A Triple Balanced Mixer in Multi-layer Liquid Crystalline Polymer (LCP) Substrate

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Abstract

The LCP-based technology provides high-Q embedded passive components that increase system performance such as insertion loss, phase noise, and noise figure. This paper presents the design of an integrated triple-balanced mixer on a multi-layer LCP-based substrate for a CDMA receiver. The designed mixer has 20 embedded passives, integrated in multi-layer LCP substrate. The mixer has the RF frequency of 1400 MHz and the LO frequency of 700MHz, resulting the 700 MHz IF bandwidth. The three-dimensional (3D) integration of 20 embedded passives reduced the size of the triple-balanced mixer to 7.9 mm x 7.13 mm x 2.1 mm for low frequency applications.

I. Introduction

High performance, low cost, and compact size are the common goal of modern hand-held communication systems. The entire RF front-end can be integrated in a package substrate that supports multiple layers and high-quality factor (Q) for RF-front end [1]. The substrate should be low loss, low water absorption, and low-cost material. In addition to the high performance substrate, high-Q embedded passive components also play a critical role in the system integration. One of emerging substrate candidates is the LCP whose process is low cost due to its compatibility with printed wired board (PWB) process. Furthermore, it provides key advantages of low loss and low water absorption, which are common requirements for the RF front-end applications [2-3].

As the demands for multimedia and ubiquitous communication service rapidly increase, combined with drives towards the reduction in size and cost, the integration of the RF front-end have been researched. Most of these researches focused on circuits around 2 GHz and higher. A highly integrated front-end module can be achieved with a combination of the superior material characteristics of LCP substrate and the embedded passive technology. In general, the front-end module consists of antennas, filters, a low-noise amplifier (LNA), mixers, and voltage-controlled oscillators (VCOs), as shown Figure 1 [4]. The mixer is a circuit that converts RF frequency into low intermediate frequency (IF) with an input of a local oscillator (LO). The IF stage, which more evenly distributes gains over the system, relaxes a filter requirement and can isolate a baseband section from a RF section.

Figure 2 shows an entire CDMA receiver, 130mm x 45mm. It has the RF front-end section with surface-mounted devices (SMD), 45 mm x 45 mm, which can be reduced to a compact front-end, 30 mm x 30 mm, using the multi-layer LCP substrate. The LCP substrate provide high-Q passive components for

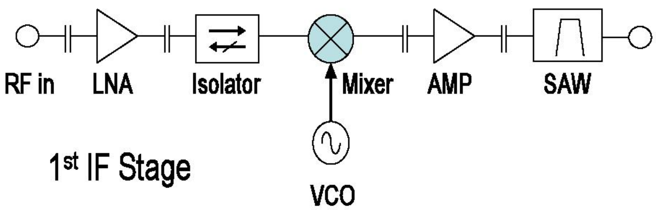


Figure 1. The RF font-end

capacitors, inductors, and matching networks with a small form factor by utilizing vertical 3D integrations [5]. This paper focuses the first down-conversion mixer, as shown in Figure 1. The target performance is as follows: the isolation characteristic of better than 20 dB between ports, and less than 10 dB conversion losses (CL). The mixer is designed as a triple-balanced configuration, as shown in Figure 3 [6], which consists of dual RF and LO baluns with a single IF balun. All five baluns are lumped-element baluns integrated into the multi-layer LCP substrate as 20 embedded passive components. Two diode quads are used for the triple-balanced mixer. This design provides the followings: a) high performance by high-Q embedded passives using the low-loss LCP substrate; b) a compact size using the multiple LCP layers; and c) a cost reduction because of a large-panel process.

