A feedforward linearization technique implemented in IF band for active down-conversion mixers

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***Abstract*— A feedforward linearization technique to cancel the third-order intermodulation (IM_3) of the down-conversion mixers is proposed, in which a low-frequency second-order intermodulation tone (IM_2) is created and multiplied by the mixer's output to generate the IM_3 tones for the cancellation. The proposed linearization technique is applied to an active mixer operating at 2 GHz. Fabricated in a 0.13-μm CMOS process and operated at 1.2 V supply, the mixer with a unit-gain IF amplifier in series delivers 8.5 dB gain and 2.5 dBm IIP_3 without linearization. The linearization technique achieves 12-dB IIP3 improvement with negligible gain reduction, less than 0.2 dB of noise penalty and an extra current of 4.2 mA.**

***Index Terms*— High linearity, linearization, feedforward, IIP_3, IM_3 cancellation, mixer, RF front-end**

I. INTRODUCTION

High linearity is an important characteristic for down-conversion mixers, as it prevents the incoming signals from being corrupted by large intermodulations from much larger surrounding in/out-of-band blockers.

Many mixer linearization techniques have been developed in the past. IM_2 injection technique inserts an IM_2 tone into the current source of the differential pair to suppress the IM_3 with little extra power consumption and noise figure (NF) degradation [1], [2]. However, it can only be used in mixers with the transconductor realized by the differential pair with a current source. Another method, derivative superposition (DS), can be used to linearize the mixers with the transconductance stage made of a single transistor. By putting a carefully-biased auxiliary transistor in parallel, the third-order derivative of the transconducting transistor is cancelled [3], [4]. However, due to the second-order harmonic generated in the parasitics-caused intrinsic feedback structures, the IM_3 suppression is limited in high frequency circuits.

This paper presents a feedforward linearization technique that is almost independent on the mixer configuration. Most of the linearization circuits are implemented in IF band, which makes this technique more robust against parasitic parameters.

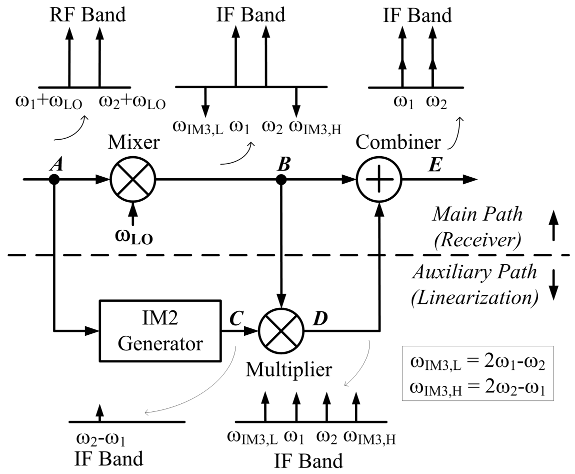


Fig. 1. The diagram of the proposed feedforward technique

II. PROPOSED FEEDFORWARD LINEARIZATION TECHNIQUE

A block diagram of the proposed feedforward scheme is given in Fig. 1, in which an auxiliary path for linearization is added in parallel to the original receiver. In the auxiliary path, IM_3 tones that have same amplitude and 180° phase difference from those at the mixer output are generated and sent back to the receiver for the cancellation. The combining of the mixer output and the cancelling IM_3 can be achieved through reusing the stage following the mixer, for example, an op-amp-based IF amplifier or filter, which appears after the mixer in a typical receiver architecture. From the systematic perspective, the combiner used in the proposed technique does not add an extra stage in the main path. The detailed operation principle and the spectrum at each node are described assuming two-tone signal applied at the input.

