

Recent Developments in Fully-Integrated RF Self-Interference Cancellation for Frequency-Division and Full-Duplex Radios

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Abstract—RF self-interference cancellation (SIC) relaxes duplexer isolation requirements in frequency-division-duplex (FDD) radios, enabling compact/tunable duplexers. RF SIC is also critical for full-duplex radios where extremely-high levels of SIC must be achieved, necessitating SIC at various points in the receiver chain. While *active* RF SIC is potentially compact and highly reconfigurable, the use of active circuitry in the canceller introduces noise, distortion and power dissipation challenges. Furthermore, and particularly for fully-integrated silicon-based SIC implementations, the bandwidth (BW) of RF SIC is limited by the frequency selectivity of the antenna interface and the wireless self-interference channel. In this paper, we present recent developments in fully-integrated RF SIC techniques that address these challenges.

I. INTRODUCTION

The simultaneous operation or *duplexing* of the transmitter (TX) and receiver (RX) of a radio poses significant challenges in the receiver due to the powerful echo or self-interference from the transmitter. Frequency-division duplexing (FDD) is an integral part of several of today's wireless systems, and requires a frequency-selective duplexer to separate the transmitter and receiver signals. Emerging reconfigurable or multi-band FDD radios require numerous off-chip duplexers, which limit the form factor. Widely-tunable RF active self-interference cancellation (SIC) is a step towards enabling compact or even tunable duplexers with relaxed TX/RX isolation.

Recent works suggest that full-duplex radios, *where the transmitter and receiver operate at the same time at the same frequency*, can greatly improve network performance [1],[2],[3]. However, full-duplex operation typically requires extremely high levels of SIC (typically >100 dB), as filtering the self interference is not an option. In order to achieve such high levels of SIC, cancellation must be pursued in RF, analog/mixed-signal and digital domains.

A fundamental challenge associated with active RF SIC is the *noise and distortion of the cancellation circuitry*, which can limit the receiver performance. A second challenge with *fully-integrated* RF SIC is the cancellation bandwidth (BW), which is typically limited by the frequency selectivity of the antenna interface and the wireless self-interference channel. Duplexers for FDD are inherently selective due to the use of high-Q filters in the TX and RX paths. Full-duplex self-interference channels can be frequency-selective due to the narrowband nature of the antennas used and presence of ambient reflections [4]. The resultant sharp changes in isolation amplitude and phase are challenging to replicate in the canceller, particularly in IC-based implementations.

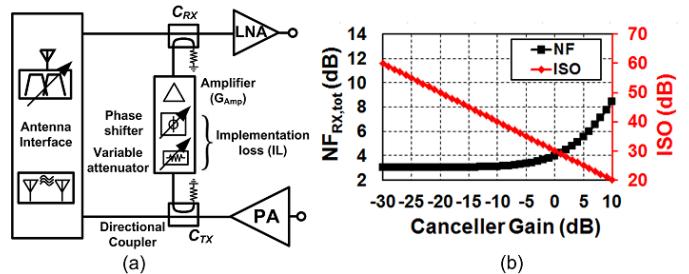


Fig. 1. (a) Transceiver block diagram with a generic active RF SI canceller. (b) Total RX NF and minimum supported inherent antenna interface isolation as a function canceller amplifier gain.

While there has been significant recent progress towards the demonstration of the feasibility of full-duplex operation, these works have typically considered radios constructed using off-the-shelf components [1],[2]. Fully-integrated implementations of RF/analog SIC are plagued with unique challenges, and only recently have IC implementations of RF/analog SIC circuitry emerged in the literature [5],[6],[7]. This paper discusses challenges associated with fully-integrated RF/analog cancellers and covers recent developments in RF SIC techniques for FDD and full-duplex applications [5],[7],[8]. In [5],[8], a Noise-Cancelling Self-interference Cancelling (NC-SIC) receiver is proposed that can support an antenna isolation as low as 20-25 dB through widely tunable active RF SIC for FDD. In addition, the noise and distortion of the active RF SIC circuitry are cancelled in the NC-SIC receiver. In [7], a wideband RF SIC technique based on frequency-domain equalization is proposed that enables >20 MHz 20 dB SIC BW for both FDD and full-duplex applications across a variety of antenna interfaces.

