

# An Integrated CMOS Passive Transmitter Leakage Suppression Technique for FDD Radios

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**Abstract** — An integrated passive transmitter (TX) leakage suppression technique is proposed for FDD Radios. A Four Port Canceller (FPC) serves a dual function as a receiver (RX) input matching network, and provides an auxiliary path from TX to RX, used for leakage cancellation, without degrading the RX noise figure (NF). The FPC is integrated with a low noise amplifier (LNA) and an emulated power amplifier (PA) in 40nm CMOS process. A cancellation of 23dB is achieved with a negligible power consumption and noise penalty.

**Index Terms**—Transmitter leakage, Fully Passive, Wideband Code Division multiple access (WCDMA), Interference suppression, SAW-Less Transceivers.

## I. INTRODUCTION

The continued demand for higher levels of access and increased data rates for a variety of wireless applications, from mobile smart phone devices to back haul point-to-point communication, continues to drive research towards high speed, wideband and low cost radios. Frequency division duplexing (FDD), rather than time division multiple access (TDMA) standards, achieve higher speeds. However, in a FDD system, since the TX and RX share the same antenna and operate at the same time using a duplexer, a non-negligible signal from the TX will “leak” through the duplexer and appear at the RX front-end. For example, in the WCDMA standard, although a duplexer will significantly suppress TX leakage (up to 50dB), a residual attenuated signal still remains at the receiver input. Thus, the TX leakage is often the largest blocker present at the RX input, making a low-noise and low-power linear receiver design very challenging. This leakage problem is exacerbated by applications such as future cognitive and software-defined radios where the duplex band would ideally be kept to a minimum, to improve spectral efficiency. An off-chip surface acoustic wave (SAW) filter is usually connected between the LNA and downconverter to further suppress the TX leakage. However, these filters are band specific, prohibiting highly programmable solutions. Moreover, additional discrete filters are area inefficient, and increase cost/power consumption.

Several recent efforts have attempted to attenuate or reduce the effect of the TX leakage in the RX signal path. A front-end on-chip high-Q passive-filter using bond

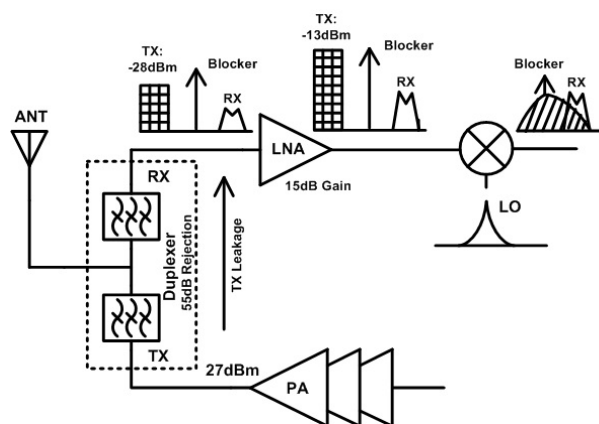


Fig.1. TX Leakage issues in FDD Radios

wires is presented in [1]. An active bandpass sink filter was proposed after the down-conversion mixer by creating a low impedance node at the down-converted input to notch out the TX leakage signal [2-3]. A feed-forward canceller that samples the reference signal from the TX output was implemented in [4]. Other methods [5-7, 9] were reported to address the self-leakage problem; however, all of the aforementioned approaches utilize an active cancellation path which is problematic from a noise and power perspective.

An ideal integrated TX leakage canceller should have the following characteristics:

- Introduce no noise, or additional power, while using minimal silicon area.
- Perform cancellation at the receiver input to relax the required RX selectivity performance.
- Present negligible loading (high impedance) to the TX-PA output.
- Minimize loss in the RX/TX signal chains.

This paper proposes to perform TX leakage cancellation at the RX input, using only passive-reactive components with minimal silicon area and negligible extra power. An example of this technique was applied to the design of a WCDMA front-end. By performing suppression at the RX input, the linearity (IP2) performance of the LNA and subsequent blocks is relaxed, leading to a lower power consumption solution. In addition, cancellation at the

LNA input helps to eliminate the need for a discrete high-Q SAW filter after the LNA.

Section II describes the TX leakage problem from the system level. A description of the proposed passive FPC is given in Section III. While Section IV presents the circuit implementation details. Section V provides measurement results, followed by concluding comments in Section VI.