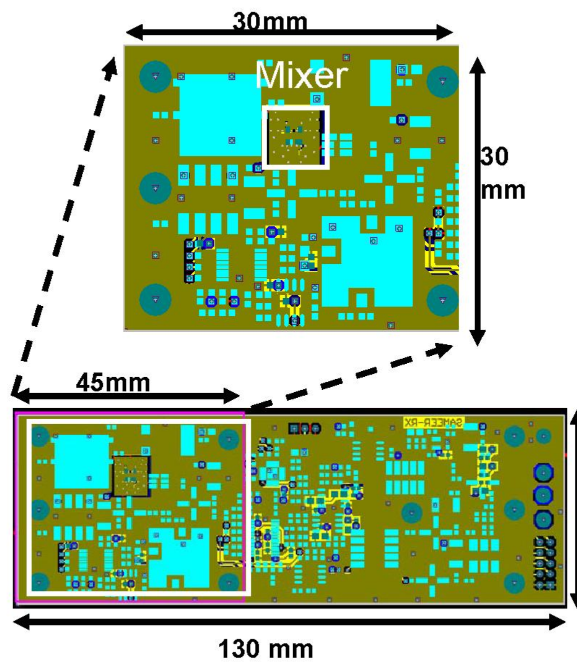


Figure 2. The layout of the CDMA receiver with SMDs, compared with a compact RF front-end module

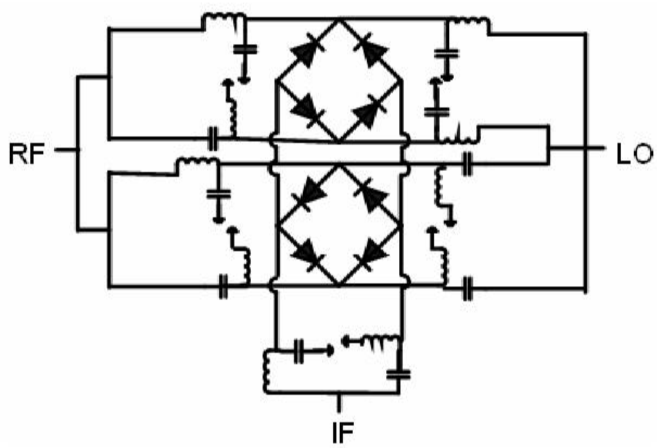


Figure 3. The schematic of a triple-balanced mixer

The paper is organized as follows: Section II describes the embedded passive technology using the multi-layer LCP process and Section III covers the integrated baluns, while Section IV explains the triple-balanced mixer and its measurement results. Finally, Section V provides conclusions.

II. High Q Embedded Passive on multi-layer LCP substrate

The size reduction of RF modules can be achieved by using embedded-passive technology. This technology with a low loss multi-layer substrate shows the promising results for new system platform, system on package (SOP) [7]. The conceptual drawing of the SOP is shown in Figure 4. The new platform utilizes a package substrate to integrate the functionalities of a system, resulting in low cost, small form factor, and high performance system solution. The implementation of high-Q passive components such as inductors, capacitors, and resistors embedded in the packaging substrate, allows designers to achieve completely integrated wireless systems [7]. A multi-layer capability and a low loss characteristic are the major advantages of the LCP for the SOP. In addition, multi-layer substrates with high-density interconnects are also critical in meeting size targets.

The embedded-passive technology plays a crucial role in the SOP platform because the passive components often occupy more than 80% of the real estate in the board, while the assembly cost accounts for around 70% of a product assembly cost [8]. The embedded-passive technology makes an overall board size smaller, leading to the higher throughput. It also helps improve the electrical performance because it eliminates soldering, which in turn improves system reliability while achieving a cost reduction and a fast time to market by removing surface-mounted devices (SMDs). Such advantages as lower cost, compactness, reliability, and higher performance make the embedded passive technology a suitable package solution for the systems as well as a key technology for the higher integration. Accordingly, the need for an extended supply of high-frequency packaging materials with high performance has become critical. Teflon and ceramic-based materials have been commonly used as high-frequency applications for many years [9].

