Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 7, No.2, April 2025, pp. 02502015-01 ~ 02502015-010
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v7i2.1579

Performance Comparison of UWB Single Balanced Schottky Diode Mixers for RF Front-End Applications in 3-10 GHz Band

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Abstract. This paper compares two single balanced mixer designs for ultra-wideband (UWB) of RF front-end at frequencies ranging from 3 to 10 GHz. The proposed mixer designs use two balun topologies for varying mixer performances. Thus, Design 1 incorporates a Coupled Line Balun and Design 2 incorporates a Branch Line Balun. Both designs make use of Skyworks' SMS7621 Schottky diodes, which have a low junction capacitance, and the Rogers RO4350B substrate, which has a dielectric constant of 3.48. The Coupled Line Balun (Design 1) offers a total length of 88 mm, whereas the Branch Line Balun (Design 2) creates a more compact structure with 48 mm. This paper's thorough analysis and measurements show each design's benefits and drawbacks in terms of circuit size and performance. The simulations and measurement results of both designs generally showed a conversion loss of less than 20 dB and LO-RF isolation of better than 50 dB.

Keywords: Coupled Line Balun, Branch Line Balun, UWB Mixer, RF Front-End

(Received 2024-03-05, Accepted 2025-03-22, Available Online by 2025-04-30)

1. **Introduction**

To support a wide range of RF front-end systems, the development of ultra-wideband (UWB) radio frequency (RF) front-end subcomponents, such as mixers [1], filters [2], switches [3], amplifiers [4], and antennas [5], is of great interest and is being actively pursued in current research. It is evident that the RF mixer is an essential part of microwave transceiver systems, and because of its intricate performance requirements, it frequently poses design challenges. Throughout history, the RF mixer has been one of the most difficult parts to design and analyze in modern microwave transceiver systems [6].

In microwave communication systems, there is an increasing need for ultra-wideband operating bandwidth with high quality and operational efficiency, lower production costs, and lower power consumption [7]. There are several uses for a single balanced diode mixer in contemporary microwave systems, including instruments, communication, radars, and microwave imaging [8-9].

This paper addresses a significant research gap in the design and performance comparison of ultra-wideband (UWB) single balanced Schottky diode mixers for RF front-end applications in the 3-10 GHz band. While there has been extensive research on various mixer designs [10-13], there is limited comparative analysis focusing on the use of different balun topologies specifically for the coupled-line and branch-line baluns in UWB mixer designs. This gap is critical because the choice of balun significantly impacts the mixer's performance, including conversion loss, isolation, and overall circuit size. By comparing these two balun topologies, the study aims to provide insights into optimizing mixer designs for better performance and compactness. Meaning that, prior works on coupled-line baluns highlight their broadband performance and impedance matching, while branch-line baluns are noted for compact size and wide frequency range applications in RF and microwave circuits.

Therefore, an ultra-wideband discrete single balanced diode mixer for UWB applications with two different types of baluns (Coupled Line and Branch Line) is compared in this paper. Furthermore, a Low Pass Filter (LPF) was incorporated into the design of the mixer to diminish the presence of undesirable signals and to ensure matching between the IF port and the mixer’s diode.

2. UWB Mixer Circuit Designs

In this section, the UWB mixer circuit design is incorporating two different types of baluns: the Coupled Line Balun and the Branch Line Balun. These baluns play a critical role in ensuring proper signal transformation and impedance matching within the circuit.

