Progress In Electromagnetics Research C, Vol. 67, 85–95, 2016

A Compact and Broadband Balun Design for LTE Applications

Issa T. E. Elfergani[1, *], Abubakar S. Hussaini[1], Jonathan Rodriguez[1, 2], Ammar H. Ali[3], Chan H. See[4], and Raed A. Abd-Alhameed[3]

Abstract—In this paper, a compact wideband planar balun is studied and investigated. The proposed balun comprises 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 is 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 dB over frequency range from 700 to 3200 MHz. 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 challenging task that balun designers are facing. In particular, special attention is given to balun designs which can be integrated on the same substrate with compact antennas for use in mobile/portable applications.

Numerous syntheses of balun structures have emerged and been presented for wideband applications with the aim of supporting 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 demonstrated in [11], a CPW balun using a multistage Wilkinson power divider for bandwidth improvement purpose [12], and the wideband balun design utilizing Wilkinson divider followed by Lange couplers for phase shifting was investigated in [13]. In [14], a wideband 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

Received 18 July 2016, Accepted 4 September 2016, Scheduled 15 September 2016

* Corresponding author: Issa Tamer E. Elfergani (i.t.e.elfergani@av.it.pt).
[1] Instituto de Telecomunicações, Aveiro, Portugal. [2] Universidade de Aveiro, Portugal. [3] Antennas and Applied Electromagnetics Research Group, School of Engineering and Informatics, University of Bradford, Bradford, BD7 1DP, UK. [4] School of Engineering, University of Bolton, Bolton, BL3 5AB, UK.

X-bands was reported in [15]. However, all of these techniques will suffer a minor increase in fabrication costs and complexity.

To reduce cost and complexity, the 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 were designed in [18]. An investigation in [19] was carried out to broaden the operational bandwidth by using a wideband balun which comprises a wideband composite right/left-handed transmission line coupled-line phase shifter as well as coupled lines power divider. In [20] a new finding 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 thought of designing a broadband balun in which composes of a distributed CRLH transmission line (TL) and Wilkinson power divider was reported in [21], and this balun is said to be different from the traditional CRLH balun. A simple and easy way to manufacture a wideband balun using a coplanar waveguide (CPW) structure was studied in [22]. A branch line balun having meandered branches and printed on a high resistive silicon substrate to achieve tight coupling was proposed in [23].

Table 1 summarizes the performances of all the aforementioned wideband baluns [6–23] in terms of operating frequency band, impedance bandwidth, size (where λ_o is the lowest operating frequency), S_{21}/S_{31} 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 than published works [6–12, 14–23]. Furthermore, the presented balun exhibits better values of S_{21} and S_{31} than previous designs in [6–14, 15, 17–21].

In contrast to [11, 16, 19–21, 23], this article proposes a printed wideband balun that accomplishes both a size reduction and the potential to simultaneously cover the whole frequency band of LTE from 700 MHz to 2600 MHz. In terms of complexity, it can be noted that the proposed balun has come up with less complexity than the works in [8, 10–14, 15]. Moreover, this proposed balun was printed on a low permittivity substrate compared to works in [11, 23], which makes the proposed balun a good candidate to be printed exactly underneath the ground plane of the authors' balanced antenna in [24] which in turn may not affect the whole system performance. Thus, this balun is proposed to be used in the measurements of any balanced feed microwave structure, since it has a wide impedance bandwidth and easy to be integrated within the layout of the ground/handset surface. The organization of this paper is as follows. 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. Finally, in Section 4 the conclusion is given.

2. 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 with size of $100 \times 50\,\mathrm{mm}^2$, 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 2 mm. The overall dimensions of the proposed balun are listed in Table 2. It should be noted that due to the non-stop progress of technology in most wireless communication, designing a 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 (700–2600 MHz). The power divider can be used as a stand-alone 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 wideband 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,

Table 1. Comparison of the performance of the published wideband baluns.