II. ACTIVE RF SIC CHALLENGES

A. SIC Requirements for FDD and Same-Channel Full-Duplex

For FDD, the transmitter SI must be suppressed sufficiently to prevent linearity issues in the RX front-end prior to analog baseband filtering. Typical commercial fixed-frequency duplexers achieve 50-55 dB isolation. If duplexers with reduced isolation are to be used to enable tunability and/or reduced form factor, RF SIC must enhance the isolation to this 50-55 dB level.

For same-channel full-duplex, the transmitter SI must be suppressed below the RX noise floor. Given a transmission power (P_{TX}) of +20 dBm, signal BW of 20 MHz, and a RX NF of 5 dB¹, to prevent RX sensitivity degradation, more than 116

1.These numbers correspond to a commercial WLAN link with 64-QAM OFDM[4].

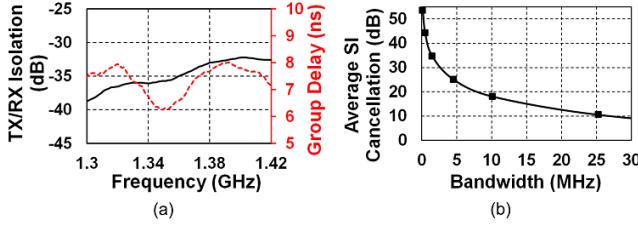


Fig. 2. (a) Measured isolation magnitude and group delay of a 1.4 GHz narrowband dipole-antenna pair. (b) Calculated average cancellation versus TX signal BW assuming flat magnitude and phase response from the canceller.

dB SIC needs to be achieved in the antenna interface as well as along the receiver chain in RF/analog and digital domains. Multi-domain cancellation for same-channel full-duplex involves several challenges. Firstly, cancellation in a certain domain can result in remaining SI signals with sharper frequency selectivity, further limiting downstream SIC BW beyond what is discussed in the following section. Secondly, the phase noise of the local oscillator can severely limit the total amount of SIC, as the delay between transmission and reception reduces the correlation between transmitted and received SI signals [9].

B. Tradeoffs and Benefits Associated with Fully-Integrated Active RF SIC

As opposed to passive cancellers, active RF cancellers are potentially compact and widely tunable, and their gain enables support of low inherent antenna interface isolation levels. However, concerns regarding noise, distortion and power consumption of the active RF canceller must be addressed.

A generic active RF SIC approach is shown in Fig. 1(a). To partially compensate for the coupling ratios of the couplers (C_{TX} and C_{RX}) and implementation losses (IL) in the canceller, an amplifier with gain G_{Amp} is used. C_{TX} must be high to avoid degrading PA efficiency and is assumed to be 15 dB. The required G_{Amp} can be related to the inherent antenna interface isolation ISO in the dB scale as:

$$ISO = C_{TX} + C_{RX} - G_{Amp} + IL. \quad (1)$$

If the noise figures of the canceller and the RX are $NF_{Canceller}$ and NF_{RX} respectively, the NF of the RX including the canceller can be calculated as:

$$NF_{RX,tot} = 10^{NF_{RX}/10} + 10^{(NF_{Canceller} + G_{Amp} - IL - C_{RX})/10}. \quad (2)$$

From (1) and (2), a larger value of C_{RX} protects the receiver from NF degradation due to the canceller but requires greater ISO to be achieved in the antenna interface. Assuming $NF_{RX}=3$ dB, $NF_{Canceller}=12$ dB, $C_{TX}=15$ dB, $C_{RX}=10$ dB, $IL=5$ dB, the $NF_{RX,tot}$ and ISO are plotted versus G_{Amp} in Fig. 1(b). In order to support antenna interfaces with as low as 20-25 dB isolation, 5-10 dB gain is required in the canceller amplifier but the overall NF will degrade by 2.5-5.5 dB. While active RF SIC enables support for lower inherent isolation in the antenna interface, there is a fundamental trade-off between antenna interface isolation and RX NF degradation. For FDD, our work in [5], which is discussed in the following section, breaks this trade-off through the insight that an active canceller that is integrated with the RX on the RFIC can be co-designed with

the RX - by embedding the canceller within a noise-cancelling low-noise transconductance amplifier (LNTA), the noise of the cancellation path is cancelled. For same-channel full-duplex, antenna isolation enhancement and/or cancellation techniques alleviate the RX NF degradation.