2.1. Design 1: Coupled Line Balun

Figure 1 shows the general diagram of single section coupled line, based on [14]. It consists of four ports: the Input port (Port 1), where the signal enters the coupler and is terminated with a characteristic impedance Z_0; the Direct port (Port 2), where the majority of the input signal travels and is also terminated with Z_0; the Coupled port (Port 3), where a portion of the input signal is coupled and appears, terminated with Z_0; and the Isolated port (Port 4), which ideally receives no signal due to isolation properties and is terminated with Z_0. There are two parallel lines that coupled over a length, *l* under the conditions, shown in Equation 1.

$$Z_{0e} Z_{0o} = Z_0^{\,2} \tag{1}$$

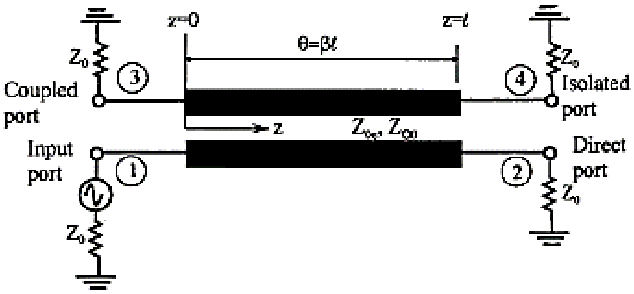

Figure 1. General diagram of single section coupled line [14]

The coupler includes a pair of parallel coupled transmission lines characterized by an Even-Mode Impedance, Z_{0e} and an Odd-Mode Impedance, Z_{0o}. These impedances define the differential behavior of coupled lines. The length of the transmission lines is denoted as *l*, with a phase constant *β* and an electrical length *θ*, shown Equation 2.

$$\theta = \beta l = \frac{\pi}{2} rads \tag{2}$$

The frequency bandwidth ratio B of a single or multi-section Coupled Line is defined as Equation 3.

$$B = \frac{f_2}{f_1} \tag{3}$$

where f_2 and f_1 are the upper and lower frequencies in between which the coupling is within the tolerance amount δ compared with its mid-band value.

Figure 2 shows the layout of a cascading three-section Coupled Line Balun, which is a device used to convert between balanced and unbalanced transmission line signals. It consists of three coupled line sections (Section 1, Section 2, and Section 3), each designed with specific physical parameters to achieve the desired impedance transformation and signal balance. This balun has four ports, including Port 1 and Port 3 are on the unbalanced side, typically connected to an unbalanced transmission line like a coaxial cable. Another two ports, Port 2 and Port 4, are on the balanced side, designed to provide signals that are equal in magnitude but opposite in phase. Even- and Odd-mode impedances values and dimensions for Coupled Line Balun are shown in Table 1.

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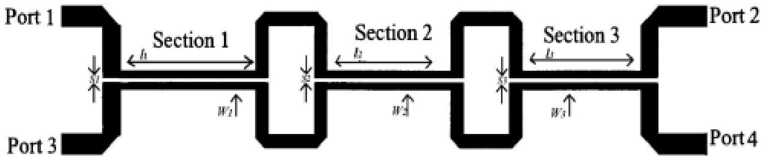


Figure 2. Layout of the three-section Coupled Line Balun

Table 1. Even- and Odd-mode impedance values and dimensions for the Couple Line Balun

	Section 1	**Section 2**	**Section 3**
Z_{0o}	72.6 Ω	172.81 Ω	72.6 Ω
Z_{0e}	34.4 Ω	36.11 Ω	34.4 Ω
Length, *L* (mm)	4.7	5.16	4.7
Width, *W* (mm)	0.86	0.16	0.86
Coupling gap, *S* (mm)	0.094	0.0398	0.09

2.2. Design 2: Branch Line Balun

The Branch Line Baluns are commonly used in numerous circuit designs, where the primary goals are size minimization and wideband operational frequencies [15]. Figure 3 shows the basic configuration of a single Branch Line Balun. This balun consists of four ports: the Input Port (Port 1, P_1), where the signal enters and is terminated with a characteristic impedance Z_0; the Direct Port (Port 2, P_2), where the majority of the input signal propagates and maintains the impedance Z_0; the Coupled Port (Port 3, P_3), which receives a portion of the input signal and is often 90° out of phase with the signal at the direct port; and the Isolated Port (Port 4, P_4), which ideally receives no signal and is terminated with Z_0. The branch-line structure consists of horizontal and vertical quarter-wavelength (λ/4) transmission line sections with impedances $Z_{0}p$ and Z_0s, respectively.

