International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 17 (2017) pp. 6514-6522
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Review of Mixer and Balun Designs for UWB Applications

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Abstract

This paper presents an important review on mixer and balun designs for several UWB (ultra-wideband) applications that generally operate in frequencies ranging from 3.1 to 10.6 GHz. This paper begins with an introduction of mixer and balun terminologies, followed by discussion and comparison of several types of mixer designs and their performance on conversion gain, noise figure, third-order intercept points input, and port-to-port isolation. Balun plays an important role in RF mixer designs as it converts the single-ended signal coming from LNA into a differential signal that suitable for mixer input terminal. Hence, baluns provide impedance transformation and matching network for structures transition in mixer designs. The previous studies are reviewed and compared in order to gain a better understanding in RF mixers. An alternative design of balun can be suggested to be utilized in mixer designs to produce overall good performance for multi- function operation in UWB applications.

Keywords: Mixer; Balun; UWB; Conversion Loss; Isolation

INTRODUCTION

Nowadays, the development of UWB RF front end sub-components such as mixer, filter, switch, amplifier and antenna is highly desired and are developed to support several RF front end systems as reported in [1]–[5]. Traditionally, RF mixer has been the most misunderstood component available in designing and analyzing the modern microwave transceiver systems [6],[7]. The most common application of mixers is in the transceiver systems where two frequencies beat together in a nonlinear element to generate two different frequencies [8]. **Figure 1** shows the diagram of a RF front end system.

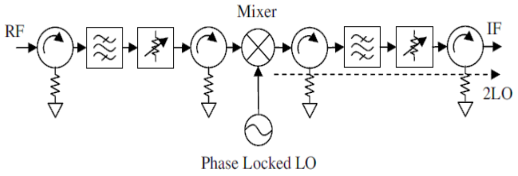

Figure 1: Typical diagram of the transceiver [9]

In general, a mixer is a three-port electronic device that uses a nonlinear or time-varying element to achieve frequency conversion [10], where two of these ports are “input” ports and the other port is an “output” port. The nomenclature for the three mixer’s ports are the Radio Frequency (RF) port, the Local Oscillator (LO) port, and the Intermediate Frequency (IF) port. This concept is illustrated in Figure 2. As a basic knowledge, there are several classes of mixer designs with different classifications, either diode or FET mixers, such as single-ended mixers, single-balanced mixers, and double-balanced mixers, where these mixers have different circuit configurations depending on their specifications and applications that may be suitable from one to another [11].

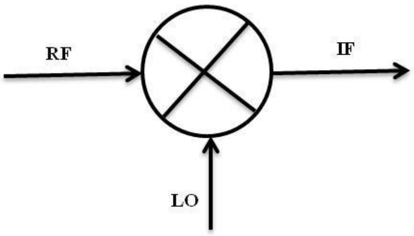

Figure 2: Ideal mixer

Nowadays, RF mixers can be designed in the form of integrated chip-sets at reasonably low cost. Several kind of semiconductor companies are constantly working toward the development of chip-sets operating at different frequencies [12]. In spite of that, other components are needed in milli-meter-wave systems, that cannot be conveniently integrated in the form of chip-sets, because they are either too large or the desired performance cannot be achieved by the integrated chip components.

RF parameters such as linearity, conversion loss, noise figure, power consumption, and port-to port isolation are important for mixer designs [13]. Several papers have presented and discussed different types of mixers. To improve the linearity of the mixer design, various linearization techniques are implemented in [14], [15], [16], and [17]. Isolation improvement is presented in a double-balanced Gilbert-cell mixer [18] and single-balanced MMIC resistive mixers [19].

