An 8-10 GHz Upconversion Mixer, with a Low-Frequency Calibration Loop resulting in better than -73dBc In-Band Spurs

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***Abstract*— An 8-10 GHz X-band upconversion quadrature mixer stage implemented in 250 nm SiGe BiCMOS is presented. Orthogonality of the spurious responses caused by clock feed through, I/Q mismatch and baseband harmonics after self-mixing was exploited to realize a baseband calibration scheme reducing all in-band spurs down to below -73dBc, for baseband signals up to a bandwidth of 2MHz and with an IF center frequency up to 100MHz. Utilizing a low-frequency output spectrum analysis of an integrated self-mixer at the upconversion mixer output for calibration, eliminates the need for expensive microwave frequency spectrum analyzers.**

***Index Terms*— BICMOS integrated circuits, Microwave integrated circuits, Built-in self-test**

I. Introduction

A number of X-Band microwave array applications, e.g. Multiple-Input Multiple-Output (MIMO) arrays [1] or RF impairment mitigation on receive architectures [2], require relative small, 100Hz - 1MHz, unique frequency offsets per array element and very low spurious responses of -70 to -80dBc. This way, orthogonality by frequency offset is achieved between signal channels in different array elements. Quadrature Upconversion Mixers (UMs) can achieve these frequency translations, but non-idealities can cause in-band spurs. Filtering these spurs is not feasible, since the frequency translations are relatively small in comparison with the RF carrier, as required by these MIMO techniques. By minimizing the non-idealities, spur levels in a UM down to -42dBc are achieved [3]. For lower spurs additional calibration is required.

The dominant in-band spurs in UMs are caused by Local Oscillator Feed-Trough (LOFT), I/Q Mismatch (IQM) and upconverted Baseband (BB) harmonics. LOFT can be compensated by applying an appropriate differential DC offset at both I/Q BB inputs. IQM can be suppressed by adding phase and amplitude offsets between the I/Q BB signals. To calibrate the system, the RF output signal could be characterized by a high-frequency Spectrum Analyzer (SA). Alternatively, the output of the UM can be downconverted by mixing it with itself using a self-mixer. It can be shown that self-mixing of the RF-output followed by DFT analysis of the resulting baseband signal, renders largely orthogonal contributions in different frequency bins for LOFT, IQM and BB harmonic distortion respectively. This is exploited in our auto-calibrating loop. This orthogonality was already shown and used in [4]. A mathematical model of mixer non-idealities and self-mixer products are derived in [5]. This work combines these methods to achieve very low spurs for X-band applications.

II. Overview

Fig. 1 shows the block schematic of the mixer and calibration loop. The gray area is integrated on-chip. An external balun and a broadband on-chip Poly Phase Filter (PPF) are used to convert the Local Oscillator (LO) to a quadrature LO signal to drive the mixer core. The differential in-phase and quadrature BB_I and BB_Q signals are generated by an external Arbitrary Waveform Generator (AWG). It also generates DC, phase and amplitude offsets in the BB signal to reduce LOFT and IQM, for coarse calibration. An on-chip Current DAC (CDAC) is used to provide fine LOFT calibration. The output of the UM is fed to the output of the chip and to the calibration loop. This loop downconverts the signal by an integrated self-mixer, whose output contains the low-frequency information on in-band RF spurs. This is amplified by an external probe and converted to the digital domain by an Analog-Digital Converter (ADC)

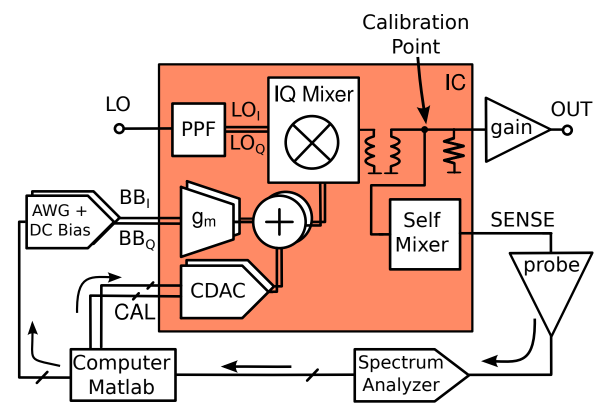


Fig. 1. Block schematic of the upconversion mixer and calibration loop.

and transformed by a Discrete Fourier Transform (DFT). This is performed by an external SA. The measured data from the SA is processed by a computer running Matlab, which controls the circuit to reduce the spurs. Since this calibration signal at the SENSE node has a relatively low frequency, the constraints on the requirements of the components in the calibration loop are very relaxed compared to having to process the actual RF spurs at node OUT.