The characteristic impedance of the transmission line and the shunt branches of a Branch Line Balun can be calculated using Equation (4) and Equation (5) as:

$$Z_{os} = Z_o|S_{21}| = Z_0\sqrt{1-|S_{31}|^2} \tag{4}$$

$$Z_{op} = \frac{Z_{os}}{|S_{31}|} = \frac{Z_{os}}{\sqrt{1-|S_{31}|^2}} \tag{5}$$

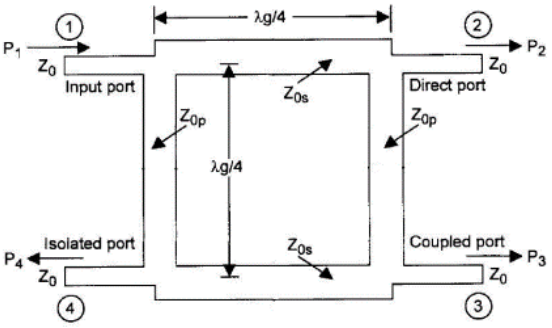


Figure 2. The basic configuration of single Branch Line Balun configuration [14]

2.3. Complete Circuit of UWB Mixers

The basic diagram of UWB Single Balanced Diode Mixer is shown in Figure 3, includes a balun, two matching networks, two Schottky diodes, and a low-pass filter (LPF). The LO signal is split evenly into the diodes, while the RF signal is divided equally with a 180° phase difference. The LO and RF signals mix in diodes, and the output is combined at the Intermediate Frequency (IF) port. The matching circuit ensures impedance matching between the RF, LO, and IF ports and the mixer circuit. This minimizes reflection and maximizes power transfer. The Schottky diodes are key non-linear components that enable the mixing process (frequency conversion). The LPF extracts the down-converted signal and isolates the IF port from LO and RF signals. The LPF removes unwanted high-frequency components (e.g., harmonics and sum frequencies) generated during mixing, isolating the desired IF signal.

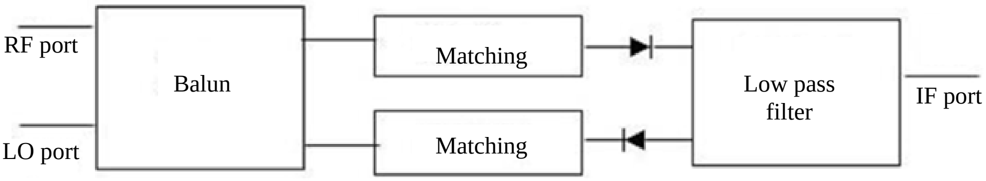


Figure 3. Basic diagram of UWB Single Balanced diode mixer

Figure 4 represent the Design 1, a UWB Single Balanced Diode Mixer prototype with a Coupled Line Balun for UWB applications. The overall dimensions of the mixer are 162 mm by 24 mm, with the total length of the Coupled Line Balun of 88 mm. Meanwhile, Figure 5 shows the Design 2, a UWB Single Balanced Diode Mixer with a Branch Line Balun for UWB applications. The overall dimensions of this mixer design are 117.88 mm by 32 mm, with the Branch Line Balun having an overall length of 48 mm. As a comparison, Design 2 is more compact than Design 1.

Both mixer circuits were designed using Rogers RO4350B substrate, with a dielectric constant of 3.48, which was used to develop the design on a microstrip transmission line. Skyworks' SMS7621 high-frequency Schottky diodes, featuring low junction capacitance, were utilized. A quarter-wave (λ/4) microstrip line was employed as the matching network between the Schottky diodes and the balun circuits. Notably, this Schottky diode mixer circuit does not require any DC bias.