Node A: Two RF signals are applied to the input of the mixer. For simplicity, the initial amplitude and phase of the signal are assumed to be A_0 and 0°. The RF frequencies are expressed as the sum of IF and LO signals for the simplification of the notation, as $A_0cos(\omega_1 + \omega_{LO})t +$

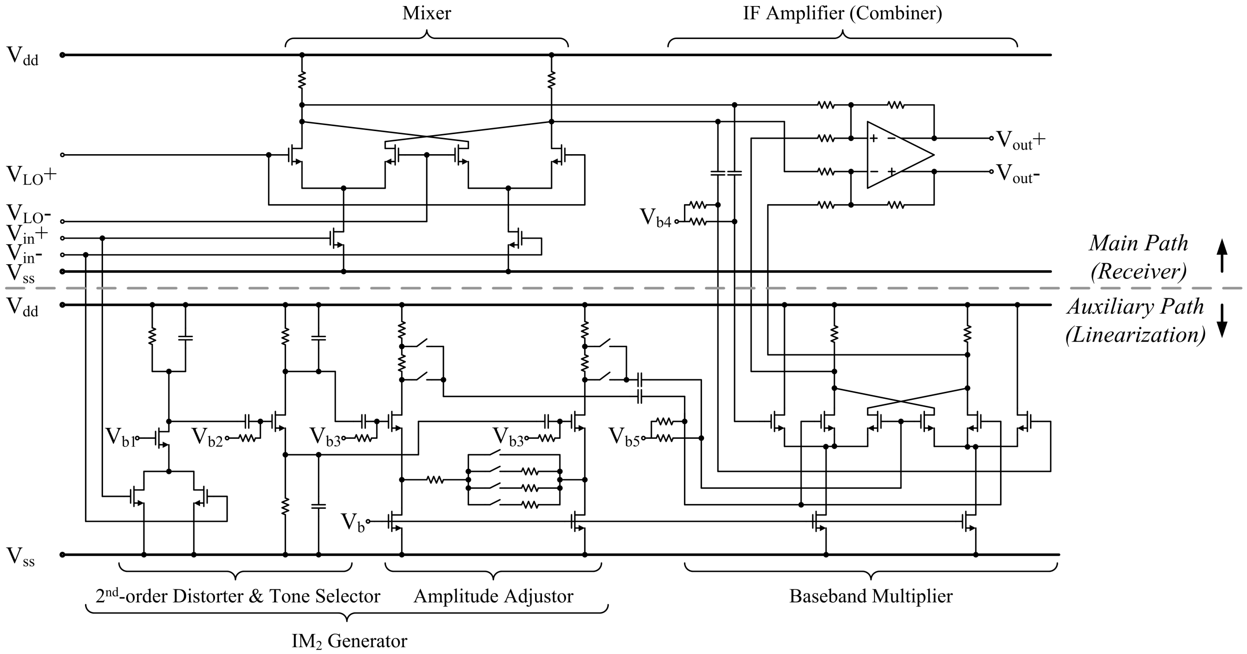


Fig. 2. The circuit implementation of the proposed feedforward technique

$A_0 cos(\omega_2 + \omega_{LO})t$.

Node B: Due to the third-order nonlinearities of the mixer, IM_3 tones are generated near the fundamental ones in the IF frequencies at the output of the mixer. The fundamental and the IM_3 tones of the mixer output can be expressed as $A_{CG}A_0 cos(\omega_1 t + \Phi_1) + A_{CG}A_0 cos(\omega_2 t + \Phi_2)$ and $a_3 {A_0}^3 cos(\omega_{IM3,L} t + \Phi_3) + a_3 {A_0}^3 cos(\omega_{IM3,H} t + \Phi_4)$, where A_{CG} and a_3 represent the conversion gain and the third-order coefficient of the mixer, respectively; $\omega_{IM3,L}$ and $\omega_{IM3,H}$ represent the two IM_3 frequencies $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$, separately, and $\Phi_{1\sim 4}$ represents the additional phase introduced to each tone by the mixer.

Node C: In the auxiliary path, a low-frequency IM_2 tone of the input signal is generated first, noted as $a_2 {A_0}^2 cos(\omega_2 - \omega_1)t$, where a_2 represents the second-order coefficient of the IM_2 generator. As the IM_2 tone stays at low frequency, its phase shift due to parasitic capacitors of the circuit can be ignored without losing accuracy.

