A Linearity Enhancement Method for CMOS Mixers using Digital Assist

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***Abstract*— A technique is presented to improve both the input 1-dB compression point (P_{1dB}) and the third-order intercept point (IP3) of a mixer using real-time knowledge of the incident RF power to the mixer plus look-up tables (LUTs) that contain measured performance data of mixer under different bias conditions. The concept is applied to an active mixer designed in-house on 130 nm CMOS technology. The mixer has a modified Gilbert-cell topology where the dc bias currents of the RF stage and the LO switching stage are independent of each other. Experimental tests reveal that the P_{1dB} of the mixer can be increased by +8.7 dB from a baseline value of -12.1 dBm to - 3.3 dBm using the digital assist and its IIP3 can be improved by +5.9 dB from -3.11 dBm to +2.83 dBm with the technique.**

I. Introduction

Mixer linearization methods that use Gm-boosted transistors [1], [2] and the associated method of derivative superposition [3], [4], [5], are directed at improving the circuit's IP3 while the P_{1dB} remains largely intact. Body biasing techniques have also been proposed to improve linearity in mixers [6]. The more basic technique of source (or emitter) degeneration at the RF input stage of a Gilbert-type downconverter can improve both the mixer's P1dB and IP3 performance at the expense of conversion gain (CG) illustrates the usual challenge faced by designers: that the metrics of a circuit cannot always be optimized to their best possible values simultaneously and tradeoffs must be made.

Smartphones and tablet computers are the ubiquitous tools that have come to define today's information age. The enormous computational power present in those devices open up many opportunities to improve the performance of the RF hardware that make up those devices. This paper presents a digital assist method for active commutating mixers that improves the P_{1dB} and IP3 performance of a mixer by making the best possible tradeoff between the two metrics with only a small sacrifice in CG. The method relies on real-time knowledge of the incident RF power to the mixer plus look-up tables (LUTs) that contain measured performance data of mixer under different bias conditions. A mixer was fabricated using 130 nm CMOS technology and demonstration test results show that the IP_{1dB} of the mixer can be improved by +8.7 dB and its IIP3 by +5.9 dB using the technique relative to the baseline performance of the mixer without digital assist.

II. Design Details

A block diagram of the proposed downconverter with its digital-assist is depicted in Fig. 1. Stored in the memory of the microcontroller are look-up-tables (LUTs) containing previously measured conversion gain (CG) and third-order intercept point (IP3) data as a function of RF input power and frequency for the mixer. The on-chip CMOS power detector senses the incident RF power level and yields a dc signal level that is subsequently fed to an analog-to-digital converter (ADC). The microcontroller reads the RF input power level from the ADC and runs an interpolation algorithm to calculate the optimal dc bias voltages of the mixer that yield its best CG and IP3 performance using the data in the LUTs. The 'dummy' power detector in Fig. 1 is identical to upper detector and its purpose is to balance the input impedance seen by the RF signal.

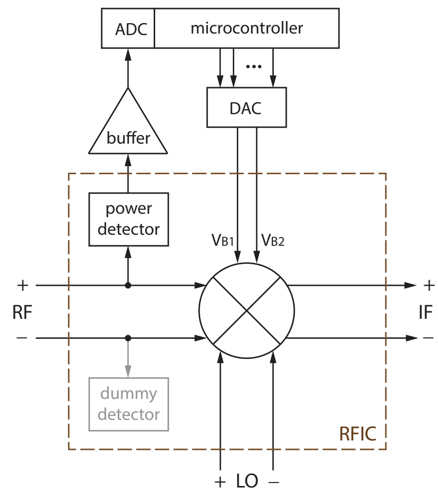

Fig. 1. Block diagram of the digitally-assisted mixer. The components inside the dashed box are on-chip while those outside the box are off-chip.