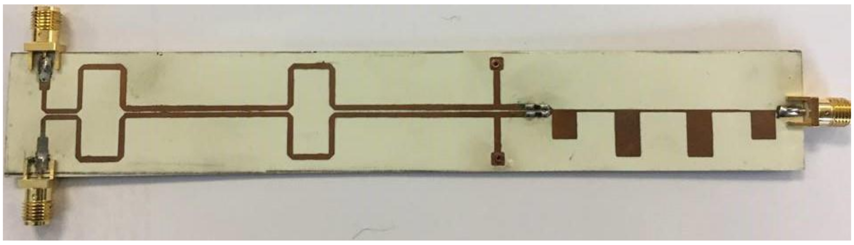


Figure 4. Design 1 - UWB Single Balanced diode mixer with Coupled Line Balun

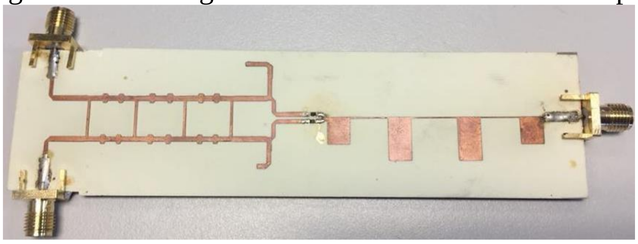


Figure 5. Design 2 - UWB Single Balanced diode mixer with Branch Line Balun

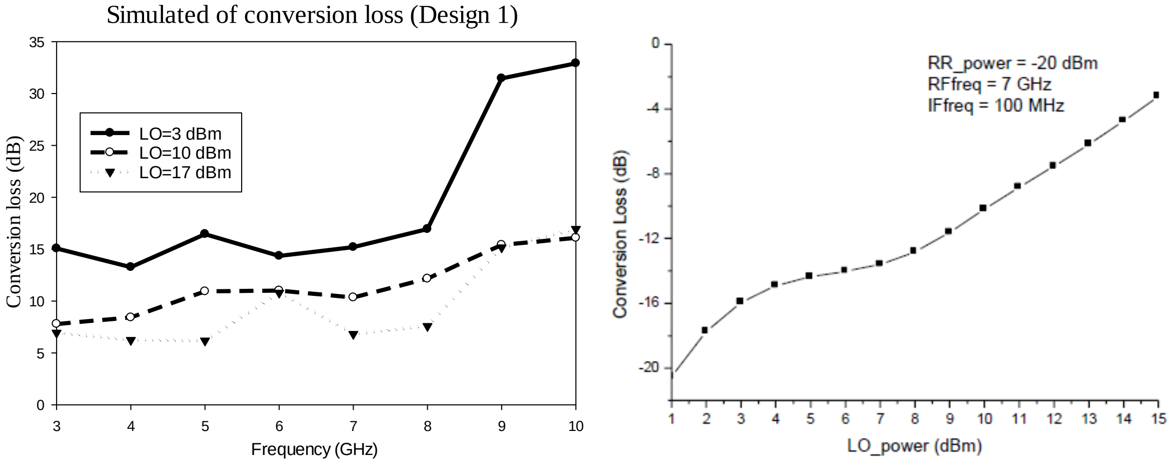
3. Results and Discussion

In this work, the ADS software was used to simulate the mixed IF signal, which was fixed at 100 MHz during the simulation and measurement. A spectrum analyzer with two signal generators was used for the measurement.

3.1. UWB Mixer with Coupled Line Balun

Figure 6(a) shows how the correlation between LO power level and conversion loss may be described as inversely proportional, with the conversion loss decreasing as LO power increases. This is achieved by altering the LO power level from 3 to 17 dBm. A conversion loss of 6 dB at 17 dBm LO power, for example, was raised to 8 dB by dictating the LO power to 10 dBm, and 13 dB at 3 dBm of LO power at 4 GHz. Frequencies between 3 and 10 GHz show this relationship.

The relationship between the conversion loss and the LO power level can be observed in Figure 6(b) when the LO power rises from 1 dBm to 15 dBm. The IF frequency was set at 100 MHz, while the RF frequency was set at 7 GHz. As LO power increases, the conversion loss drops from 20 dB to 3 dB, and it may possibly drop further.



