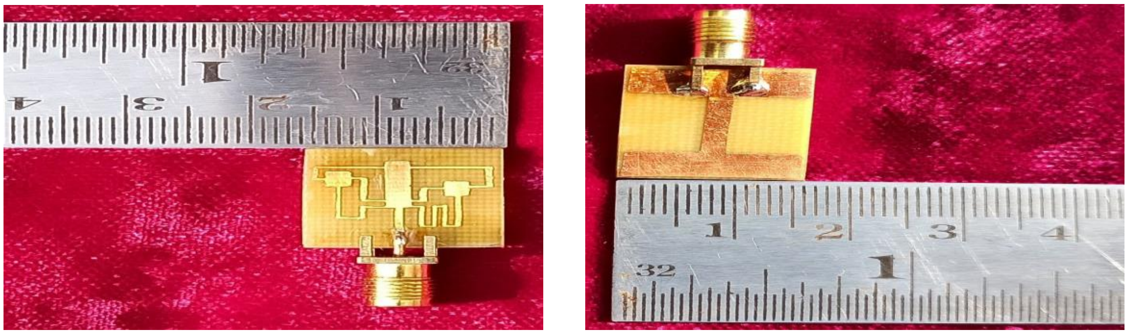
Two prototypes of the proposed compact tri-band antenna with double winding structures were fabricated and measured to analyze its performance. The dimension of the prototypes are 18.6 X 15.6 mm2 and the proposed compact antenna prototypes were fabricated on low-cost FR4 substrate with a thickness of 1.6mm. The double winding structure on the left side of the central resonator (A) performs a step-down transformer operation. The prototype of step-down configuration tri-band antenna with a double winding structure is shown in fig 2. Similarly, the double winding structures incorporated at the right side of the central resonator (A) achieves step-up transformer operation. The prototype of step-up configuration tri-band antenna with a double winding structure is shown in fig 3.



(a) (b)

Fig 2 Prototype of Triband Antenna step-down configuration

(a) Top View (b) Bottom View



(a) (b)

Fig 3 Prototype of Triband Antenna step-up configuration

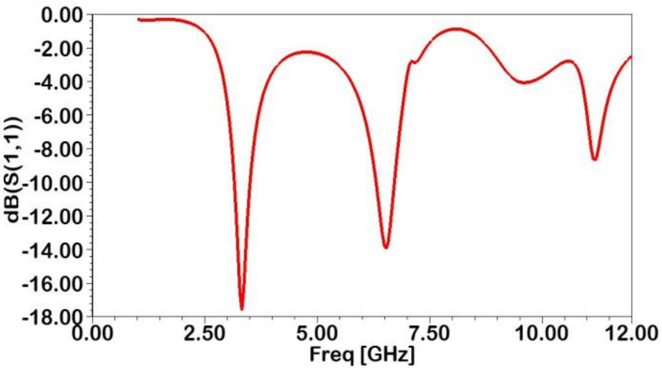
(a) Top View (b) Bottom View

III. RESULTS AND DISCUSSION

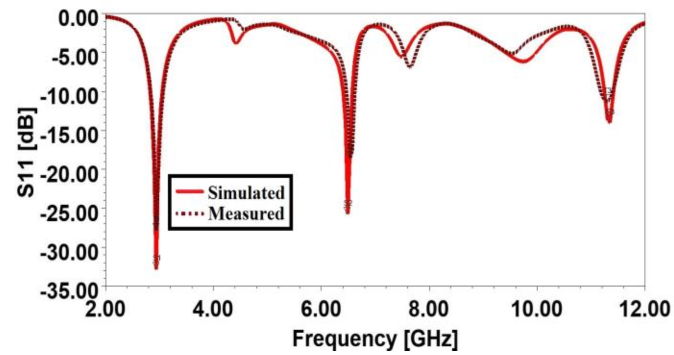
For the validation of the proposed design, the compact triband antenna was simulated in a commercially available simulator ansys high frequency simulation software (HFSS) and the measurement is done in MS2026MC master vector network analyzer (VNA) 8FT chamber. The measurement results of the prototypes match closely with the simulated results and authenticate the projected design theory of the compact triband antenna. Due to fabrication tolerance, chamber calibrations, and relative permittivity dispersion there is a slight shift in frequency between the simulation and measured results. The simulation and measured results of the antennas with and without double winding structures are summarized below.

