Wideband, Low Profile Coupling Suppression Circuit for Simultaneous Transmit and Receive System Based on Hybrid Finite Impulse Response and Resonator Topology

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ABSTRACT

In-band full-duplex (IBFD) systems can double the spectral efficiency by enabling simultaneous transmission and reception within the same band. Key to realizing full-duplex radios is the cancellation of the self-interference (SI) that couples from the transmitting antenna into the receiving path. This is done by introducing a self-interference cancellations (SIC) circuit to significantly reduce the coupled transmit signal and avoid receiver’s desensitization. Additionally, SI suppression becomes more challenging across broader bandwidths. This paper presents a novel, wideband, and low profile SIC circuit based on a hybrid Finite Impulse Response (FIR) and resonator filter topology. The latter is optimized to provide an average of 22dB cancellation across 800MHz in the L-band. Conventional, SIC circuits require a filter bank with at least two FIR filters to achieve such a wide bandwidth. Conversely, our FIR resonator design is low profile with a circuit size nearly half of that of a filter bank. Simulations show a minimum cancellation of 15dB and a maximum cancellation of 45dB. A prototype was fabricated and tested, showing an average of ∼20dB cancellation which is in good agreement with our simulation. Further, measured results show a minimum cancellation of 15dB and maximum cancellation of 27dB.

INDEX TERMS

Coupling signal, in-band full duplex, simultaneous transmit and receive, self-interference cancellation.

I. INTRODUCTION

In the currently congested spectrum, in-band full-duplex (IBFD) wireless communication, also known as simultaneous transmit and receive (STAR), extends its benefits for spectrum allocation and reuse [1], [2], [3], [4]. Indeed, an IBFD system can theoretically double the spectral efficiency by allowing concurrent transmission and reception at the same operational frequency. The implementation of the IBFD system is extremely challenging because of the strong self-interference (SI) that leaks from the transmitting to the receiving chains [5], [6], [7]. In many cases, the SI is ∼60–90dB stronger than the desired received signal [8]. Typically, the SI includes coupled direct, noise, and reflected/multipath signals, in addition to harmonics from the power amplifier (PA). Therefore, it is very challenging to predict and suppress the SI below the receiver’s noise floor [2], [9], [10]. For instance, for WiFi applications, the noise floor is about -90dBm. If the transmit power is 10dBm, then at least 100dB of self-interference cancellation (SIC) is necessary for successful implementation of IBFD communication system.

To achieve such a high SIC level, coupling suppression circuits are required at the transceiver’s front-end, as depicted in Fig. 1. SIC circuits have been typically designed to achieve 1) passive antenna cancellation, 2) radio frequency (RF) cancellation, and/or 3) digital cancellation. Examples of passive cancellation techniques employ decoupling circuits between antenna elements [9], [11], [12], beamforming...
architectures [10], [13], or circulators [14], [15], [16]. Typically, the first two techniques employ multiple antenna elements, implying increased hardware complexity. Alternatively, a single antenna is used in STAR systems using a circulator between the transmit and receive chains. However, commercially available circulators have a limited port-to-port isolation of 25dB [15]. In our previous work, we used combination of two circulators and an SIC circuit. The topology yielded an average isolation of 55dB across a 20MHz of bandwidth [16].

Larger SIC have been reported across much smaller bandwidths. In [17], researchers implemented a multi-antenna system with 60dB isolation over 5MHz of bandwidth. In [18], a 16-tap filter consisting of multiple fixed delay lines and an attenuator are used to achieve 47dB SI cancellation across a narrow band of 80MHz. A time-domain narrow-band cancellation employing a filter with four tap delay lines and attenuators was able to show 30dB of cancellation over a bandwidth of 30MHz in [19]. In [20], a 30dB decrease in Tx/Rx coupling over 110MHz was achieved by using two narrow-band tunable resonators in the antenna array near field. A finite impulse response (FIR) filter was used in another STAR design to provide 25dB of cancellation across 500MHz [3]. The bandwidth of this device was eventually increased to 1GHz by cascading multiple FIR filters [21]. However, this cascading technique requires more space and increased hardware complexity. In another study [22], a filter bank concept is introduced in the design of the ultra-wideband (UWB) RF-SIC filter to produce 20dB cancellation over a narrow band of 80MHz. A time-domain narrow-band cancellation employing a filter with four tap delay lines and attenuators was able to show 30dB of cancellation across 110MHz in [19]. In [20], a 30dB decrease in Tx/Rx coupling over 110MHz was achieved by using two narrow-band tunable resonators in the antenna array near field. A finite impulse response (FIR) filter was used in another STAR design to provide 25dB of cancellation across 500MHz [3]. The bandwidth of this device was eventually increased to 1GHz by cascading multiple FIR filters [21]. However, this cascading technique requires more space and increased hardware complexity. In another study [22], a filter bank concept is introduced in the design of the ultra-wideband (UWB) RF-SIC filter to produce 20dB cancellation over a 1GHz bandwidth. However, using a filter bank implies increased coupling and hence less isolation.