One of the most common Issues in UWB transceiver systems designs is that the LNA (as the first component located after antenna) is usually single-ended and the output of this component should be directly connected to the mixer which has a differential input structure [20]. One suitable solution to this is to build a balun (unbalanced to balance converter) where the balun circuit plays a major role in generating differential output signals that characterize balanced amplitude and phase, to convert the single-ended signal into a differential signal suitable for the input terminal of the mixer [16],[21]. In general, transformers have a smaller size and higher bandwidth ratio than other kinds of baluns such as Marchand baluns and rat-race couplers [22]. Hence, the mixers exploit planar transformer balun in [23] and an active Marchand balun in [24] for UWB applications.

This paper is organized as follows. Firstly, an introduction of mixers and baluns is presented in section I. In section II, a comparison of UWB mixer designs is reviewed. Potential of UWB balun for mixer designs is presented in section III. Finally, technique suggested for mixer design enhancement is reported in section IV.

UWB MIXER DESIGN

There are many mixer designs that have been studied based on different mixer types for UWB implementations. Table 1 shows the different types of mixer designs, which are compared in terms of mixer type and power supply that the device uses. Several researches have been conducted on down-conversion mixers in order to introduce a double-balanced mixer for UWB applications with good performance of the device. For instance, the authors in [25] have presented a design of Complementary Metal–Oxide–Semiconductor (CMOS) down-conversion mixer based on the double-balanced cell architecture where the current-bleeding method is employed in order to increase the linearity and improve the conversion gain. The design can be used in a variety of applications such as Wi-Fi, WiMAX, and GSM. Meanwhile, in [26], [27], and [28], the authors presented mixer designs as parts of the UWB Receiver Front-End using down-conversion mixer based on the double-balanced cell architecture using different topologies which are current-reuse technique, conventional CMOS Gilbert cell, and special biasing technique, respectively.

In addition to that, a mixer with an active balun has been designed and fabricated in [20]. This design utilizes the folded configuration with isolated RF and LO stages that have a completely independent DC biasing. This design proposes the p-type MOSFETs for switches, where in the RF stage, an NMOS-PMOS stacked architecture is used to enhance the conversion gain and linearity of the mixer, while the LO stage has PMOS switches to maintain the power consumption and to keep the noise figure low. Figure 3 shows the circuit schematic where the VDDs are the supply voltage of the sub-threshold RF stage and they are generated by the internal biasing circuits.

Moreover, an active mixer has been presented in [29], the mixer in this paper is designed with a Gilbert-type configuration implemented of bleeding current technique and resonating technique incorporated for tail capacitance, resulting in the enhancement of both conversion gain and noise figure performance, hence, a switched capacitance network is used to control the resonant frequency of the tail capacitance, where the current bleeding is used to recompense the loss of conversion gain caused by the switched capacitance network. However, there is a trade-off between parametes such as conversion gain and power consumption.

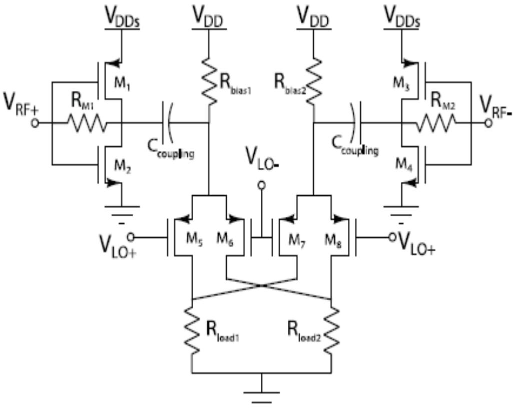

Figure 3: Schematic of folded architecture mixer [20]

An up-conversion mixer based on the active double-balanced Gilbert-cell mixer has been designed and simulated in [30]. This design implemented a current injection technique to obtain a low power consumption. Linearity of the mixer is improved by adding an additional capacitor in parallel with the intrinsic gate-source (GS) capacitor of a transconductance stage. Figure 4 shows the schematic of the proposed mixer.