A) Return Loss (S11) Analysis

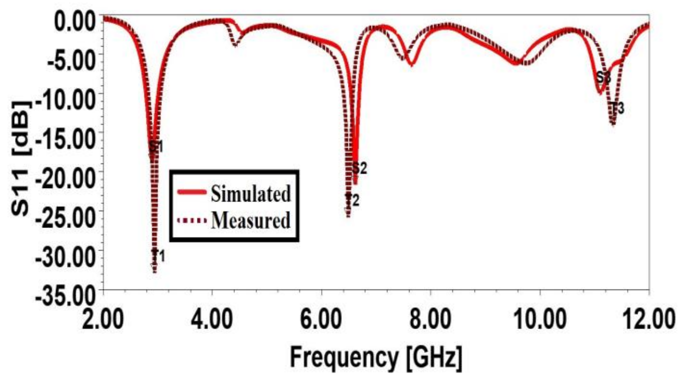
The return loss (S_{11}) performance of the prototypes both in simulated and measured results achieve less than -10 dB in all the tri frequency bands of operation. The compact antenna without winding structures is the basic antenna design of the presented work which achieves dual-band operation at 3.32 GHz and 6.53 GHz respectively with improved return loss (S_{11}) performance of -17.60dB and -13.94dB respectively. The first frequency band of operation covers from 3.15 GHz to 3.50 GHz achieve broad bandwidth of 350 MHz and the second operating band covers from 6.31 GHz to 6.71GHz.a notable bandwidth of 400MHz is achieved. Triband frequency of operation is achieved by incorporating double winding structures next to the central resonator (A) of the basic antenna structure proposed without winding structures. The two prototypes of the compact triband antenna which include step down transformer configuration and step up transformer configuration are measured using a VNA and good association with the simulated results is achieved with less than 2% frequency shit. The measurement results of return loss performance (S_{11}) of the compact tri-band antenna with double winding step-down configuration are -32.81dB, -25.73dB, and -14.00dB respectively at three operating frequencies such as 2.94 GHz, 6.48GHz, and 11.34 GHz. Similarly, the measured return loss performance of the compact tri-band antenna with double winding step-up configuration are -18.81dB, -21.63dB, and -10.02dB respectively at three operating frequencies such as 2.90 GHz, 6.61GHz, and 11.3 GHz. Furthermore, the bandwidths of 230 MHz (2.82 GHz - 3.05 GHz), 180 MHz (6.40 GHz - 6.58GHz), and 180 MHz (11.19 GHz - 11.37 GHz) were measured for the prototype of step-down transformer configuration. The measured bandwidths of 240 MHz (2.84 GHz - 3.08 GHz), 170 MHz (6.45 GHz - 6.62GHz), and 190 MHz (11.10 GHz -11.29 GHz) were achieved in step-up transformer configuration. The return loss performances of all the antennas in the presented work is shown in fig 4. The 10db return loss bandwidths for all the operating frequencies of the antennas proposed in this work is summarized in table 2.



(a)



(b)



(c)

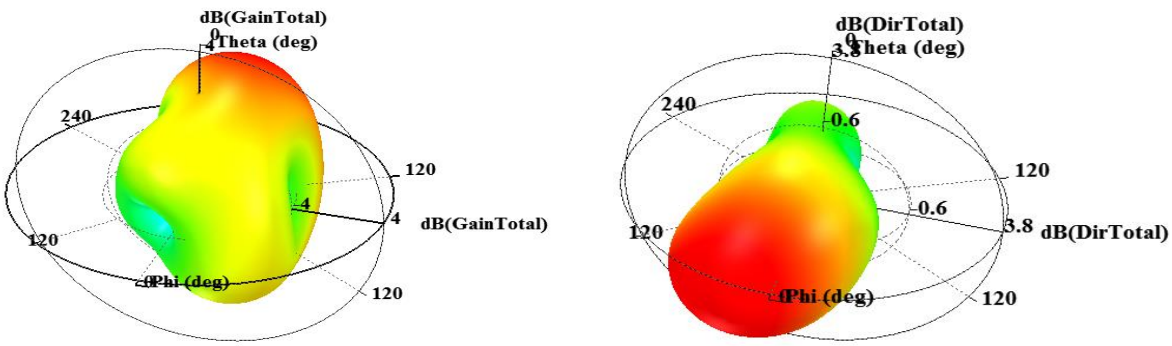
Fig 4 Return Loss Performance a) Dual Band Antenna without windings (simulated) b) Triband Step-down configuration Antenna c) Triband Step-up configuration Antenna

Table 2 Antenna configurations and Bandwidth % achieved.

