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 (IM3) of the down-conversion mixers is proposed, in which a low-frequency second-order intermodulation tone (IM2) is created and multiplied by the mixer’s output to generate the IM3 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 IIP3 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, IIP3, IM3 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. IM2 injection technique inserts an IM2 tone into the current source of the differential pair to suppress the IM3 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 IM3 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.

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, IM3 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 IM3 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 $A_0\cos(\omega_1 + \omega_{LO})t +$
The input signal is generated first, noted as
\[ V_{\text{in}} = A_0 \cos(\omega_2 + \omega_{\text{LO}}) t. \]

**Node B:** Due to the third-order nonlinearities of the mixer, IM3 tones are generated near the fundamental ones in the IF frequencies at the output of the mixer. The fundamental and the IM3 tones of the mixer output can be expressed as
\[ ACG A_0 \cos(\omega_1 t + \Phi_1) + ACG A_0 \cos(\omega_2 t + \Phi_2) \]
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 \( ACG \) 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 IM3 frequencies \( 2\omega_1 - \omega_2 \) and \( 2\omega_2 - \omega_1 \), separately, and \( \Phi_{1-4} \) represents the additional phase introduced to each tone by the mixer.

**Node C:** In the auxiliary path, a low-frequency IM2 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 IM2 generator. As the IM2 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 IM3 cancellation, only third-order products are listed here for simplicity, given as
\[ v_D \approx A_{IM3} \cos(\omega_1 t + \Phi_2) + A_{IM3} \cos(\omega_2 t + \Phi_1) \]
\[ + A_{IM3} \cos(\omega_{IM3,L} t + \Phi_1) \]
\[ + A_{IM3} \cos(\omega_{IM3,H} t + \Phi_2). \]

where
\[ A_{IM3} = 1/2 K_m a_2 ACG A_0^3 \]
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 IM3 tones. Assuming a unit gain of the combiner, the signals at Node E can be expressed as
\[ v_E = ACG A_0 \cos(\omega_1 t + \Phi_1) + A_{IM3} \cos(\omega_1 t + \Phi_2) + ACG A_0 \cos(\omega_2 t + \Phi_2) + A_{IM3} \cos(\omega_2 t + \Phi_1) + a_3 A_0^3 \cos(\omega_{IM3,L} t + \Phi_3) + a_3 A_0^3 \cos(\omega_{IM3,L} t + \Phi_4) + a_3 A_0^3 \cos(\omega_{IM3,H} t + \Phi_3) + a_3 A_0^3 \cos(\omega_{IM3,H} t + \Phi_4) \]

According to (3), the IM3 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:
\[ a_3 = -\frac{1}{2} K_m a_2 ACG \]
\[ \Phi_1 = \Phi_3 \]
\[ \Phi_2 = \Phi_4. \]

Condition described in (4a) can be fulfilled by adjusting \( a_2 \) and \( K_m \), with \( ACG \) and \( a_3 \) regarded as constants once
the mixer is designed. Furthermore, the four tones of the mixer output located at \( \omega_1, \omega_2, 2\omega_1 - \omega_2 \) 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 cannot 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 \( \times \) 2 mm\(^2\). The active area is 0.4 \( \times \) 1.4 mm\(^2\).

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 IIP\(_3\) 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.
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

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 IIP$_3$ improvement over a large two-tone space with negligible noise and gain degradation at the cost of 4.2 mA extra current.

REFERENCES


