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A coupled-line balun for ultra-wideband single-balanced diode mixer

M. Y. Algumaei*, N. A. Shairi, Z. Zakaria, A. M. Zobilah, N. Edward
Microwave Research Group (MRG),
Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia
*Corresponding author, e-mail: mswnf@yahoo.com

Abstract

A multi-section coupled-line balun design for an ultra-wideband diode mixer is presented in this paper. The multi-section coupled-line balun was used to interface with the diode mixer in which it can deliver a good impedance matching between the diode mixer and input/output ports. The mixer design operates with a Local Oscillator (LO) power level of 10 dBm, Radio Frequency (RF) power level of -20 dBm and Intermediate Frequency (IF) of 100 MHz with the balun characteristic of 180° phase shift over UWB frequency (3.1 to 10.6 GHz), the mixer design demonstrated a good conversion loss of -8 to -16 dB over the frequency range from 3.1 to 10.6 GHz. Therefore, the proposed multi-section coupled-line balun for application of UWB mixer showed a good isolation between the mixer's ports.

Keywords*: balun, conversion loss, coupled-line, diode mixer, ultra-wideband*

1. Introduction

The growing demand for ultra-wide operational bandwidth with high quality and operational efficiency, lower manufacturing cost, and lower power consumption has become more widespread in microwave communication systems. Mixer is a key component of RF front-end systems that uses a nonlinear or time-varying element to achieve frequency conversion where it converts signals from one frequency to another [1, 2]. A single-balanced Schottky diode mixer finds enormous applications in the modern microwave systems. There are several applications such as in microwave imaging, radars, communication, instrumentation, etc. Many of these applications concentrate on the frequency range between 3 to 11 GHz [3-5].

Active mixers produce higher conversion gain, smaller chip size, and better noise performance [6, 7]. However, these mixers also have specific drawbacks, such as high DC power consumption and narrow operation bandwidth. Relatively, they also have a low linearity of signal power, whereas passive mixers have significant advantages such as better linearity, wider bandwidth, and lower power consumption. Several studies using a pair of diode technique have been presented in [8-11]. However, these studies did not achieve a wide operation bandwidth and high isolation between the mixer ports (RF, IF, and LO).

Therefore, in this paper, a coupled-line balun comprised of several sections of coupled-line was implemented in a single-balanced mixer design. The single-balanced mixer design was based on two Schottky diodes. The balun circuit provides a good impedance matching to the diode mixer and it provides a 180° phase shift over UWB frequency (3.1 to 10.6 GHz). Besides that, a low pass filter (LPF) was used in the mixer design to attenuate the unwanted signals and also to match the diode mixer with the IF port. Thus, the advantages of this design are the implementation of the coupled-line balun in UWB mixer design in order to minimize the complexity of the circuit with a good performance of conversion loss and isolation.

2. Coupled-line Balun and Mixer Design

2.1. Multi-Section Coupled-line Balun Design

A coupled-line circuit has been used in different research works as baluns [12]. In this paper, a multi-section coupled-line microstrip was designed as a balun and was implemented in

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a single-balanced Schottky diode mixer. The balun was realized by cascading five of the coupled-lines to interface the Schottky diodes in the mixer design.

Figure 1 depicts the diagram of a basic single-section coupled-line balun. It produced a balanced output to the load terminations Zout from an unbalanced input with source impedance Zin. The quarter-wavelength at the coupled-line was matched to the center frequency of operation and one of the coupled-line terminals was terminated (SC or OC) to ensure full reflection.

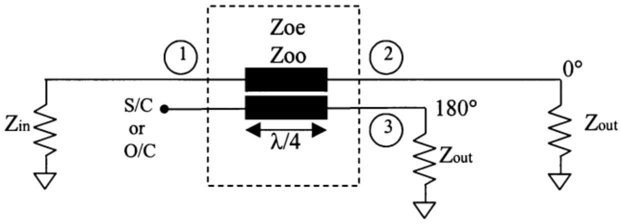

Figure 1. Quarter-wave coupled-line balun [12]

Generally, the impedances Zout are different from Zin. For instance, in balanced diode mixers, balanced signals from a source need to be fed to a pair of diodes, which may have a different impedance from the 50 Ω source impedance. Additionally, to produce balanced outputs, the balun circuit also needs to perform impedance transformation between the input/source impedance Zin and the output/load impedances Zout.