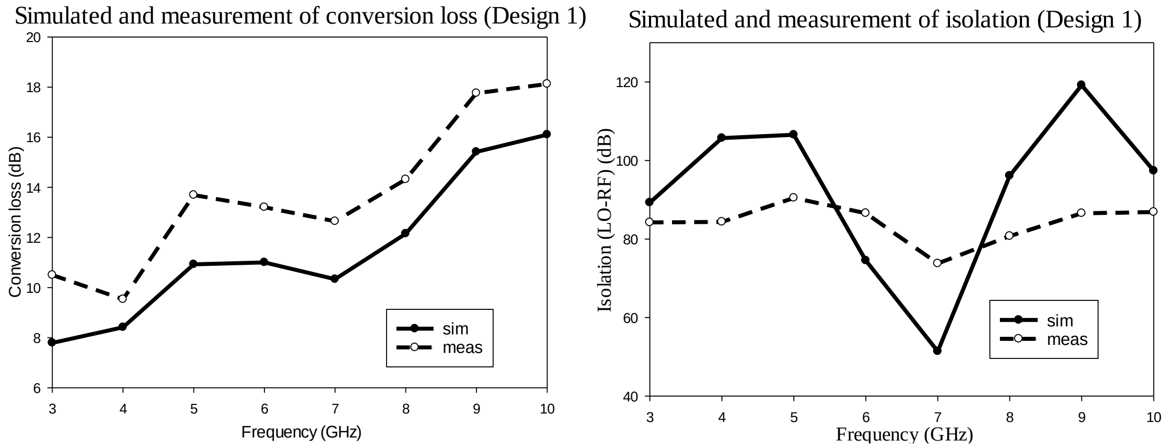
Simulated of conversion loss (Design 1)

(a)

(b)

Figure 6. (a) Simulated conversion loss with different levels of LO power vs RF frequency of UWB Single Balanced diode mixer (Design 1), (b) Simulated conversion loss vs. LO power level, RF frequency = 7 GHz, IF = 100 MHz and RF power = -20 dBm

Figure 7(a) shows the conversion loss of a UWB single balanced diode mixer with a Coupled Line Balun, showing less than 16.1 dB in simulation and 18.13 dB in measurement at a 10 dBm LO power level, with discrepancies due to factors like cable loss or fabrication issues. Figure 7(b) highlights the isolation performance, exceeding 51.38 dB in simulation and 60.64 dB in measurement, with differences attributed to solder wire resistance.


Simulated and measurement of conversion loss (Design 1)

Simulated and measurement of isolation (Design 1)

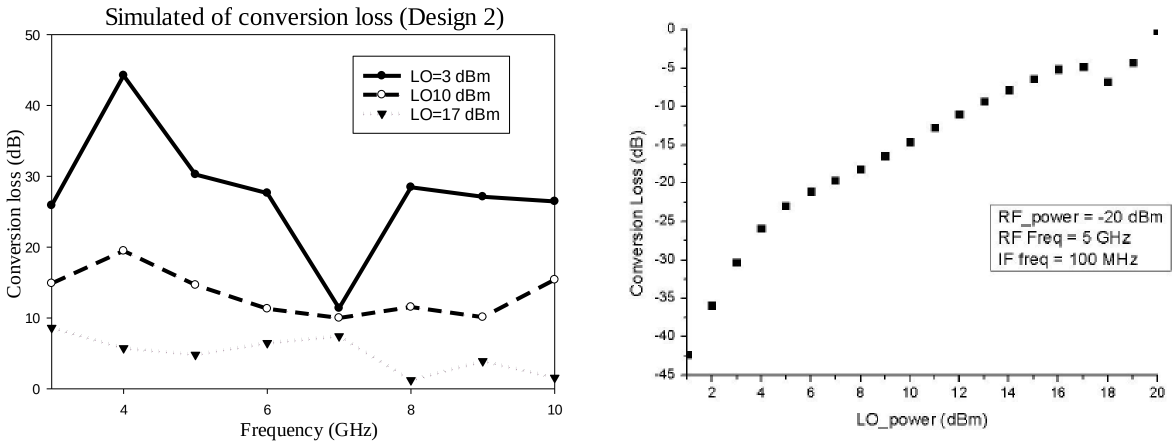
(a) (b)

