**A Compact and Broadband Balun Design for LTE Applications**

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**ABSTRACT**

In this paper, a compact wideband planar balun is studied and investigated. The proposed balun comprises of a broadband Wilkinson divider followed by non-coupled lines to attain wideband 180° phase shift. Due to the inherent broadband characteristics of the proposed structure, good performance are accomplished in terms of phase and amplitude balance. The balun is optimally designed and validated by experiments. Both measured and computed results have shown a return loss better than -10 dB, an insertion loss around of -3.15 dB with a maximum absolute phase and amplitude imbalance around 2.5° and 0.2 dBover frequency range from 700 to 3200MHz. Both practical and computed results of the present balun are in good agreement.

1. **INTRODUCTION**

Various communication systems emerged in the last decade due to the rapid development of wireless communication systems to satisfy the increasing demand of service and transmission speed. Different frequency bands are employed in these systems, such as the LTE 700/2600 MHz, GSM 900/1800 MHz, WLAN 2400/5200/5800 MHz and WiMax 3500/5500 MHz. This provides the impetus for wideband and multiband baluns to cover all or parts of these frequency bands, leading to compact, low cost, accommodating-multiple-band systems.

Baluns are significant elements in several modern wireless communication systems such as balanced mixers [1], push-pull amplifiers [2], passive filter [3] and also commonly exploited to support the feeding network of two wires balanced antennas whereby the balanced current should be on each arm .This will help to preserve balanced radiation patterns [4, 5].

To meet the requirements of most contemporary wireless communication, size reduction and bandwidth enhancement are considered as the most the challenging task that balun designers are facing. In particular, special attention is given to balun designs in which can be integrated on the same substrate with compact antennas for usein mobile/portable applications.

Numerous syntheses of balun structures have been emerged and presented for wide band applications with the aim of support of the developing broadband technologies [6-18]. The most popular types of wideband baluns include the planar marchand baluns [6-7], broadband balun based on composite right/left-handed transmission line [8 -9], three-line balun with wide bandwidths using exact synthesis designed as in [10], balun with multi sections coupled-lines was demonstrated [11], a CPW balun using a multistage Wilkinson power divider for bandwidth improvement purpose [12], and the wide band balun design utilizing Wilkinson divider followed by Lange couplers for phase shifting was investigated in [13], in [14] a wide band structure is modelled using a three-section Wilkinson divider assembly and two 3-dB quadrature couplers. Furthermore, designing multi-layered wideband baluns to operate in the C- and X-band was reported in [15]. However, all of these techniques will suffer a minor increase in fabrication costs and complexity.

To reduce cost and complexity, authors in [16] proposed the planar transmission line baluns consisting of a power divider and non-coupled-lines phase shifter. An effort on the Wilkinson wideband balun using metamaterial was proposed in [17]. Parallel strips to operate in broadband bandwidth was designed in [18]. An investigation in [19] was carried out to broaden the operational bandwidth by using a wide band balun which comprises of a wideband composite right/left-handed transmission line coupled-line phase shifter as well as coupled lines power divider. In [20] a new findings to design a microstrip balun with the aid of electromagnetic bandgap (EBG) cell and a high-pass π-network made with an interdigital capacitor was investigated. Another though of designing a broadband balun in which composes of a distributed CRLH transmission line (TL) and Wilkinson power divider was reported in [21], this balun is said to be a different from the traditional CRLH balun. A simple and easy to manufacture a wide band balun using coplanar waveguide (CPW) structure was studied in [22]. A branch line balun having meandered branches and printed on high resistive silicon substrate to achieve tight coupling was proposed in [23].

Table I summarizes the performances of all the aforementioned wideband baluns [6-23] in terms of operating frequency band, impedance bandwidth, size (where λo is the lowest operating frequency), S21/S31 values, employed technologies/techniques and complexity. By examining all the aforementioned wideband baluns, it was found that the proposed balun has the advantage of accomplishing a broader frequency range compared to published works [6-12, 14-23]. Furthermore, the present balun exhibits better values of S21 and S31 compare to previous designs in [6-14, 15, 17-21].

In contrast to Refs. [11, 16, 19-21, 23], this article proposed a printed wideband balun that accomplishes both a size reduction and the potential to simultaneously cover the whole frequency band of LTE from 700MHz to 2600MHz. In terms of complexity, it can be noted, that the proposed balun has come up with less complexity compared to work in [8, 10-14, 15]. Moreover, owing to the low permittivity substrate of the proposed balun design compared to works in [11, 23], this makes the proposed balun such a good candidate to be printing on the same substrate with balanced antennas [24]. Thus, this balun is propose to be used in the measurements of any balanced feed microwave structure, since it has a wider impedance bandwidth and easy to be integrated within the layout of the ground/handset surface. The organization of this journal constitutes the following: in section 2 we develop the design of the balun; whilst in section 3, we provide numerical results for the proposed design in terms of simulation and physical measurements of the working prototype; and finally in section 4 the conclusion is given.