The linearity of the RF SI canceller is critical, since the (third-order) distortion products generated by the canceller at the RX input behave like SI. For FDD, SI itself is not an issue as it is outside the RX band and will be filtered away. However, gain compression induced by the SI, second-order intermodulation in the downconversion mixers, reciprocal mixing and cross modulation between the SI and an unknown in-band jammer (quantified by triple beat or TB) are all factors that can degrade RX sensitivity. In [8], a detailed analysis for FDD proves that a (relaxed) receiver with an active RF SI canceller at its input is far more power efficient than a highly-linear receiver that meets cross-modulation distortion requirements in the face of powerful modulated TX SI. Another advantage of active RF SIC is that the canceller can be deactivated to save power when the TX is off or operating at low output power levels. For same-channel full-duplex, the RF SI canceller must be linear enough to keep its distortion products below the RX noise floor. Alternately, digital cancellation of these distortion products can be pursued but is potentially computationally intensive and challenging.

C. Challenges Associated with Fully-Integrated RF SIC BW

RF SIC bandwidth is typically limited by the selectivity of the antenna interface [4]. A highly frequency-selective isolation is characterized by sharp variations in magnitude and phase response with frequency. A sharply-varying phase response is representative of a large group delay in the isolation path. Wideband RF SIC requires replication of the antenna interface isolation in the RF canceller. Generation of large time delays in a fully-integrated CMOS implementation is fundamentally challenging. In [1], bulky PCB-based delay lines occupying a form factor of 10 cm x 10 cm have been used to replicate the delay spread of a same-channel full-duplex SI channel comprising a circulator-based antenna interface. But such approaches are not amenable to silicon integration. Conventional compact silicon-based RF SI cancellers will exhibit a flat magnitude and phase response. Measurements of the isolation magnitude and group delay of a 1.4 GHz narrowband dipole-antenna pair are shown in Fig. 2(a). Using these responses, the average SIC for an OFDM signal centered at 1.36 GHz with 50 sub-carriers given a flat magnitude and phase response from the canceller is calculated and plotted versus TX signal BW in Fig. 2(b). Such a canceller is only useful for signals with less than 8 MHz BW assuming >20 dB average SI cancellation is required.

III. NC-SIC RECEIVER: LOW-NOISE ACTIVE RF SIC

The Noise-Cancelling Self-Interference Cancelling (NC-SIC) receiver architecture [5], [8] addresses the challenges associated with the noise and distortion of the active RF SIC circuitry for FDD applications. This is accomplished by embedding the active RF SIC in a noise-cancelling architecture. The noise-cancelling concept is a technique that allows the achievement of wideband input matching in low-noise