## II. SYSTEM CONSIDERATIONS

The TX leakage problem is illustrated in Fig.1, using WCDMA as a point of discussion. Assuming a TX output power of 27dBm and 50dB suppression through the duplexer, a residual -23dBm TX leakage will be present at the LNA. Assuming an LNA gain at the TX frequency of 15dB, the TX leakage is amplified to -8dBm. In the absence of a SAW filter, the -8dBm TX jammer will appear directly at the LNA output, placing the burden of the IIP2 performance on the mixer; in this example an  $IIP2 > 45\text{dBm}$  is necessary[3]. In addition, any undesired strong blockers close in frequency to the RX band, will cross-modulate with the TX leakage signal, possibly falling into the RX band.

Additional coupling mechanisms are present in modern integrated transceivers using on-chip spiral inductors for matching-networks, resonant-loads, oscillators and resonant peaking. These large inductors, even with the use of guard rings, results in non-negligible electromagnetic coupling between the TX and RX paths. While isolation could be improved by increasing the distance between TX and RX paths, this solution results in an increase in die size and fabrication cost.

Coupling through the substrate is another significant issue. In MOS devices, substrate coupling primarily occurs through the bias-dependent source/drain-to-substrate junction capacitance. The highly non-linear nature of the junction-capacitance makes this coupling-mechanism extremely difficult to model accurately. Other non-negligible coupling mechanisms include different paths of coupling through capacitive, and wire-bond inductance.

In the proposed system, the TX and RX are fabricated on the same die to account for the substrate-coupling mechanisms described above. Moreover, an on-board FBAR filter has been used to model the main leakage path through duplexer.

## III. FOUR PORT CANCELLER (FPC)

The FPC, shown in fig.2, is the key component of the TX leakage cancelling technique. The primary signal

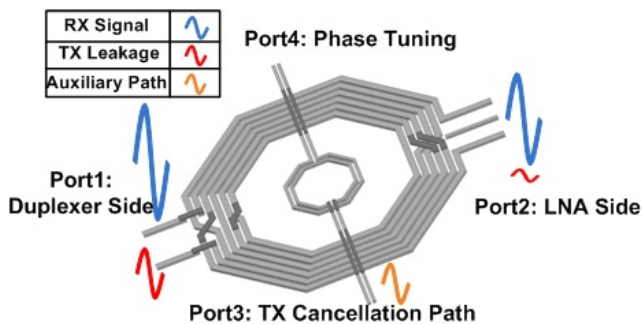


Fig.2. Four Port Canceller (FPC)

received at the antenna side travels from port-1 to port-2 along with any leakage signal from the transmitter. To cancel the TX leakage component at port-2, a portion of the TX output signal is intentionally coupled into the RX path through port-3 of the FPC, as shown in Fig.2. The amplitude and phase of the coupled TX signal is controlled by varying the termination reactance on port-3 and port-4 of the transformer. Also, it is noteworthy that the FPC is completely absorbed in the transformer-based LNA matching network and therefore, does not consume any additional area.

Since the duplexer has a rejection of approximately 50dB at the TX frequencies, any cancellation technique must track the amplitude of the attenuated leakage signal, and generate the opposite phase. This is achieved using two techniques. First, ports 3 and 4 are weakly coupled with ports 1 and 2. Second, a switched capacitor and varactor bank was introduced between the output of the PA matching network and the canceller input, to tune the phase and amplitude of the TX-signal entering the FPC.

Extensive electromagnetic simulations have been done to verify the functionality of FPC in HFSS. With a pure resistive load to mimic the RX input impedance, the FPC shows more than 40dB attenuation over a bandwidth of  $\sim 800\text{ MHz}$ .

## IV. IMPLEMENTATION

The circuit diagram of the integrated WCDMA front-end with passive TX leakage cancellation is shown in Fig.3. In the proposed system, an LNA and an emulated PA are fabricated on the same die, to demonstrate a real scenario with various on-chip coupling schemes. The FPC is connected between an on-chip PA matching network and the LNA. The full cancellation path is shown in Fig. 3. To ensure both the minimal loading effect on the PA output matching network and amplitude tuning range,  $C_{1B}$  is optimally chosen. In the simulation, more than  $1\text{ k}\Omega$