Node D: The baseband multiplier multiplies the baseband signals at *Node B* by those at *Node C*, generating four third- and four fifth-order tones located around the fundamental tones of the mixer output. As the fifth-order products are small and not related with IM_3 cancellation, only third-order products are listed here for simplicity, given as

$$\begin{aligned} v_D \approx & A_{IM3} cos(\omega_1 t + \Phi_2) + A_{IM3} cos(\omega_2 t + \Phi_1) \\ & + A_{IM3} cos(\omega_{IM3,L} t + \Phi_1) \\ & + A_{IM3} cos(\omega_{IM3,H} t + \Phi_2) \end{aligned} \tag{1}$$

where

$$A_{IM3} = 1/2 K_m a_2 A_{CG} {A_0}^3 \tag{2}$$

and K_m is the multiplying gain of the baseband multiplier. The phase shift of this operation is ignored too as the multiplication is operated in the IF band.

Node E: Signals at *Node D* is added to those at the mixer output through a combining circuit to cancel the IM_3 tones. Assuming a unit gain of the combiner, the signals at *Node E* can be expressed as

$$\begin{aligned} v_E = & A_{CG}A_0 cos(\omega_1 t + \Phi_1) + A_{IM3} cos(\omega_1 t + \Phi_2) \\ & + A_{CG}A_0 cos(\omega_2 t + \Phi_2) + A_{IM3} cos(\omega_2 t + \Phi_1) \\ & + a_3 {A_0}^3 cos(\omega_{IM3,L} t + \Phi_3) + A_{IM3} cos(\omega_{IM3,L} t + \Phi_1) \\ & + a_3 {A_0}^3 cos(\omega_{IM3,H} t + \Phi_4) + A_{IM3} cos(\omega_{IM3,H} t + \Phi_2) \end{aligned} \tag{3}$$

According to (3), the IM_3 can be cancelled if the corresponding tones at same frequency have the same amplitude and 180° of phase difference. This requirement can be translated to the following conditions:

$$a_3 = -\frac{1}{2} K_m a_2 A_{CG} \tag{4a}$$

$$\Phi_1 = \Phi_3 \tag{4b}$$

$$\Phi_2 = \Phi_4 \tag{4c}$$

Condition described in (4a) can be fulfilled by adjusting a_2 and K_m, with A_{CG} and a_3 regarded as constants once the mixer is designed. Furthermore, the four tones of the mixer output located at ω_1, ω_2, $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$ experience approximately equal phase shifts when going through the mixer as they are close to one another, i.e. $\Phi_1 \approx \Phi_2 \approx \Phi_3 \approx \Phi_4$. Thus, the (4b) and (4c) can also be met.

It is worth noted that while the IM_3 tones are successfully cancelled, the fundamental tones of the mixer output are decayed by two third-order products from the linearization scheme, as illustrated in both Fig. 1 and Eq. 3. However, as the amplitude of this added tone is much smaller compared to the fundamental tone of the mixer output, its influence to the mixer gain is small enough to be neglected.

Throughout the derivation, the mixer is regarded as a ”black box” with only input and output signals involved, indicating that this method is independent on the mixer topology. Additionally, the generation of the cancelling IM_3 is mostly accomplished in low frequencies, which makes this method insensitive to the parasitic devices.

III. CIRCUIT IMPLEMENTATION

The proposed linearity technique is applied to a current commutating mixer to improve its IIP_3 performance. The circuit schematic is shown in Fig. 2, where it can be observed that every operation of the proposed technique can be realized with commonly-used circuit topologies.

The mixer to be linearized adopts a Gilbert cell configuration with its tail current source omitted, as shown in Fig. 2. This mixer configuration is employed as it shows the versatility of the proposed linearization technique. Due to the absence of the current source of the differential pair, this mixer can not be linearized by the IM_2 injection method, but it can be well linearized by the proposed technique. An IF amplifier is assumed to follow the mixer in the main path receiver, and is reused as the combiner of the proposed scheme.

The IM_2 generator consists of a second-order distorter made of the squaring circuit, a tone selector and an amplitude adjustor made of common source amplifier with source degeneration. The tone selector is realized by the low-pass filters integrated at the load of each stage and is used to pick out the IM_2 tone at $\omega_2 - \omega_1$ among all the second-order harmonics. What is more, a multiplier that fully works in the IF band is adopted.