LCP can have a single, a double, and a triple LCP configuration as a multi-layer stack-up. The double-balanced LCP stack-up, very suitable for a strip-line configuration that is excellent for electromagnetic shielding, is shown in Figure 5. The stack-up includes three diclad LCP layers that are bonded together by a lower melt adhesive. The diclad layers consist of half ounce copper and one 25 um thick LCP. The LCP dielectric layer has a dielectric constant of 2.95 and a loss tangent of 0.002. In Figure 5, the cross-section shows a eight- metal-layer design where the bottom metal layer is used as a microstrip ground reference. The top metal layer of the cross-section is used for surface-mounted diode quads and for the incorporation of high Q (>100) inductors. The ability to form micro-vias in the stack up is essential for increased component density as well as for increased routing density. For such application micro-vias can be fabricated in the LCP layers to increase component density. The micro-vias are formed by using an ultra violet (UV) source. Via diameters of < 100um are formed in the LCP layers with extremely high yield and robustness. The LCP process is in fact capable of stacking up to twelve LCP diclad layers which in effect can provide very high component densities of Ls and Cs per unit area. The characterization of high-Q inductors and 3D capacitors can be shown in [2]. The reported high-Q components will directly affect the performance of RF circuits such as the insertion loss of filter, the phase noise of VCO [10], and the noise figure of LNA [11].

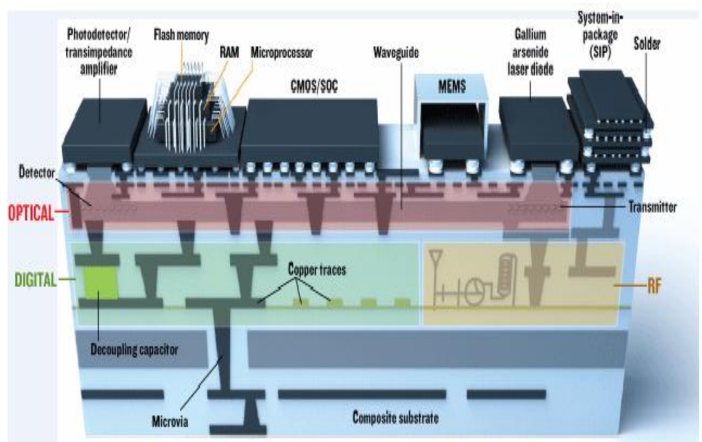


Figure 4. The conceptual drawing of the SOP [6]

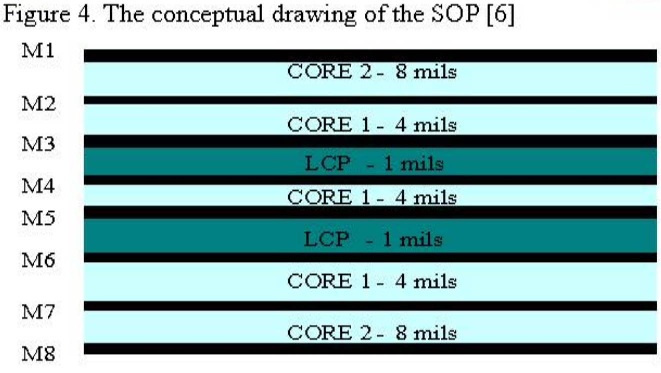
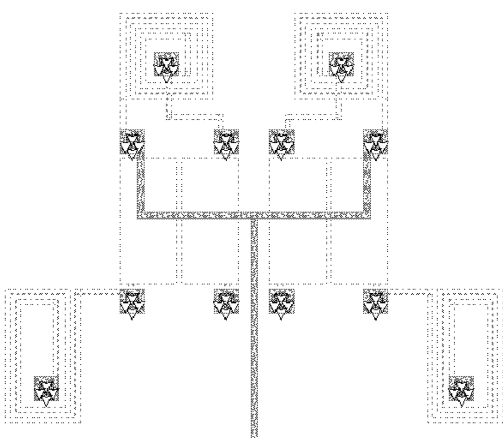


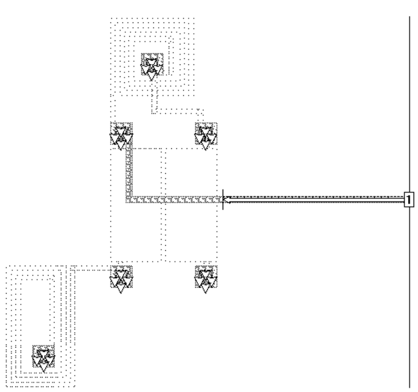
Figure 5. The cross-section of the multi-layer LCP substrate

