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Design of A Compact Single-Balanced Mixer for UWB Applications

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Abstract

The design and implementation aspects of a new single-balanced mixer for ultra-wideband (UWB) applications are presented in this study. The proposed mixer utilizes a miniaturized UWB ring coupler as a balun, consisting of a pair of in-phase and inverted-phase transitional structures. The well-balanced UWB performance of the ring coupler, aside from the optimized diode matching, results in improved conversion loss and inter-port isolations for a wide bandwidth. The size of the implemented single-balanced diode mixer is reduced to about 60% of the area of the conventional single-balanced ring diode mixer. The measured results of the proposed mixer exhibit an average conversion loss of 7.5 dB (minimum 6.7 dB) and a port-to-port isolation of greater than 18 dB over a UWB frequency range of 3.1–10.6 GHz. The measured results agree well with the simulated results.

Key Words: Planar Transitions, Ring Coupler, Schottky Diode, Single-Balanced Mixer, Ultra-Wideband.

I. INTRODUCTION

Microwave mixers perform the frequency conversion of incoming microwave signals, and their operating principle is mostly based on the nonlinear behavior of diodes or transistors. Frequency translation is commonly used in numerous modern microwave system applications ranging from radar and radio astronomy to mobile communications and biological sensing. The selection of mixer topology is based on its required performance. Transistor-based mixers are typically used in applications in which the cost is more important than the performance of the mixer. Conversely, Schottky diode-based mixers utilizing hybrid couplers as their baluns are often used for challenging and high-performance applications. For a diode-based mixer, the bandwidth limitation of the balun typically dominates the overall performance of the mixer, which inspired recent studies on the design of wideband mixer circuits based on various types of baluns [1].

Ultra-wideband (UWB) systems, which have a frequency band of 3.1–10.6 GHz, were authorized for three types of systems: imaging systems, vehicular radar systems, and communication and measurement systems [2, 3]. These systems require modules with a compact size, low cost, and low power over the UWB frequency range. A frequency mixer is one the most important components of UWB systems and is continuously facing challenges in attaining a compact size with a low conversion loss over a wide bandwidth.

Various studies have been conducted to improve the bandwidth performance of the mixers [4–10]. To construct a balanced mixer, a well-designed broadband balun with inherent isolation, cancelation of local oscillator (LO) noise, low intermodulation products, and good conversion efficiency was re-

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commended. Broadband hybrid couplers as mixer baluns were implemented with a combination of different kinds of transmission lines, such as coplanar waveguide and slot line [5], Gilbert cell [6], substrate integrated waveguide (SIW) couplers [7, 8], and multi-layer ring hybrid [9]. In [7, 8], SIW couplers were utilized to design single-balanced mixers. However, these mixers with SIW couplers exhibited high conversion losses because of high leakage related to the required vias. In [9], a low conversion loss was achieved by using a high-performing multi-layer ring coupler. However, the design and implementation of these types of balanced mixers were complicated, thus causing a high cost for fabrication.

In addition, the design of a high-performance mixer involves good impedance matching at each mixer port and requires the removal of undesired frequency products using resistive loads or reactive terminations. Resistive loads tend to increase mixer conversion loss. In [10], the authors implemented a single-balanced ring mixer utilizing a reduced-size ring coupler [11] and resistive elements for impedance matching. However, the measured conversion loss of the ring mixer in [10] was still comparatively higher. Continued efforts to achieve a low conversion loss of microwave mixers with miniaturization were the motivation of this research.

In this study, a new design method for the reduced-size single-balanced diode mixer with an UWB planar ring coupler (180° hybrid) as the balun, consisting of in-phase and inverted-phase transitions is presented. The implemented mixer comprises a miniaturized ring coupler, two low-barrier surface-mount Schottky diodes, and a matching circuit with two high-performance single-layer capacitors. Moreover, nonlinear mixer simulations and 3D EM simulations were performed to predict the performance of the mixer with reasonable agreement.

II. DESIGN OF THE UWB MIXER

The proposed single-balanced mixer is designed for down-converted UWB applications in which a flat intermediate frequency (IF) is required. This mixer can also be used for up-conversion. The conventional design methodology of a two-diode single-balanced mixer utilizing a ring coupler (180° hybrid) is adopted for this design. Instead of using a conventional ring coupler as a mixer balun, a UWB ring coupler presented by Kim et al. [11] is utilized. Fig. 1(a) shows an equivalent circuit of the single-balanced diode mixer, and Fig. 1(b) illustrates a configuration block diagram of the proposed diode mixer utilizing the UWB ring coupler. A layout structure of the proposed single-balanced diode mixer utilizing the reduced-size ring coupler as the balun is shown in Fig. 1(c).