IV. MEASUREMENT RESULTS

The mixer was fabricated in a standard $0.13\mu m$ CMOS process. The die micrograph of the design is shown in Fig. 3, which occupies a chip area of 1.2 × 2 mm^2. The active area is 0.4 × 1.4 mm^2.

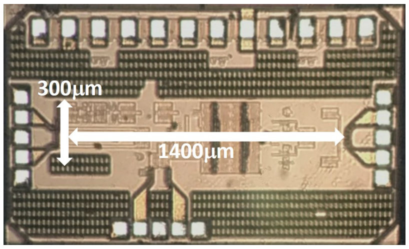


Fig. 3. Die micrograph of the mixer

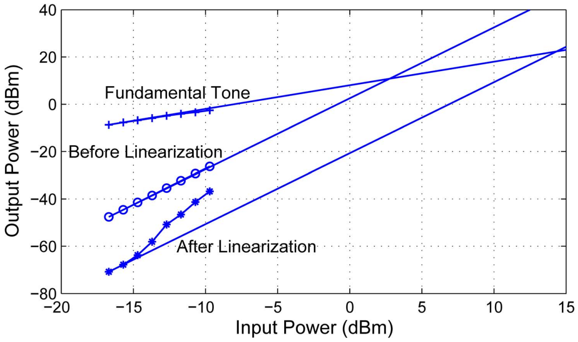


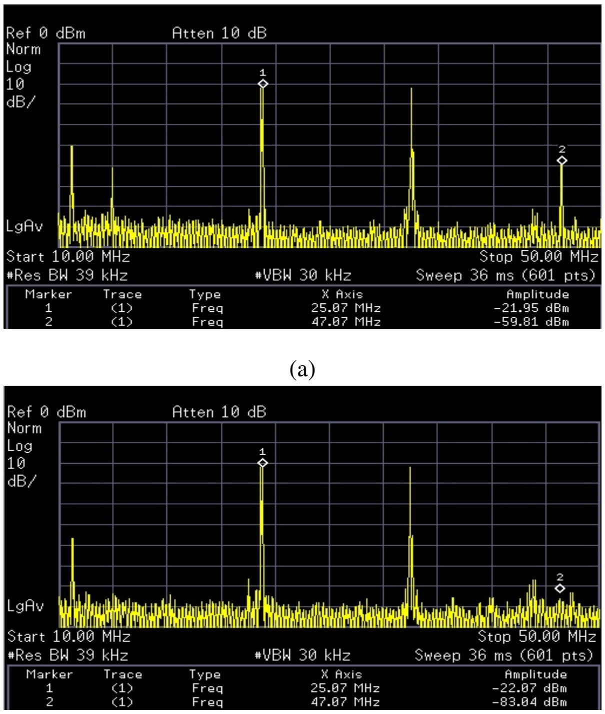
Fig. 4. Measured IIP_3 of the mixer

For comparison, the IM_3 generation circuits are turned on and off to enable and disable the cancellation. As the IF amplifier following the mixer is designed to have a unit gain and a simulated IIP3 of above 35 dBm, its effects to the gain and the IIP_3 of the mixer in both cases are negligible during the measurement.

The mixer is measured with an LO of -2 dBm located at 2 GHz. The mixer and the IF amplifier consume 4 mA and 4.4 mA under 1.2V voltage, separately, and the linearization part consumes 4.2 mA when it is turned on.

With two RF signals located at 2.025 GHz and 2.035 GHz applied, a conversion gain of 8.5 dB is obtained and is almost unchanged when the linearization part turns on and off. As can be seen in Fig. 4, the IIP_3 of the mixer is 2.5 dBm and the proposed linearization technique can improve it by 12 dB. As the input power is increased beyond -15 dBm, the IM_3 suppression becomes less effective. However, this typically is not a big concern as -15 dBm input power is sufficiently large for the mixers in most of the wireless receiver applications.