A detailed schematic diagram of the CMOS commutating mixer designed as a test-case for the proposed digital assist method is shown in Fig. 2. The mixer is a modified Gilbert cell where the dc bias currents of the RF stage and the commutating core are isolated from one another through capacitor C_{RF}, which leads to more flexibility in establishing the DC operating point of the mixer [4]. Series peaking inductors (L_{RF}) are used between the RF and LO stages to extend the RF bandwidth of the mixer.

Transistors M_1-M_2 constitute the RF transconductor stage of the mixer and devices M_3-M_4 are diode-connected FETs which simplify the biasing arrangement at the drains of M_1-M_2. The dc bias current of the RF stage, I_{B1}, is controlled through the dc voltage V_{B1} at the gates of M_1 and M_2. Transistors M_7-M_{10} constitute the LO switching core of the

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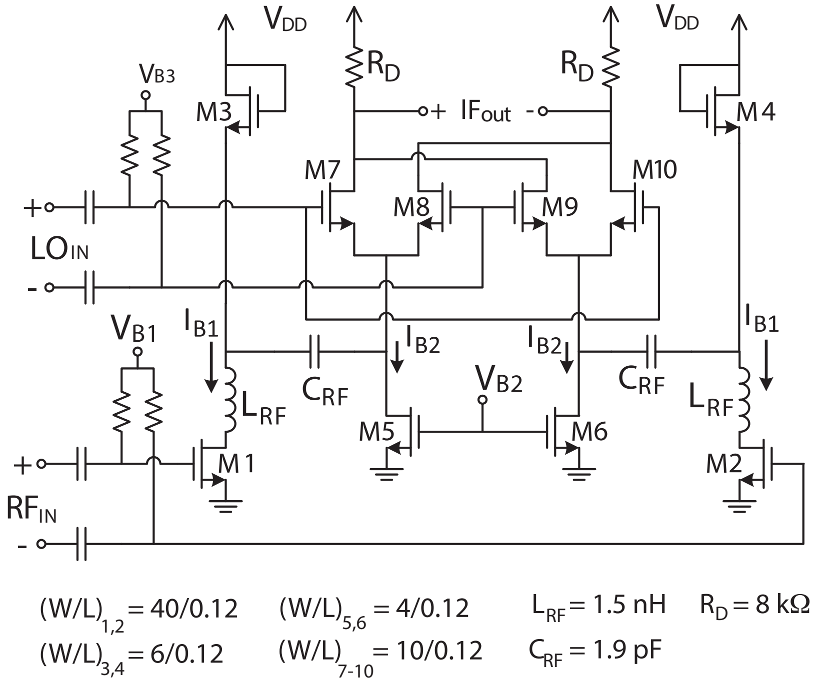

Fig. 2. Downconverter mixer schematic

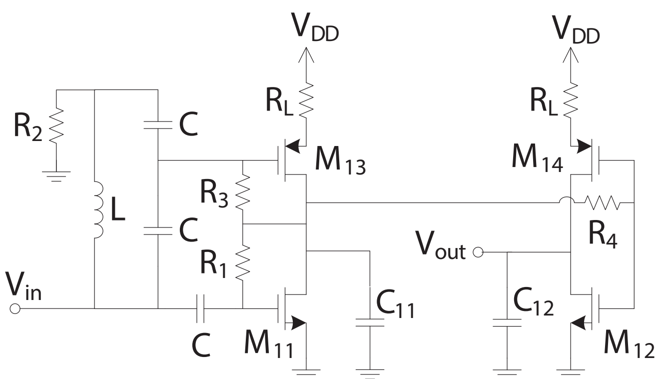

Fig. 3. RF power detector circuit schematic, after [7].