III. Design of Embedded baluns (RF, LO, and IF)

The lumped balun composed of two PI networks resulting in a power splitting with 180 phase difference. RF and LO baluns in the designed mixer consist of two integrated lumped baluns, as Figure 6 (a) shows. The RF and LO baluns, which consist of two lumped baluns, were initially simulated by the circuit simulator, agilent advanced design system (ADS), with ideal components. Then, the designed baluns were simulated by a EM solver, SONNET [12]. The simulator can not solve the entire RF or LO balun because of the electrically large size of the dual balun with a 3 mil minimum line width. This memory issue was solved by using the segmented simulation method, provided in the solver, as shown in Figure 6 (b). Once all three simulations, including the simulation of the left half, the right half, and the feed line, the overall S parameter responses, which are shown as the line with the circles in Figure 7, were constructed. Figure 7 (a) and (b) show the measured results, solid lines, with the simulation results of the LO and the IF baluns, respectively. In addition, the results are summarized in the table 1 and 2. For the LO balun, the amplitude imbalance of 1 dB was achieved from 780 to 900 MHz. Although IF balun has high S11, it achieved the good amplitude and phase imbalance, and it has -4.23 dB of S21 and -4.22 dB of S31. However, the high S11 caused the higher insertion loss.

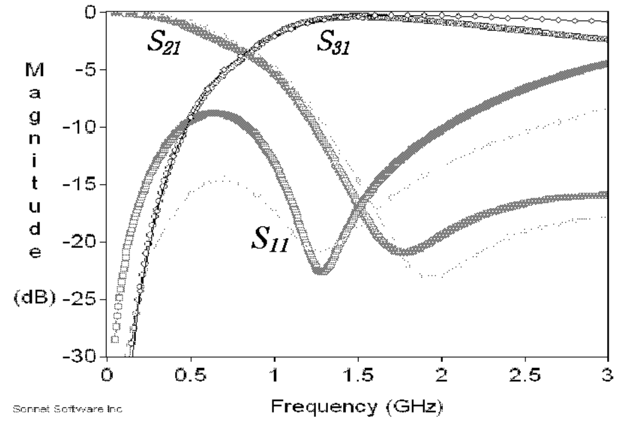


(a) The layout of the LO balun

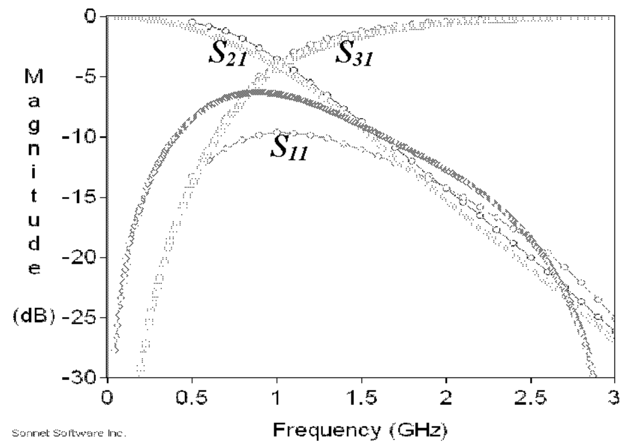


(b) A set up for the segmented simulation

Figure 6. The lumped balun (LO) and segmented simulation



(a) The S parameters of the LO balun



(b) The S parameters of the IF balun

Figure 7. The measured results of the embedded baluns with the simulation results

Table 1. The performance of the LO Balun

Frequency (MHz)	840 (LO)
S11 (dB)	-10.1
S21 (dB)	-3.64
S31 (dB)	-3.74
Amplitude Imbalance (dB)	0.21
Phase Imbalance (°)	9.2

