A High IIP2 Direct-Conversion Mixer using an Even-Harmonic Reduction Technique for Cellular CDMA/PCS/GPS applications

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Abstract — **An even-harmonic reduction technique to enhance IIP2 performance in direct conversion mixer is proposed based on a simplified analysis of second-order intermodulation. Using the proposed technique, IIP2 performance can be improved while reducing sensitivity to operating condition and output load mismatch. Direct conversion mixers for Cellular CDMA, PCS, and GPS applications are designed and fabricated in 0.35um SiGe BiCMOS process. Measurement results show 40dB improvement and reduced sensitivity of IIP2, which are consistent with simulation results.**

Index Terms — **Intermodulation distortion, harmonic analysis, mixers, receivers, BiCMOS analog integrated circuits.**

I. Introduction

Increasing demand for smaller and cheaper multi-band/multi-mode mobile handsets has motivated the development of a direct conversion receiver which eliminates the need for external IF SAW filters and an IF local oscillator source. However, several challenging issues appear in a direct conversion receiver compared to a heterodyne receiver [1], [2]. One of the most important design issues is a second-order intermodulation around DC, which gets removed by channel selection IF SAW filters in the heterodyne architecture.

The most dominant source of second-order intermodulation in a direct conversion receiver is the down-conversion mixer [3]. Conventionally low noise amplifier (LNA) has a dc-decoupling structure for output matching. Base-band filters and variable gain amplifiers (VGA) have local feedbacks to reduce distortion. Both dc-decoupling structure and the feedback circuitry reduce the second order intermodulation.

Generally a double-balanced Gilbert-cell type mixer with active transconductance is used for a down-converter in a direct conversion receiver. In a *perfectly* balanced case, the even-order distortion caused by device nonlinearity would not appear in the signal path. In a practical situation where load mismatch and LO switching pair asymmetry exist, the even-order intermodulation appears in the signal path.

The second-order intermodulation (IM2) in a balanced mixer signal is composed of two parts; differential-mode and common-mode products. The former is mainly generated by the LO switching pair asymmetry. The latter is mostly generated by non-linearity of active transconductance stages and output loads mismatch due to the physical limitation of asymmetry and processing tolerances of fabrication technology [4].

Many techniques to improve IIP2 performance has been investigated such as careful layout, reducing the nonlinearity of active transconductance by emitter degeneration or harmonic termination, trimming or intentionally giving some mismatches to the LO switching pair and the output load [4], [5]. However, IIP2 performance of mixers using above techniques is reported to be sensitive to load mismatch and operating conditions such as supply voltage, temperature, fabricated location and etc.

In this paper, a direct conversion mixer IIP2-enhancing technique using even-harmonic reduction loops is introduced based on a simplified analysis of second-order intermodulation. This technique improves IIP2 performance while reducing its sensitivity to operating condition and load mismatch. To verify the proposed technique, direct conversion mixers for Cellular CDMA, PCS, and GPS applications have been designed and fabricated. The measurement results show 40dB improvement and reduced sensitivity.

II. The Concepts and Simple Analysis Of Second-order Intermodulation

In double-balanced mixer structure, the output second order intermodulations at single-ended outputs are derived as follows;

$$\begin{aligned} V_{IM2.out\_single+} &= (I_{IM2.c} + I_{IM2.d}/2)\cdot(R + \Delta R/2) \\ V_{IM2.out\_single-} &= (I_{IM2.c} - I_{IM2.d}/2)\cdot(R - \Delta R/2) \end{aligned} \quad (1)$$

where $I_{IM2.c}$ and $I_{IM2.d}$ are common and differential output second-order intermodulations, respectively, and R and Δ R are output load resistor and mismatch of output load, respectively. Assuming that $I_{IM2.c} >> I_{IM2.d}$ and R >>

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Δ R, the second-order intermodulations at differential outputs and single-ended outputs are easily simplified as

$$V_{IM2.out\_diff} = I_{IM2.c} \cdot \Delta R + I_{IM2.d} \cdot R$$
$$V_{IM2.out\_single} \approx I_{IM2.c} \cdot R \quad (2)$$

As shown in (2), the output intermodulations at differential output mainly depends on both asymmetries and nonlinearities, while that at single-ended output only does on nonlinearities. Thus second-order intermodulation at single-ended output ($V_{IM2.out\_single}$) can be predictable by calculation and simulation.

III. Proposed IIP2-enhancing technique using even-harmonic reduction loop

In order to diminish the common-mode portion in (2), the proposed method is to reduce $I_{IM2.c}$ using active even-harmonic reduction feedback loop. $I_{IM2.c}$ can be reduced without deteriorating fundamental output using even-harmonic reduction loop. The proposed even-harmonic reduction loop makes the opposite current of $I_{IM2.c}$ after sensing it using active feedback loop.