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

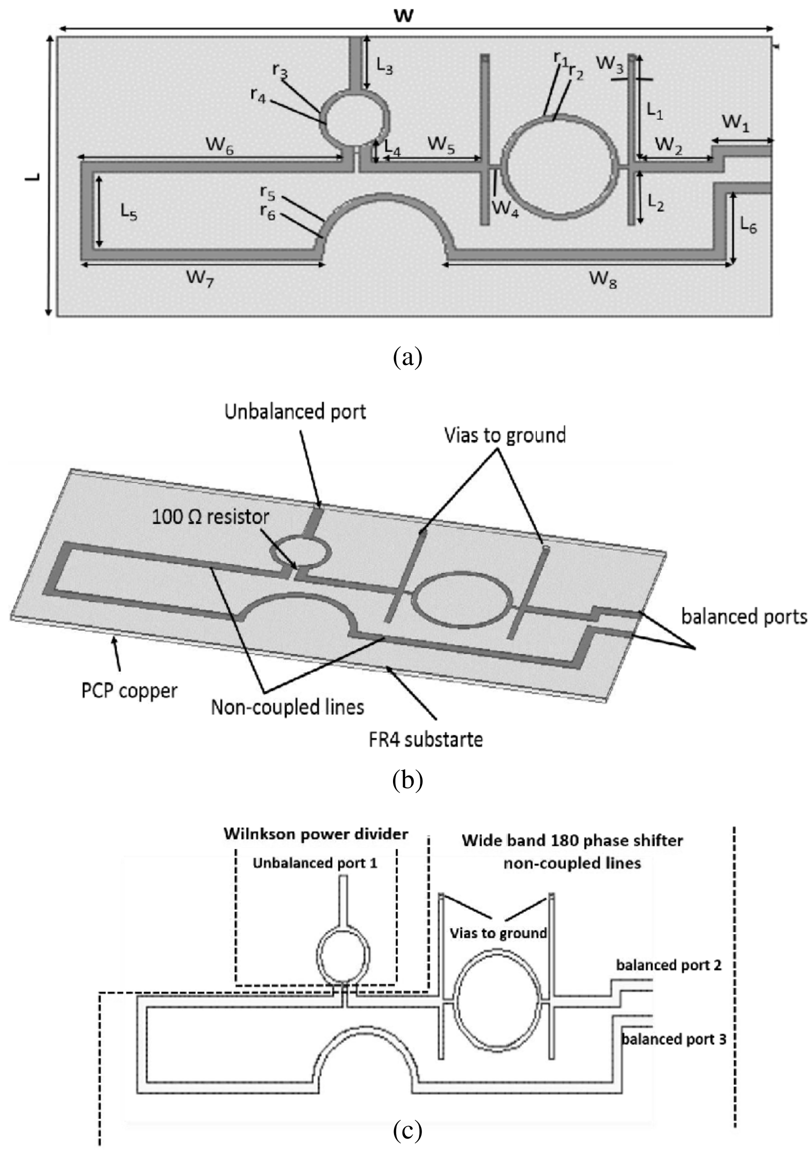


Figure 1. Geometry of Proposed antenna. (a) Top view. (b) 3D. (c) Schematic view of the proposed balun.

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 exists 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 wideband balun made up of a modified wideband Wilkinson power divider [26] and improving 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 (700 MHz–3200 MHz). The proposed balun has some similarities to the authors' previous work [16], but the size is reduced, and as mentioned earlier due to the exploitation of wideband characteristics of the Wilkinson

Table 2. The overall dimensions of proposed balun.