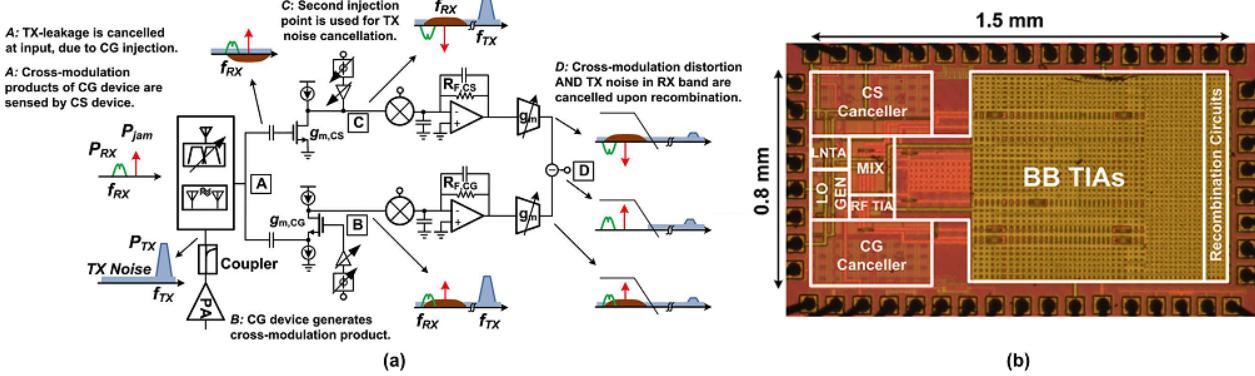


Fig. 5. (a) Operation of the NC-SIC receiver architecture for FDD - simultaneous cancellation of the self-interference at the receiver input, noise of the cancellation circuitry, distortion of the cancellation circuitry and transmitter noise in the receiver band. (b) Chip microphotograph of a 0.3-1.7GHz blocker-tolerant NC-SIC receiver in 65nm CMOS.

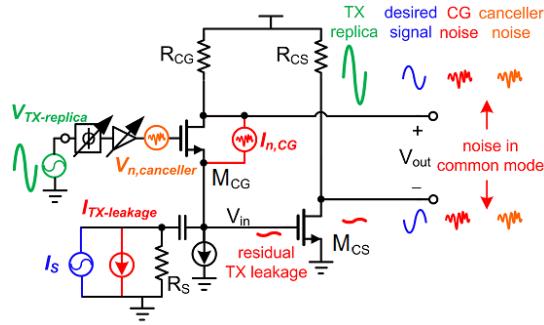


Fig. 3. Noise-Cancelling Self-Interference Canceller (NC-SIC): embedding the self-interference canceller in a noise-cancelling LNA.

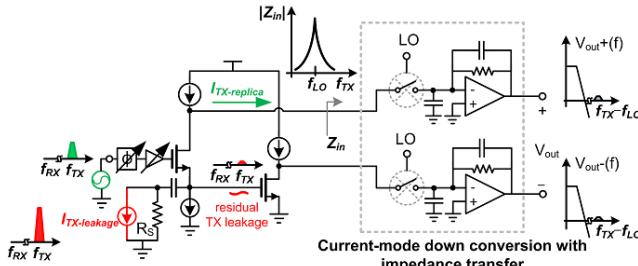


Fig. 4. Noise-Cancelling Self-Interference Cancelling Receiver (NC-SIC RX).

amplifiers (LNAs) with ideally no noise penalty through the use of a voltage-sensing stage (the common-source transistor M_{CS} shown in Fig. 3) in parallel with a matching stage (common-gate transistor M_{CG} in Fig. 3) [10], [11]. When the outputs of the two stages are combined differentially, the noise from the matching device is cancelled while the desired signal adds constructively.

The NC-SIC technique repurposes the common-gate (CG) device for SIC. By driving the gate of the CG device with an appropriately-scaled TX replica signal, the SI can be cancelled right at the input of the LNA. The advantage of such an approach is that the entire noise from the active canceller, including the transistor M_{CG} , the variable-gain amplifier and the phase shifter, is completely cancelled through the noise cancelling property, as the common source device M_{CS} senses the noise from the canceller and then subtracts it at the output.

Therefore, in the proposed scheme, SIC is achieved right at the LNA input with ideally no noise penalty.

The current generated by the CG device that cancels the SI at the input will create a large voltage swing at the CG output, which can severely degrade receiver linearity. This challenge can be dealt with through current-mode receiver design - in Fig. 4, a current-mode downconversion stage with impedance transfer from baseband consisting of passive mixers and baseband transimpedance amplifiers (TIAs) is inserted before the combining network to filter out the large OOB self-interference current before the achievement of voltage gain. The structure has evolved into a Noise-Cancelling, Self-Interference Cancelling RX (NC-SIC RX).

It should be noted that this SI current in the CG path limits the applicability of the NC-SIC technique in this form to FDD applications where the SI is outside the receiver band and can be filtered away. An interesting variant of the NC-SIC technique was developed concurrently and introduced in [6] where the SI is not cancelled at the input, but rather at the combined output. This enables the use of the technique for full-duplex but limits the SI level that can be tolerated due to its presence at the LNA input.