1. **BALUN DESIGN PROCEDURE**

Figure 1 illustrates the circuit layout of the miniaturized printed wideband balun. The proposed balun was modelled using HFSS software packages [25]. The balun was printed and fabricated on a single layered printed circuit board size of 100 × 50 mm2 FR4 material with thickness of 0.8 mm, relative permittivity 4.4 and loss tangent 0.017. The non-coupled lines have a uniform width of 2mm. The overall dimensions of proposed balun were listed in Table II. It should be noted that due to the non-stop progress of technology in most wireless communication, a designing compact and wideband balun is highly favoured. Therefore, due to the broad-band characteristics of the Wilkinson power divider and the non-coupled phase shifter lines, the proposed balun may be expected to operate across a reasonably broadband bandwidth.

Wilkinson power dividers have been heavily considered for many applications and purposes due to their simple structure, familiarity, excellent applicability and expandability to new application such as LTE (700-2600MHz). The power divider can be used as standalone power divider and also for example can be integrated within the circuit of the balun. In general, such a power divider consists of two in-phase output ports. Therefore, to be used as a balun, further circuit elements must be connected to output ports for out of phase characteristic.

For a wide band operation, the proposed balun was designed with a wideband power divider and non-coupled-line broadband 180 phase shifter lines, as depicted in Figure 1. The function of the power divider is to split the input port which is the unbalanced port (P1) into two output balanced ports, namely (P2, P3).This is done by adding a 100 ohm resistor between those two outputs. The two output balanced ports should be attached to the two phase shifter lines. If the 180° phase difference exist between such two lines, then undoubtedly their output singles will have the same magnitude and be 180° apart in phase.

The performance of balun will be limited by the reason of employing the conventional WPD. Therefore, a wide-band balun made up of a modified wide-band Wilkinson power divider [26] and improved a non-coupled-line broadband 180 phase shifter [27] is studied and investigated within this work.

The synthesis of the proposed wideband balun was implemented by initially choosing suitable values for the attaching elements of the line in order to generate a phase-shift at the design frequencies, while maintaining a reasonable overall length. At that point, the related parameters for the line were studied to prove/verify the 180 phase difference over the wide range of targeted frequency (700MHz-3200MHz). The proposed balun has some similarities with the authors’ previous work [16], but the size is reduced and as mentioned earlier due to the exploitation of wide-band characteristics of the Wilkinson power divider and the non-coupled phase shifter lines within this study, the present balun has a larger bandwidth from 700-3200MHz.

Taking the advantage of the wideband balun in [16], the proposed wideband balun can be modelled after running several simulation analyses of the main parameters such the variation of the substrate. Also, rearranging, resynthesizing and resizing the transmissions lines as well as relocating the elements according to the specific frequency range have led to achieving the broad-band operation of interest. Moreover, by looking on how the present balun elements were synthesized and collocated on a single PCB copper , this makes it to be easily integrated with authors balanced antennas such that found in [24-26] which in turn can lead to simple and compact a signal system device structure. The simplicity and effective integration of this balun with above-mentioned antenna to make as one system lie in using the ground plane of the balun as an antenna PCB, while locating the planar balun synthesis on the underneath side. Furthermore, by employing a low dielectric constant, this will effectively maintain the antenna efficiency and radiated power and therefore, improve the whole system performance.

To evaluate the effectiveness of substrate permittivity, the variation of the permittivity of the substrate against the response of S11, S21 and S31 is investigated within this study as depicted in Figure 2. In this analysis, four standard commercial materials including (RT/duroid 6010 εr =10.2 δ= 0.0023), (Roger RT 6006 εr =6.15 δ= 0.0019), (FR4 6006 εr =4.4 δ= 0.017) and (RT/duriod 5870 εr = 2.33 δ= 0.0012) have been analysed to represent four different level of the substrate permittivity. Notably, the proposed balun geometry parameters were re-optimized and elevated for the aforementioned substrate to achieve acceptable S11 i.e. below 10dB of the unbalanced port and the sufficient transmission responses (S21, S31) between the unbalanced port and the two balanced ports over the whole targeted frequency range from 700MHz to 3200MHz as depicted in Figure 2.