As depicted in Figure 1, the balun circuit comprises of a pair of coupled-lines section, which are λ/4 at the center of operational frequency. One of the four coupled-line section terminals was terminated (SC or OC) with full reflection, most usually in a short circuit [13, 14]. However, it can be used in an open circuit for some other cases. Based on Figure 1, the S-parameters describing the balun operation were given by

$$S11 = 0 \tag{1}$$

$$S21 = -S31 \tag{2}$$

The coupled-line odd- and even-mode impedances required for this balun circuit operation can be obtained from the corresponding four-port network depicted in Figure 2. In Figure 2, the short/open (SC or OC) terminal was replaced by a load impedance Zin to form a symmetrical network

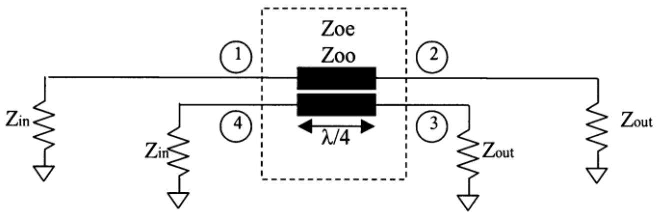

Figure 2. Four-port network for even- and odd mode [14]

Therefore, the required odd- and even-mode impedances can be obtained as follows, In the short-circuit case:

$$\text{Zoo} = \sqrt{\frac{Z_{out}Z_{in}}{2}} \text{, Zoe} = \infty \tag{3}$$

In the open-circuit case:

$$\text{Zoo} = \sqrt{2Z_{out}Z_{in}} \text{ , Zoe} = 0 \tag{4}$$

In (3) and (4) clarified the difficulties in the implementation of the multi-section coupled-line balun circuit. To approximate the desired open or short circuits in the even mode, very high or very low even-mode impedances were required in the design.

Figure 3 is a schematic diagram of the multi-section coupled-line balun. It consisted of three sections of the coupled-line balun which was designed to cover from 3.1 to 10.6 GHz band. Meanwhile, Figures 4, 5, and 6 show the simulated S-parameters of the balun design for a different additional section. It showed that by adding more sections, it improved the insertion loss at S(3,1) that was required in the mixer design.