In our previous study, we developed a novel hybrid 6-tap FIR and resonator design to achieve >25dB cancellation across 500MHz [23]. In this paper, we extend the design of our FIR-resonator circuit [23], depicted in Fig. 2, to operate across 800MHz of bandwidth. A prototype is fabricated and tested from 1GHz to 1.8GHz, for L-band applications [24], [25]. Notably, the L-band is used for satellite navigation, mobile service, aircraft surveillance, as well as digital audio and multimedia broadcasting. In our study, we used a single FIR resonator that achieved a minimum of 15dB to maximum 27dB cancellation. To our best knowledge, this is the first SIC circuit based on an FIR resonator topology to cover such a large bandwidth using a simple and low cost design.

The paper is organized as follows: Section II describes the IFBD cancellation technique in the analog stage. Circuit design and optimization of the wideband FIR resonator are detailed in Section III. Prototype fabrication and measurements are given in Section IV. Section V depicts the antenna and RF isolation. Section VI demonstrates the performance comparison with other RF-SIC filter. Section VII concludes the paper.

FIGURE 1. A bi-static STAR system with a cancellation filter implemented at the analog stage.

II. CHANNEL MODELING AND RF COUPLING SUPPRESSION TECHNIQUE

The analog SIC stage, shown in Fig. 1, consists of a power splitter at the transmitter, an RF-SIC circuit, and a power combiner at the receiver. As such, the transmit (Tx) signal is equally split into two signals, both denoted as \( s(t) \), where one signal is fed to the Tx antenna and the other one is fed to the cancellation circuit. Notably, the RF-SIC circuit is designed and optimized to have an impulse response \( h_{\text{cancellation}}(t) \) that conjugately matches the impulse response \( h_{\text{leakage}}(t) \) of the coupling channel between the Tx and receive (Rx) antenna. Since the scattering parameters are related to the channel impulse response, using [3]:

\[
h_{\text{leakage}}(t) = \frac{S(2, 1)(1 - \Gamma_L)(1 - \Gamma_S)}{(1 - S(1, 1)\Gamma_L)(1 - S(2, 2)\Gamma_S) - S(2, 1)\Gamma_L S(1, 2)\Gamma_S} (1)
\]

where, \( \Gamma_L \) and \( \Gamma_S \) are the reflection at the source and load of the two-port network formed by the Tx and Rx ports. Under matching conditions, \( \Gamma_L = \Gamma_S = S(1, 1) = S(2, 2) = 0 \). Hence, (1) become

\[
h_{\text{leakage}}(t) = S(2, 1) (2)
\]

The coupled signal \( y_{\text{coupled}}(t) \) at the Rx antenna is expressed as,

\[
y_{\text{coupled}}(t) = s(t) \ast h_{\text{leakage}}(t) (3)
\]

Similarly, the signal \( y(t) \) at the output of the RF-SIC circuit is expressed as,

\[
y(t) = s(t) \ast h_{\text{cancellation}}(t) (4)
\]

Hence, at the combiner output of the receiver chain, we get

\[
c(t) = s(t) \ast h_{\text{leakage}}(t) + s(t) \ast h_{\text{cancellation}}(t) (5)
\]
which can be rearranged such as

\[ c(t) = s(t) * (h_{\text{leakage}}(t) + h_{\text{cancellation}}(t)) \]  

(6)

To achieve maximum suppression of the coupled signal, we need to minimize \( c(t) \). Ideally, we need \( c(t) \approx 0 \). That is,

\[ h_{\text{leakage}}(t) + h_{\text{cancellation}}(t) = 0 \]  