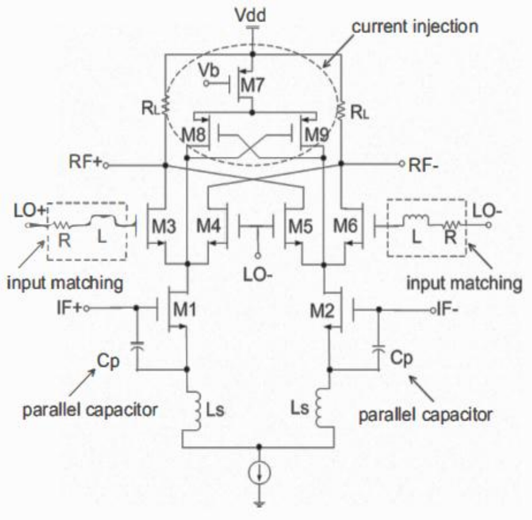

Figure 4: An equivalent circuit of the UWB mixer [30].

In addition to that, in [31], a front-end RF transmitter with an up-conversion mixer has been proposed. An improvement on the double-balanced Gilbert mixer structure has been made by implementing the current-reused bleeding technique to enhance the linearity and reduce the power of the mixer.

Meanwhile, a front-end RF receiver for UWB application in [32] utilizes double-balanced quadrature passive mixers due to their low power consumption as the absence of DC current through switches can effectively eliminate flicker or low-frequency (1/f) noise. Therefore, this mixer cannot work in the ideal current switching mode. In other words, this mixer works partially in the voltage switching mode, resulting in linearity degradation

A bulk-injection mixer is designed in [33], the mixer in this paper utilizes the Gilbert-cell topology based on a four-terminal device (MOS transistor). The Radio Frequency (RF) and Local Oscillator (LO) signals are respectively applied to the gate and bulk of the device, whereas the Intermediate Frequency (IF) signal output is produced from the drain. This mixer reduces the stacking transistors of the traditional Gilbert-cell architecture that reduce power consumption. However, the noise figure is comparatively high because of the active mixer topology.

Several mixers are designed based on the four Schottky barrier diodes in a ring configuration. The diode ring is self-biased by the Local Oscillator (LO) signal. Hence, they do not need DC bias to operate and they have high-speed switching capability [34]. For instance, the authors in [35] exploited the double-balanced (ring configuration) mixer based on the planar balun. This mixer consists of a microstrip-to-slotline transition, which can effectively block IF and DC components in a wide band. A good result is achieved in this mixer; however, a compact low pass filter is needed in order to connect to the IF port so as to provide a better isolation. The structure of the balun is showed in **Figure 5.**

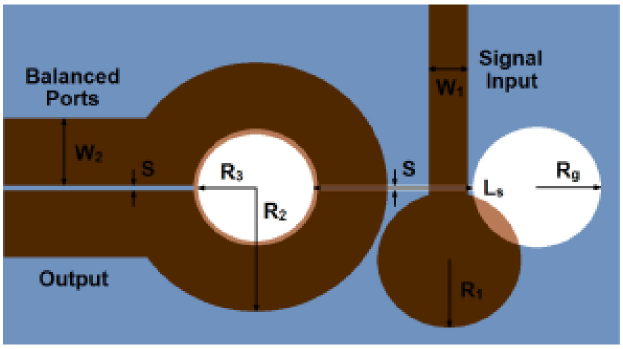

Figure 5: The Structure of microstrip-to-slotline transition balun [30].

In addition to that, a double-balanced diode in a ring configuration mixer is presented in [36]. The design uses two transformers as baluns to convert the unbalanced single ended of LO and RF input ports to a balanced configuration, hence the IF signal is taken at the virtual ground point of the four diodes ring in order to enhance the isolation between the LO and the IF ports. This design discusses the simulation results of conversion gain and OIP3 (third order input intercept point). However, this design needs to be fabricated to validate the simulated results. The ring mixer basic diagram is showed in Figure 6.