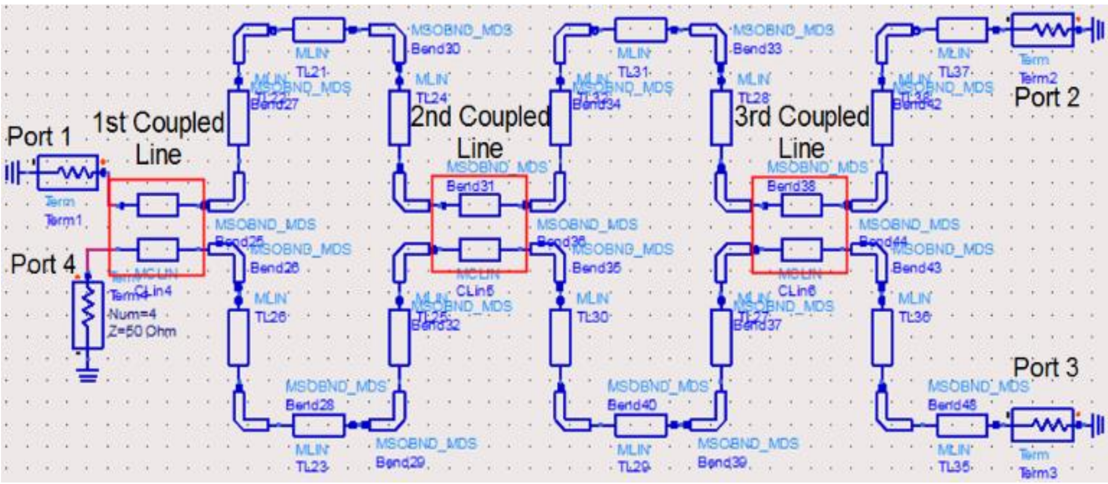

Figure 3. Schematic diagram of multi-section coupled-line balun

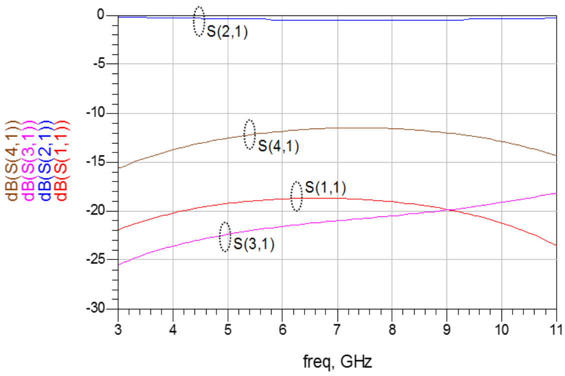

Figure 4. S-parameters of the single section coupled-line balun

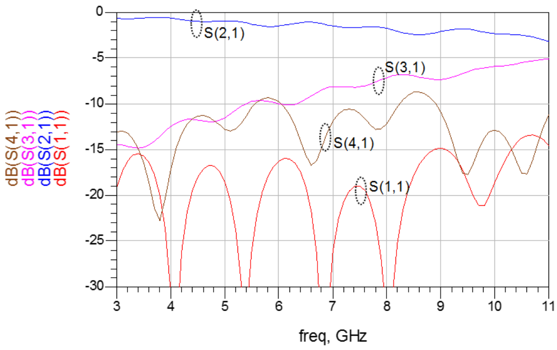

Figure 5. S-parameters of the cascaded two section coupled-line balun

Besides, it is well-known that by properly choosing the even-mode and odd-mode impedances of the different sections, the bandwidth of the coupler can be increased and thus, the simulated results indicated in Figure 6 show that the insertion loss S(2,1) and S(3,1) were around -5 dB and the return loss S(1,1) was less than -10 dB over a wideband range. In Figure 7, the phase shift of 180° between port 2 and 3 was shown by observing the S(2,1) and S(3,1) values.

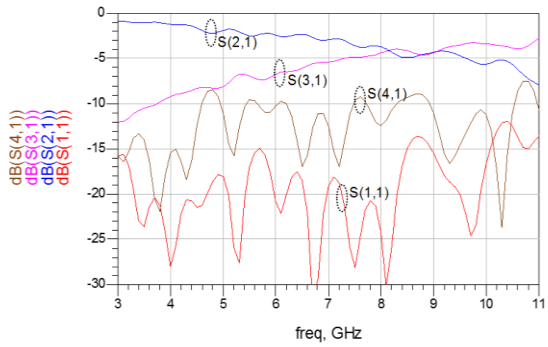

Figure 6. S-parameters of the cascaded three section coupled-line balun

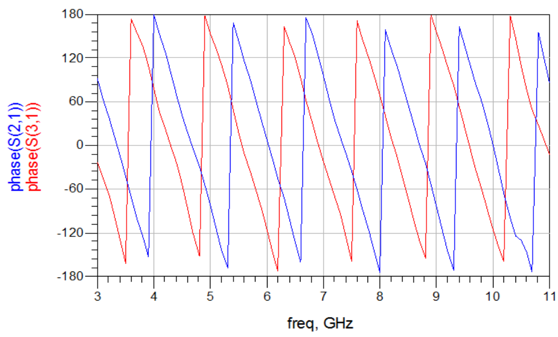

Figure 7. Phase response of the three-section coupled-line balun at port 2 and port 3

2.2. Balanced Diode Mixer Design

The designed multi-section coupled-line balun was implemented into a single-balanced diode mixer as shown in Figure 8. The Figure is a basic circuit configuration for single-balanced diode mixer where two Schottky diodes were used by connecting to the multi-section balun and a low pass filter.

