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

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Abstract
This paper presents a compact tri-band antenna with double winding structures for 3G/4G/5G base station applications. The proposed compact tri-band antenna design with double winding structure fed by a coplanar waveguide (CPW) reduces the installation space and mutual coupling between close frequency operation bands suitable for base band applications. The proposed antenna design can be configured for step-up and step-down transformer operation using double winding structures on either side of the central resonator with an ability to attain reversibility of transformer operation. The proposed compact tri-band 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 voltage standing wave ratio (VSWR). Two prototypes of tri-band ultra-wideband (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 mm² achieving three frequency bands of operations at 2.9 GHz, 6.5 GHz, and 11.3 GHz with improved return loss < -10 db and VSWR < 1.8.

Keywords MIMO · Transformer · Tri-Band · Microstrip Antenna · Coplanar waveguide

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1 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), global system for mobile (GSM) 850/900 (824–894/890–960 MHz), wireless local area network (WLAN) (2412–2482 MHz, 5150–5825 MHz), and universal mobile telecommunication systems (UMTS) (1710–1880/1850–1990/1920–2170 MHz). Systems that operate in fifth-generation (5G) technology and devices that operate in multiple bands have been developed hastily to satisfy the raising demand for wireless data services. Multiband antenna is an inevitable 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 [1]. 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. 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 limit 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 [2–4]. The insertion of these structures with the antenna design redistributes current distribution and resonates with the increase in the efficiency of radiation at extra mode. The frequency band of operation for multiband antennas can be varied by incorporating slots, stubs, or strips into 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.

The 3G (1.6 GHz – 2 GHz) and 4G (2 GHz—8 GHz) wireless communication systems will coexist with 5G (3 GHz -30 GHz) communication systems in a single base station for an 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. A tri-band dual polarized square loop antenna for baseband applications with high port isolation is proposed [5]. A tri-band E-shaped antenna for WLAN and multiple input and multiple output (MIMO) applications is proposed [6]. A Compact bow-Tie antenna achieves tri-band operation by introducing a couple of metal strips without increasing the area of the antenna structure [7]. Monopole antenna with dual inverted-L slots in the compact radiator achieves tri-band operation for WLAN/Worldwide interoperability for microwave access (WiMAX) applications [8]. A Compact patch antenna incorporated with composite transmission line structures achieves tri-band operations [9]. The offset-fed inverted F-shaped vehicular antenna achieves tri-band operation without the need for an external matching network [10]. A compact monopole antenna fed by a coplanar strip achieves tri-band operation and omnidirectional radiation pattern using open-ended slots [11]. A Compact monopole antenna implemented with metal pattern and matching stub operates in tri frequency bands for USB dongle applications [12].
Multiband circularly polarized antenna with a compact structure achieves tri-band operations using metallic strips and split ring resonators (SRR) [13]. A Circularly polarized single feed single patch antenna achieves tri-and operation using stubs and slots [14]. A Tri-band antenna for radio frequency identification (RFID) application with fractal geometry is proposed [15]. A Square slot antenna designed for WLAN/ WiMAX applications achieves a tri-band of operation using L-shaped strips [16]. A Tri-band reconfigurable UWB antenna with improved performance and reduced harmonics is achieved using single a winding structure [17]. Various multiband antennas for base station applications have been proposed such as dual-polarized filtering antenna [18], low profile omnidirectional antenna [19], dual polarized scalable antenna for 5G base stations [20], coplanar dual-band cavity backed antennas [21], compact dual-band antenna with filtering elements [22], aperture-shared dual band antennas [23]. Multi-band antennas with filtering structures subdue the mutual coupling that arises due to close operating frequency bands but the bandwidth achieved in these literature [24–27] is not suitable for 2G/3G/4G/5G wireless applications. Moreover, asymmetry radiation pattern, wide bandwidth requirement, and reduced mutual coupling are the important design consideration for base station applications which is not been addressed to the fullest so far.

In this paper, a tri-band 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 derivation of design parameters for tri-band 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 find close correlation with the simulated results and it is a real testament to the effectiveness of the proposed design.