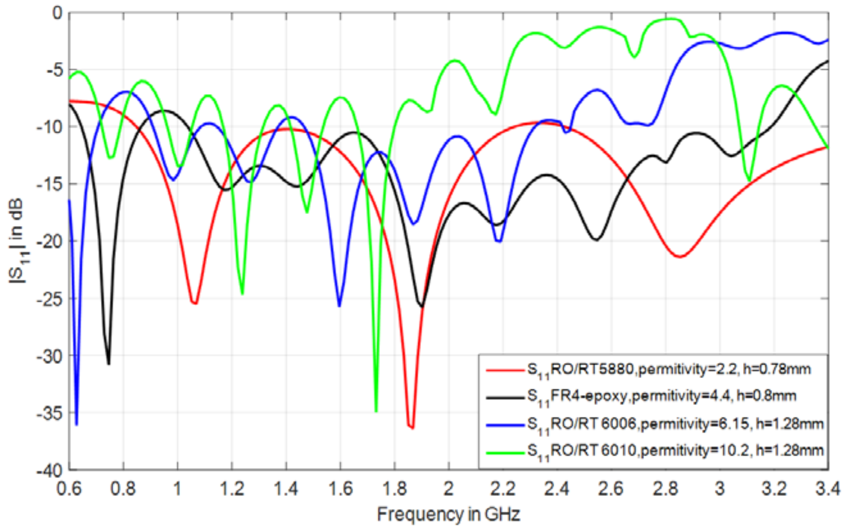
Parameters	Value in mm	Parameters	Value in mm
W_1	10	L_2	10
W_2	13	L_3	10.5
W_3	1.2	L_4	2.25
W_4	2.2	L_5	16
W_5	18.5	L_6	17.75
W_6	43.5	r_1, r_2	10, 9
W_7	40	r_3, r_4	6, 5
W_8	44	r_5, r_6	12, 11
L_1	21	L, W	50, 100

power divider and the non-coupled phase shifter lines within this study, the present balun has a larger bandwidth from 700–3200 MHz.

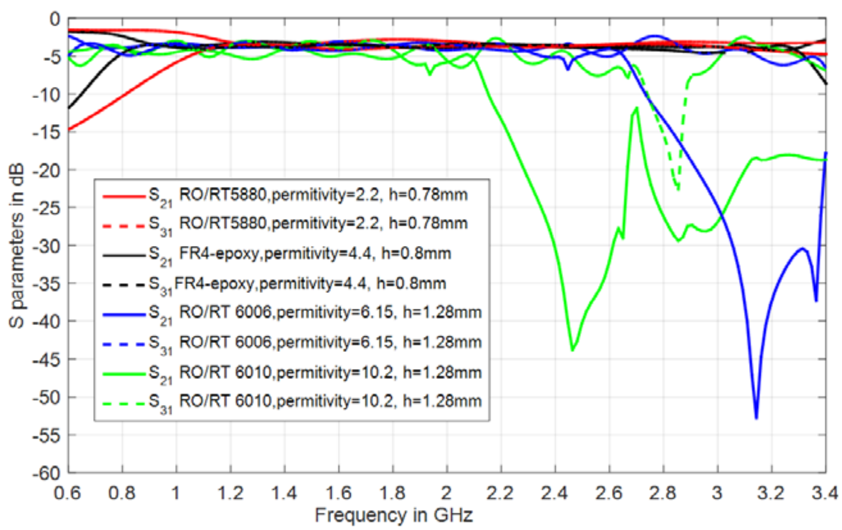
Taking the advantage of the wideband balun in [16], several design models were attempted against various types of dielectric substrates to achieve the proposed wideband balun. Also, rearranging, resynthesizing and resizing the transmissions lines as well as relocating the elements according to the specific frequency range have led to achieving the broadband operation of interest. Moreover, the present balun elements were synthesized and collocated on a single PCB copper that can be easily integrated with the authors' previous balanced antenna published in [24], which in turn can lead to a simple and compact signal system device structure. The simplicity and effective integration of this balun with above-mentioned antenna to make as one system lie in printing the proposed balun on the 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 S_{11}, S_{21} and S_{31} is investigated within this study as depicted in Figure 2. In this analysis, four standard commercial materials including (RT/duroid 6010 $\varepsilon_r = 10.2$ $\delta = 0.0023$), (Roger RT 6006 $\varepsilon_r = 6.15$ $\delta = 0.0019$), (FR4 6006 $\varepsilon_r = 4.4$ $\delta = 0.017$) and (RT/duriod 5870 $\varepsilon_r = 2.33$ $\delta = 0.0012$) have been analysed to represent four different levels of the substrate permittivity. Notably, the proposed balun geometry parameters were re-optimized and elevated for the aforementioned substrate to achieve acceptable S_{11}, i.e., below 10 dB of the unbalanced port and the sufficient transmission responses (S_{21}, S_{31}) between the unbalanced port and the two balanced ports over the whole targeted frequency range from 700 MHz to 3200 MHz as depicted in Figure 2.