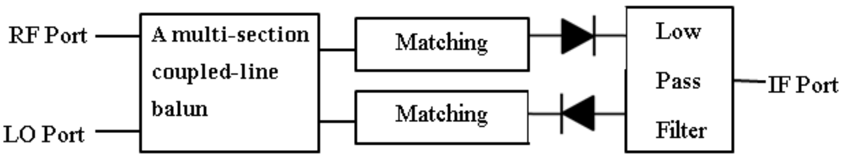

Figure 8. A multi-section coupled-line balun in the circuit of single-balanced diode mixer

In between the coupled-line balun circuit and Schottky diodes, a λ/4 of microstrip-line was used to provide the matching networking. The selection of the Schottky diode is critical for use in the mixer design which involves a trade-off between cost, convenience, ease of manufacture, and performance. However, the diode should have strong non-linearity, lower noise, lower distortion, and better frequency response in the operation region. Therefore, a packaged diode made up of silicon (SMS7621) was selected due to its features and applications which operated successfully at frequencies up to 12 GHz.

IF signal was extracted from the common node of two Schottky diodes and coupled it into the IF port through a low pass filter (LPF). The selection of LPF in the down-conversion mixer offered very good RF and LO suppression [15]. It was used to extract the frequency range of down conversion. The LPF was simulated with ADS software and designed by using a microstrip line with cut-off frequency at 2 GHz. This filter provided a matching network between IF port and diodes. No DC bias was required for this Schottky diodes mixer circuit.

Figure 9 shows the fabricated multi-section coupled-line balun integrated into a single-balanced diode mixer. It was fabricated on Roger RO4350B with a dielectric constant of 3.48.

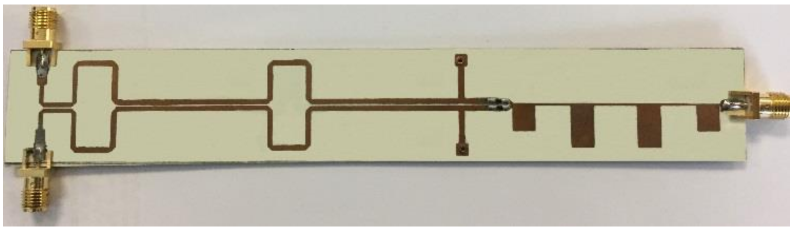

Figure 9. Fabricated of the multi-section coupled-line balun in single-balanced diode mixer

The mixed IF signal was fixed at 100 MHz in the simulation and measurement, in which it was simulated by ADS software and measured by Spectrum Analyzer. By putting the LO power level of 10 dBm and RF power of -20 dBm, Figure 10 shows the simulated and measured conversion loss of the single-balanced diode mixer versus RF frequencies from 3 to 10 GHz. It showed that the conversion loss was in the range of -8 to -16 dB. The difference between simulation and experiments results is due to some factors such as cable loss and fabrication process.

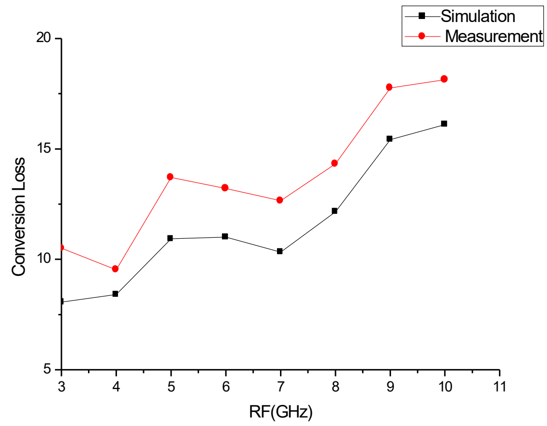

Figure 10. Simulated and measured conversion loss vs. RF

Meanwhile, Figure 11 shows the simulated conversion loss versus LO power level from 1 to 15 dBm at frequency of 7 GHz and IF of 100 MHz. It showed that conversion loss will reduce if LO power is increased.