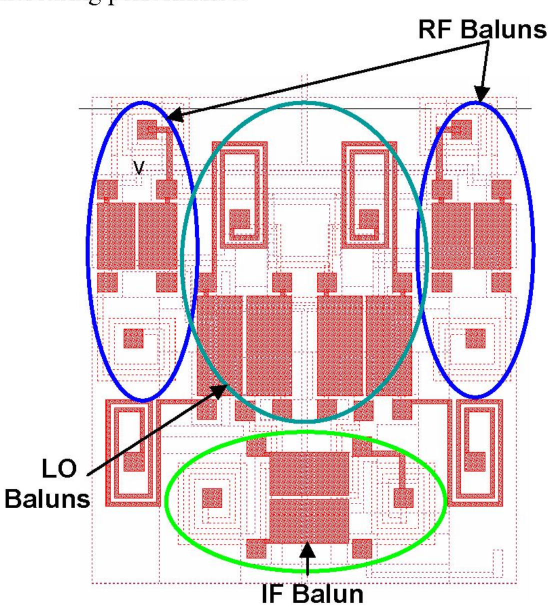
Table 2. The performance of the IF Balun

Frequency (MHz)	1000 (IF)
S11 (dB)	-6.44
S21 (dB)	-4.23
S31 (dB)	-4.22
Amplitude Imbalance (dB)	0.1dB
Phase Imbalance (°)	0.2

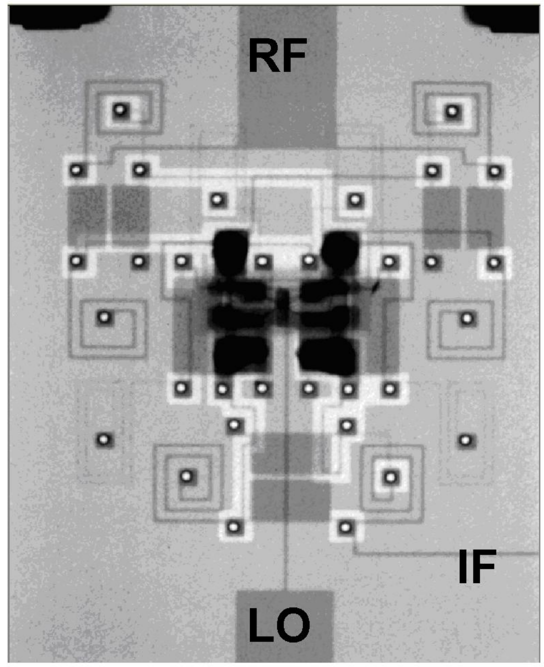
IV. The Design of the Triple-Balanced Mixer

The designed individual baluns, the RF, the LO, and the IF, was combined with two quad diode packages for the triple-balanced mixer in the multi-layer LCP substrate. The topology was chosen because it has a good port-to-port isolation characteristic, a superior linearity, and better even-mode suppression over a single- balanced mixer. The good isolation between the ports results from an inherent isolation by separate baluns. The mixer consists of the two double-balanced mixers, shown in Figure 3. Three separate baluns and eight diodes improve isolations between the ports and linearity because an input signal is handled by a twice as many diodes [13]. The mixer also be able to keep this high isolation even if the RF and the IF bandwidths overlap with each other [14]. The one of the main disadvantages is an increased complexity because it has eight diodes and three baluns. This will be extremely challenging particularly in the low frequency range around 1.5GHz or lower. Another disadvantage of this type of mixer is the increase in an LO power by 3 dB.

