A Baseband Technique for Automated LO Leakage Suppression Achieving < -80dBm in Wideband Passive Mixer-First Receivers

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***Abstract* — A baseband technique is presented to detect and suppress LO leakage in wideband passive mixer-first receivers. Using a variable shunting resistance on the RF port, the LO leakage signal is modulated, down-converted and detected from baseband outputs. Current DACs injecting to the baseband port are up-converted and can be adjusted to cancel LO leakage. Suppression of LO on the RF port < -80dBm is shown with a fully automated algorithm without the aid of RF spectrum monitoring.**

***Index Terms* — Harmonic mixing, local oscillator (LO) leakage, mixer, passive mixer, receiver, software-defined radio (SDR), wideband receiver.**

I. INTRODUCTION

A recent advance in software-defined radio receivers (SDRs) is the passive mixer-first receiver. These receivers allow flexible tuning of input impedance, operating frequency, and bandwidth while maintaining high linearity, low noise figure, and high rejection of interferers [1, 4].

In these receivers, eliminating the RF low noise amplifier (LNA) between the passive mixer and antenna allows greater control of the RF port at surprisingly little cost in noise, but loses the reverse-isolation of the LNA.

Thus, any signal that couples from the LO or baseband ports of the mixer to its RF port will directly leak onto the antenna port of the receiver. LO leakage can range from -70dBm to -50dBm, violating the ≈-70dBm FCC limitation on transmissions out of band [2]. In addition, such leakage can desensitize a receiver by directly saturating it or generating a time-varying DC offset under varying antenna conditions.

Techniques for suppressing LO leakage have been demonstrated for other radio architectures with varying success. An RF power detector and digital control loop were used for a direct up-conversion transmitter to inject DC offsets into the baseband, achieving suppression from -30dBm to -58dBm [3]. In a direct conversion transceiver, a variable attenuator and phase shifter delivered an anti-phase LO signal to cancel the original leakage, suppressing from -15dBm to -52dBm [5]. Both methods require active RF spectrum monitoring which is often not practical, and work on relatively strong leakage signals.

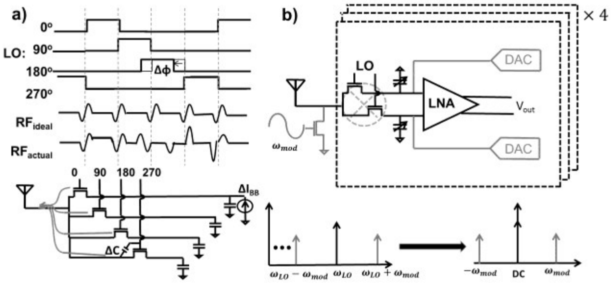

Fig. 1. a) Mechanisms for LO leakage in passive mixers, b) Detection scheme for measuring leakage at the baseband

For reliable suppression below -70dBm, as required by many receivers, other techniques are needed.

In this paper, we present a passive mixer-first receiver with current DACs that inject onto the baseband sampling capacitors. Using a variable shunting impedance on the RF port, we modulate the LO leakage away from the LO frequency and down-convert it to the baseband where a fully automated algorithm determines the appropriate DAC injections for suppression. This algorithm does not require active monitoring of the RF port or additional circuitry for leakage detection, making it a practical and inexpensive solution for passive mixer-first receivers.

II. CONCEPT/THEORY

A. Mechanisms of LO leakage

Ideally, a symmetric CMOS passive mixer generates no LO leakage at its fundamental frequency. However, several types of asymmetry can result in leakage. One set of mechanisms result from charge coupling through the passive mixer switches as shown in Figure 1. As each switch is turned on and off, charge will be driven onto the RF port through a source-drain capacitance. Ideally, in an N-phase mixer, N charge pulses per LO period will occur at symmetric time intervals, leaking at multiples of the LO's Nth harmonic (RF_{ideal} in Fig. 1). However if the transistors have non-identical capacitance (ΔC in Fig. 1) or threshold voltage, charge pulses with different amplitudes will be generated. This perturbation results in periodic injection at the fundamental frequency.

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A second related leakage mechanism comes from asymmetry in the phase or amplitude of the LO pulses themselves. Slight differences in phase delay in the LO ($\Delta\varphi$ in Fig. 1) can result in charge injection pulses not being distributed symmetrically, again inducing leakage at the fundamental.