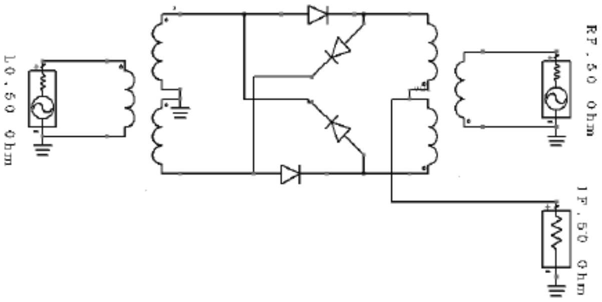

Figure 6: Diode double balanced ring mixer [36].

Table 1: Summary of different types of mixer design for several studies

Ref	Year	Author(s)	Type of mixer	Power supply (v)	Device Technology	Result	Remarks
[35]	2016	Xin Cao et al.	Double balanced diode ring mixer	Self-biased	Silicon	Conversion gain <15 dB Return loss > 10 dB Insertion loss < 0.2dB Isolation > 25 dB	*Operating frequency from 3.1 GHz to 10.6 GHz. * The design is simple, low cost and broadband approach.
[36]	2014	Abhay Chaturvedi et al.	Double balanced diode ring mixer	Self-biased	metal-semiconductor	Conversion loss = 5.022 dB OIP3 = 4.737 dBm	*Operating frequency from 3.1 GHz to 10.6 GHz. * The advantages of the mixer are low cost.

[25]	2014	Chin-I Yeh et al.	Down-conversion (double balanced cell structure) mixer	1.8	0.25 µm CMOS	Conversion gain = 7.6–9.6 dB IIP3 = −4 dBm Return loss < −9 dB. Noise figure = 13.1 dB	*Operating frequency from 0.9 GHz to 10.6 GHz. * The advantages of the mixer are excellent properties of linearity and low noise figures. * Isolation is very good.
[20]	2013	Hossein Kassiri B et al.	Double balanced (based on the folded architecture) mixer	1.2	130 nm CMOS	Conversion gain = 14.9 dB Noise figure = 6.9 – 10.3 dB Max IIP3= 9.2dBm at 7GHz	*Operating frequency from 3.1 GHz to 10.6 GHz. * The advantages of the mixer are high gain, high linearity, very low power and excellent noise performance.
[29]	2010	Boyu Hu et al.	Double-balanced (Gilbert-type configuration) mixer	1.8	0.18 µ m CMOS	Conversion gain = 17 dB Noise figure = 7.31dB IIP3= -5.7dBm	*Operating frequency from 3.43 GHz to 7.66 GHz. * The advantages of the mixer are impressive conversion gain, low noise figure over a wide frequency range.
[26]	2010	Bo Shi et al.	Down-conversion (double balanced quadrature) mixer	1.5	0.13 µm CMOS	Conversion gain = 29 dB Noise figure = 4 - 5.1 dB IIP3= -14 dBm Return Loss <-10 dB	*Operating frequency from 3.1 GHz to 10.6 GHz. *The proposed balun-mixer provides direct interface to LNA without the need for a separate balun with a good conversion gain and low noise figure.
[30]	2010	S.A.Z Murad et al.	Up-conversion (double-balanced Gilbert-cell) mixer	1.2	TSMC 0.18 µm CMOS	Conversion gain = 2.3dB Noise figure =19 dB IIP3= 12.5dBm Power consumption =7.1 mW	*Operating frequency from 3.0 GHz to 5.0 GHz. *The mixer is useful for application that require high linearity transmitter because of its superior linearity and low power consumption.
[27]	2009	Yang Gao et al.	Down-conversion (double-balanced Gilbert-cell Architecture) mixer	1.8	SMIC 0.18 µm CMOS	Conversion gain = 9 - 11.5dB Noise figure = 10.8-13.2dB IIP3= (-10.5) -(-8.2) dBm Power consumption = 11.3 mW.	*Operating frequency from 3.1 GHz to 4.8 GHz. * The advantages are high conversion gain, high linearity, low noise figure and good power consumption.
[31]	2009	Wen-Shan Hxiao et al.	Up-conversion (double-balance Gilbert structure) mixer	1	0.18 µm CMOS	Conversion gain = 6.5dB Noise figure = 12 – 13 dB IIP3= 11.6-dBm Power consumption = 11 mW Isolation > 40 dB	* Operating frequency from 3 GHz to 5 GHz. * The advantage of the design is a good isolation.
[32]	2008	Weinan Li et al.	Double-balanced quadrature passive mixers	1.2	0.13µm CMOS	Conversion gain = 22dB Noise figure = 3.3dB IIP3= -14dBm	*Operating frequency from 3.1 GHz to 4.7 GHz. * The advantages are good