(7)

or

\[ h_{\text{leakage}}(t) = -h_{\text{cancellation}}(t) \]  

(8)

By taking the Fourier Transform (FT) \([26]\) of (8), we obtain,

\[ \int_{w_{\text{low}}}^{w_{\text{high}}} h_{\text{cancellation}}(w)e^{-j\omega w}dw = -\int_{w_{\text{low}}}^{w_{\text{high}}} h_{\text{leakage}}(w)e^{-j\omega w}dw \]  

(9)

Hence,

\[ H_{\text{cancellation}}(j\omega) = -H_{\text{leakage}}(j\omega) \]  

(10)

From (10), we conclude:

\[ |H_{\text{cancellation}}(j\omega)| = |H_{\text{leakage}}(j\omega)| \]  

(11)

and

\[ \angle H_{\text{cancellation}}(j\omega) = 180^\circ + \angle H_{\text{leakage}}(j\omega) \]  

(12)

In this paper, we present a novel RF-SIC circuit based on a series combination of FIR circuit taps and a stub resonator with a frequency response \( H_{\text{cancellation}}(j\omega) \) that satisfies (11) and (12). We note that, in the digital domain, the FIR filter is realized by a series of delays lines \((\tau_1, \tau_2, \ldots, \tau_M)\) and tap coefficients \((b_0, b_1, \ldots, b_M)\) \([26]\). In the analog domain, tap delays and coefficients are realized by RF microstrip delay lines and attenuators, respectively. A microstrip open stub acts as a resonator with an impulse response:

\[ h_{\text{resonator}}(t) = r\delta(t - \tau_r) \]  

(13)

where \( r \) and \( \tau_r \) are the coefficient and time delay of the resonator filter, respectively. Hence, referring to Fig. 2, at the output of the resonator filter, the signal is:

\[ y_{\text{res}}(t) = s(t) * h_{\text{resonator}}(t) = rs(t - \tau_r) \]  

(14)

The cascade impulse response of the hybrid FIR resonator can be expressed as

\[ h_{\text{cancellation}}(t) = rb_0\delta(t - \tau_r) + rb_1\delta(t - \tau_1 - \tau_r) + \ldots + rb_M\delta(t - \tau_M - \tau_r) \]  

(15)

Hence, the filter signal \( y(t) \) at the output of the FIR resonator can be written as:

\[ y(t) = s(t) * h_{\text{cancellation}}(t) \]

\[ = rb_0s(t - \tau_r) + rb_1s(t - \tau_1 - \tau_r) + \ldots + rb_Ms(t - \tau_M - \tau_r) \]  

(16)

or

\[ y(t) = rb_0s(t - \tau_r) + \sum_{k=1}^{M} rb_k s(t - \tau_k - \tau_r) \]  

(17)

The transfer function of the FIR resonator is given by Fourier transform \([26]\) of its impulse response given by (17):

\[ H_{\text{FIR-Resonator}}(j\omega) = re^{-j\omega \tau_r} (b_0 + \sum_{k=1}^{M} b_k e^{-j\omega \tau_k}) \]  

(18)

The use of an additional resonator within the FIR topology fundamentally changes how the FIR filter behaves across a wide bandwidth. (18) shows how the addition of the resonator affects the FIR response and introduces additional degrees of freedom for the approximation of the signal to be canceled across a wider bandwidth. The innovation comes from a filter bank having individual FIR responses which are superimposed with one another while an FIR resonator accomplishes better performance with a single FIR response including the resonator’s contribution, as shown in (18).

The goal is to find the solution for the delay taps \((\tau_1, \tau_2, \ldots, \tau_M)\), tap coefficients \((b_0, b_1, \ldots, b_M)\), and the resonator parameter \((r, \tau_r)\) in such a way that the FIR resonator response conjugately matches the channel response (SI coupling response) to achieve maximum SIC cancellation.