Antenna Configurations	**Band of Operation**	**Operating Frequency (MHz)**	**Achieved Bandwidth (MHz)**	**Bandwidth (%)**
Antenna Without Windings	Dual Band	3322 6531	350 400	10.5% 6.2%
Step Down Transformer configuration	Tri-Band	2940 6530 11260	230 180 180	7.8% 2.7% 1.5%
Step Up Transformer configuration	Tri-Band	2900 6610 11090	240 170 190	8.2% 2.5% 1.7%

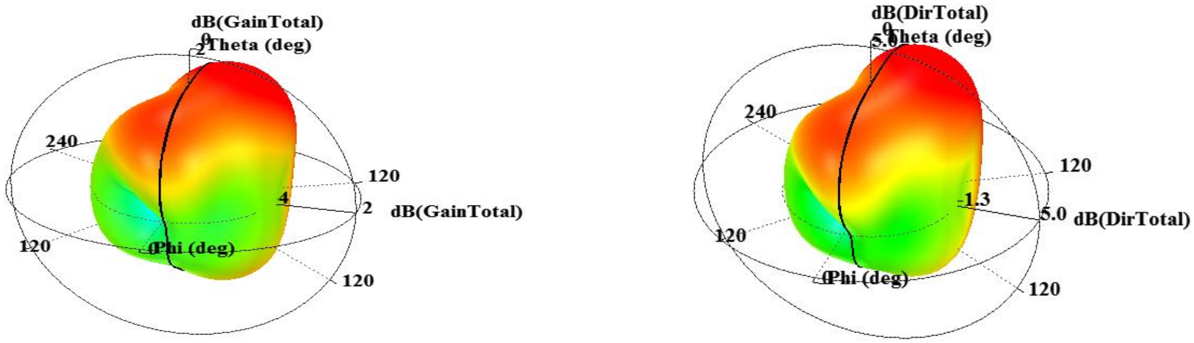
B) Maximum Gain, Directivity, and VSWR Analysis

The VSWR performance of the proposed compact triband antenna is excellent and achieves less than 1.8 in all the operating frequencies. The peak gain and directivity of the dual-band basic antenna without double winding structures are 2.6 dB and 3.1 dB. The peak gain and directivity performance of the dual-band antenna without windings is shown in Fig 5. The peak gain and directivity of the tri-band step-down configuration antenna are 1.9 dB and 5.2 dB. The peak gain and directivity performance of the tri-band step-down configuration antenna with double winding structures is shown in Fig 6. The peak gain and directivity of the tri-band step-up configuration antenna are 1.4 dB and 4.5 dB. Fig 7 shows the gain and directivity performance of the compact tri-band step-up configuration antenna with double winding structures. Fig 8 displays the simulated VSW performance of all the proposed antenna structures. The directivity of the projected antenna structures varies from 3-5dB. Comparative performance analysis of the projected antennas with and without double winding structures is depicted in table 3.



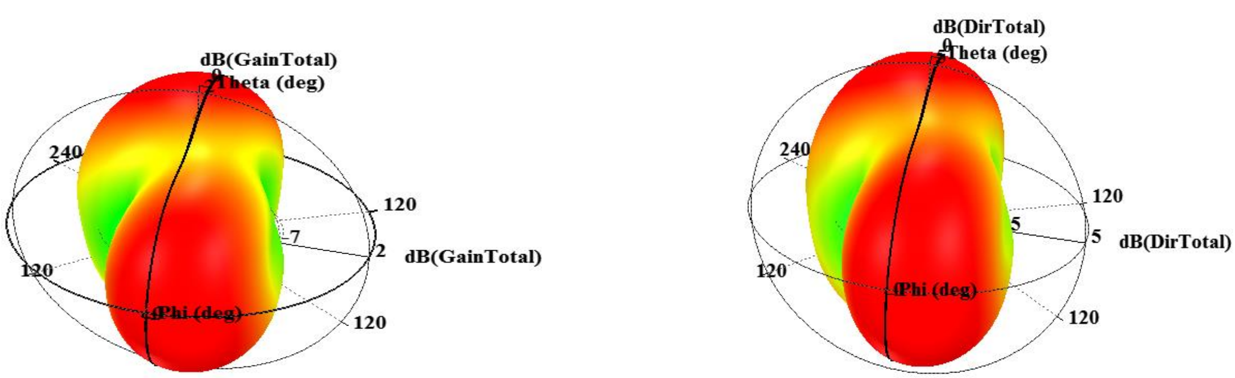
(a) (b)