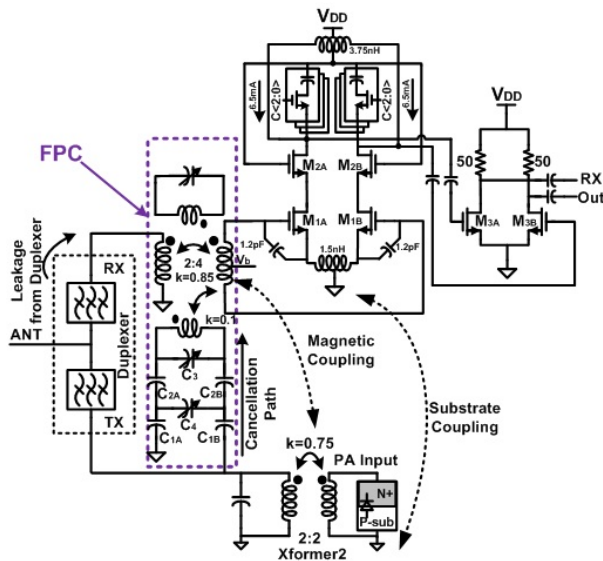


Fig.3. CMOS WCDMA LNA with TX leakage suppression

parallel resistance is observed while maintaining a reasonable amplitude tuning range.

The RX portion consists of a differential LNA driving a differential buffer. To achieve a good noise figure, the FPC provides some passive gain (~6dB) by making the transformer turns ratio 2:4.

On the TX side, to capture the magnetic-coupling between transmitter and receiver coils, the PA output matching network was integrated on-chip. The input to the PA matching network can interface to either a testboard PA, or applied with a signal generator, both of which deliver a  $P_{sat}$  of 30dBm. The matching network consists of a single-ended to single-ended transformer, which is designed to drive an antenna load of 50Ω. To replicate the effect of substrate leakage from the TX, an nwell-to-psub

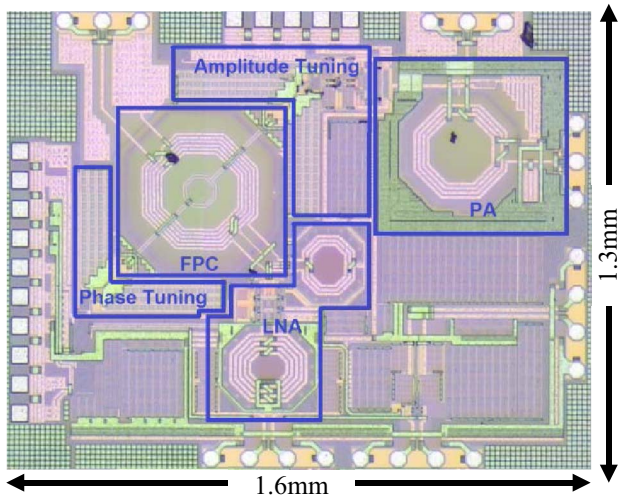


Fig.4. Chip Micrograph

diode has been added in-parallel with the primary winding. The diode was sized to mimic the total active region (NMOS device Area: 22400um<sup>2</sup>) of an output transistor in a WCDMA PA [8].

## V. MEASUREMENT RESULTS

The fully integrated WCDMA front-end with TX leakage suppression technique is fabricated in a 40nm 6-metal TSMC CMOS process and occupies 1.6mm x 1.3mm including bond pads. The die is assembled with the testboard using chip-on-board packaging. A die photo is shown in Fig.4.

The LNA gain, input matching network, and noise figure are measured with the duplexer, the results of which are shown in Fig.5. Since the duplexer has a 1.5dB insertion loss from antenna side to RX side, the peak conversion gain of the combiner and LNA is 20.4dB with a gain variation of 1.2dB within 60MHz RX band. The input matching S11 is <-9dB across the bandwidth.

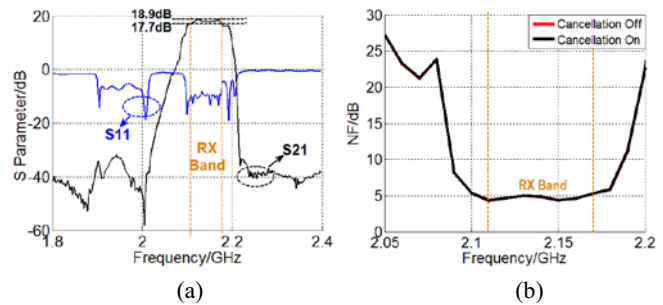


Fig.5. RX Performance (a) S parameter (b) Noise Figure

The NF is measured with both FPC enabled and disabled with an estimated TX leakage power at the RX input around -30dBm. The RX measured double-sideband NF is approximately 5dB, see Fig.5 (b). The contributions to the NF are estimated to be 1.5dB attenuation from the duplexer, an additional loss of 1-1.5dB from the FPC/RX matching network, and 2-2.5dB NF from LNA. The passive gain (~6dB) from FPC helps to lower the power consumption of LNA while achieving a reasonable gain and noise figure. Due to the fully passive structures, no noise penalty is observed with both FPC enabled and disabled (Fig.5 (b)).