As can be seen, by employing the material with a low permittivity ($\varepsilon_r = 2.33$), the proposed balun operates over the frequency range from 1.0 to 3.3 GHz which does not meet the lower band of LTE, i.e., 700 MHz 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 700 MHz to 2500 MHz. On the 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 occurred (return loss should be greater than 10 dB). However, by employing the FR4 material, the proposed balun achieves return loss below 10 dB in the aggregated bandwidth from 700 MHz to 3200 MHz or 128%. The FR4 substrate has several advantages such as lower permittivity and lower cost than Roger RT 6006 and RT/duroid 6010. Although the RT/duriod 5870 $\varepsilon_r = 2.33$ has made up of lower permittivity than FR4, 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 an 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.



(a)



(b)

Figure 2. The variation of the permittivity of the substrate against the S_{11}, S_{21} and S_{31}.

3. RESULTS AND DISCUSSIONS

The simulated and measured S_{11} of the presented balun are depicted in Figure 3. The simulated results show a broadband performance of the reflection coefficient (S_{11}) less than -10 dB over the 700–3200 MHz frequency range indicating that the device is perfectly matched. The transmission parameters (S_{21} and S_{31}) have an average value around -3.1 dB over the aggregated bandwidth. S_{21} varies from -2.99 dB to -3.1 dB, while S_{31} changes from -2.95 dB to -3.15 dB. These also indicate that the synthesis and layout configuration in this work is an effective assembly to implement a broadband planar balun which can cover the whole frequency range of LTE bands from 700 MHz to 2600 MHz.

To validate the simulated return loss of unbalanced ports and the isolation between the two balanced ports of the balun system, the above-mentioned balun design is fabricated on an FR4 material with 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 S_{11} 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 losses