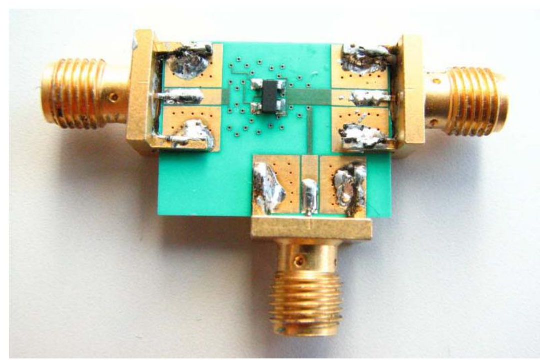
Figure 8 (a) shows the layout of the triple-balanced mixer. The previously designed lumped balun using embedded passives has been used. As described in Section I, the RF and the LO balun had dual baluns, while IF balun was realized using a single balun. Agilent Two HSMS-2829 silicon Schottky quad diodes were surface-mounted to both the top layer and the bottom ground layer. In addition, they are directly connected to the embedded baluns by thru-hole vias. Figure 8(b) shows the X-ray picture of the designed mixer. In this picture, all 20 embedded inductors and capacitors can be seen, and a good layer-to-layer registration is also observed. Figures 8 (c) and (d) show the photograph of the fabricated mixer. The size of the mixer is 7.9 mm x 7.13 mm x 2.1 mm. Given the size of the diode quad, 2.35 mm x 2.9 mm, the embedded passive technology with the multi-layer LCP substrate played a key role in reducing size and increasing performance.



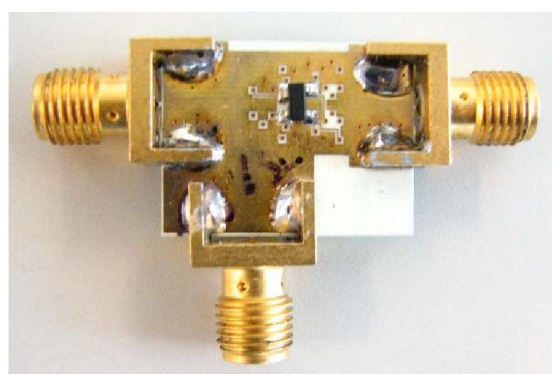
(a) The layout of the designed mixer



(b) The X-ray picture of the designed mixer



(c) The photograph of the designed mixer: top

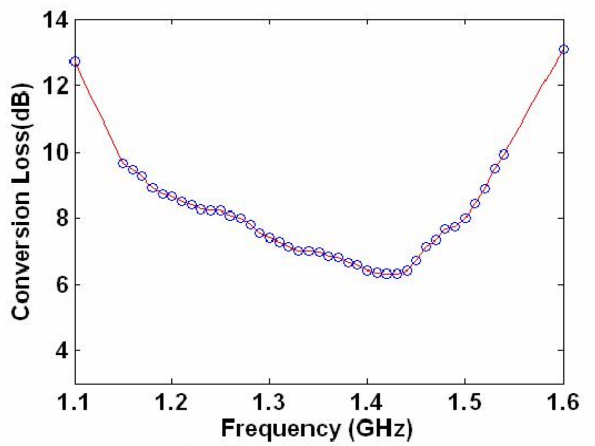


(d) The photograph of the designed mixer: bottom

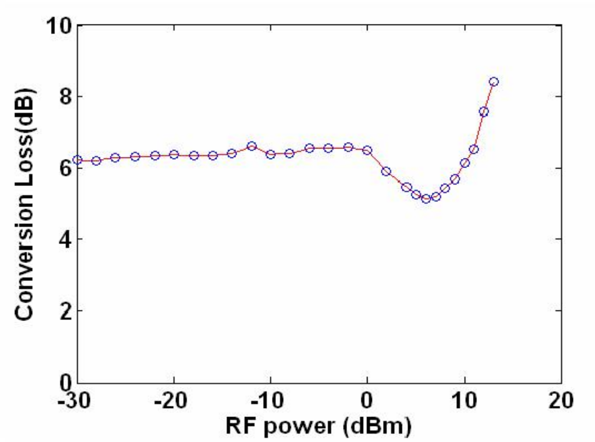
Figure 8. The designed triple-balanced mixer

The measured performance of the mixer is shown in Figure 9. The measurement set-up was as follow: Two separate signal generators fed the RF and the LO signal into the mixer, while the spectrum analyzer, which displayed the output power in dBm, is connected to the IF port. Therefore, the difference between the RF and the LO signal power is a conversion loss (CL). Figure 9 (a) shows the CL with 700MHz of IF. The CL of 6.3 dB to 8 dB was achieved from 1260 MHz to 1490 MHz with the RF power of 30 dBm.