The linearity was measured using a two-tone test, with two tones at 10MHz offset from a 2.14GHz center frequency. The IIP3 is 3dBm. This performance is obtained while consuming 10mW from a 1V supply.

To test the TX self-leakage suppression, two signals are injected into the FPC, one through the RX input and the other is applied to the TX input. An average suppression of 23dB is observed both on spectrum analyzer and

oscilloscope over the entire WCDMA TX band with different power level inputs. The measurement results of leakage suppression are in Fig.6.

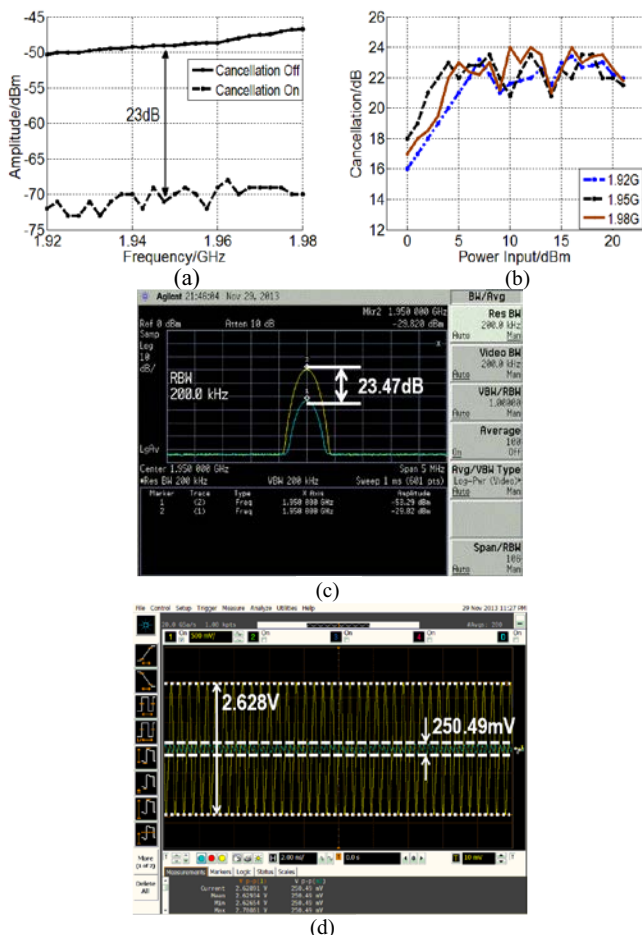


Fig.6. TX Suppression (without duplexer) (a) Suppression over Band (b) Suppression with different power input (c) Freq Domain: TX suppression @1.95G (d) Time Domain: TX Suppression @1.95G

## VII. CONCLUSION

A passive transmitter leakage suppression technique is proposed for WCDMA front-ends. A new FPC structure shows promise with a measured suppression up to 23dB. A detailed circuit performance/comparison is shown in Table I.

The proposed leakage suppression technique introduces a negligible penalty with respect to NF and power consumption, while the state-of-art [3-4] cancellers usually double the power consumption and increases the NF by at least 0.4dB through the introduction of the auxiliary cancellation path.

TABLE I: PERFORMANCE SUMMARY AND COMPARISON

	Tech/ ( $V_{DC}$ )	TX Suppress	NF wo/ NF w <sup>2</sup>	Gain	Idc wo/ Idc w <sup>4</sup>
[3]	65nm/ 2V	6.5dB <sup>1</sup>	3.1dB /4.9dB	45dB	22mA /42mA
[4]	180nm /1.8V	23.4dB	2.4dB /2.84dB	25.4dB	9.1mA /19.6mA
[9]	65nm/ NA	>30dB	4.2dB /5dB	19- 34dB	74.6mA/ 87.6mA <sup>5</sup>
This Work	40nm/ 1V	23dB	5dB/ 5dB <sup>3</sup>	18dB <sup>3</sup>	10mA/ 10mA

<sup>1</sup>Calculated from IIP2 improvement.

<sup>2</sup>NF wo/w: Noise Figure with auxiliary path off/on.

<sup>3</sup>Includes duplexer loss/noise figure around 1.5dB.

<sup>4</sup>Power consumption with auxiliary path off/on

<sup>5</sup>Calculated from 1V supply and includes LO divider power.

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