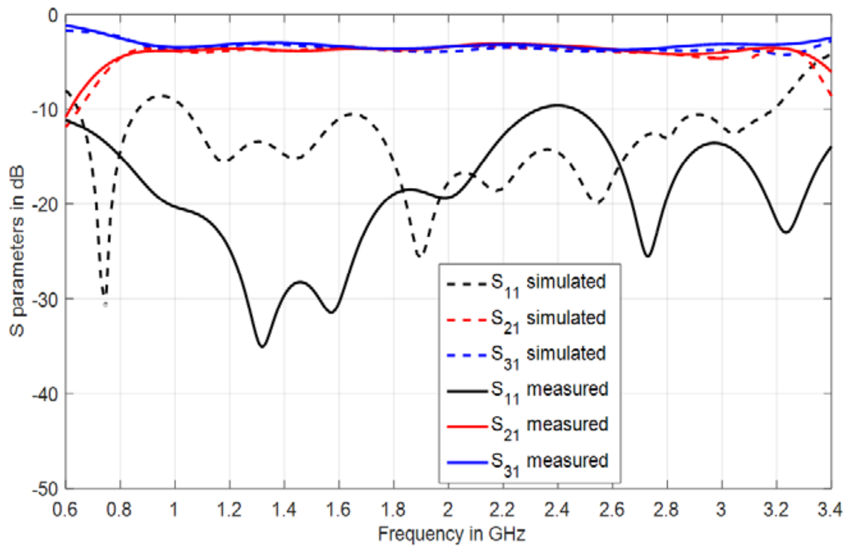
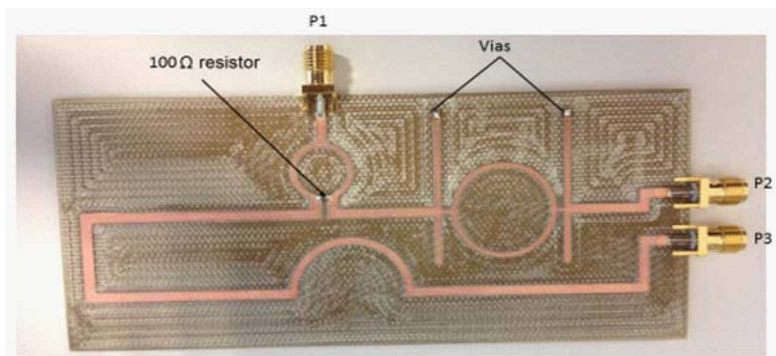
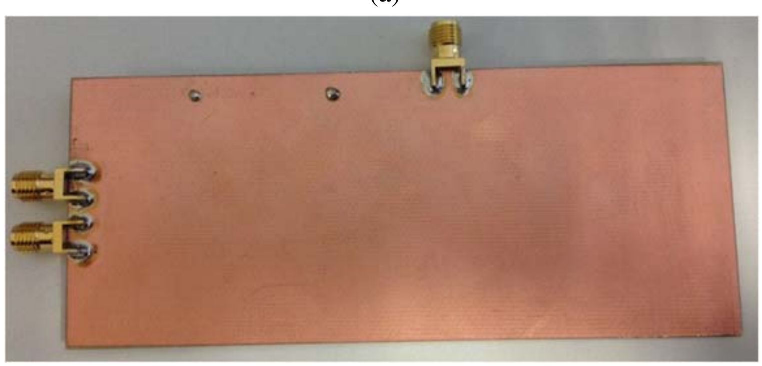


Figure 3. Simulated and measured S-parameters of the developed balun.



(a)



(b)

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

at the two output ports are $S_{21} = -3.15\,\text{dB}$ and $S_{31} = -3.1\,\text{dB}$, respectively. It is observed that the measured S_{11}, S_{21} and S_{31} 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, effect of soldering and variation of the dielectric loss. The fabrication tolerance and 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 S_{32} simulated result is less than $-11\,\text{dB}$ from 700 MHz to 1300 MHz and less than $-15\,\text{dB}$ across the band from 1300 MHz to 3200 MHz, while the measured results show an isolation of better than $-15\,\text{dB}$ over the entire frequency range of interest defined within this work as demonstrated in Figure 5.

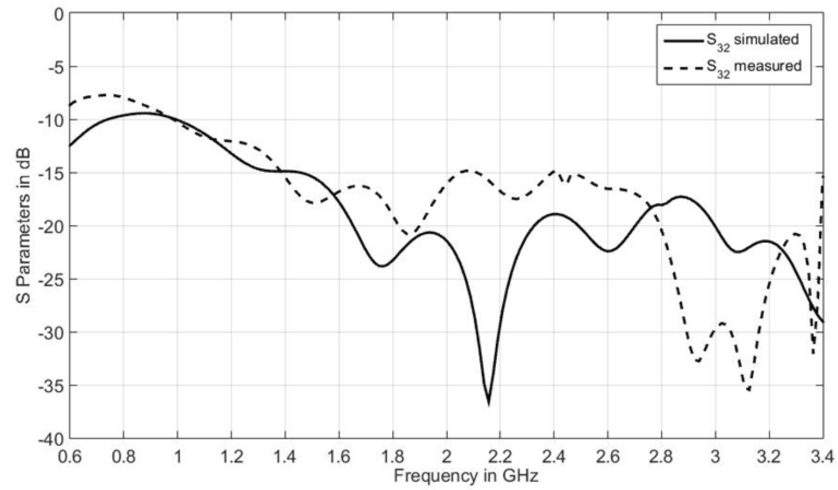


Figure 5. Simulated and measured Isolation (S_{32}) for proposed wide band balun.