Figure 7. (a) Simulated and measured results for UWB Single Balanced diode mixer using Coupled Line Balun (Design 1), (a) conversion loss, (b) isolation

3.2. *UWB Mixer with Branch Line Balun*

In this simulations and measurement, the mixer was set to an IF signal at 100 MHz. By altering the LO power level from 3 to 17 dBm, Figure 8(a) shows the relationship between LO power level and conversion loss can be interpreted as inversely proportional where the conversion loss will drop when LO power is raised.

The relationship between the LO power level and the conversion loss can be seen in Figure 8(b). The RF frequency was fixed at 5 GHz and IF frequency at 100 MHz. The conversion loss decreases from 40 to 3 dB where it could be even lower with higher LO power.

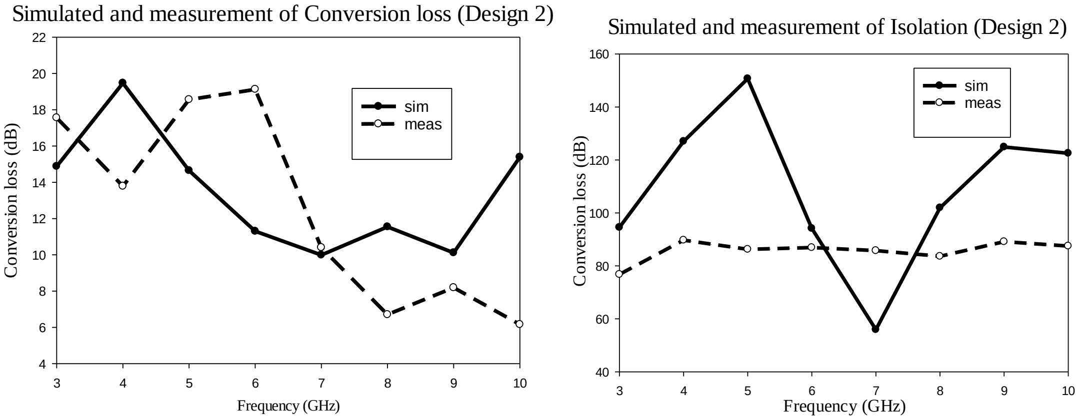

Simulated of conversion loss (Design 2)

(a) (b)

Figure 8. (a) Simulated conversion loss with different levels of LO power vs. RF frequency of UWB Single Balanced diode mixer (Design 2), (b) Conversion Loss vs. LO power level, RF frequency = 5 GHz, IF = 100 MHz and RF power = -20 dBm

Figure 9(a) shows the results of the conversion loss simulation and measurement for a UWB single balanced diode mixer using Branch Line Balun for UWB applications. The conversion loss with a 10 dBm LO power level was less than 19.47 dB (in simulation) and 19.13 dB (in measurement). There might be a number of reasons for the difference between the simulation and measurement results, including cable loss or coupling issues during the fabrication process.

Figure 9(b) shows the simulated isolation values for a UWB single balanced diode mixer using Branch Line Balun for UWB applications. The isolation reached more than 55 dB (in simulation) and 60 dB (in measurement) with a 10 dBm LO power level. The difference in results could be due to additional resistance of solder wires.