Finally, LO leakage can result from asymmetry in baseband circuitry injecting different amounts of DC current or voltage on the different baseband inputs (ΔI in Fig. 1). These slight offsets are then up-converted by the mixer to generate LO leakage.

Because these sources of LO leakage can result from systematic mechanisms (i.e. layout asymmetry) or random mechanisms (i.e. device mismatch), the leakage magnitude is difficult to simulate and predict, and cannot be entirely eliminated by careful design. We therefore sought to develop a technique for measuring and cancelling such leakage dynamically.

Note that there are other mechanisms for LO leakage general to direct conversion receivers and not specific to passive mixer-first designs, such as magnetic coupling to bondwires, which are not dealt with here.

B. LO leakage measurement and suppression

With the transparency of passive mixers, a reasonable method for suppressing LO leakage is to inject an appropriate set of currents on the baseband ports of the mixer, such that the resulting up-converted signal precisely cancels the intrinsic leakage. To account for the magnitude and phase of this intrinsic signal, the cancelling signal must inject onto both I and Q ports with appropriate sign and magnitude.

Since LO re-radiation is down-converted to DC by the mixer, in principle, it is possible to detect the radiation (and its cancellation) by monitoring the DC offset of the receiver itself. However, direct conversion receivers have many mechanisms for generating DC offset, which submerge the leakage mechanism in larger, unrelated DC voltages. To isolate DC due to LO leakage, we add a shunting resistor (transistor) across the RF input and modulate its impedance which can be turned on when calibrating out LO leakage. This resistance modulates the LO re-radiation and generates sidebands offset from the LO frequency. These sidebands are down-converted to the modulation frequency and read through the quadrature baseband, providing magnitude and phase information about LO leakage. This technique has the advantage of not requiring active monitoring of the RF spectrum.

C. Algorithm

To achieve fully automated leakage suppression, we developed an algorithm that uses the detection scheme described earlier to learn the proper channel injections needed for the DACs. This algorithm avoids the need for manual tuning, and requires only a minimal number of initial calibrations.

In the language of linear algebra, we can represent the relationship between DAC injections and the detected LO re-radiation at the baseband by the following equation:

$$y = Dx + y_o, \tag{1}$$

where y is a 2x1 vector of the detected LO leakage in the I and Q channels, y_o is the original LO leakage, x is a vector of differential I/Q current injections, and D is a matrix where D_{ij} corresponds to the magnitude of the modulation seen by channel j when DACs inject on channel i. We invert this linear equation to find an optimal vector of DAC injections x^* such that $Dx^* = -y_o$, driving the LO re-radiation to $y \approx 0$.

III. System Architecture

Figure 2 shows the block diagram for the receiver. It consists of an 8-phase passive mixer-first receiver driven by an on-chip LO covering a frequency range from 0.1 to 1.4 GHz. The mixer outputs are amplified with differential LNAs with both real and complex feedback [1].

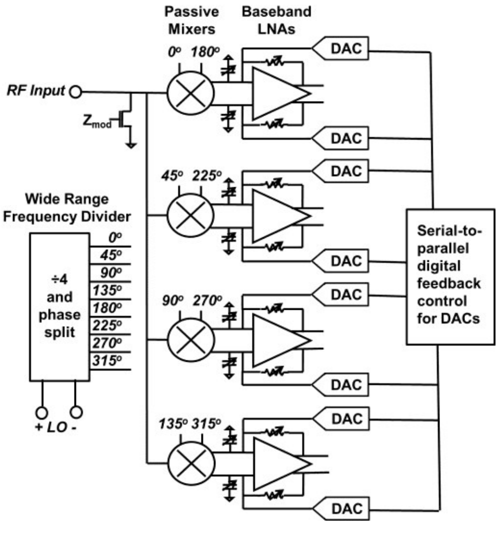

Fig. 2. System diagram for the receiver

The 10-bit class AB current DACs have a cascoded current mirror architecture, and can source/sink current with an LSB of 30nA onto the sampling capacitors of each baseband input independently, and digital inputs are clocked in sequentially at >10Mbps.