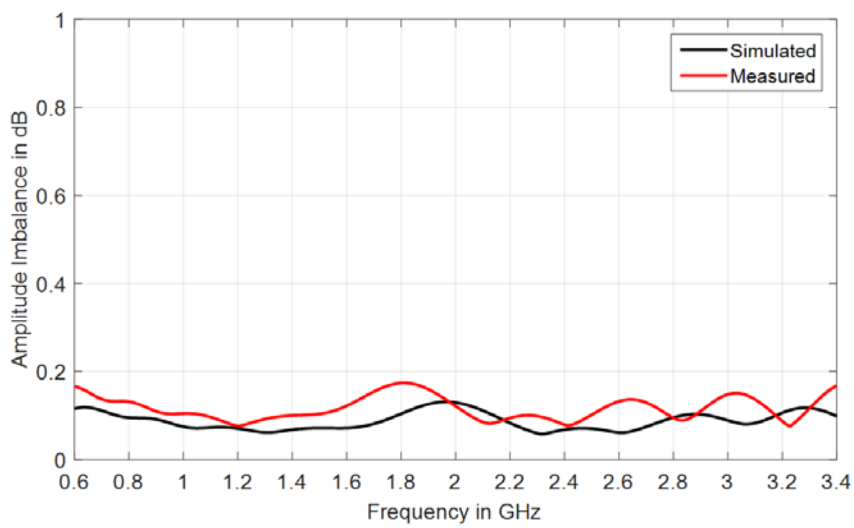


Figure 6. Simulated and measured amplitude imbalance.

Figure 6 depicts the simulated and measured amplitude imbalance defined by $|S_{21}|-|S_{31}|$ of the present balun. One can note that from Figure 6, in particular, the proposed design shows the lowest imbalance, with a value varying from 0.1 to 0.2 dB over the whole bandwidth. Thus, the proposed balun has come up with such a 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 the proposed wideband design are within the range of $177.4^\circ \sim 182.5^\circ$ ($182^\circ \pm 2.5$). This is an indication that the bandwidth of 128.28% has been achieved within the phase difference of $180^\circ \pm 2.5$.

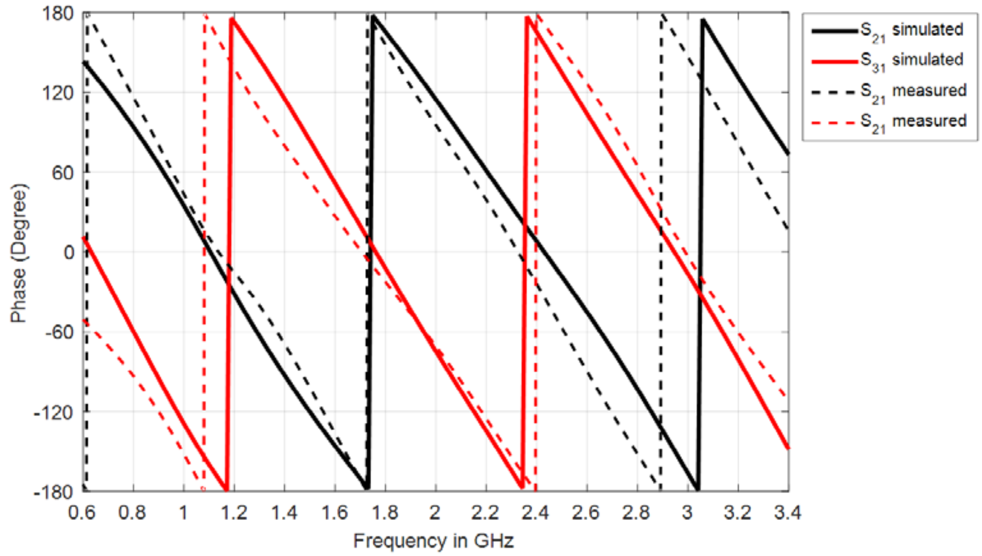


Figure 7. Simulated and measured phase response between the two balanced ports (port 2 and port 3).