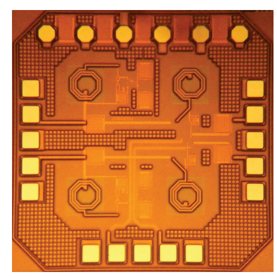

Fig. 4. Photograph of fabricated CMOS mixer and power detector

mixer and their dc bias current, I_{B2}, is established through the dc voltage V_{B2} applied to the gates of M_5-M_6. It is the voltages V_{B1} and V_{B2} which are adjusted by the microcontroller so that the mixer yields the best possible linearity and IMD performance depending on the strength of the RF incident signal.

The power detector used here is shown in Fig. 3 is based on the detector proposed by Li *et al* and the reader is referred to [7] for a detailed explanation of its operation.

Any number of microcontrollers available on the market can be used to implement the digital assist algorithm. In this proof-of-concept demonstration the PIC18F87J11 microcontroller from Microchip Technology was selected because it is easily programmable in the C language and has built-in data converters.

III. Experimental Results

The RFIC containing the mixer and the power detector was fabricated using a standard 130 nm CMOS process. A microphotograph of the chip is shown in Fig. 4. The microcontroller and interface circuitry were located off-chip on a prototyping board.

Data gathering

Fig. 5 shows the measured response of the power detector. The plot depicts the output voltage as a function of RF input power at three representative signal frequencies: 2, 4 and 8 GHz. The detector response is stored in a LUT and the digital assist algorithm does a linear interpolation using the detector's measured response data to estimate RF input power level if it falls in between two measured points.

The mixer's CG and IP3 response was characterized over a range of mixer bias voltages and RF input power levels in order to populate the mixer LUT used for the digital assist algorithm. For both the CG and IP3 measurements, the RF power was swept from -24 dBm to -18 dBm in steps of 2

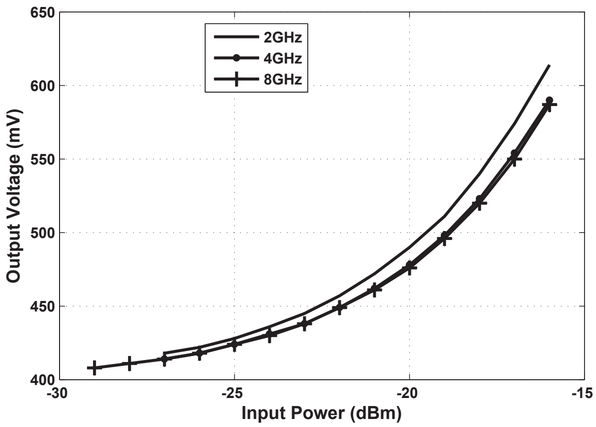

Fig. 5. Measured response of the power detector versus RF input power. The detector's response was measured at three frequencies: 2, 4 and 8 GHz.

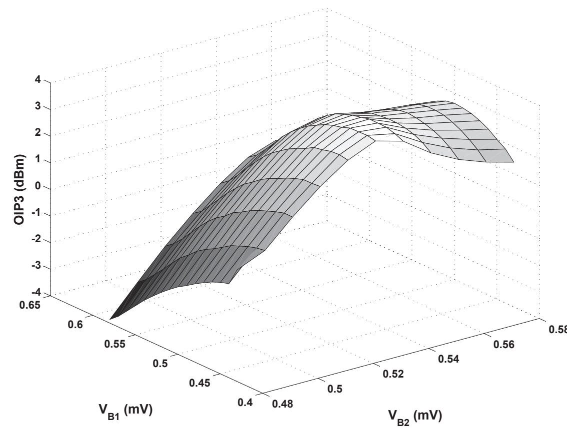

Fig. 7. Measured surface plot of the mixer OIP3 without digital control as a function of V_{B1} and V_{B2} and an RF input power of -18 dBm at 4 GHz.