Fig 5 Dual Band Antenna without windings a) Peak Gain b) Directivity



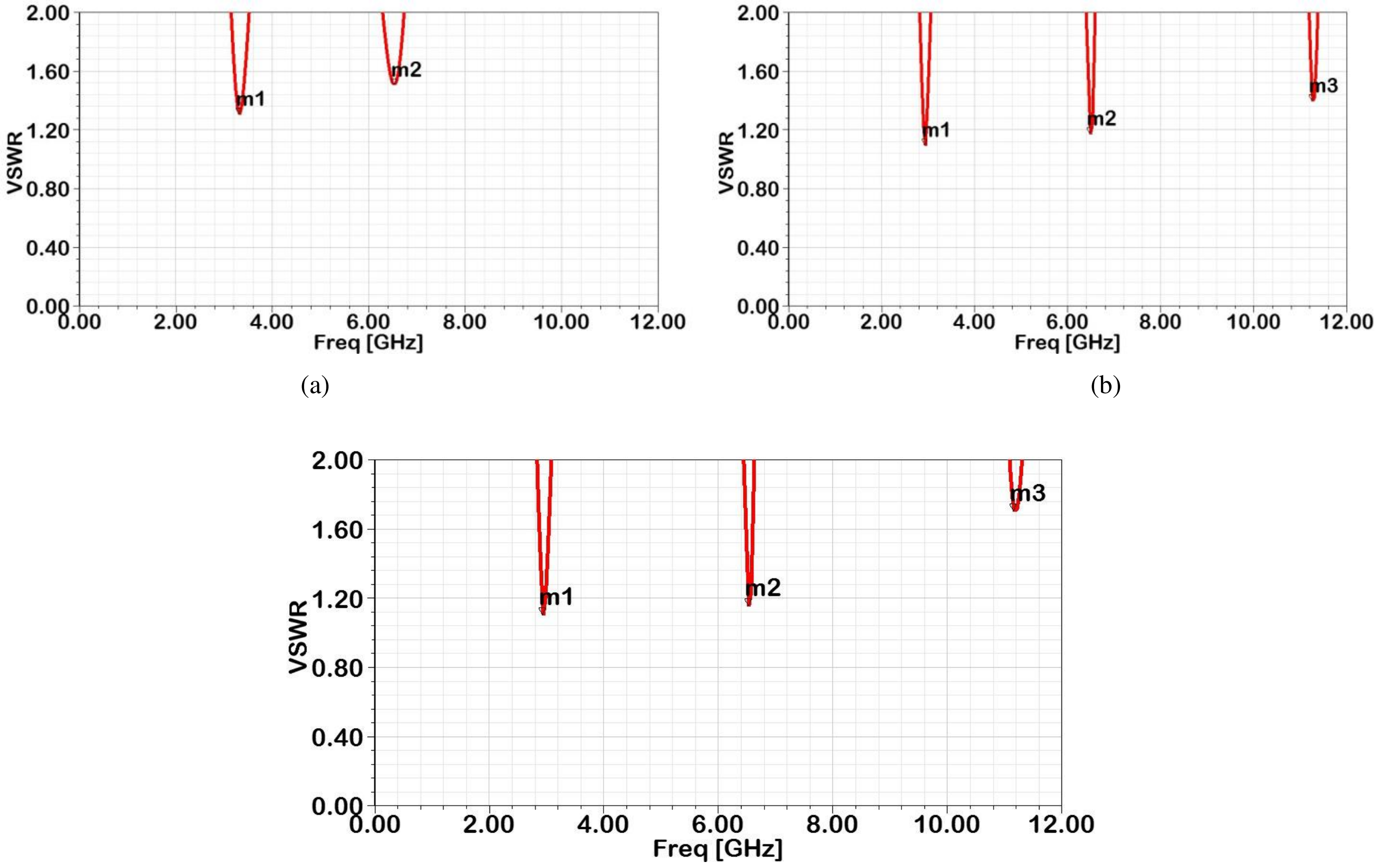
(a) (b)

Fig 6 Triband Step-down configuration Antenna a) Peak Gain b) Directivity



(a) (b)

Fig 7 Triband Step-down configuration Antenna a) Peak Gain b) Directivity



(a) (b)

(c)

Fig 8 Simulated VSWR a) Dual Band Antenna without windings b) Triband Step-down configuration Antenna c) Triband Step-up configuration Antenna