4. 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. However, taking into account the impractical size of such a balun to be embedded within mobile handset and GPS circuit applications could be considered as an interesting case study to reduce the antenna size constraint for future work.

ACKNOWLEDGMENT

This work is carried out under the grant of the Fundacão para a Ciência e a Tecnologia (FCT — Portugal), with the reference number: SFRH/BPD/95110/2013 and funded by national funds through FCT/MEC (PEst-OE/EEI/LA0008/2013 — UID/EEA/50008/2013).

REFERENCES

1. Gao, Y., Z. Tang, B. Zhang, and Y. Q. Wu, "Ultra-wideband double balanced mixer utilizing a compact planar balun," *Microwave Journal*, Vol. 57, No. 5, 172, May 2014.
2. He, J., H. Qureshi, W. Sneijers, D. A. Calvillo-Cortes, and L. C. N. de Vreede, "A wideband 700 W push-pull Doherty amplifier," *Microwave Symposium (IMS), 2015 IEEE MTT-S International*, 1–4, Phoenix, AZ, May 17–22, 2015.
3. Jung, E. Y. and H.-Y. Hwang, "A balun-BPF using a dual mode ring resonator" *IEEE Microw. Wireless Compon. Lett.*, Vol. 17, No. 9, 652–654, Sep. 2007.