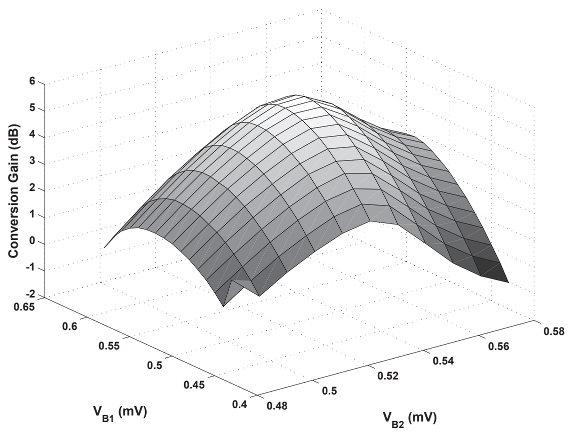

Fig. 6. Measured surface plot of the mixer CG without digital control as a function of V_{B1} and V_{B2} and an RF input power of -18 dBm at 4 GHz.

dBm and the bias voltages V_{B1} and V_{B2} were swept from 0.43 V to 0.58 V and from 0.46 V to 0.58 V, respectively, both in steps of 10 mV. For the CG measurements the RF signal frequency was set to 4 GHz and for the IP3 measurements, a series of two-tone tests were carried out using a pair of signals centered at 4 GHz and spaced 1 MHz apart. The data was gathered with the aid of the test automation software LabView.

Representative surface plots of the measured CG and the OIP3 coordinate of IP3 as a function of V_{B1} and V_{B2} taken at $P_{RF,in} = -18$ dBm are shown in Figs. 6 and 7, respectively. The surface plots visually corroborate the well-known and important fact alluded to earlier: that best IP3 performance does not coincide with best CG and that tradeoffs are needed in practical engineering applications between the two metrics because both cannot be maximized simultaneously. The digital assist algorithm proposed in this paper is designed to make the tradeoff between CG and IP3 by calculating the bias voltage V_{B1} and V_{B2} that produces the best possible result for both metrics based on the incident power of the RF tone.

Demonstration of the digital assist technique

To demonstrate the operation of the digital assist technique, the following tests were done:

1) the baseline power response of the mixer without digital assist is measured at a representative frequency of 4 GHz with V_{B1} and V_{B2} fixed at 0.51 V and 0.54 V, respectively. The results, plotted in Fig. 8, show that the mixer has a baseline IP_{1dB} and OP_{1dB} of -12.1 dBm and -6.6 dBm, respectively.
2) a two-tone test is carried out on the mixer without digital assist using tones spaced 1 MHz apart at 4 GHz. The results (Fig. 9) show that the baseline IIP3 and OIP3 of the mixer are -3.1 dBm and -1.8 dBm, respectively.
3) the power response of the mixer with digital assist is measured at 4 GHz. In this case, as the RF input power changes, the microcontroller calculates the voltages V_{B1} and V_{B2} that yield the best combination of CG and IP3 performance. The resulting power response curve in Fig. 10 shows a slight drop in CG of 1 dB but an improved IP_{1dB} of -3.3 dBm, which is +8.8 dB better than the baseline IP_{1dB}. Meanwhile, the OP_{1dB} increases by +3.8 dB to -2.8 dBm.
4) the two-tone test is done on the mixer with digital assist using using the same algorithm as in step 3). The results, plotted in Fig. 11, show that digital assist improves the IIP3 of the mixer by +5.9 dB to 2.8 dBm and the OIP3 by +0.76 dB to 2.56 dBm.

The LO-RF port-to-port isolation of the mixer was measured with and without digital assist and it remains better