The receiver was fabricated in 65nm CMOS with area of 2.7 mm^2, consumes 57.6-73.6mW of power from 0.1-1.4GHz with gain of 25 $\pm$ 3dB, and has a noise figure generally less than 6dB for 0.2-1.1GHz with an IIP2 of +23.14dBm and an IIP3 (out-of-band) of +17.0dBm. Note that the differences in performance compared to prior work [1] are due to a difference in mixer switch resistance ($R_{switch} \approx 30$ ohms), and not to the LO suppression techniques described here.

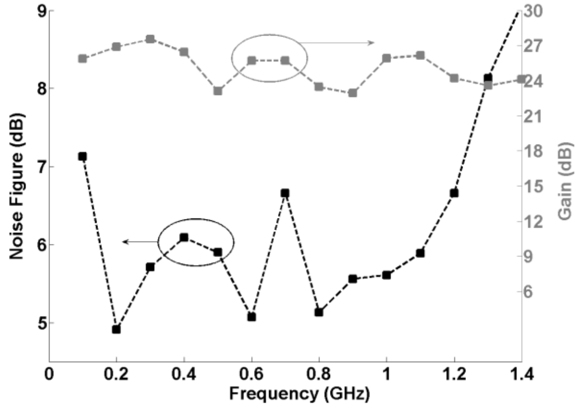

Fig. 3. Measured results of noise figure/gain versus frequency

III. EXPERIMENTAL RESULTS

To test whether the leakage can be cancelled by baseband injection, we injected sinusoidal weighted DC offsets across the 8 channels. These DC offsets are up-converted by the mixer to the LO frequency. By adjusting the phase and amplitude of the injected DC offset we can suppress the re-radiation. As shown in Fig. 4 and 5, there is an optimal phase and amplitude in which LO leakage is minimized.

For the automated algorithm, we confirm that our DACs are linear, a fundamental assumption of our matrix algebra as shown in Fig. 6. For initial calibrations, we measure the baseline (no DAC injection) leakage and then find the rows of matrix *D* by injecting the DAC currents independently and monitoring the detected leakage across the I and Q ports. In each case we extract the LO leakage by correlating the I and Q baseband outputs with the normalized input modulation signal.