Using proposed method, (2) is calculated as

$$V_{IM2.out\_diff} = I_{IM2.c}/T \cdot \Delta R + I_{IM2.d} \cdot R$$
$$V_{IM2.out\_single} = I_{IM2.c}/T \cdot R + I_{IM2.d}/2 \cdot R \quad (3)$$

where T is the feedback loop gain of even harmonics. Assuming the loop gain is very large, the equation is simplified as

$$V_{IM2.out\_diff} \approx I_{IM2.d} \cdot R$$
$$V_{IM2.out\_single} \approx I_{IM2.d}/2 \cdot R \quad (4)$$

As shown in the above, the second-order intermodulation products in the mixer with proposed active even-harmonic reduction loop is estimated to be mainly determined by the differential mode IM2 which is caused by the asymmetry of the LO switching pair not by the non-linearity of active transconductance stages and the output loads mismatch. However IIP2 is affected a little by asymmetries in a practical case because the loop gain cannot be maximized due to stability problem and limiting gain bandwidth (GBW).

IV. Circuit Design

A. Block Diagram

The block diagram of the implemented direct-conversion mixers is shown in Fig. 1. This chip consists of three bands of mixer core, common output folding stage, output load and IM2 cancellation stage using the proposed even-harmonic reduction technique, and LO distribution circuits. As shown in the Fig. 1, three bands of mixer core share the common output folding stage and the following stages to save the die area because they are not operating simultaneously.

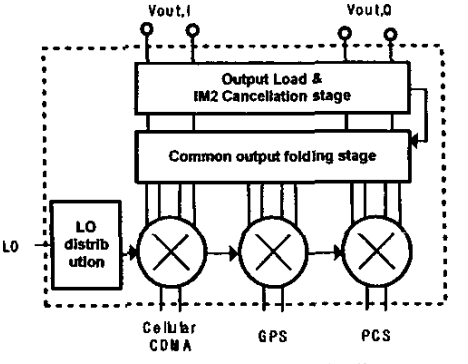

Fig. 1. Block diagram of implemented direct-conversion mixers for Cellular CDMA/PCS/GPS applications.

B. Mixer Topology

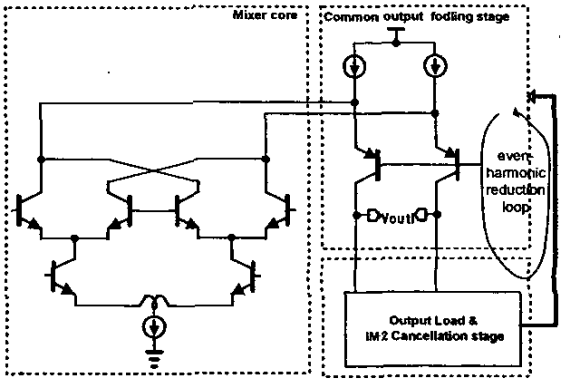

Fig. 2. Simplified folded mixer schematic with IM2 cancellation stage using even-harmonic reduction technique for I-channel of one band.

Simplified folded mixer schematic for I-channel of one band is shown in Fig. 2. The mixer core has the double-balanced structure with active transconductance including inductor degeneration. The common output stage has the current folding structure to guarantee voltage headroom in low supply voltage. The output loads & IM2 cancellation stage has resistive output load and even-harmonic reduction loop to enhance IIP2 performance.

C. LO distribution

LO distribution circuits are designed to make performances insensitive to LO power. LO distribution block consists of divider-by-2 circuit for Cellular CDMA mixer, poly-phase-filter and limiter for PCS mixer, and internal VCO for GPS mixer.

V. Measured Results

A microphotograph of the direct-conversion mixer for Cellular CDMA, PCS, and GPS applications is shown in Fig. 3. The chip was fabricated in ST-Microelectronics' 0.35um BiCMOS process and occupies 2.3mm × 1.9mm die area. This chip is packaged in a 6mm × 6mm MLF 36-pin chip-scale package.

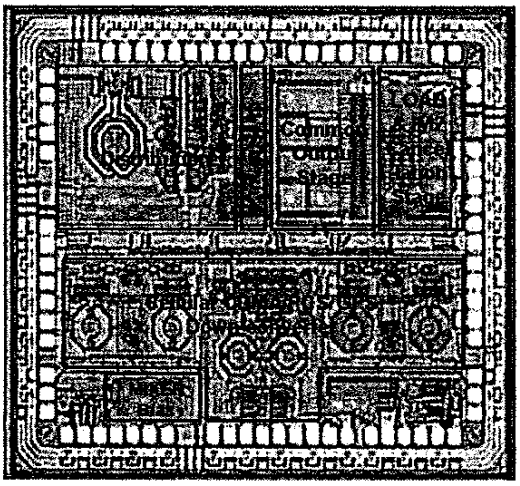

Fig. 3. Chip microphotograph.