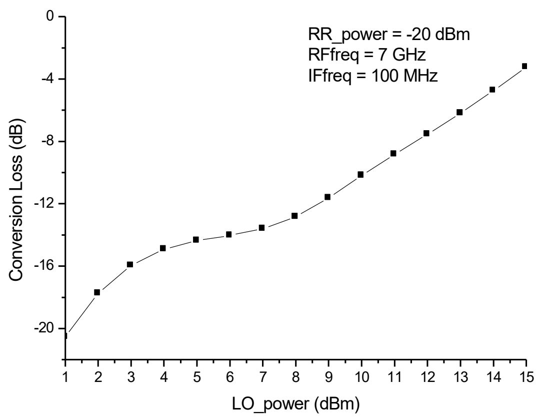

Figure 11. Conversion loss vs. LO power level at 7 GHz with IF=100 MHz

Table 1 is the summary and comparison between the proposed mixer and other mixers based on different techniques at UWB frequency range. Thus, the advantage of this design is the implementation of coupled-line balun in UWB mixer design in order to minimize the complexity of the circuit in [16-18] that have been used two baluns circuit and four diodes for double balanced mixer. Another important trend is that narrow bandwidth mixers tend to have lower conversion loss in part due to the difficulty in maintaining circuit balance over the wider bandwidth, however, the single balanced mixer in [19] achieves a conversion loss around 12.5 dB and isolation of 20 dB. In [20], the Wideband single balanced mixer designed and developed at DC power of 0.5 V and LO power of 15 dBm to achieve a conversion loss of 11 dB and isolation of 30 dB. The proposed mixer have the highest isolation result compared to the published results of mixers in Table 1.

Table 1. Comparison of UWB mixer designs

Ref	RF GHz	Diode	Power	LO dBm	Converson loss	Mixer type	Isolation	Balun type
[16]	3.1 – 10.6	Silicon diode	Self-biased	10	8 -10	Double balanced	>25	Planar (microstrip-to-slotline transition)
[19]	2.5–7.0	0.18 µm CMOS	Self-biased	6	12.48	Single balanced	>20	Integrated Ruthroff-type
[17]	3.0-5.0	0.18 µm CMOS	1.2-V	2	2.3	Double balanced	NA	NA
[20]	7.0-34	0.25-µm GaAs	0.5 V	15	11	Single balanced	>30	Edge-coupled Marchand
[18]	3.1-10.6	130 nm CMOS	1.2-V	NA	14.9	Double balanced	>25	Wideband PRODYN Balun
This work	3.1 – 10.6	Schottky diode	Self-biased	10	8 -16	Single balanced	>50	Coupled-Line

3. Conclusion

A multi-section coupled-line microstrip was designed as a balun and was implemented in a single-balanced Schottky diode mixer. The design was simulated in the ADS software and measured for verification. By using a multi-section coupled-line balun as a matching circuit together with the mixing process function from Schottky diodes, this mixer achieves a good conversion loss from -8 to -16 dB over UWB frequencies of 3.1 to 10.6 GHz. It was set with an LO driven power of 10 dBm and fixed IF of 100 MHz; thus, it would be able to achieve a good isolation between the mixer ports and could be integrated with other components such as UWB antenna [21,22], filter [23], amplifier [24] and switch [25] for a complete UWB RF front-end system.

Acknowledgments

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References

[1] Oxley TH. 50 years development of the microwave mixer for heterodyne reception. *IEEE transactions on microwave theory and techniques*. 2002; 50(3): 867-76.

[2] D Pozar. Microwave Engineering. 4th ed. New York: John Wiley & Sons. 2012.

[3] VNK Chang, I Bahl. RF and Microwave Circuit and Component Design for Wireless systems. John Wiley & Sons, Inc. 2002.

[4] Su CC, Lin CM, Hung SH, Huang CC, Wang YH. Analysis of Three-Conductor Coupled-Line 180 Hybrid for Single-Balanced Subharmonic Mixer Design in 0.15- m pHEMT Technology. *IEEE Transactions on Microwave Theory and Techniques*. 2014; 62(10): 2405-14.

[5] F Marki, C Marki. Mixer Basics Primer. Marki Microwave. 2010.

[6] Svitek R, Raman S. 5-6 GHz SiGe active I/Q subharmonic mixers with power supply noise effect characterization. *IEEE microwave and wireless components letters*. 2004; 14(7): 319-21.

[7] Hung SH, Lee YC, Su CC, Wang YH. High-isolation millimeter-wave subharmonic monolithic mixer with modified quasi-circulator. *IEEE Transactions on Microwave Theory and Techniques*. 2013; 61(3): 1140-9.