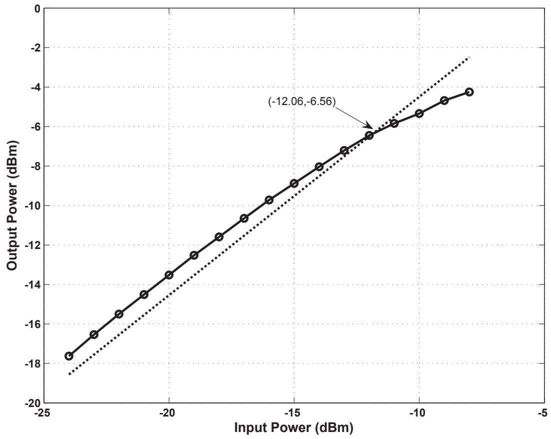

Fig. 8. Measured power response of the mixer without digital assist at 4 GHz RF

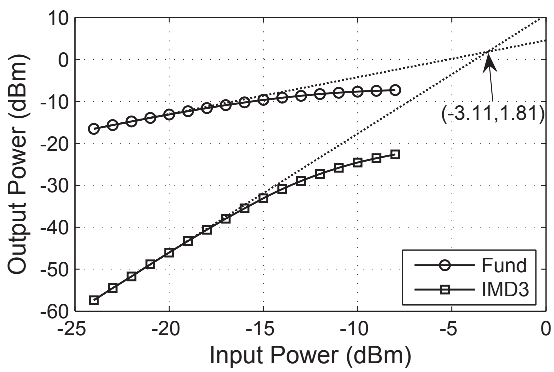

Fig. 9. Measured two-tone test results taken at a center frequency of 4 GHz without digital assist.

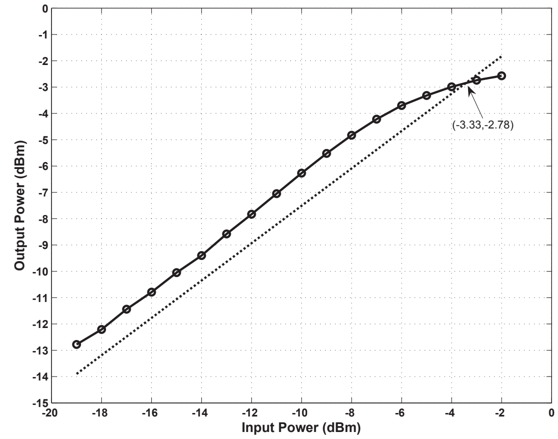

Fig. 10. Measured power response of the mixer at 4 GHz with digital control of its CG as a function of RF input power.

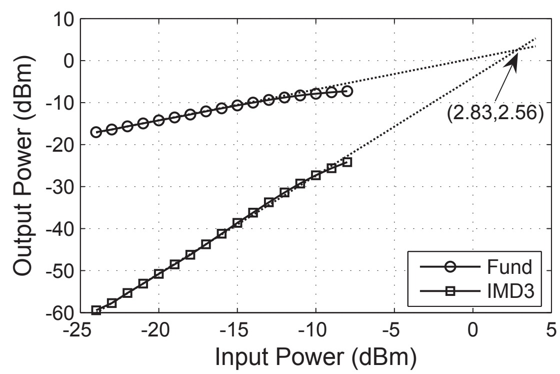

Fig. 11. Measured two-tone test output power versus input power of mixer with CG controlled by digital means at 4 GHz RF

than -53 dB in both cases. A performance summary of the mixer with and without digital assist is shown in Table I.

TABLE I

DIGITALLY ASSISTED MIXER TEST SUMMARY

metric	**With Dig. Assist**	Without Dig. Assist
DC power† (mW)	2.06−3.27	3.27
RF Freq. (GHz)	4	4
Average CG (dB)	5	6
IP_{1dB} (dBm)	-3.33	-12.06
IIP3 (dBm)	2.83	-3.11
LO to RF (dB)	< -53	< -53

† RFIC only

IV. CONCLUSION

Simultaneously maximizing the CG, P_{1dB} and IP3 performance of a mixer, or almost any other active circuit, is challenging because the two metrics are at odds with each other: improving one can deteriorate the other(s). We have a demonstrated a method that uses real-time information about the power of the input signal to the mixer and data stored in LUTs to calculate the best tradeoff between P_{1dB} and IP3 at minimal cost to its CG.

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