III. Implementation

Fig. 2 shows the circuit implementation of the UM. The BB input signal and DC bias voltage, generated by a Keysight M8190A AWG and an HP4156B controllable DC source, are applied to a g_m stage. It is linearized to reduce harmonic distortion, realized by strong degeneration at the cost of BB conversion gain.
The external AWG is directly connected to the base of a heterojunction bipolar transistor differential pair which input is high-ohmic. The g_m is dimensioned in such a way that for a BB signal with an amplitude of $90mV_{pp}$, the harmonic distortions are below -70dBc. Two 7-bits CDACs operating at DC, with 100nA LSB resolution provide an extra means of calibration by changing the 2mA bias collector currents per transistor in the mixer core for extra fine LOFT calibration down to -86dBc, thereby reducing the requirements on the dynamic range of the external DC bias source. The external LO is converted to LO_I and LO_Q signals, by the PPF; this filter is dimensioned for low phase and amplitude offsets between 8 and 12GHz. This conversion results in an estimated loss of at about 14dB from LO to LO_I (and to LO_Q). The quadrature clock signals are applied to a double balanced mixer stage. A transformer and 50Ω termination resistors provide matching for off-chip RF measurements. The transformer also provides increased voltage headroom to lower noise and to increase linearity. The self-mixer is implemented as a Gilbert cell mixer, with increased gain and less degeneration, when compared to the UM. The input signal of the self-mixer is relatively small, hence linearity is not of prime importance. Noise however is an issue at these low signal levels. This is compensated by longer integration times of the output signal. The self-mixer is designed to be as symmetrical as possible and is positioned between the two differential output lines on-chip and has a very small area to reduce cross-talk. As an external ADC, to convert the low-frequency signal at node SENSE, a Keysight N9030A PXA SA is used. This SA also performs the DFT.
Fig. 3a shows the die micrograph; the IC is implemented in 250nm SiGe BiCMOS. The die has a total area of 2.1mm x 2.1mm. The multi-layer PCB is shown in Fig. 3b. It has perpendicularly oriented RF strip line interconnects, RF shielding and absorbers to increase off-chip LO isolation from input-to-output to 65dB.

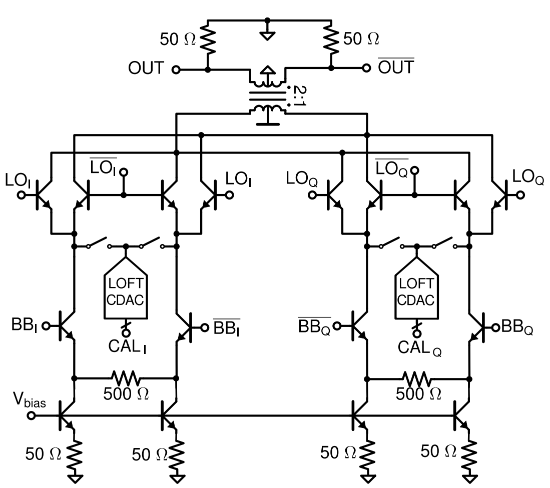
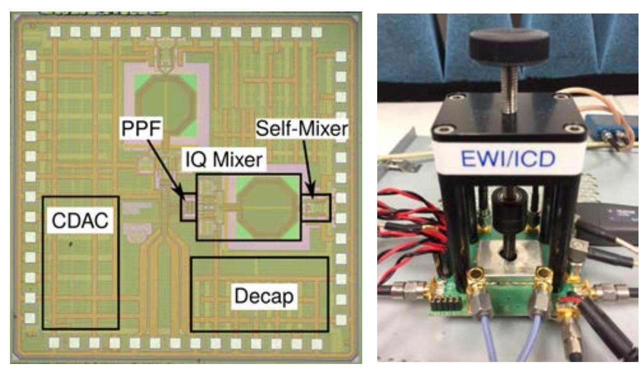


Fig. 2. Circuit schematic of the I/Q mixer.



(a) (b)

Fig. 3. (a) Die photo, 2.1mm x 2.1mm 250nm SiGe BiCMOS. (b) Multi-layer Rogers PCB and shielding for optimal isolation.