As the overall performance of the mixer depends on the performance of the hybrid coupler and the matching network, designing a hybrid coupler with good amplitude and phase balance is one of the key design aspects. The design of the ring structure employs a pair of UWB in-phase and inverted-phase transitions as presented in [11]. That is, three in-phase and an inverted-phase planar transitions are used in the places of ¼λ and ¾λ line sections, respectively, as shown in Fig. 1(b) and (c).

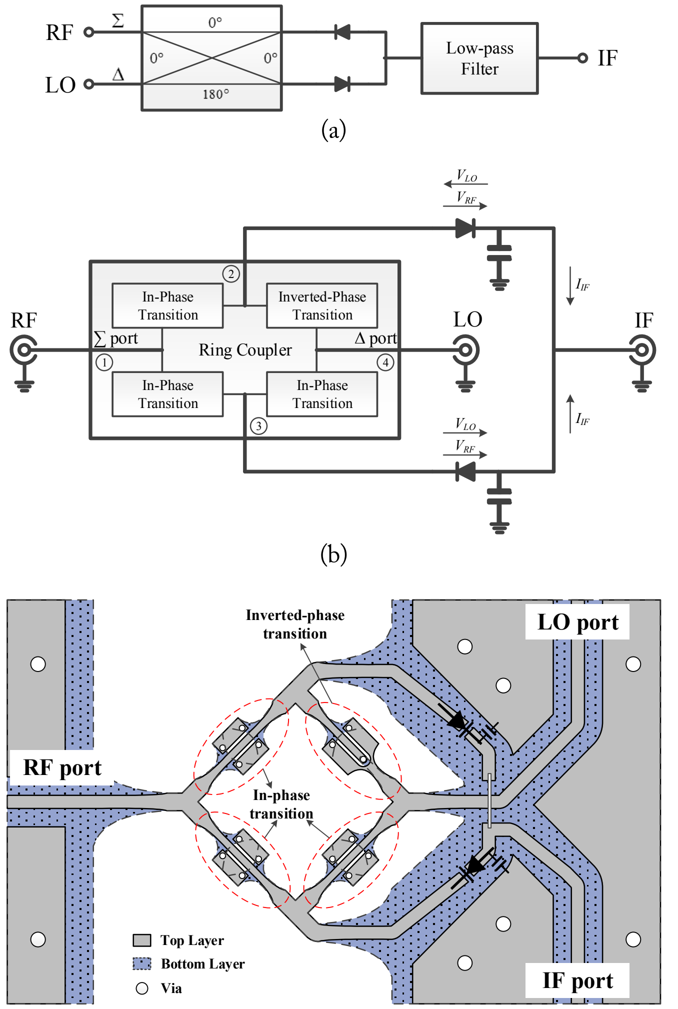

Fig. 1. UWB single-balanced diode mixer utilizing a reduced-size ring coupler. (a) Equivalent circuit, (b) configuration block diagram, and (c) layout structure.

To design in-phase and inverted-phase transitions of the ring coupler, consecutive transitions from a double-sided parallel strip line (DSPSL) to a coplanar waveguide (CPW) and then to a DSPSL are utilized, thus resulting in a good phase and amplitude balance. The top signal line of the DSPSL is transformed into the center signal conductor line of the CPW for both transitions, and the bottom ground line of the DSPSL is transformed into the side ground conductors of the CPW through two vias and tapering. The width of the conductor lines is adjusted to maintain the impedance of the structure. For in-phase transition, the identical transition is used to convert the CPW back to the DSPSL. However, the 180° phase difference is achieved by switching the signal line to the ground line for the inverted-phase transition. The signal line of the CPW is transformed into the ground conductor of the DSPSL by via, and the ground conductors of the CPW are transformed into the top signal line of the DSPSL, as shown in Fig. 1(c). An additional DSPSL to the microstrip line (MSL) transition is also introduced to place the diodes to the ring coupler and to feed the radio frequency (RF) and LO signals.