2 Design and Fabrication

The compact tri-band antenna with reduced mutual coupling and improved bandwidth for base station applications is achieved by using three resonators (A, B1, and B2). The design achieves reversibility of transformer operation using double winding structures which provides the flexibility to operate both in step-up and step-down transformer configurations. However, the proposed design is very simple and compact to reduce the installation space making it highly reliable for base station applications.

2.1 Design

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 is a very important feature 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 on either side 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 the 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 Eqs. (1) and (2)

\[
\lambda_g = \frac{c}{f \sqrt{\varepsilon_{\text{eff}}}} \quad (1)
\]

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

where \(\lambda_g\) is the guided wavelength, \(C\) is the velocity of light, \(f\) is the fundamental mode resonant frequency, \(\varepsilon_{\text{eff}}\) and \(\varepsilon_r\) 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 Eq. (3). The length and width of the feed are determined using Eqs. (4) and (5). Table 1 depicts the dimensions of the proposed compact tri-band antenna with and without windings.

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

\[
L_f = \frac{\lambda_g}{4} \quad (4)
\]

\[
W_f = \frac{2h}{\pi} \left\{ (B - 1 - \ln (2B - 1) + \left( \frac{\varepsilon_r - 1}{2\varepsilon_r} \right) \right\} \times \left\{ \ln (B - 1) + 0.39 - \left( \frac{0.61}{\varepsilon_r} \right) \right\} \quad (5)
\]

Where, \(h = \frac{0.0606\lambda}{\varepsilon_r} \) and \(B = \frac{60\pi^2}{\varepsilon_{\text{eff}} z_0} \)
The effective length ($L_{\text{eff}}$) is determined through Eq. (6)

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

(6)

2.2 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
Table 1  Dimensions of the proposed compact tri-band antenna

| Antenna Structure                        | Parameters | Dimensions (mm) |
|------------------------------------------|------------|-----------------|
| Basic antenna without winding structure  | 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     | 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       | 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 low-cost FR4 substrate with a thickness of 1.6 mm. The double winding structure on the left side of the central resonator (A) performs a step-down transformer operation. The prototype of a 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) achieve step-up transformer operation. The prototype of a step-up configuration tri-band antenna with a double winding structure is shown in Fig. 3.

3 Results and Discussion

For the validation of the proposed design, the compact tri-band 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 tri-band 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.

3.1 Return Loss (\(S_{11}\)) 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 -17.60 dB and -13.94 dB respectively. The first frequency band of operation covers from 3.15 GHz to 3.50 GHz achieving broad bandwidth of 350 MHz and the second operating band covers from 6.31 GHz to 6.71 GHz. A notable bandwidth of 400 MHz is achieved. Tri-band 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 tri-band 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 shift. The measurement results of return loss performance ($S_{11}$) of the compact tri-band antenna with double winding step-down configuration are -32.81 dB, -25.73 dB, and -14.00 dB respectively at three operating frequencies such as 2.94 GHz, 6.48 GHz, and 11.34 GHz. Similarly, the measured return loss performance of the compact tri-band antenna with a double winding step-up configuration is -18.81 dB, -21.63 dB, and -10.02 dB respectively at three operating frequencies as 2.90 GHz, 6.61 GHz, and 11.3 GHz. Furthermore, the bandwidths of 230 MHz (2.82 GHz—3.05 GHz), 180 MHz (6.40 GHz—6.58 GHz), and 180 MHz (11.19 GHz—11.37 GHz) were measured for the prototype of the step-down transformer configuration. The measured bandwidths of 240 MHz (2.84 GHz—3.08 GHz), 170 MHz (6.45 GHz—6.62 GHz), 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 are shown in Fig. 4. The 10dB return loss bandwidths for all the operating frequencies of the antennas proposed in this work are summarized in Table 2.