						LO-RF isolation = 180dB	noise figure and wide bandwidth with low power consumption.
[33]	2007	Kung-Hao Liang et al.	Down-conversion (bulk-injection) mixer	1.8	TSMC 0.18 µm CMOS	Conversion gain =5.7 dB Noise figure =15 dB IIP3= -5.7dBm Power consumption =0.48 mW Isolation >30 dB	*Operating frequency from 0.5 GHz to 7.5 GHz. * it can be used in modern wireless communications, such as WLAN and mobile phone, low-voltage, low-power consumption operation because of the limitation of battery.
[28]	2005	Bo Shi et al.	Down- conversion (double-balanced Gilbert) mixer	2.7	0.25 µm SiGe BiCMOS.	Power gain = 20.6 - 21.8 dB Noise figure = 4.1 - 6.2 dB IIP3= -12.7 dBm LO-to-RF Isolation > 56 dB	* Operating frequency from 3.1 GHz to 10.6 GHz *The design used bipolars which help to minimize the second order distortion caused by the non-ideal duty cycle of the LO signal

POTENTIAL OF UWB BALUN FOR MIXER DESIGN

Several research works have been conducted on the UWB balun in order to introduce novel balun designs with different types and techniques used in [37]–[43]. For example, in [37], a novel ultra-broadband Balun/1800 power divider utilizing the microstrip-slot-line-microstrip transition is reported. This design is fabricated on RO4003c substrate, LTCC, and Sapphire where the results of all designs showed less than 3 dB of insertion loss and more than 10dB of return loss over the frequency range. Hence, the potential of the balun has been investigated as a part of a double-balanced mixer and a frequency doubler. Figure 7 shows the equivalent circuit of the reported balun where the block circled A is correlating with the input microstrip radial stub, block B and C are correlating with the radial stubs on the slotlines, and block D and E are correlating with the radial stubs of the output microstrip lines.

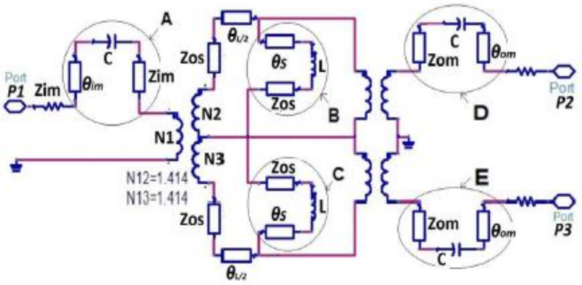

Figure 7: Equivalent diagram of Balun [37].

In [38], a novel UWB balun is presented. The presented balun is composed of two mutually perpendicular planes. By mounting the vertical plane with a double-sided parallel-strip line (DSPSL) into the horizontal feeding plane guarantees a complete ground and frequency-independent phase difference. Moreover, to enhance the UWB matching performance, seven-section quarter-wavelength transformers are connected in series. The measurement results showed, the return loss S11 is more 13 dB, but the insertion loss reached 5.3 dB.

In addition to that, a marchand balun circuit in a multilayer technology is developed in [39]. The basic structure of the marchand balun with a single layer is developed with a double layer structure in order to enhance bandwidth and coupling coefficient. The simulated results showed an improvement on return loss exceeding 18 dB over the passband from 4.5 GHz to 8.5 GHz.