Simulated and measurement of Conversion loss (Design 2)

Simulated and measurement of Isolation (Design 2)

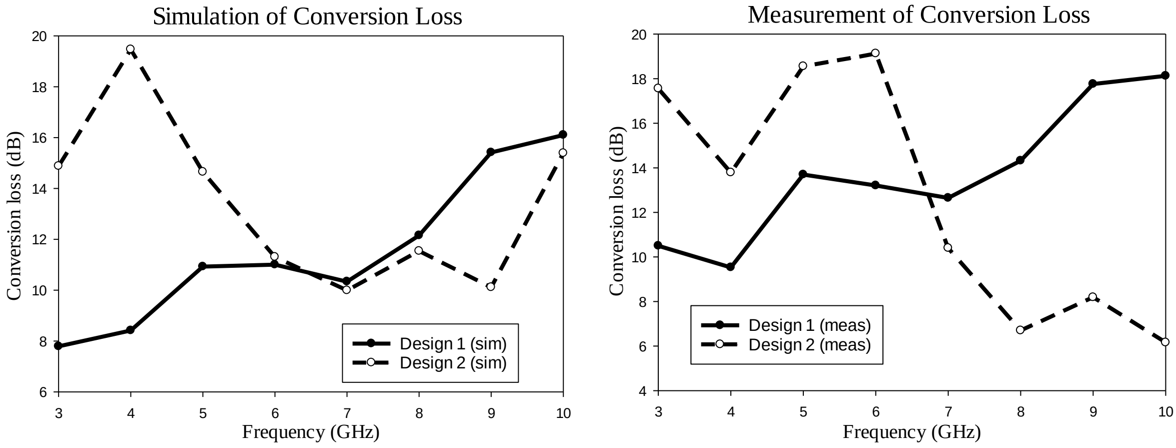
(a)

(b)

Figure 9. (a) Simulated and measured results for UWB Single Balanced diode mixer using Branch Line Balun (Design 2), (a) conversion loss, (b) isolation

3.3 Comparison

Figure 10 shows the simulated and measured conversion loss of both designs. For simulated, Design 1 consistently shows better conversion loss performance, particularly in the lower and higher ends of the frequency range. Design 2 demonstrates higher loss fluctuations, peaking notably at certain frequencies. For the measured results, it follows a similar trend, though with slight variations likely due to real-world factors such as fabrication tolerances or cable losses: In this case, Design 1 maintains its advantage, with lower conversion loss across most frequencies. Design 2 mirrors the simulation trends but with slightly higher measured values.


Simulation of Conversion Loss

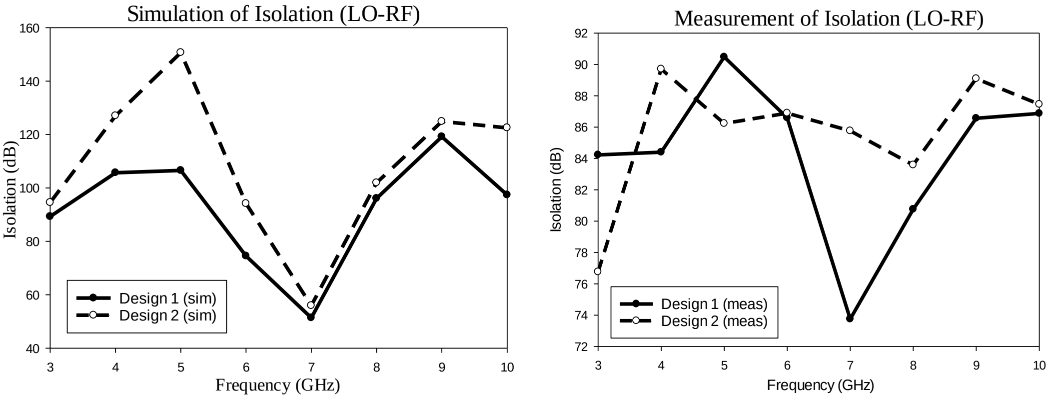
Measurement of Conversion Loss

(a)

(b)

Figure 10. Comparison Design 1 and Design 2 of conversion loss for UWB Single Balanced diode mixer, (a) simulation, (b) measurement

Figure 11 shows the isolation (LO-RF) comparison of Design 1 and Design 2. For simulation, Design 1 achieves better isolation in the middle of the band but shows a slight drop towards the upper frequencies, while Design 2 demonstrates a more stable but lower isolation throughout the range. The measured results reflect the simulation trends, though with some variations: Design 1 performs better overall in isolation, with peaks matching or exceeding 90 dB while Design 2 provides stable but relatively lower isolation values.