As a good conversion loss at a low LO power level is desirable along with low cost and easy mounting, a Skyworks low-barrier Schottky diodes (SMS7621-079) is utilized. Adequate port-to-port isolation of the mixer, especially RF-to-LO isolation, is achieved because of the good performance of the ring coupler. However, the RF and LO port return losses depend on the diode impedance matching in the structure. The matching circuit for each diode consists of a series stub and a single-layered 8.2 pF capacitor with a high self-resonant frequency. By using a high-performance capacitor instead of a shunt stub, the circuit size can be reduced and high-frequency leakage signals into the IF port can also be prevented.

The RF signal is fed through port 1 (Σ port), the LO signal is applied to port 4 (Δ port), the RF signals are considered to be in phase at the junctions of diodes, and the LO pump signal is applied as an inverted phase. The orientation of the diodes is reversely installed with each other, as shown in Fig. 1(b). Therefore, the junction conductance waveforms of the diodes are in phase. The mixing components are generated from time-varying conductance (or resistance) of the diodes at the difference or the sum of the high frequencies. The mixing components also contain a series of harmonic products. The time-varying conductance waveform can be considered a pulse train of

$$g(t) = G_0 + G_1\cos(\omega_p t) + G_2\cos(2\omega_p t) + G_3\cos(3\omega_p t) + \ldots.. \quad (1)$$

Therefore, the mixing components between the RF and the harmonics of ω_p can be obtained. As the RF signals and conductance waveforms are in phase at the diode junctions, the resultant IF voltages at each diode are in phase with the RF voltages. Accordingly, the IF signal is extracted at the diode node, passing through the following external low-pass filter.

III. Simulation and Measurement Results

1. Reduced-Size Ring Coupler

The top and bottom views of the fabricated reduced-size ring coupler are shown in Fig. 2. A Rogers RO4003 with a thickness of 0.2032 mm (8 mil) is used for the fabrication. The performance of the reduced-size ring coupler is optimized using CST Microwave Studio and verified with the EM simulator of AWR Microwave Office. Fig. 3 compares the simulated and measured results when the reduced-size ring coupler is excited at port 1 (Σ port). The averaged insertion loss ($|S_{21}|$ & $|S_{31}|$) is 3.5 dB, return loss ($|S_{11}|$) is 15 dB, and isolation ($|S_{41}|$) is 25 dB over a frequency range of 3–11 GHz. Fig. 4 compares the simulated and measured results of the phase differences of the in-phase and inverted-phase balun output ports. The phase difference of the in-phase outputs ($\angle S_{31} - \angle S_{21}$) is less than +2.5° and that of the inverted-phase outputs ($\angle S_{34} - \angle S_{24}$) is less than +5° over the UWB frequency range of 3.1–10.6 GHz.

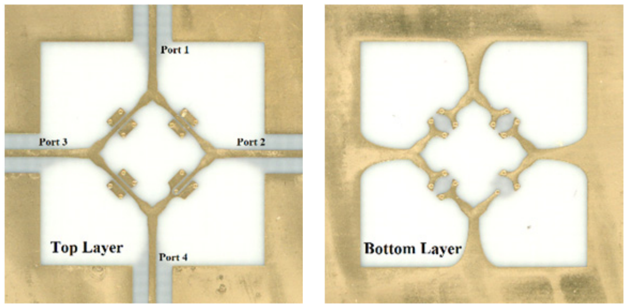

Fig. 2. Fabricated UWB modified reduced-size ring coupler.

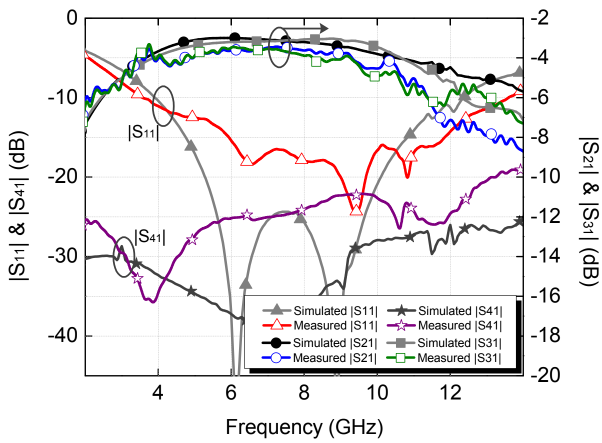

Fig. 3. Simulated and measured results of the modified ring coupler with port 1 excitation.