[8] Yu C, Li Z, Zhao M. *A K-band low conversion loss single balanced mixer with GaAs Schottky barrier diode. InAdvanced Materials and Processes for RF and THz Applications (IMWS-AMP).* 2016 IEEE MTT-S International Microwave Workshop Series. 2016: 1-3.

[9] Meherwal SK, Diwate SR. Design a RF Mixer using ADS. *Int. Res. J. Eng. Technol*. 2016; 3.

[10] Ebrahimian H, Ojaroudi M, Ojaroudi N, Ghadimi N. Distributed Diode Single-Balanced Mixer Using Defected and Protruded Structures for Doppler Radar Applications. *Applied Computational Electromagnetics Society Journal*. 2015; 30(3): 313-318

[11] Shafique MQ, Rana IE. Design of a Low-Cost High Isolation Subharmonic Mixer in mm-waves using Schottky Diodes. *Journal of Space Technology*. 2015; 5(1): 123-133.

[12] Ang KS, Leong YC, Lee CH. Multisection impedance-transforming coupled-line baluns. *IEEE Transactions on microwave theory and techniques*. 2003; 51(2): 536-41.

[13] RK Mongia, IJ Bahl, P Bhartia, J Hong. RF and Microwave Coupled-Line Circuits, Ed, 2nd. Cananda. Artech House. 2007.

[14] SA Mass. Microwave Mixers. 2nd ed. London. Artech House. 1993.

[15] Nguyen NT, Van Tran S, Nguyen DB, Mai L. *Design and implement a single balanced mixer at S band*. Advanced Technologies for Communications (ATC), 2015 International Conference. 2015: 637-641.

[16] Cao X, Tang Z, Wang F. Design of a double balanced mixer based on a novel planar UWB balun. *IEICE Electronics Express*. 2016; 13(6): 20160026-20160026.

[17] Murad SA, Pokharel RK, Kanaya H, Yoshida K. *A 3.0–5.0 GHz high linearity and low power CMOS up-conversion mixer for UWB applications*. Electron Devices and Solid-State Circuits (EDSSC), 2010 IEEE International Conference. 2010: 1-4.

[18] Kassiri BH, Deen MJ. *Low power highly linear inductorless UWB CMOS mixer with active wideband input balun*. Wireless Symposium (IWS), 2013 IEEE International. 2013: 1-4.

[19] Chiou HK, Chung HY. 2.5–7 GHz single balanced mixer with integrated Ruthroff-type balun in 0.18 µm CMOS technology. *Electronics Letters*. 2013; 49(7): 474-5.

[20] Nguyen T, Riddle A, Fujii K, and Pham A. Development of Wideband and High IIP3 Millimeter-Wave Mixers. *IEEE Transactions on Microwave Theory and Techniques*. 2017; 65(8): 1–9.

[21] Azizi MS, Hasan N, Salleh A, Othman A, Aris NA, Mohamad NR, Ramli MH. Compact Ultra-Wideband Antenna Using Coplanar Stripline (CPS)-Fed. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*. 2017; 9(2-5): 17-20.

[22] Al-Gburi AJ, Ibrahim IM, Zakaria Z. Band-notch Effect of U-shaped Split Ring Resonator Structure at Ultra Wide-band Monopole Antenna. *International Journal of Applied Engineering Research*. 2017; 12(15): 4782-9.

[23] Bruster A, Ruslan E, Zakaria Z, Hashim N, Mutalib MA, Saifullah N. *Tunable notch response for ultra wide-band bandpass filter*. Control System, Computing and Engineering (ICCSCE), 2015 IEEE International Conference. 2015: 492-497.

[24] Sapawi R, Mohamad DH, Yusuf DS, Sahari SK, Salleh DN, Hazis NA, Murad SA. CMOS Power Amplifier Design Techniques for UWB Communication: A Review. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*. 2017; 9(2-10): 1-8.

[25] Hsu CY, Chuang HR. *A 3-10GHz Broadband CMOS T/R Switch for UWB Applications*. European Microwave Integrated Circuits Conference. 2006: 452-455.