The SIC is computed as follows \([3]\).

\[ SIC_{\text{dB}} = 20\log_{10}\left[ \frac{1}{2} \left| H_{\text{leakage}}(j\omega) \right|^2 \times \left| \frac{H_{\text{cancellation}}(j\omega)}{H_{\text{leakage}}(j\omega)} \right|^2 + 2 \left| H_{\text{leakage}}(j\omega) \right| \times \left| H_{\text{cancellation}}(j\omega) \right| \times \cos(\angle H_{\text{cancellation}}(j\omega) - \angle H_{\text{leakage}}(j\omega)) \right] \]  

(19)

### III. ANALOG STAGE ARCHITECTURE FOR RF COUPLING SUPPRESSION

#### A. ANTENNA DESIGN

In this paper, we consider a two-element monopole antenna, one for Tx and another for Rx, as depicted in Fig. 3. Details of the antenna design, fabrication, and testing are provided in our previous work \([23]\). Figs. 4 and 5 show the channel coupling response \((\text{viz.}, \text{magnitude and phase of the transmission coefficient } S_{21})\) between the Tx and Rx antennas measured from 1 to 1.8GHz. The goal is to design an SIC FIR resonator...
B. FILTER STAGE
The antenna response determines how the filter step will be implemented. It is possible for an antenna’s response to be weakly linear or completely non-linear. We are able to carry out regression analysis in a manner that is determined by the behavior of the antenna response. Both linear and non-linear approaches may be used using the regression analysis. In this particular instance, the behavior of the antenna has a weakly linear in character. For this reason, we have performed a linear regression analysis [22]. The antenna response, as well as the first and second order errors, are shown in Fig. 6. The divergence of the antenna response from the linear phase approximation is referred to as first and second order errors. The filter stage is determined by the second-order divergence in linear regression [22]. As can be observed, in order to achieve SIC cancellation throughout 800MHz, we need a filter with three stages. However, in this investigation, we chose to conduct broadband cancellation by substituting the filter bank with a FIR resonator. It is also important to note that the assessment of cancellation is necessary since we do broadband cancellation. As illustrated in Fig. 7, the amplitude and phase matches between the FIR resonator response and that of the antenna coupling need to be within 1.57dB and 5.27°, respectively, in order to obtain a cancellation level of 21dB over a broad bandwidth.

C. CIRCUIT OPTIMIZATION OF THE FIR-RESONATOR FILTER
We considered a 6-tap FIR-resonator filter (see Fig. 2 for the circuit and Fig. 8 for the microstrip layout). In this section, we only considered the circuit layout and used the
Differential Evolution (DE) optimization algorithm. Notably, DE performs well with multi-variable optimization if the specified problems has a well-tuned solution and there is no need for an initial estimate \cite{27}. Optimization was conducted from 1 to 1.8GHz. The filter taps weighted coefficients were found to be \( b_k = \{0, 12, 7, 12, 5, 3\} \) dB with time delay values \( \tau_k = \{15, 109, 10.3, 10.6, 5\} \) ps at center frequency (viz. 1.4 GHz). Also, the resonator’s parameters were found to be \( r = 0\) dB and \( \tau_r = 4\) ps. Using these values, the response of the FIR-resonator is compared against the measured antenna coupling response. As shown in Figs. 9 and 10, the FIR resonator responses (magnitude and phase) closely matches the antenna coupling response. Based on the antenna and FIR-resonator response, SIC was computed using \eqref{eq:19}. Results are plotted in Fig. 11 showing an average of 22dB of SIC across 800MHz.

D. ELECTROMAGNETIC (EM) SIMULATION OF THE FIR-RESONATOR

The EM layout of the FIR-resonator circuit, based on the circuit optimization, is depicted in Fig. 8. Notably, time delays and tap coefficients were replaced by microstrip transmission lines and attenuators, respectively. Specifically, the minimum thickness of the trace line for the cooper layer is .5mm. A resonator is added by inserting an open stub at the beginning of the copper trace of the FIR-resonator. Six lumped attenuators representing surface mount components are inserted on each tap of the FIR-resonator. The purpose of the lumped attenuator is to adjust gain for approximating the channel coupling. Notably, the filter is matched to 50-\( \Omega \) at the input and output ports. The length of the resonator is 0.5mm \( \times \) 0.5 mm, while the length of the FIR filter is 44 mm \( \times \) 37mm. The area of the resonator is 0.015% of the size of the FIR filter’s area. Notably, if we only consider FIR resonator, the total size is 1628.25mm\(^2\). Conversely using a filter bank with two filters, the size is 3256mm\(^2\). As such, using an FIR resonator reduces the size of the circuit by nearly half in comparison to the FIR filter bank. In addition, using a higher dielectric constant (\( \epsilon_r = 9.2 \)) results in a lower footprint of the SIC circuit design.