Meanwhile, the authors in [40] used a broadband three-port coupled transmission line balun derived from a four-port network. This design delivers a good impedance matching with less complexity. The balun results showed the input port matching parameter (return loss) S11 less than 9.7 dB over the frequency range 0.8 GHz up to 8 GHz. The insertion loss S21 and S31 are around 4 dB loss, that tends to get increased over higher frequencies.

A compact ultra-wideband planar microstrip-to-coplanar strips balun is designed in [41]. This balun utilized the UWB planar dipole with circular arms. The structure of transition from strip to the circular arm is significant for suitable operation of the dipole. The results showed that the return loss is more than 12.8 dB over the UWB frequency range. where the obtained results assured that the configuration of the compact planar balun can be redesigned on another substrate and maintain good performance over the UWB frequency range.

In addition to that, in [42], a study on the design and performance of a typical UWB balun has been reported. The design uses electromagnetic bandgaps (EBGs) in order to get a stop-band of above than 10.6 GHz, where the simulation results showed a wide and deep stop-band place of above than 11 GHz and with stop-levels around 30 dB. The typical wide-band transition from microstrip (MS) to paralled-stripline (PS) is showed in Figure 8. Meanwhile, authors in [43] utilized the Dolph-Tchebycheff transmission-line taper as the taper profile for the balun transformer. The balun showed acceptable performance with maximum reflection in the order of 10 dB. Figure 9 shows the configuration of the geometry of the balun transformer.

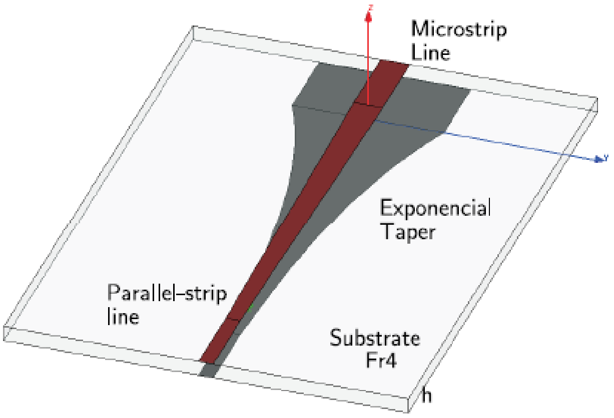

Fig. 8 Standard exponential MS-PS Balun structure.

Table 2 shows the comparison of the previous research works on UWB baluns according to the different types and techniques used in the last decade.

Table 1: Comparison of previous research works in UWB BALUN

No	Author / Year	Type of balun	Remarks
[37]	Ajay K. Poddar et al. 2016	Microstrip/slotline transitions.	The balun was designed at frequency from 4 GHz up to 45 GHz. This work is implemented easily on Rogers substrate, LTCC/ceramic and MMIC package as well, maintaining the good result of return loss and insertion loss.
[38]	Yongle Wu et al. 2016	Vertically mounted planar (VMP) structure.	The balun is designed at frequency from 0 GHz up to 8 GHz. The design is simulated and fabricated, there is a good agreement between the simulation and measurement showed a good return loss and regular insertion losses.
[39]	Raaed T. Hammed et al. 2015	Marchand balun circuit in multilayer technology.	The balun is designed at frequency from 3.1 GHz to 10.6 GHz. The circuit is designed on Rogers Ceramic TMM10I substrate. the design achieved a strong coupling coefficient that required for a broad-band balun design.
[40]	Srikanth Itapu et al. 2015	Multi-section transforming coupled-line.	The balun is designed at frequency from 0.8 GHz to 8 GHz. The design was fabricated on a FR4 substrate, the advantages are straightforwardly handled, compact, and exhibit a broad frequency spectrum.
[41]	Lukasz SOROKOSZ et al. 2011	Ultra-wideband planar (microstrip-to-coplanar strips) balun.	The balun was designed at frequency from 3.1 GHz to 10.6 GHz. The design is fabricated on Taconic RF-35 substrate, in this design only simulation results which are satisfying and qualify for the fabrication.
[42]	Pedro Luis Carro et al. 2008	Planar EBG structures.	The balun is designed at frequency from 3.1 GHz to 10.6 GHz. The design is fabricated on a FR4 substrate, and the design used bandgaps to reduce bandwidth.
[43]	E.T. Rahardjol et al. 2007.	Stripline.	The balun is designed at frequency from 3 to 10 GHz. The design is fabricated on a FR-4 material. 3D integrated structure has been realized not 2D due to the complexity in mechanical construction.