By embedding the canceller within the noise-cancelling LNTA, the conventional RX-side passive coupler is eliminated, with the LNTA CG device providing that functionality. However, it should be noted that while the LNTA common-source (CS) device is protected from the SI, the CG device still sustains large SI voltage swing at its gate node due to the CG canceller injection, and can generate cross-modulation distortion together with an incident in-band CW jammer. Interestingly, the cross-modulation distortion of the CG device gets cancelled as well upon baseband recombination, as it is sensed by the CS device, generating a distortion current that is in phase with the distortion current in the CG path (Fig. 5(a)). This is similar to the distortion cancellation property of noise-cancelling LNAs [11] and implies that active RF SIC has been achieved with no noise or distortion penalty.

In FDD, unlike full duplex, the TX leakage signal and TX noise in the RX band lie at different frequencies. Consequently, their transfer functions through the antenna interface will be different and cancelling one does not imply cancellation of the other. Therefore, the TX noise in the RX band will remain in

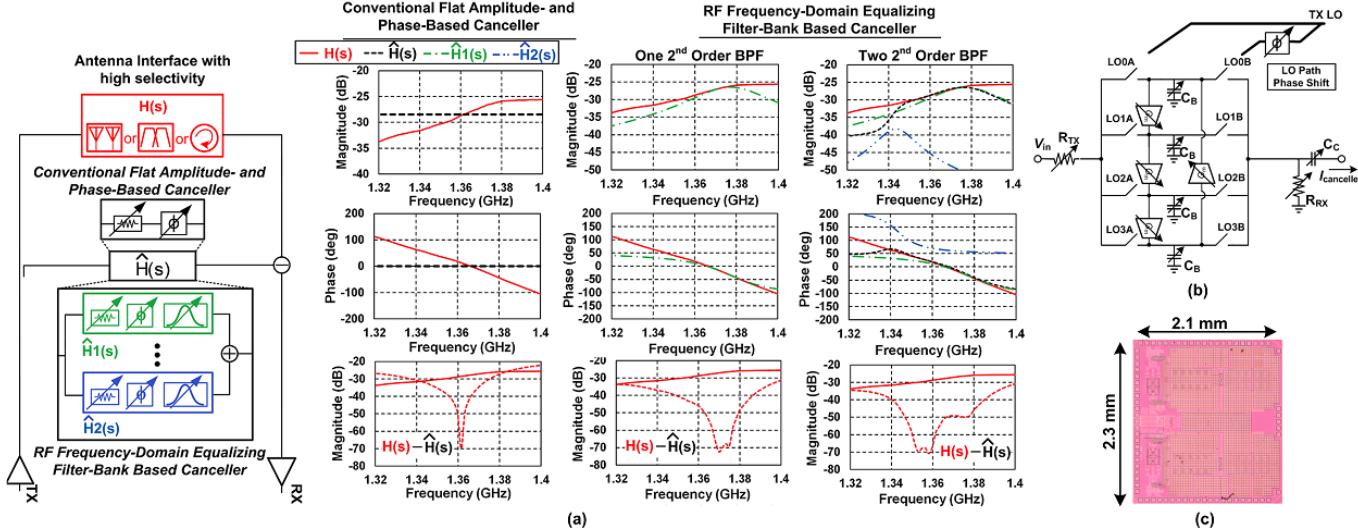


Fig. 6. (a) Frequency-domain equalization-based (FDE-based) RF SIC concept. (b) N-path Gm-C filter implementation with embedded variable attenuation and phase shifting and widely reconfigurable Q and center frequency. (c) Chip microphotograph of a 0.8-1.4 GHz receiver in 65 nm CMOS employing the reconfigurable FDE-based RF SI canceller.