Table 3 Performance Comparison of the compact triband antenna structures

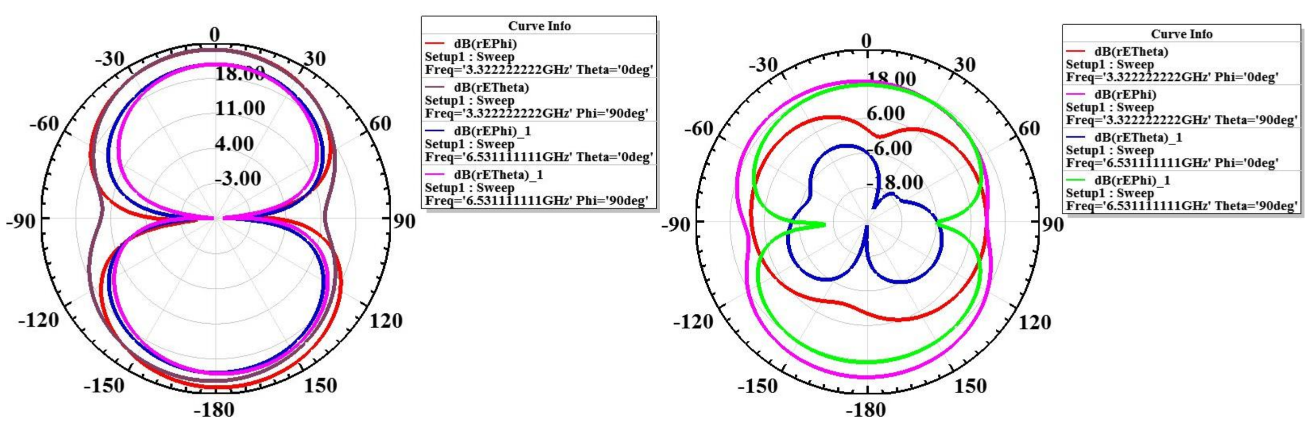
Design Structure	Band of Operation	Frequency (GHz)	VSWR	Gain (dB)	Directivity (dB)
Antenna Without Windings	**Dual-band**	3.3	1.3	2.3	3.1
		6.5	1.5		
Step Down Transformer configuration	**Tri-band**	2.9	1.0	1.9	5.2
		6.5	1.1		
		11.3	1.3		
Step Up Transformer configuration	**Tri-band**	2.9	1.1	1.4	4.5
		6.5	1.1		
		11.3	1.7		

C) Radiation Pattern and Radiated Power Analysis

The Radiation pattern of the antennas presented in the work is shown in fig 9, 10, and 11. The E and H plane results of the proposed compact tri-band antenna with step down and step up configuration achieves a stable omnidirectional radiation pattern in all the operating frequency bands. The implementation of a double winding structure in the antenna structure next to the central resonator achieves step-down and step-up transformer configurations. The output current is significantly increased in step-down transformer configuration however to balance the input and output power the output current is reduced in step-up transformer configuration. The output voltage is increased than the input source voltage in step-up transformer operation whereas the output voltage is reduced in step-down transformer operation. In the proposed antenna design theory maximum radiation efficiency is achieved without winding structures and the incorporation of a double winding structure varies the radiation efficiency according to the position of windings depending upon step up and step down configurations. Table 4 depicts the comparison of radiated power efficiency for the proposed antenna structures.

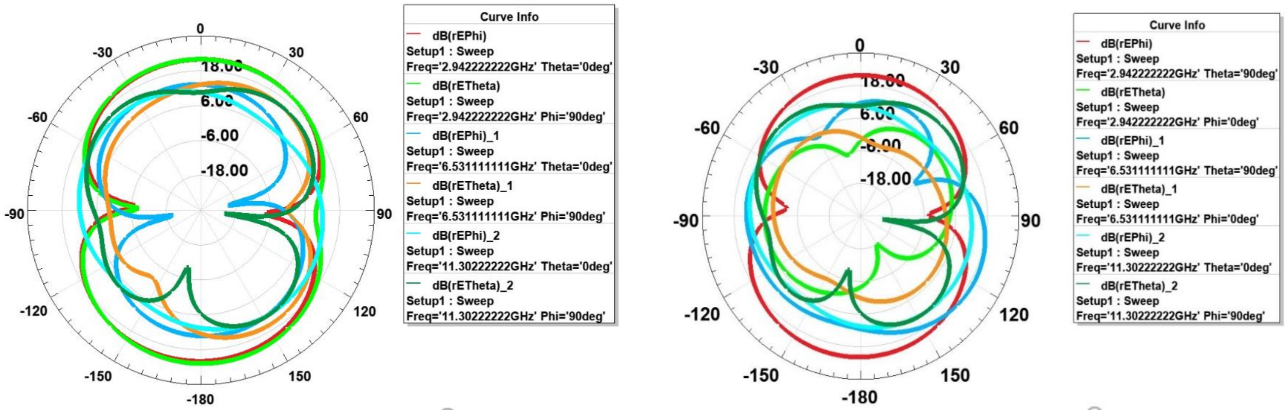
Table 4 Comparison of radiated power efficiency of the compact triband antenna structures