(a) (b)

Figure 11. Comparison Design 1 and Design 2 of isolation (LO-RF) for UWB Single Balanced diode mixer, (a) simulation, (b) measurement

Table 2 provides a comparative summary of several ultra-wideband (UWB) single balanced diode mixer designs, including the proposed designs (Design 1 and Design 2) and other designs from related research. The proposed designs, operate in the 3 to 10 GHz frequency range using Schottky diodes and are self-biased. Both require an LO level of 10 dBm and exhibit conversion losses of 16 dB (Design 1) and 19 dB (Design 2), with excellent LO-RF isolation values of >50 dB (Design 1) and >55 dB (Design 2), showcasing their high performance as compared to others. In comparison, the design in [22] uses Schottky diodes, achieving a conversion loss of 13 dB but the LO-IF isolation is just 23 dB only. Other designs, mixers with FET [20] and HEMT [23], produced high LO-RF isolation values of 44.83 dB and 38 dB, respectively. However, the LO level is higher than 10 dBm compared to Design 1 and Design 2.

Table 2. Summary and comparison between the proposed UWB Single Balanced diode mixer (Design 1 and Design 2) and other related research mixer designs using single balanced diode

Ref.	**Freq. (GHz)**	**Diode/transistor use**	**Power supply**	**LO level (dBm)**	**Conv. loss (dB)**	**LO-RF Isolation (dB)**
[16]	4 – 4.2	Schottky	Self-biased	20	> 10	Low isolation
[17]	2.31-2.34	Schottky	Self-biased	20	13	Not mention
[18]	7.8 - 12.2	Schottky	Self-biased	24.6	6.9	Not mention
[19]	92 - 102	Schottky	Not mention	10	11	42
[20]	115 - 120	FET	Not mention	13	14.4	44.83
[21]	24.25-29.5	Diode CMOS 180 nm	Not mention	16	7.9	18
[22]	2.2 - 2.6	Schottky	Not mention	7	11	23
[23]	32 - 50	HEMT	Self-biased	15	11.2	38
[24]	75-110	Schottky	Not mention	5	10	Not mention
D1	3 - 10	Schottky	Self-biased	10	16	>50
D2	3 - 10	Schottky	Self-biased	10	19	>55

One significant advantage of the proposed designs is their LO-RF isolation performance, with values exceeding 50 dB, which is significantly higher than the isolation achieved by other designs. This enhanced isolation makes the proposed mixers (Design 1 and Design 2) better than the others. However, the proposed designs have a higher conversion loss of 16 and 19 dB, as compared with other designs. For example, several designs achieved conversion losses as low as 6.9 dB and 7.9 dB, demonstrating a performance trade-off. This demonstrates that while the proposed mixers outperform in isolation, there is potential for improvement in reducing conversion loss. This design can be used in any wireless communication technology that requires RF/microwave devices, for example in [25] and [26].

Conclusion

The proposed single balanced mixer designs, utilizing compact Coupled Line and Branch Line baluns, demonstrate a good performance over a wide bandwidth for UWB applications. Operating within the 3–10 GHz frequency range, the comparison performance for the mixers showed maximum conversion losses of 16 dB (Design 1) and 19 dB (Design 2), with LO-RF isolation exceeding 50 dB and 55 dB, respectively. These findings are particularly significant for practical applications in modern wideband communication systems, such as 5G and satellite communications.

Acknowledgements

The authors would like to greatly express their thanks and appreciation to the Centre for Research and Innovation Management (CRIM) and Universiti Teknikal Malaysia Melaka (UTeM) for their help in completing this research work.

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