![Image](image_url)

**Fig. 4** Return loss performance **a** dual band antenna without windings (simulated) **b** tri-band step-down configuration antenna **c** tri-band step-up configuration antenna

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4 Maximum Gain, Directivity, and VSWR Analysis

The VSWR performance of the proposed compact tri-band 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 are 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 are 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. Figure 7 shows the gain and directivity performance of the compact tri-band

| Antenna configurations          | Band of operation | Operating frequency (MHz) | Achieved bandwidth (MHz) | Bandwidth (%) |
|--------------------------------|-------------------|---------------------------|--------------------------|---------------|
| Antenna without windings       | Dual band         | 3322                      | 350                      | 10.5%         |
|                                |                   | 6531                      | 400                      | 6.2%          |
| Step down transformer configuration | Tri-band         | 2940                      | 230                      | 7.8%          |
|                                |                   | 6530                      | 180                      | 2.7%          |
|                                |                   | 11,260                    | 180                      | 1.5%          |
| Step up transformer configuration | Tri-band         | 2900                      | 240                      | 8.2%          |
|                                |                   | 6610                      | 170                      | 2.5%          |
|                                |                   | 11,090                    | 190                      | 1.7%          |

Fig. 5 Dual band antenna without windings a peak gain b directivity

Fig. 6 Tri-band step-down configuration antenna a peak gain b directivity
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 step-up configuration antenna with double winding structures. Figure 8 displays the simulated VSWR performance of all the proposed antenna structures. The directivity of the projected antenna structures varies from 3 to 5 dB.

4.1 Radiation Pattern and Radiated Power Analysis

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Fig. 9  Radiation pattern of the antenna without winding structure a H-Plane b E-Plane

Fig. 10  Radiation pattern of tri-band 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 tri-band Step-up configuration Antenna a H-Plane b E-Plane
antenna structure next to the central resonator achieves step-down and step-up transformer configurations. The output current is significantly increased in the step-down transformer configuration however to balance the input and output power the output current is reduced in the 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 3 depicts the comparison of radiated power efficiency for the proposed antenna structures.

The proposed compact tri-band antenna with double winding structures achieves improved return loss and bandwidth performance compared to the tri-band and dual-band antenna structures proposed in the literatures [24–27]. The proposed double winding antenna structure performs better compared to the single winding antenna structure [17] in both step-up and step-down transformer configurations. Comparative performance analysis of the projected antenna with single winding structures is depicted in Table 4.

### 5 Conclusion

A compact tri-band antenna, which covers tri-band operating frequency from 2.84 GHz to 3.08 GHz, 6.45 GHz to 6.62 GHz, 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 the tri-band operation. The proposed compact tri-band 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 mm² in dimension, tri-band operation, and stable radiation pattern makes it highly suitable for 3G/4G/5G base station applications.

### Table 3  Comparison of radiated power efficiency of the compact tri-band antenna structures

| Antenna structure                              | Solution frequency (GHz) | Power            | 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                   |                              |
Table 4  Performance Comparison of the compact tri-band antenna structures

| References | Design structure     | Windings | Band of operation | Freq (GHz) | RL (dB) | VSWR | Radiated efficiency % | Maximum gain (dB) |
|------------|----------------------|----------|-------------------|------------|---------|------|------------------------|--------------------|
| [17]       | Step down Transformer| Single winding | Tri-band         | 3.1        | −25.3   | 1.1  | 39                     | 0.9                |
|            |                      |          |                   | 6.6        | −20.7   | 1.2  |                       |                    |
|            |                      |          |                   | 9.9        | −23.9   | 1.1  |                       |                    |
| Proposed work | Step down transformer | Double winding | Tri-band         | 2.9        | −27.2   | 1.0  | 57                     | 1.9                |
|            |                      |          |                   | 6.5        | −22.1   | 1.1  |                       |                    |
|            |                      |          |                   | 11.3       | −15.6   | 1.3  |                       |                    |
| [17]       | Step up transformer  | Single winding | Tri-band         | 3.2        | −12.1   | 1.6  | 37                     | 0.8                |
|            |                      |          |                   | 6.6        | −10.5   | 1.8  |                       |                    |
|            |                      |          |                   | 11.0       | −27.6   | 1.0  |                       |                    |
| Proposed work | Step up transformer  | Double winding | Tri-band         | 2.9        | −26.4   | 1.1  | 49                     | 1.4                |
|            |                      |          |                   | 6.5        | −23.1   | 1.1  |                       |                    |
|            |                      |          |                   | 11.3       | −11.5   | 1.7  |                       |                    |

The proposed double winding antenna structure performs better compared to the single winding antenna structure [17] in both the defined configurations (step up and step down transformer configurations) hence it is highlighted in bold case.
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Data Availability and Materials 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.

Declarations

Conflict of interest The authors declare that they have no conflicts to the content of this article.

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