IV. Calibration Technique

The calibration loop reduces the strengths of the dominant spurs at the ”calibration point”. In Fig. 4 two (uncalibrated) spectra are plotted of the mixer and self-mixer output for an 8GHz LO signal with a 1MHz single tone BB signal. The orthogonality mentioned in section I follows from the self-mix products. The products at the output of the self-mixer have a name starting with ”S”. These products can be grouped into four frequency bins, shown in TABLE I. For orthogonal calibration, the terms in bold should be dominant in their respective bins. This is ensured if the second and third harmonic BB components (BB2H and BB3H) are significantly small compared to the carier. These can be minimized

TABLE I
SELF-MIX PRODUCTS

Bin	Self-mix components	First order spectral contributions (**dominant**)
0	SCarrier	**Carrier∗Carrier**
1	SLOFT	**LOFT∗Carrier**, LOFT∗IQM, Carrier∗BB2H
2	SIQM	**IQM∗Carier**, IQM∗BB3H, LOFT∗BB2H
4	SBB3H	**BB3H∗Carrier**, BB3H∗IQM

by reducing the BB amplitude, which is observable in the calibration loop from a very low SBB3H spur. The second step is to reduce LOFT by first coarsely tuning both the differential DC offsets of the I/Q BB signals generated by the DC bias sources. Additional fine tuning is achieved by the on-chip LOFT CDACs. Thirdly, the IQM is reduced by subsequently adding amplitude and phase offsets between the I/Q BB signals. The strengths of SLOFT, SIQM and SBB3H at the output of the self-mixer are measured by an external SA. These values are processed Matlab, after which they are used to control the AWG, DC bias sources and CDACs. A gradient descent algorithm finds the minimums of SLOFT and SIQM. The calibration algorithm is used for both single tone and broadband BB signals. When generating a broadband signal, the mixer is first calibrated using a single tone at the IF center frequency, f_c of the BB signal. Next, a broadband signal of 101 equispaced tones with bandwidth, BW, is generated by the AWG. Such a broadband signal has no influence on LOFT, but its IQM performance is frequency-dependent and degrades away from f_c, causing an increased average IQM compared to a single tone. This is caused by frequency-dependent I/Q imbalances at the BB input, such as different cable lengths or low pass filter poles. Careful PCB and BB input design minimizes this frequency dependency.

V. EXPERIMENTAL RESULTS

Fig. 5 shows that a minimum of LOFT and IQM can be found, sweeping the calibration settings. It also shows that this can be done nearly orthogonally from each other. When the differential DC offsets of the BB are swept, LOFT is varied 50dB, while IQM changes only 1dB. When IQM is varied over 45dB, by sweeping the phase offset between the I/Q signals, LOFT varies 5dB.

The calibration is verified by directly measuring the strengths of LOFT and IQM, using an external RF SA directly connected to the output of the UM. These external LOFT and IQM strengths are compared with the strengths of SLOFT and SIQM measured by the calibration loop. Since the loop calibrates the UM to have minimal spurs at the "calibration point" shown in Fig. 1, non-idealities introduced between this point and an external SA are not compensated by the loop. These non-idealities are e.g. external RF crosstalk and imbalances. These result in offsets between the minimums of LOFT and SLOFT and between IQM and SIQM. Measurements verify that these offsets do not vary during operation, under the condition that the external coupling does not vary. Because the offsets between the minimums in the internal SLOFT and SIQM and the external LOFT and IQM are constant for constant crosstalk, calibrating towards minimum (external) LOFT and IQM can be achieved by incorporating these offsets in the calibration algorithm. This is done in the calibration below.

Fig. 6 shows measured spectra of the RF output before and after calibration. With the proposed calibration algorithm, observing *only* the output signal of the self-mixer in the calibration loop, spurs are suppressed from -5dBc down to

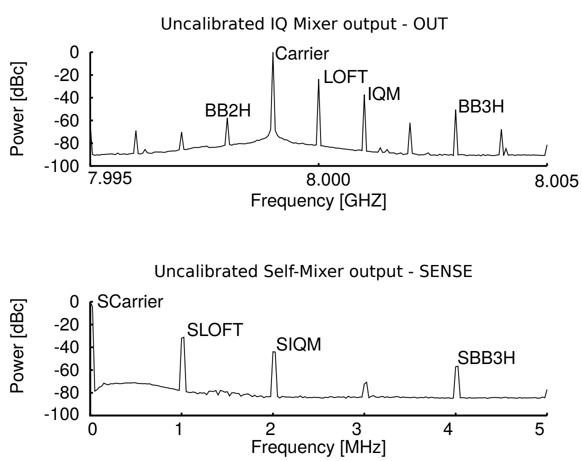


Fig. 4. Uncalibrated measured spectra at the output of the UM at node OUT and at the the output of the self-mixer at node SENSE.