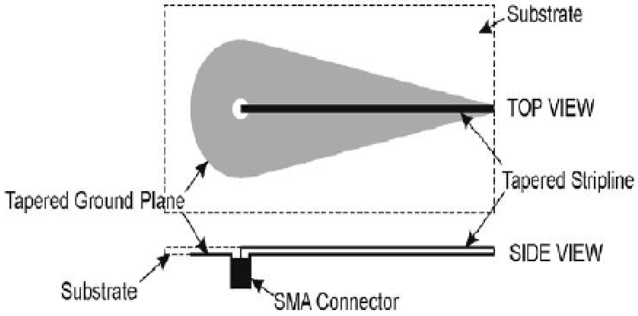

Figure 9: Geometry of the balun transformer

TECHNIQUES SUGGESTED FOR MIXER DESIGN ENHANCEMENT

From literature studies, the balanced mixer is the mixer of choice. From the design point of view, balanced mixers demonstration better power handling capability, low LO noise and high port-to-port isolation. The limitation of these mixers designs is more complex. However, several studies had attempted to overcome the complexity by built a balun.

The mixers based on the ring or star diodes configurations balun were used widely, due to broad bandwidth and low cost. For instance , A wide band passive fundamental wave mixer based on the novel broadband balun was simulated and fabricated in [44]. design results showed typical conversion loss of 9 dB, high gain compression and return loss about 10 dB covered the frequency range from 3 GHz to 50 GHz. however, this type of balun has matching difficulty and high Insert loss. Besides that, In [45] authors proposed A Ka-band double balanced mixer based on the Marchand balun. This mixer operates on the frequency range from 27 GHz to 44 GHz. the LO-to-RF isolations is higher than 20 dB. But, the balun is 3D structure and simulated insertion loss is high in UWB range frequency.

This review paper recommends the use of multi-section transforming coupled-line balun based on the quarter-wavelength coupled-line presented in [46], By cascading several of these coupled-line sections, very high even-mode impedances can be obtained , resulting of good balun amplitude and phase balance. In addition, the multisession structure has advantages of Less complex, good impedance matching and consistent 180° phase shift over operating frequency.

CONCLUSION

This paper has reviewed several types of mixer and balun designs for UWB applications. The mixer designs are presented and reviewed based on the parameters such as conversion gain, noise figure, third-order intercept points input, and port-to-port isolation. It is found that there is a trade-off between the parameters performances such as power level, conversion loss and isolation. It is also found that the Gilbert mixers are widely used in many proposed active mixers due to relatively good conversion gain performance. However, in recent years, the studies tend to favor a balanced mixer based on the Schottky diode as these balanced mixers demonstrate better power handling capability, low LO noise, and high port-to-port isolation. Besides, several types of ultra-wideband (UWB) baluns have been reviewed, most of the baluns utilize 180° phase difference between the balanced ports 2 and 3. Finally, some baluns designs such as multisection coupled-line microstrip balun are suggested in this paper to improve the overall mixer design.

ACKNOWLEDGEMENTS

We are grateful to UTeM Zamalah Scheme, Centre for Research & Innovation Management (CRIM), Centre for Telecommunication Research and Innovation (CeTRI) and Universiti Teknikal Malaysia Melaka (UTeM) for their encouragement and help for supporting financially to complete this research work.

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