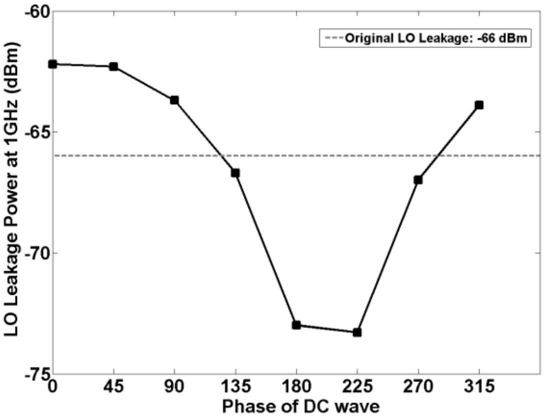

Fig. 4. Measured response of leakage versus the sinusoidal injection phase

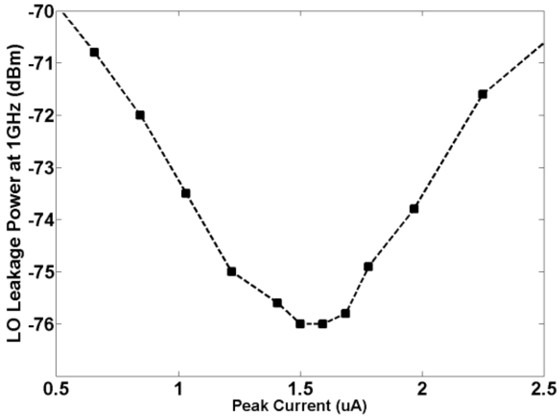

Fig. 5. Amplitude tuning at the optimal 225 degree phase

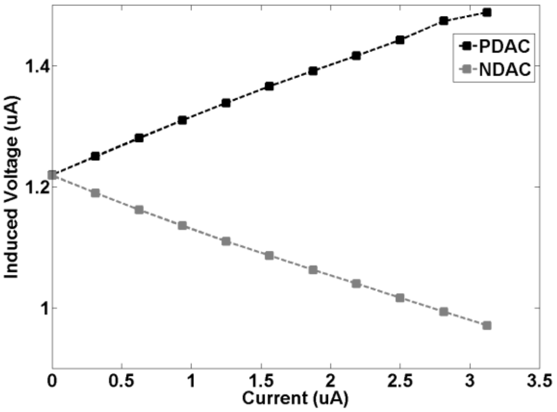

Fig. 6. Linear response curves for the NFET and PFET DACs

For a chip with an original leakage of -64.5dBm at 699.75 MHz (comparable to prior work [1, 4]), the automated algorithm improved leakage to -80.1dBm shown in a spectrum analyzer plot in Fig. 7. In Fig. 8, we show that the results of the algorithm, run at 700MHz, provide suppression across a range of frequencies around 700MHz. Fig. 9 shows the result of applying this technique across a decade of frequency (recalibrated at every point). We note that we had $<$ 0.5 dB noise figure degradation from 100-700 MHz and $<$1.5 dB of noise figure degradation for higher frequencies. Critically, all the calibrations were performed without resorting to any RF test equipment, and so can be performed on the fly in a deployed wireless system.

IV. CONCLUSION

We have presented a passive mixer-first receiver with current DACs in digital feedback, and shown how this architecture can suppress LO leakage without resorting to any RF test equipment. We detect LO leakage by modulating the leakage on the RF port and reading back through the receiver itself show both manual and automatic algorithms to suppress this leakage < -80dBm. This technique uses solely baseband circuitry, eliminating the need for expensive RF spectrum monitoring. This exemplifies the concept of an automatic SDR, and yields interesting avenues to explore how baseband measurements can ascertain RF port properties.

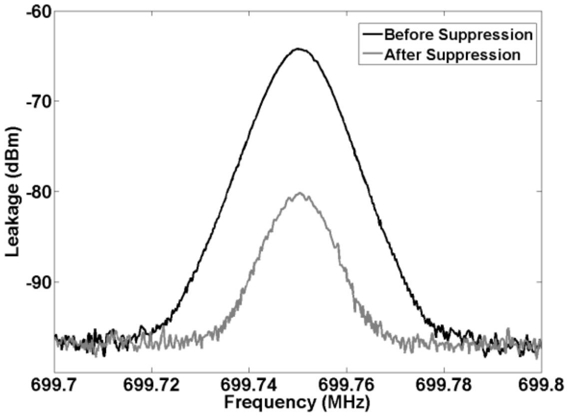

Fig. 7. Spectrum analyzer plot of suppression at 699.75 MHz

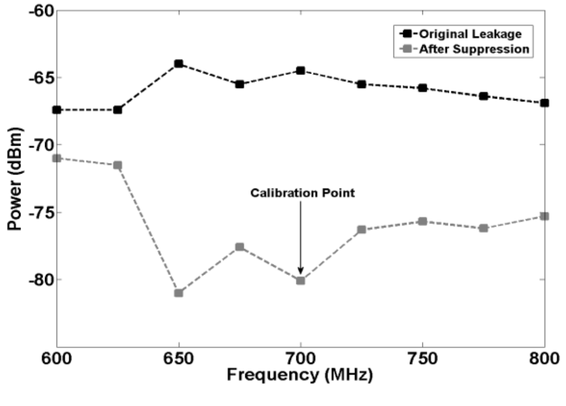

Fig. 8. Bandwidth of 700MHz calibration

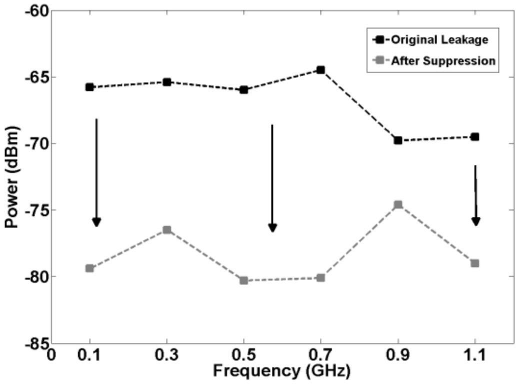

Fig. 9. Results of automated suppression across frequency with calibrations

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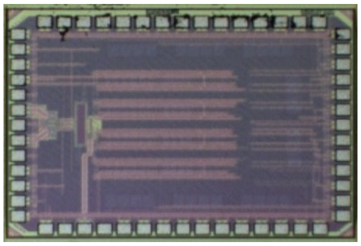

Fig. 10. Microphotograph of the fabricated receiver