This prototype is appropriate to prove the proposed technique of second order inter-modulation. For even-harmonic reduction the feedback loop gain has about 40dB, which is limited by stability problem.

The comparison between simulated IP2 and measured IP2 is given in Table I. It shows that the proposed technique improves the IIP2 performance by an amount of loop gain compared to the simple analysis without even-harmonic reduction technique and measured IIP2 with the proposed technique is similar to simulated one.

Fig. 4 shows the variation in IIP2 along the down-conversion channel once the mixer has been trimmed. It can be seen that the IIP2 decreases as the down-conversion channel goes up to 5MHz, but it is almost flat within the down-conversion channel bandwidth of 630kHz.

Fig. 5 shows the measured sensitivity of improved IIP2 as a function of the controlled imbalance in the mixer output load resistor. It can be seen that the IIP2 of Cellular CDMA band is around 80dBm and the variation is small. It also shows that the IIP2 variation of PCS band is larger than that of Cellular CDMA band because the LO distribution of PCS band is much more complex. The measured sensitivities of IIP2 in Fig. 4 and Fig. 5 show that is IIP2 is insensitive to operating condition and mismatch due to proposed IIP2-enhancing technique.

TABLE I
IIP2 Comparison Between Simulation and Measurement

	Cellular CDMA	PCS
Simulated IIP2 without even-harmonic reduction	43 dBm	43 dBm
Simulated IIP2 with even-harmonic reduction	82.1 dBm	79 dBm
Measured IIP2 with even-harmonic reduction	81 dBm	79.8 dBm

Although the output stage of three bands of mixer is shared in this design, the mixer core of each bands are designed and optimized independently because the linearity and noise requirement of each bands (Cellular CDMA, PCS, and GPS) are different. The measured results of direct conversion mixers are shown in Table II.

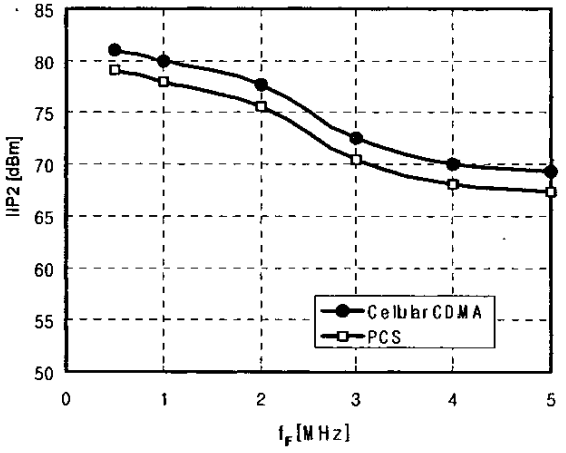

Fig. 4 Measured sensitivity of IIP2 performance as a function of output frequency.

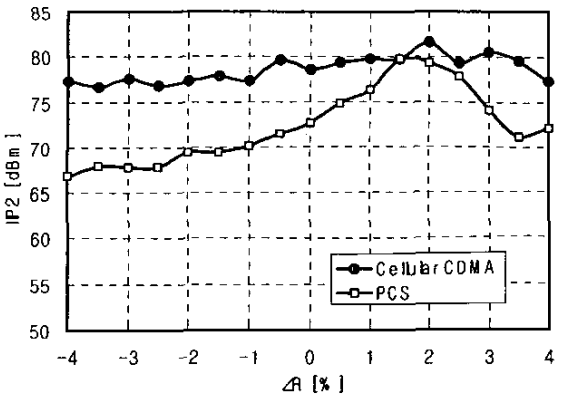

Fig. 5 Measured sensitivity of IIP2 performance as a function of output load mismatch

TABLE II
MEASURED PERFORMANCE OF DIRECT CONVERSION MIXERS

	Cellular CDMA	PCS	GPS
Voltage Gain	20.2 dB	18.3 dB	45.7 dB
NF(DSB)	7.27 dB	8.8 dB	1.6 dB
IIP3	10 dBm	10.3 dBm	-30 dBm
IIP2	81 dBm	79.8 dBm	26 dBm
LO-to-RF isolation	-97,2 dBm	-87.2 dBm	-107dBm
Current consumption	32 mA	32 mA	24 mA
Supply voltage	2.7 V	2.7 V	2.7 V

VII. CONCLUSION

This paper presents an even-harmonic reduction technique to enhance IIP2 performance in direct conversion mixer is proposed based on simplified analysis of second-order intermodulation. Thanks to this technique, IIP2 performance can be improved while reducing sensitivity to operating condition and output load mismatch. Multi-band/multi-mode direct conversion mixers for Cellular CDMA, PCS, and GPS applications are implemented in 0.35um SiGe BiCMOS process. Measured results show 40dB improvement and reduced sensitivity of IIP2, which are consistent with simulation results.

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