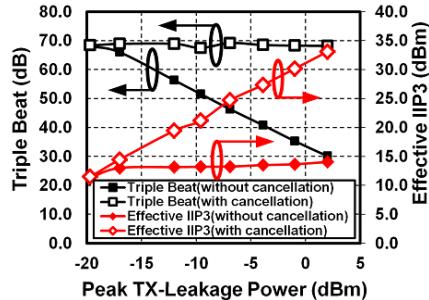


Fig. 7. Receiver triple beat and effective IIP3 measurement without cancellation and with cancellation using the CG canceller. The baseband circuits adjust the weights on the CG and CS paths for optimum TB performance.

both the CG and CS paths, and can desensitize the receiver. Since noise is small, TX noise can be cancelled down the receiver chain [12]. A second injection point is introduced in current mode at the output of the CS device (Fig. 5(a)). With appropriate scaling using this CS canceller, TX noise can be nulled upon baseband recombination. Noise penalty of the CS canceller is alleviated by the CS gain.

A wideband (0.3-1.7 GHz) NC-SIC receiver was implemented in 65nm CMOS (Fig. 5(b)). The reader is directed to [8] for additional details related to theoretical analysis of the noise and distortion cancellation as well as the circuit design. Cancellation of up to +2 dBm of peak SI is demonstrated at the receiver input. Triple beat (TB) measurements are conducted with and without SIC using a two-tone OOB TX leakage signal and an in-band continuous-wave (CW) jammer signal. In the absence of cancellation, the TB is only 30 dB for +2 dBm of peak SI, which is consistent with the receiver's measured OOB IIP3 of +12-14 dBm (Fig. 7). When SIC is enabled, a TB of around 68 dB is maintained independent of the SI level, corresponding to an *effective* IIP3 of +33 dBm at +2 dBm of peak SI (Fig. 7). The associated increase in receiver NF is only 0.8 dB for the same CG canceller and baseband recombination settings that maximize the triple beat at +2 dBm of peak SI. When noise cancelling is

disabled, the NF increase is as much as 7 dB [5], thus validating the claims.

IV. FDE-BASED WIDEBAND ACTIVE RF SIC

As mentioned earlier, RF SIC BW is typically limited by the frequency selectivity of the antenna interface isolation and that of wireless self-interference channels. A conventional flat amplitude- and phase-based canceller can only perfectly replicate the isolation at a single frequency point. In order to extend the cancellation BW, a reconfigurable filter that can adaptively emulate the frequency-dependent isolation is required. The frequency-domain equalization-based (FDE-based) active RF SIC technique introduced in [7] and depicted in Fig. 6(a) employs a bank of reconfigurable 2nd-order bandpass filters to accomplish this. A 2nd-order bandpass filter combined with amplitude and phase scaling features four degrees of freedom, namely center-frequency, Q, absolute amplitude and absolute phase. These can be leveraged for the replication of not just the amplitude and phase at a frequency point, *but also the slope of the amplitude and the slope of the phase (i.e. group delay)*, enhancing cancellation bandwidth. The group delay of a 2nd-order bandpass filter is proportional to the Q, and upward/downward shifts of center frequency enable replication of positive/negative amplitude slopes. *A bank of such filters with independently controllable parameters enables such replication at multiple points in different subbands, further enhancing cancellation bandwidth.*

A key requirement, however, is the availability of high-Q, highly-linear, reconfigurable RF bandpass filters on silicon. Recently, N-path filters have emerged as a promising solution [13]. The Q of an N-path filter may be altered via the baseband capacitor (C_B) and the center-frequency may be shifted without changing the LO frequency using clockwise/counter-clockwise-connected baseband Gm cells [13] (Fig. 6(b)). Interestingly, phase shifting can be embedded in the LO path in a two-port (input/output) 2nd-order bandpass N-path filter by phase shifting the LOs driving the switches on the output side (Fig. 6(b)). Analysis reveals that this introduces constant phase shifts with no other impact on close-in frequency response.