4. Alhaddad, A. G., R. A. Abd-Alhameed, D. Zhou, I. T. E. Elfergani, C. H. See, P. S. Excell, and M. S. Bin-Melha, "Low Profile Balanced Handset Antenna with Dual-Arm Structure for WLAN Application," *IET Microwaves, Antennas and Propagation*, Vol. 5, 1045–1053, 2011.
5. Li, X., L. Yang, S. X. Gong, and Y. J. Yang " Dual-band and wideband design of a printed dipole antenna integrated with dual-band balun," *Progress In Electromagnetics Research Letters*, Vol. 6, 165–174, 2009.
6. Tseng, C.-H. and Y.-C. Hsiao, "A new broadband marchand balun using slot-coupled microstrip lines," *IEEE Microwave and Wireless Components Letters*, Vol. 20, No. 3, 157–159, Mar. 2010.
7. Zhang, Z. Y., Y. X. Guo, L. C. Ong, and M. Y. W. Chia, "Improved planar marchand balun with a patterned ground plane," *Int. J. RF Microw. CAE*, Vol. 15, No. 3, 307–316, May 2005.
8. Xu, H.-X., G.-M. Wang, X. Chen, and T.-P. Li, "Broadband balun using fully artificial fractal-shaped composite right/left handed transmission line," *IEEE Microwave and Wireless Components Letters*, Vol. 22, No. 1, 16–18, Jan. 2012.
9. Unghee Park, Member, KIICE, "A wilkinson-type balun using a composite right/left-handed transmission line," *J. lnf. Commun. Converg. Eng.*, Vol. 11, No. 3, 147–152, Sep. 2013.
10. Lee, H. M. and C. M. Tsai, "Exact synthesis of broadband three-line baluns," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 1, 140–148, Jan. 2009.
11. Sun, S., L. Zhu, L. Wei, H. Peng, and K. S. Ang, "Multisession vialess microstripline balun with backside aperture and floating patches," *Microwave and Optical Technology Letters*, Vol. 49, No. 2, 253–254, Feb. 2007.
12. Lim, J. S., U. H. Park, J. J. Koo, Y. C. Jeong, and D. Ahn, "A 800- to 3200-MHz wideband CPW balun using multistage Wilkinson structure" *Proceedings of IEEE MTT-S International Microwave Symposium Digest*, 1141–1144, San Francisco, CA, USA, Jun. 11–16. 2006.
13. Rogers, J. and R. Bhartia, "A 6 to 20 GHz planar balun using a Wilkinson divider and lange couplers" *IEEE MTT-S Symp. Dig.*, 865–868, 1991.
14. Park, U.-H. and J.-S. Lim, "A 700- to 2500-MHz microstrip balun using a wilkinson divider and 3-dB quadrature couplers," *Microwave and Optical Technology Letters*, Vol. 47, No. 4, 333–334. Nov. 20, 2005.
15. Peng, W. and X. Quan, "A wideband microstrip balun structure," *Proceedings of IEEE MTT-S International Microwave Symposium (IMS)*, 1–3, Tampa, FL, USA, Jun. 1–6, 2014.
16. Zhou, D., R. A. Abd-Alhameed, C. H. See, and P. S. Excell, "Design of wideband balanced folded-arms dipole antenna for mobile handsets," *Electromagnetics*, Vol. 29, No. 8, 641–651, 2009.
17. M. A. Antoniades and G. V. Eleftheriades, "A broadband Wilkinson balun using microstrip metamaterial lines," *IEEE Antennas and Wireless Propagation Letters*, Vol. 4, No. 1, 209–212, 2005.
18. Jin, S., Z. Rongguo, C. Chang, K. Hyoungsoo, and Z. Hualiang, "Design of a wideband balun using parallel strips," *IEEE Microw. Wireless Compon. Lett.*, Vol. 23, 125–127, 2013.
19. Wu, Y., Z. Zhuang, L. Jiao, and Y. Liu, "A compact planar wide-band balun with high isolation based on coupled-line and composite right-left-handed transmission line," *Microwave and Optical Technology Letters*, Vol. 58, No. 2, 372–376, Feb. 2015.
20. Lin, C.-M., C.-C. Su, S.-H. Hung, and Y.-H. Wang, "A compact balun based on microstrip EBG cell and interdigital capacitor," *Progress In Electromagnetics Research Letters*, Vol. 12, 111–118, 2009.
21. Cao, W., F. Guo, and B. Wang, "Design of a broadband balun based on composite right/left handed structure," *Microwave and Optical Technology Letters*, Vol. 52, No. 6, 1310–1312, Jun. 2010.
22. Chen, G.-Y. and J.-S. Sun, "Stepped coupled-line balun design for enhanced bandwidth operation," *Microwave and Optical Technology Letters*, Vol. 49, No. 8, 1877–1879, Aug. 2007.
23. Singh, H., A. Karmakar, and K. Singh, "Broadband branch line balun using meander line on silicon substrate," *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*, Vol. 4, No. 2, 7–11, Nov.–Dec. 2012.

24. Elfergani, I. T. E., A. S. H. J. Rodriguez, and R. A. Abd-Alhameed, "A compact dual-band balanced slot antenna for LTE applications," *PIERS Proceedings*, 524–527, Prague, Jul. 6–9, 2015.
25. HFSS version 14, Ansys Inc, USA, 2013, Available at:http://www.ansys.com/. Accessed on Oct. 10, 2014.
26. Zhang, Z., Y.-C. Jiao, S.-F. Cao, X.-M. Wang, and F.-S. Zhang, "Modified broadband schiffman phase shifter using dentate microstrip and patterned ground plane," *Progress In Electromagnetics Research Letters*, Vol. 24, 9–16, 2011.
27. Razzaz, F., M. A. S. Alkanhal, and A.-F. Sheta, "UWB Wilkinson power divider using tapered transmission lines," *PIERS Proceedings*, 882–884, Moscow, Russia, Aug. 19–23, 2012.