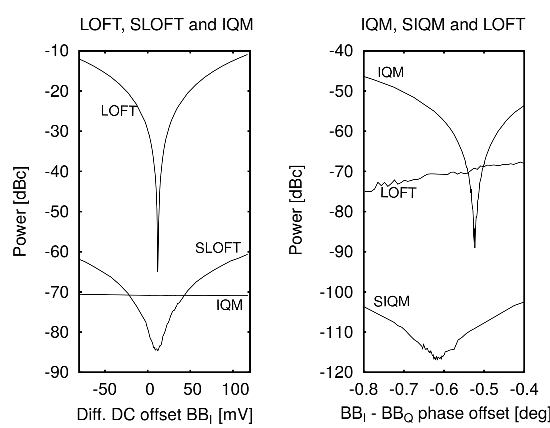


Fig. 5. Measurement of the strengths of LOFT and IQM at node OUT and SLOFT and SIQM at node SENSE, as function of two calibration variables.

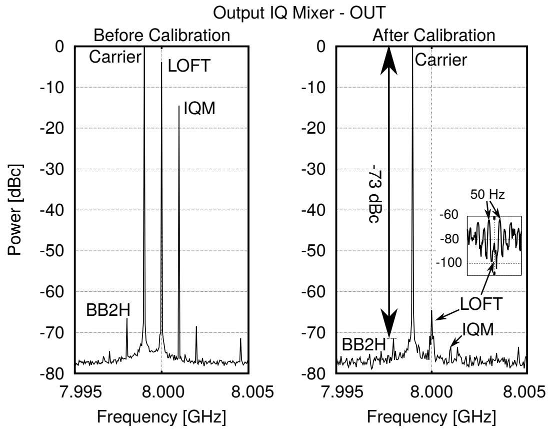


Fig. 6. Spectrum and node OUT, before and after calibration.

-73dBc. After calibration the highest spur results from the BBH2. Measured OIP2 is 60.0dBm, and OIP3 is 22.8dBm, indicating that the g_m stage is linearized enough, so that the upconverted BB harmonics are below -70dBc at RF for BB amplitudes lower than -90mV$_{pp}$. These harmonics limit the performance of the architecture to -73dBc. In our measurement setup, a mains 50Hz tone is up-converted by the LO, resulting in spurs around LO of -64dBc. To properly demonstrate pure LOFT, the inset in Fig. 6 shows the calibrated output spectrum with a 10Hz resolution bandwidth which demonstrates that LOFT is reduced to -85dBc.

Up to a BW of 2MHz and an IF f_c of 100MHz, the average IQM is lower than -73dBc. Above 10GHz LO frequencies, the gain of the self-mixer drops, which decreases the ADC input signal magnitude and which thereby limits the spur suppression calibration capabilities above 10GHz.

The available power gain from LO to OUT, excluding the external gain stage, is -22.3dB. This value includes the loss of about 14dB in the PPF for quadrature clock generation. The measurements are carried out with an LO power of 0.5dBm, with the LO just under compression and a BB signal amplitude of 90mV$_{pp}$ differential. The -1dB compression point of the LO input is 1.5dBm. The cable, balun and PCB losses are measured and de-embedded in all measurements. TABLE II summarizes the measurements results and compares against recent publications with different calibration schemes. The proposed work has significantly lower spurs, while performing a low-frequency calibration.

TABLE II
COMPARISON TABLE.

	[5]	[6]	[3]	this work
Technology	0.18μm CMOS	65nm CMOS	0.25μm BiCMOS	0.25μm BiCMOS
LO Freq. (GHz)	5.24	3.1-4.8 6.3-9	8-10	8-10
Calibration method	Low-Freq Env. Det.	High-Freq. Error Ampl.	No Cal.	Low Freq. Self-Mixer
LOFT suppression	-43.3dBc @5.2GHz	-40dBc @8.184GHz	-42dBc @10GHz	-85dBc @8GHz
IQM suppression	-45.3dBc @5.2GHz	-65dBc @8.184GHz	-42dBc @10GHz	-85dBc @8GHz
Harmonic suppression at 1 V$_{pp}$ BB	-52dBc @5.2GHz	-48dBc @8.184GHz	-40dBc @10GHz	-52dBc (1) @8GHz
Output Power	8dBm (2)	-12dBm	-12.5dBm	-21.8dBm
V$_{supply}$	1.8 V	1.2 V	4 V	3.3 V
Current	280 mA	175 mA	51 mA	60 mA
Active Area	18 mm^2 (3)	3.75 mm^2	0.55 mm^2	2.2 mm^2

[1] Circuit operates at 90mV$_{pp}$, [2] Max. gain setting,
[3] Full Tx and Rx.

VI. CONCLUSION

A linear X-band upconversion mixer, enabling small frequency translations, implemented in 250 nm SiGe BiCMOS was presented. Orthogonality of the LOFT, IQM and BB3H spurs after self-mixing was exploited to realize a BB calibration scheme using a low-frequency calibration loop. This reduced all in-band spurs at the output of the UM down to below -73dBc on-chip, up to a BB BW of 2MHz and IF f_c up to 100MHz.

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