Fig. 5 provides the output spectrum of the mixer before and after linearization, which shows the IM_3 suppression evidently. Additionally, the spectrum also shows that the gain is not affected by the linearization technique. With the aforementioned frequency setting, the IM_2 tone of the mixer output lies left to down-converted IF by 5 MHz, as shown at the leftmost of the spectrum in Fig. 5. As can be seen, the proposed method does not affect the amplitude of IM_2 tone. What is more, it does not interfere other linearization technique to suppress the IM_2 tone either.



```
Start 10.00 MHz                                    Stop 50.00 MHz
#Res BW 39 kHz          #VBW 30 kHz          Sweep 36 ms (601 pts)
  Marker    Trace     Type        X Axis             Amplitude
    1        (1)      Freq      25.07 MHz           -21.95 dBm
    2        (1)      Freq      47.07 MHz           -59.81 dBm
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(a)

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Start 10.00 MHz                                    Stop 50.00 MHz
#Res BW 39 kHz          #VBW 30 kHz          Sweep 36 ms (601 pts)
  Marker    Trace     Type        X Axis             Amplitude
    1        (1)      Freq      25.07 MHz           -22.07 dBm
    2        (1)      Freq      47.07 MHz           -83.04 dBm
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(b)

Fig. 5. Output spectrum of the mixer (a) before and (b) after linearization

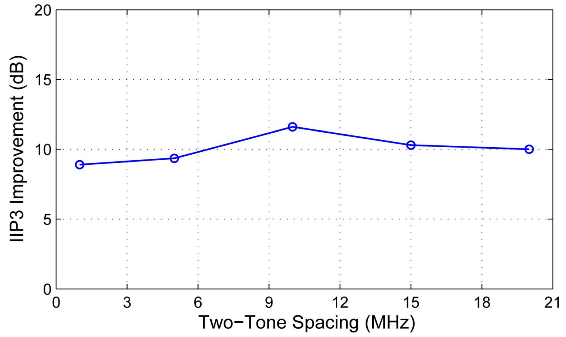

Fig. 6. Measured IIP_3 improvement as a function of two-tone spacing with an input power of -16 dBm

Fig. 6 shows the IIP_3 improvement of the linearization technique as a function of two-tone spacing with the input power of -16 dBm. As can be observed, the IIP_3 improvement achieves its peak when the two-tone spacing is 10 MHz, and it remains above 9 dB in a large range from 1 MHz to 20 MHz. The two tone space of the cancellation is dependent on the bandwidth of the auxiliary path, which is further dependent on the current consumption. The cancellation can be achieved with a larger two tone space at the cost of more power consumption.

TABLE I
PERFORMANCE SUMMARY AND COMPARISON TABLE

Parameter	This Work	[1][1]	[2][2]	[3]
Year	—	2013	2008	2004
Process (μm)	0.13	0.18	0.18	0.18
Frequency (GHz)	2	2.1	0.9	2.4
IIP3/ΔIIP3 (dBm)	14.5/+12	15/+10.5	0.2/+10.6	9/+6.5
Gain/ΔGain (dB)	8.5/0	15/0	22/0	16.5/+0.5
NF/ΔNF (dB)	17.9/+0.2[3]	14/0	5.3/0	14.2/+0.9
Voltage (V)	1.2	1.8	1.5	1.8
Current/ΔCurrent (mA)	12.6/+4.2[4]	4.5/+0.5	13/+0.3	3/+0.1

[1] Simulation results.
[2] The results are that of the front-end, including a LNA and a mixer.
[3] The NF of the mixer and the IF amplifier as a whole is measured.
[4] The mixer, IF amplifier and linearization circuits consume 4 mA, 4.4 mA and 4.2 mA respectively.

Table I summarizes the measured performance of the mixer in both unlinearized and linearized cases. And a performance comparison with other state-of-the-art linearization techniques are also demonstrated in the same table.

V. CONCLUSION

A feedforward scheme to suppress the IM_3 of the mixer is proposed, in which IM_3 for cancellation is generated through the multiplication of low-frequency IM_2 signals and the IF fundamental signal of the mixer output. The cancellation is insensitive to parasitics of the circuit, as the generation of IM_3 is fully realized in IF band. Besides, this technique has superior versatility as its success does not rely on the topologies of the mixer to be linearized. The circuit implementation achieves an above-10-dB IIP3 improvement over a large two-tone space with negligible noise and gain degradation at the cost of 4.2 mA extra current.

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