As can be seen, by employing the material with a low permittivity (εr = 2.33 ) the proposed balun operates over the frequency range from 1.0 to 3.3 GHz in which has not met the lower band of LTE i.e., 700MHz as shown in Figure 2; thus cannot achieve the targeted bandwidth. It is also found that with Roger RT 6006 material, the balun has a wide bandwidth covering the spectrum from 700MHz to 2500MHz. On other hand, when the proposed balun was loaded with high permittivity substrate of RT/duroid 6010, it was noted that the bandwidth was diminished and mismatching was occurred (return loss should be greater than 10 dB). However, by employing the FR4 material the proposed balun achieves return loss below 10dB in the aggregated bandwidth from 700MHz to 3200MHz or 128%. The FR4 substrate has several advantages such as lower permittivity and lower cost compared to Roger RT 6006 and RT/duroid 6010. Although the RT/duriod 5870 εr = 2.33 has made up of lower permittivity compared to FR4, however, it suffers from narrower bandwidth as shown in Figure 2 wherein does not meet the desired range of frequency that has been defined within this study. Moreover, loading the proposed balun with FR4 material makes it feasible to be incorporated with many other microwave structures with the same substrate. This can assure that the whole system performance may not be impaired.

1. **RESULTS AND DISCUSSIONS**

The simulated and measured S11 of the present balun is depicted in Figure 3. The simulated results show that a broadband performance of the reflection coefficient (S11) less than −10 dB over the 700–3200 MHz frequency range indicating that the device is perfectly matched. The transmission parameters (S21 and S31) are having an average value around −3.1 dB over the aggregated bandwidth. The S21 varies from -2.99dB to -3.1dB, while S31 changes from -2.95 dB to -3.15 dB. These also indicates that the synthesis and layout configuration in this work is an effective assembly to implement a broadband planar balun in which can cover the whole frequency range of LTE bands from 700MHz to 2600MHz.

To validate the simulated return loss of unbalanced ports and the isolation between the two balanced ports the balun system, the above-mentioned balun design is fabricated on FR4 material a thickness of 0.8 mm, dielectric constant of 4.4, and loss tangent of 0.002 referring to the design dimensions as described in Figure 1. The prototype layout of the balun is described in Figure 4. The measured S11 for the unbalanced port is said to be below -10 dB (i.e., equivalent to VSWR≤ 2) in the frequency range from 700 MHz to 3200 MHz, or 128% operation band. The measured insertion loss at the two output ports are *S*21 = *-*3.15dB and *S*31 = *-*3.1dB, respectively. It is observed that, the measured S11, S21 and S31 are in acceptable agreement with their simulated counterpart results. The insignificant discrepancy between the computed and practical outcomes may be attributed to the effects of connector losses, the effect of soldering and variation of the dielectric loss. The fabrication tolerance and the uncertainty of the termination resistor may also contribute to the discrepancy.

It is also found that the good isolation over the aggregated bandwidth has been accomplished. The S32 simulated result performs less than -11 dB from 700MHz to 1300MHz and less than -15 dB across the band from 1300MHz to 3200MHz, while the measured results shown an isolation of better than -15dB over the entire frequency range of interest defined within this work as demonstrated in Figure 5.

Figure 6 depicts the simulated and measured amplitude imbalance defined by |S21|–|S31| of the present balun. One can note that, from Figure 6, in particular, the proposed design denotes the lowest imbalance, with a value varies from 0.1 to 0.2 dB over the whole bandwidth. Thus, the proposed balun has come up with such characteristic to realize wideband converter between balanced and unbalanced circuits.

Figure 7 plots the phase response between the two balanced ports of the designed balun. The out of phase characteristic between Ports 2 and 3 of proposed wide band design are within the range of 177.4° ~ 182.5° (182° ±2.5) . This is an indication that the bandwidth of 128.28 % has been achieved within the phase difference of 180° ± 2.5.

1. **CONCLUSION**

A simple single-layer printed balun utilizing Wilkinson power divider and phase shifter lines covering the frequency spectrum bandwidth between 700 and 3200 MHz has been presented and tested. The fabricated balun has low insertion loss of 3.1 dB, good isolation better than -10 dB, maximum absolute amplitude imbalance of 0.2 dB and phase imbalance of 2.5°. The simulated outcomes are found to be in a reasonable agreement with practical results. In addition to the aforementioned advantages, the proposed balun provides additional benefits due to the very compact single-layer configuration and non-coupled lines, which allows printing it on a different type of substrates, and can be seamlessly incorporated with any balanced feed microwave structure on the same low-permittivity substrate for accomplishing high efficiency performance. In conclusion, the design can be considered a good candidate for microstrip microwave circuits such as antenna feeding networks.