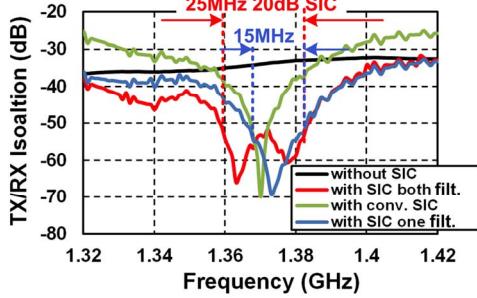


Fig. 8. Cancellation measurements across the 1.4 GHz narrowband dipole-antenna pair: TX/RX isolation after theoretical flat amplitude- and phase-based SIC as well as measured SIC with one and two filters enabled.

Variable attenuation (amplitude scaling) can be introduced by reconfiguring R_{RX} and R_{TX} relative to each other (Fig. 6(b)).

A 0.8-1.4 GHz receiver with an FDE-based RF canceller comprising a bank of two 2nd-order bandpass filters was implemented in 65nm CMOS (Fig. 6(c)). The reader is directed to [7] for additional details related to the circuit design. The receiver was measured with a variety of antenna interfaces including (i) a custom-designed 0.8 GHz/0.9 GHz LTE-like FDD duplexer employing surface-mount-device (SMD)-based 2nd-order LC filters with 3.2 dB/2.7 dB TX/RX insertion loss, 115 MHz TX/RX separation and only 30 dB worst-case isolation, and (ii) a 1.4 GHz narrowband dipole-antenna pair for full-duplex with peak isolation group delay of 8 ns and worst-case magnitude of 34 dB (shown in Fig. 2(a)). The FDE-based canceller enables >20 MHz 20 dB SIC BW in both cases.

Specifically, across the full-duplex antenna pair, the SI canceller achieves a 20 dB cancellation BW of 15/25 MHz with one/two filters enabled - an increase of 5/8\$times\$ over a conventional canceller (Fig. 8). The associated NF increase is 0.9-1.2 dB/1.1-1.5 dB. SIC of up to -8 dBm of peak in-band TX leakage at the RX input is measured. As a result of SIC, negligible gain compression of a desired signal is observed at this leakage level (as opposed to nearly 22 dB of compression in the absence of SIC). SIC also improves the impact of receiver nonlinearity on the TX leakage itself - effective in-band IIP3 increases from -20 dBm to +2 dBm and effective in-band IIP2 increases from +10~dBm to +68 dBm. Measurements have also been conducted with a 1.37 GHz 27 MHz-BW RRC-filtered 64-QAM signal across the antenna pair, and 20 dB average cancellation is observed (shown in Fig. 9). This measurement was performed in an anechoic chamber, and measurements in other environments are ongoing.

V. CONCLUSION

While progress has been made in the implementation of IC-based RF SI cancellers, several open problems remain. Small-form-factor antenna interfaces for FDD and full-duplex with sufficient inherent isolation are of interest. Adaptive calibration techniques that configure these cancellers as the antenna impedance and environment vary are an important topic for research. Joint RF, analog and digital cancellation in the

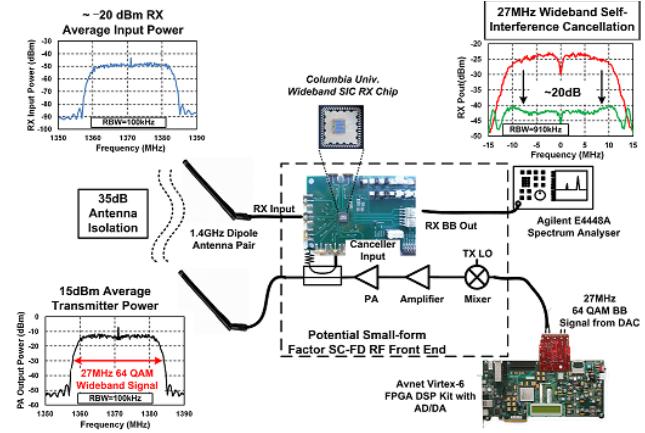


Fig. 9. Wideband RF SIC of a 1.37 GHz 27 MHz-BW RRC-filtered 64-QAM signal demonstrating 20 dB average cancellation.

presence of oscillator phase noise levels that are typical of integrated oscillators is also an important problem.

ACKNOWLEDGMENT

This work was supported by the DARPA RF-FPGA program.

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