Antenna Structure	Solution Frequency (GHz)	Power	dBm	Watt	Radiated Efficiency %
Without Windings	6.5	Accepted Power	27.60	0.57	66%
		Radiated Power	25.81	0.38	
Double Winding – Step-down Transformer	6.5	Accepted Power	27.85	0.60	57 %
		Radiated Power	25.43	0.34	
Double Winding – Step-up Transformer	6.5	Accepted Power	26.96	0.49	49 %
		Radiated Power	23.88	0.24	



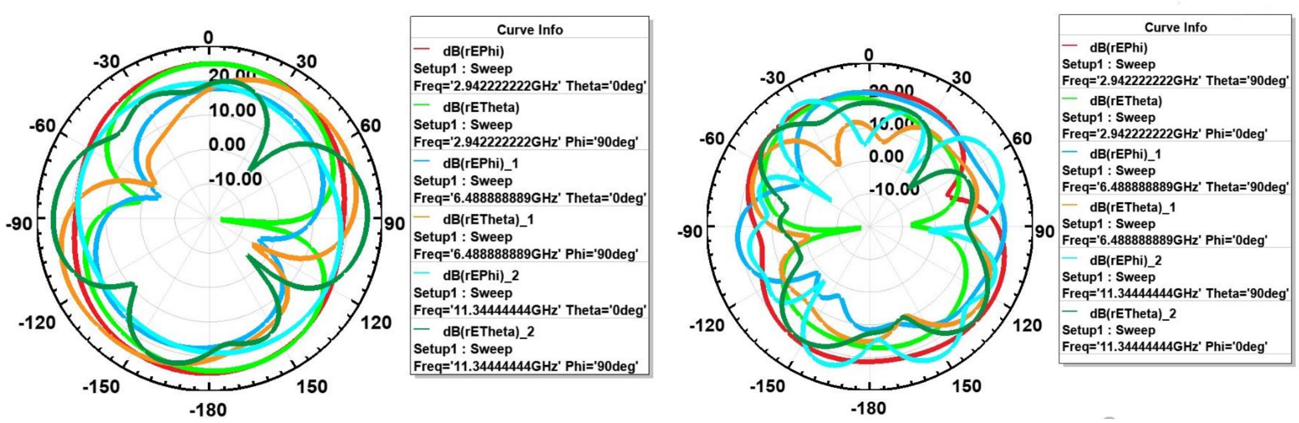
(a)Theta 0 and Phi 90 (b)Theta 90 and Phi 0

Fig 9 Radiation Pattern of antenna without winding structure (a) H-Plane (b) E-Plane



(a) Theta 0 and Phi 90 (b) Theta 90 and Phi 0

Fig 10 Radiation Pattern of triband Step-down configuration Antenna (a) H-Plane (b) E-Plane



(a)Theta 0 and Phi 90 (b) Theta 90 and Phi 0

Fig 11 Radiation Pattern of triband Step-up configuration Antenna (a) H-Plane (b) E-Plane

IV. CONCLUSION

A compact tri-band antenna, which covers triband operating frequency from 2.84 GHz to 3.08 GHz, 6.45 GHz to 6.62GHz, and 11.10 GHz to 11.29 GHz for 3G/4G/5G base station application is projected and analyzed in this article. By incorporating double winding structures on either side of the central resonator step-up and step-down configuration is accomplished with tri-band operation. The proposed compact triband antenna is then designed, simulated, fabricated, and measured. The close association between the measured and simulated results validates the proposed design concept. The compact size of the antenna measuring 18.6 X 15.6 mm^2 in dimension, triband operation, and stable radiation pattern makes it highly suitable for 3G/4G/5G base station applications.

V. DECLARATION

Ethics approval and consent to participate - Not Applicable

Consent for publication - Not Applicable

Availability of data and material: All datasets and materials used for supporting the conclusions of this article are available and the authors are ready to share as per the journal policies.

Conflicts of Interest/Competing Interests: The authors declare that they have no conflicts to the content of this article

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