We note that, in this simulation, we considered the S-parameters of actual components provided by vendors. Here also, DE optimizer was used to fine tune the layout to closely match the antenna coupling response. Figs. 9 and 10 show the simulated magnitude and phase response of the EM layout. Fig. 11 shows that an average 22dB of RF coupling suppression was achieved across 800MHz in EM simulation.

IV. FABRICATED FIR-RESONATOR

The FIR-resonator was fabricated using low-cost commercial off-the-shelf (COTS) components on a TMM10 substrate from Rogers company with \( \epsilon_r = 9.2 \) and \( h = 60\)mil (viz. 1.5mm). The total dimension of the SIC circuit is 44mm \( \times \) 37mm. The fabricated prototype is shown in Fig. 12. Notably, we used Mini circuits PAT series attenuators (PAT 0dB, 12dB, 7dB, 12dB, 5dB, 3dB). The fabricated FIR-resonator prototype was measured using a two-port vector network analyzer (VNA). Measured magnitude and phase response are depicted in Fig. 13 and 14, respectively. Clearly, results are in
good agreement with the simulation ones. This implies 20dB SIC cancellation across 800MHz, as shown in Fig. 15.

V. ANTENNA AND FIR RESONATOR
In this study, we connected the antenna shown in Fig. 3 to the RF-SIC circuit. Doing so, 33dB isolation is obtained across 800 MHz, as illustrated in Fig. 16. As expected, the antenna isolation contributed to an additional isolation of 11 dB [23].

VI. COMPARISON WITH OTHER STATE-OF-ART RF-SIC FILTER
Table 1 shows a performance comparison of the RF-SIC with other state-of-art self cancellation topologies. With the early STAR RF-SIC approaches, it is possible to achieve cancellation of up to 20dB for extremely narrowband signals with a bandwidth of 5MHz [17]. Other realizations of the STAR RF-SIC filter were able to achieve cancellation of up to 47dB over an 80MHz bandwidth [18]. Undoubtedly, each of these methods was narrowband. Research on wideband RF STAR filters, on the other hand, has shown a 25dB cancellation over 500MHz by only implementing a FIR filter [3].
research [21], [22], by creating a filter bank, RF isolation of up to 22dB was achieved while simultaneously increasing the bandwidth to 1GHz. However, the implementation of this approach results in complicated circuitry and also creates coupling between the many filters. As part of our research, we have developed a simple FIR resonator that is capable of offering a cancellation of 22dB over 800MHz. In addition to the wideband cancellation, it boasts a low-profile characteristics, as a result of using a simple resonator instead of a filter bank. The FIR resonator accomplishes nearly 50% size reduction of the filter bank, while concurrently reducing both the hardware and design complexity of the system.

VII. CONCLUSION

We presented a simple and low profile RF-SIC circuit for IBFD systems that achieves 20dB of interference suppression across 800MHz bandwidth. The circuit is based on a hybrid multi-tap FIR filter with a resonator stub. A prototype was fabricated and tested to validate the design. To the best of our knowledge, this simple design the first to achieve RF-SIC cancellation across such a large bandwidth.

TABLE 1. Performance comparison with the state-of-the-art STAR SIC filters in RF domain.

| Reference | Bandwidth | TX-RX isolation | Technology |
|-----------|------------|------------------|------------|
| [3]       | 500MHz     | 25dB             | FIR filter |
| [17]      | 5MHz       | 20dB             | QHx220 chip |
| [18]      | 80MHz      | 47dB             | 16 tap filter |
| [19]      | 50MHz      | 30dB             | Multitap RF canceller RF canceller |
| [20]      | 100MHz     | 36dB             | Near field filter |
| [21]      | 1GHz       | 25dB             | Filter bank (Multiple FIR filters) |
| [22]      | 1GHz       | 20dB             | 3 stage filter bank |
| **This work** | **800MHz** | **22dB**         | **FIR resonator (single circuit topology), since no filter bank is required, no coupling exists.** |

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