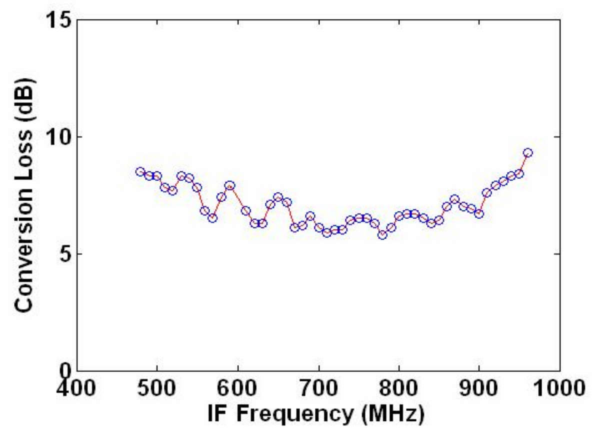
Figure 9 (b) shows the conversion loss with respect to a RF input power at 1430MHz with 13dBm of the LO power. The CL was approximately 6 dB, and input P1dB was 11 dBm. Figure 9 (d) shows the CL with respect to the IF bandwidth. From 600 to 920 MHz, less than 7 dB of the CL was achieved, and less than 9 dB of the CL was achieved from 480 to 960MHz. Figure 9 (d) shows the isolation from the RF to the LO and from the LO to the IF. The former is from 20 to 35 dB, and the latter is 20 to 46.8 dB. As mentioned in Section 1, the designed triple-balanced mixer was able to meet the target specification, at least 20 dB isolation when the RF and IF overlap with each other. From the LO to the RF, more than 24 dB isolation was achieved from 760 to 1900 MHz and more than 30 dB isolation from the LO to the IF was achieved from 480 to 1000 MHz. These high isolations are mainly from the baluns at each port.



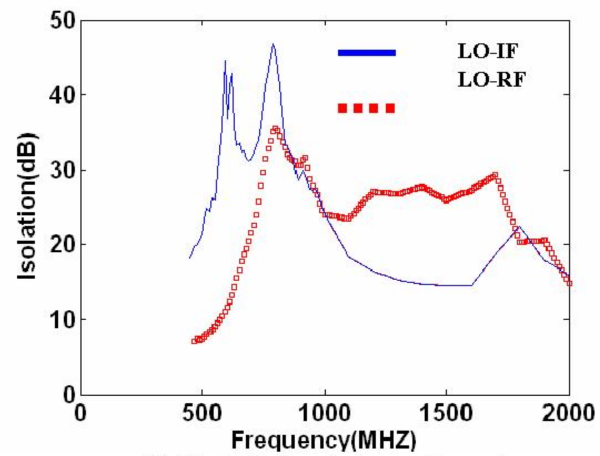
(a) CL vs RF frequency



(b) CL vs RF power



(c) CL vs IF freqeuncy



(d) The isolations between the ports

Figure 9. The performance of the designed triple-balanced mixer

V. Conclusion

The embedded passive technology combined with the balanced-LCP substrate has been used to implement the compact triple-balanced mixer. The mixer is the part of the entire CDMA receiver board, 130mm x 45mm, and it replaces the SMD mixer. First, the LO and the IF dual baluns were designed, and they showed good magnitude and phase imbalances. For the EM simulation, the segmented simulations were performed and the combined S parameters were constructed. With a carefully consideration for the couplings between components, the mixer was designed. Individual EM simulation results with a diode model were used for the circuit simulation.

The mixer with five baluns and two diode quads was measured as 7.9 mm x 7.13 mm x 2.1 mm and it was able to keep its conversion loss below 7 dB for IF bandwidth from 600 to 920 MHz with 13 dB of LO power. It also has shown good isolations between the ports. This results show that the size reduction of the system can be achieved by the high-Q embedded passive components in the multi-layer LCP substrate without severe performance degradations. Further size reduction of the receiver can be achieved with the integration of the entire RF front-end.

Acknowledgment

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