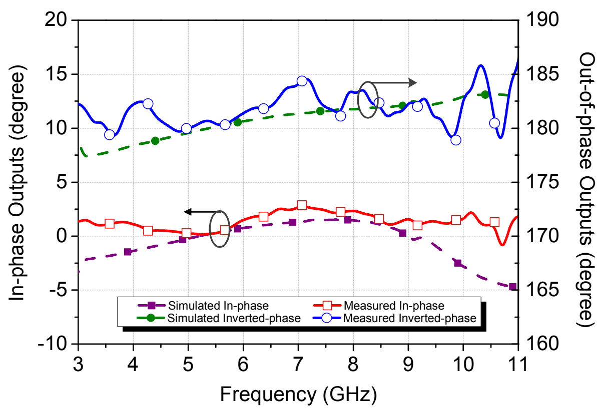

Fig. 4. Simulated and measured results of the phase differences for the in-phase and invert-phase output ports.

2. UWB Mixer

The overall performance of the proposed mixer is simulated using a nonlinear mixer simulation combined with the EM simulation. For harmonic-balanced simulations of the mixer, the Microwave Office (AWR) circuit simulator was used. Also, the CST Microwave Studio was used to perform EM simulations of the ring structure, and then the results were cross-checked with the AWR Microwave Office EM simulator. For the nonlinear circuit simulation, the SPICE model of the diode (SMS7621-079, low-barrier Schottky diodes) is utilized.

The proposed mixer is fabricated on a Rogers RO4003 substrate with a thickness of 0.2032 mm (8 mil). Fig. 5 shows the top and bottom views of the fabricated single-balanced ring mixer. The size of the fabricated mixer is 20.3 × 12.7 mm (800 × 500 mil), which is about 40% of the area of the 5.8 GHz conventional ring mixer shown in Fig. 6.

Conversion loss is one of the most important performance factors of a mixer. As sustaining a circuit balance over a wide range of frequencies is difficult, the wideband mixers are likely to have a high conversion loss, and achieving a low conversion loss is relatively challenging. Fig. 7 shows the simulated and measured conversion losses over the UWB frequency of 3.1–10.6 GHz. The proposed mixer exhibits a relatively flat conversion loss of about 7.5 dB over this wide frequency range. The conversion loss is measured at an IF frequency of 100 MHz by varying the RF and the LO frequencies from 2 to 12 GHz. Moreover, a conversion loss of about 7.5 dB is achieved for the IF frequency range of DC to 400 MHz, which is measured by fixing the RF frequency and sweeping the LO frequency, and vice versa.

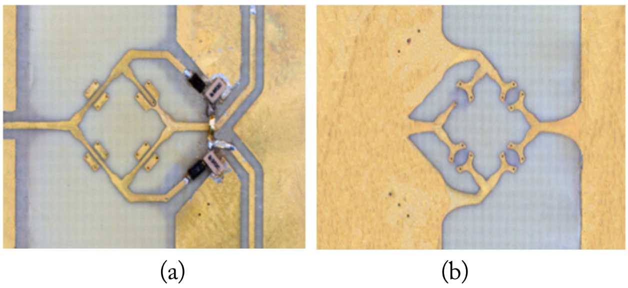

Fig. 5. Fabricated single-balanced mixer with 8 mil RO4003 substrate: (a) top view and (b) bottom view. The dimension is 800 × 500 mil.

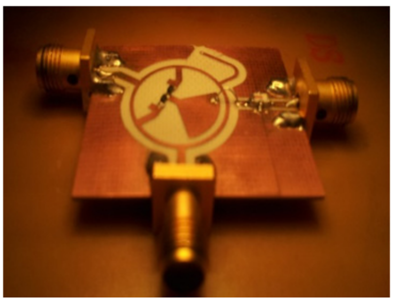
Fig. 6. Fabricated 5.8 GHz conventional ring mixer. The dimension is 1,770 × 1,575 mil.

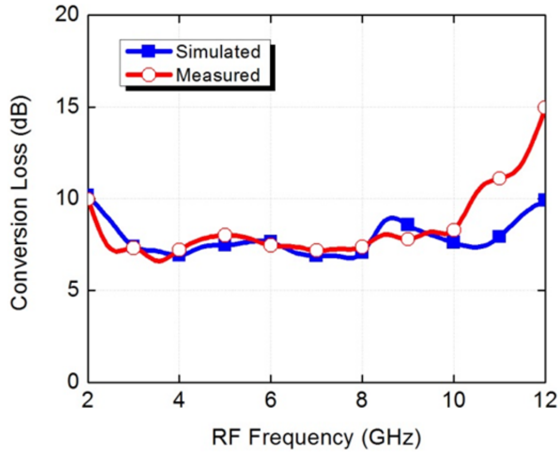

Fig. 7. Simulated and measured conversion loss.