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**Table and Figures Captions:**

**Table I:** Comparison of the performance of the published wideband baluns.

**Table II:** The overall dimensions of proposed balun.

**Figure 1:**  Geometry of Proposed antenna, (a) Top view, (b) 3D, (c)Schematic view of the proposed balun.

**Figure 2:** The variation of the permittivity of the substrate against the S11, S21 and S31.

**Figure 3:** Simulated and measured S-paramters of the developed balun.

**Figure 4:** Prototype of proposed balun, (a) Top view, (b) Bottom view.

**Figure 5:** Measured and simulated Isolation (S32) for proposed wide band balun.

**Figure 6:** Simulated and measured amplitude imbalance.

**Figure 7:** Simulated and measured phase response between the two balanced ports (port 2 and port 3).

Table I :

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Ref | Operating Frequency Band (GHz) | BW (%) | Size | S21,S31 (dB) | Techniques | Cost and Complexity |
| 6 | 1.11-2.93 | 90.09 | 0.15 λO x 0.051 λO x 0.0018 λO | 3.27-3.8, 3.23-4.12 | Marchand and slot-coupled microstrip lines | moderate |
| 7 | 1.2-3.3 | 93 | 0.28 λO x 0.14 λO x 0.0032 λO | 2.2-4.3, 4.3-4.4 | Marchand balun using a patterned ground plane | moderate |
| 8 | 1-2.25 | 83.3 | 0.09 λO x 0.10 λO x 0.0033 λO | 2.9-3.6, 2.8-3.8 | artificial fractal shaped  composite right/left handed transmission line | high |
| 9 | 0.97–1.46 | 40 | 0.16 λO x 0.11 λO x 0.0016 λO | 3.28, 3.4 | Wilkinson power divider | moderate |
| 10 | 1-3 | 100 | 0.22 λO x 0.11 λO x 0.0067 λO | 3.8, 3.7 | Coupled-line and multilayer structures | high |
| 11 | 1.8-3.6 | 66 | 0.25 λO x 0.36 λO x 0.0076λO | 4.75, 4.9 | multisection vialess | high |
| 12 | 0.8-3.2 | 120 | 0.36 λO x 0.52 λO x 0.0020λO | 4.3,4.2 | Multistage  Wilkinson Structure | high |
| 13 | 6 to 20 | 107 | NA | 1.75,1.8 | Wilkinson divider and Lange couplers for phase shifting. | high |
| 14 | 0.7-2.5 | 112.5 | 0.18 λO x 0.11 λO x 0.0011λO | 4.1,4.3 | Wilkinson divider and two 3-dB quadrature couplers | high |
| 15 | 6.1 - 13.3 | 74.22 | 0.67 λO x 1.06 λO x 0.032λO | 3.9,4.1 | Mutli-layers | high |
| 16 | 1.4-2.4 | 52 | 0.56 λO x 0.23 λO x 0.0037λO | 1.65 | Wilkinson power divider and phase shift lines | low |
| 17 | 1.17 to 2.33 | 66.28 | 0.22 λO x 0.22 λO x 0.029λO | 4, 4.1 | Metamaterial Lines | low |
| 18 | 0.72 - 2.05 | 96.37 | 0.17 λO x 0.14 λO x 0.018λO | 3.3, 3.1 | parallel strip and phase inverter | low |
| 19 | 1.5–3.78 | 82.9 | 0.433 λO x 0.13 λO x 0.038λO | 3.21, 3.31 | Coupled-line (CL) and composite right/left-handed transmission line (CRLH TL). | low |
| 20 | 2.6–4 | 42 | 1.47 λO x 1.39 λO x 0.006λO | 3.8,3.8 | electromagnetic bandgap (EBG) and an interdigital capacitor is presented | moderate |
| 21 | 1 to 3.3 | 106.9 | 0.115 λO x 0.094 λO x 0.005λO | 3.7, 3.8 | Composite right/left  handed structure | low |
| 22 | 1.2-2.8 | 80 | NA | 3.6-4.8, 3.4-4.6 | Stepped coupled-line | moderate |
| 23 | 1.4 - 1.9 | 30 | 0.76 λO x 0.68 λO x 0.0031λO | 2.95,3.11 | Meander lines | low |
| Proposed | 0.7-3.2 | 128.28 | 0.23 λO x 0.11 λO x 0.0018λO | 2.99-3.1, 2,95,3.15 | Wilkinson power divider and phase shift lines | low |

Table II:

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | Value in mm | Parameters | Value in mm |
| W1 | 10 | L2 | 10 |
| W2 | 13 | L3 | 10.5 |
| W3 | 1.2 | L4 | 2.25 |
| W4 | 2.2 | L5 | 16 |
| W5 | 18.5 | L6 | 17.75 |
| W6 | 43.5 | r1,r2 | 10, 9 |
| W7 | 40 | r3,r4 | 6,5 |
| W8 | 44 | r5,r6 | 12,11 |
| L1 | 21 | L,W | 50,100 |

Figure 1:

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Figure 2

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Figure 3

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Figure 4:

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Figure 5:

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Figure 6:

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Figure 7:

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