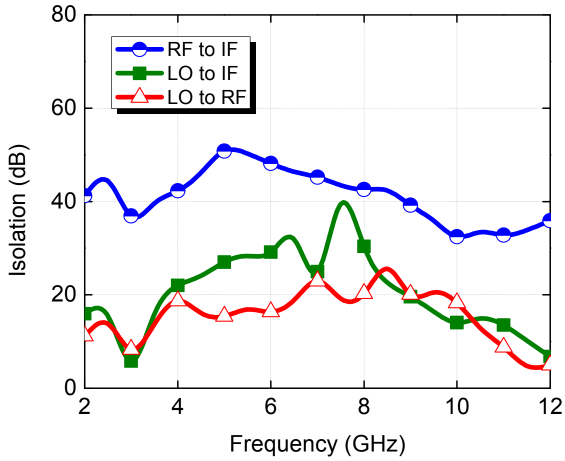

Fig. 8. Measured results of port-to-port isolation.

With an ideal balun, a complete LO signal isolation can be achieved at the RF port. However, in practice, some amount of power leaks from one port to another port of the mixer because of imperfect balun fabrication, imbalance in the properties and placement of diodes and components, and impedance mismatch of diodes.

In the proposed mixer implementation, by adopting a proper design of the ring coupler and matching circuit, the port-to-port isolation of the proposed mixer is greater than 18 dB at 3.1–10.6 GHz, as shown in Fig. 8. At the IF port, an external low-pass filter is used, and more than 20 dB port-to-port isolations from RF-to-IF and LO-to-IF are obtained. In Fig. 9, a comparison of the simulated and measured 1 dB compression points (P1dB) of the proposed mixer is shown. The measured input P1dB is +6 dBm.

Table 1 summarizes the performance of the proposed mixer compared with those of some recently reported mixers. The

Table 1. Performance comparison of single-balanced mixers

	Proposed mixer	[7]	[8]	[9]	[10]
Frequency range (GHz)	3.1–10.6	8.5–12	20–26	7–13	3–12
Bandwidth (%)	109.5	34.15	26.08	60	120
Size (mm)	20.3 × 12.7	95 × 45	70 × (NA)	NA	25.4 × 25.4
Conversion loss (dB)	6.7–8.2	6.8–10	10	5.4–6.9	8.1–9.3
LO-RF isolation (dB)	>18	NA	20	>20	>20
LO power (dBm)	8	8	13	9	8
Topology	Ring coupler	SIW coupler	Ring coupler	Ring coupler	Ring coupler

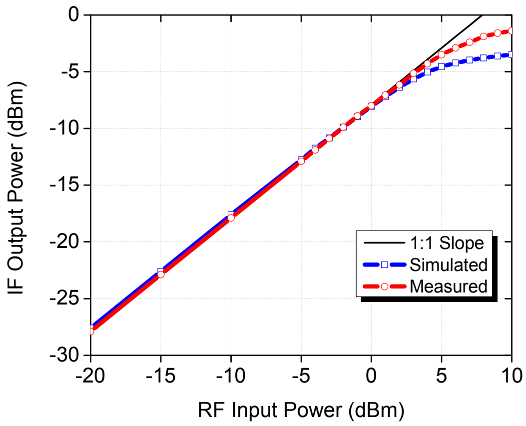

Fig. 9. Simulated and measured 1 dB compression point.

proposed mixer clearly exhibits better overall performance than the previously published mixers [7–10], especially in term of conversion loss, size reduction, and bandwidth performance.

IV. Conclusion

The design and implementation methods of a new single-balanced mixer with UWB have been presented. The mixer utilizes a compact ring coupler consisting of in-phase and inverted-phase transitions, which provide a well-balanced UWB performance. The size of the proposed mixer is reduced to about 60% of the area, which is 800 × 500 mil (20.3 × 12.7 mm), unlike conventional ring mixers. The proposed mixer exhibits a flat conversion loss (average 7.5 dB, minimum 6.7 dB) and good inter-port isolations of more than 18 dB over a frequency range of 3.1–10.6 GHz with an IF frequency range of DC to 400 MHz.

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