A T/R Antenna Pair with Polarization-Based Reconfigurable Wideband Self-Interference Cancellation for Simultaneous Transmit and Receive

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***Abstract*—This paper proposes a transmit and receive (T/R) antenna pair with a novel wideband self-interference cancellation (SIC) feature for simultaneous transmit and receive (STAR) or full-duplex applications. The T/R antennas have orthogonal linear polarizations and an auxiliary port which is cross-polarized with the receive port is introduced on the receive antenna. Introduction of a reconfigurable reflective termination on the auxiliary port reflects the coupled signal to cancel the self interference at the RX port. The reconfigurable termination mimics the required conductance and susceptance across a wide frequency range to achieve wideband SIC. When SIC is activated, isolation between the T/R antenna pair is higher than 50 dB over 300 MHz centered at 4.6 GHz. The proposed cancellation technique provides 20 dB improvement in the T/R isolation over 400 MHz. It can be reconfigured in the presence of environmental changes and reflections to recover the degradation in the cancellation. The antenna pair is also employed in a transceiver built using off the shelf components and 70 dB total SIC is achieved in conjunction with digital cancellation.**

I. Introduction

Recently, it has been demonstrated that STAR radios which can transmit and receive at the same time and at the same frequency are feasible and can double the data throughput [1]. To enable STAR, the strong leakage from the transmitter to the receiver, which is referred to as self interference (SI), needs to be suppressed below the receiver noise floor. SI arises from the inherent coupling in typical antenna interfaces as well as environmental reflections. Depending on the transmitted power and signal bandwidth, a total self-interference suppression of approximately 100 dB or more must be achieved. This requires enhancing T/R isolation at the antenna, and self-interference cancellation in the antenna, RF/analog and digital domains [2].

Suppressing SI at the antenna is crucial to relax the requirements on the receiver's RF and analog circuitry and the RF/analog and digital cancellation circuits. Antenna-domain SI mitigation can be divided into two approaches. The first approach targets minimization of the inherent mutual coupling between T/R antennas by employing cros-polarized antennas [2] or shadowing the near fields of T/R antennas [3]. Although good isolation over wide bandwidth can be achieved, this approach lacks the ability to combat the SI caused by environmental reflections which are unknown during design process and can vary during in-field operation.

The second approach, which will be referred to as antenna cancellation, introduces another coupling path between antennas to cancel the SI at the receiver input. Antenna cancellation, if it is tunable, can combat environmental reflections. Tunable resonators between antenna elements are used in [4] and 40 dB isolation is achieved over 12 MHz at 3.3 GHz. In [5], the bandwidth of cancellation was extended using two sets of tunable resonators but the bandwidth was still limited to 55 MHz for 40 dB isolation at 3.3 GHz. Neither of these works demonstrated SIC under environment changes.

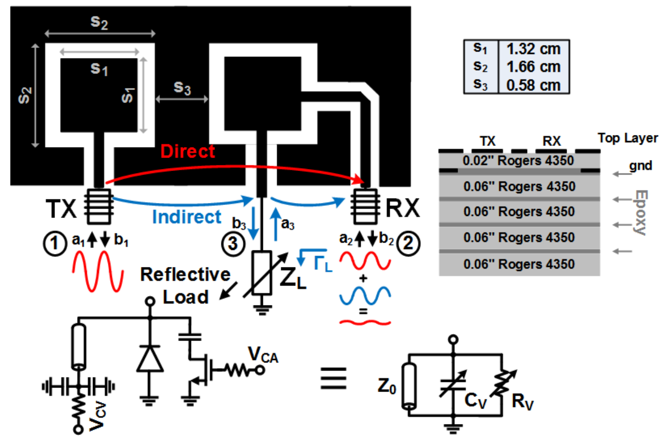

Fig. 1. Diagram of the proposed antenna pair with polarization-based reconfigurable wideband self interference cancellation. It employs orthogonal polarizations for T/R antennas. An auxiliary port which is terminated with a variable reflective termination is introduced to achieve wideband SIC.

This work proposes a T/R antenna pair employing a novel reconfigurable wideband antenna cancellation technique for STAR applications. When SIC is activated, it can achieve 50 dB isolation over 300 MHz at 4.6 GHz (*4x better fractional SIC bandwidth at 10 dB higher isolation than [5]*). 50 dB isolation can be maintained in the presence nearby reflectors as well by reconfiguring the antenna cancellation. Although it has been designed at 4.6 GHz for proof of concept, this technique can easily be scaled up in frequency and can even be implemented on silicon at millimeter-wave frequencies.

II. Concept

Fig. 1 shows the diagram of the proposed T/R antenna pair. It consists of collocated transmit and receive antennas with orthogonal polarizations to increase the initial isolation between T/R ports. A co-polarized port with the transmitter is introduced at the receiving antenna and terminated with a variable reflective termination to achieve self interference cancellation. As depicted in Fig. 1, there are two different coupling paths between T/R ports- the direct coupling path and the indirect coupling path created by introducing the auxiliary port. In the indirect path, the signal from transmitter first couples to the auxiliary port, reflects from the variable termination and then couples into the receive port to achieve

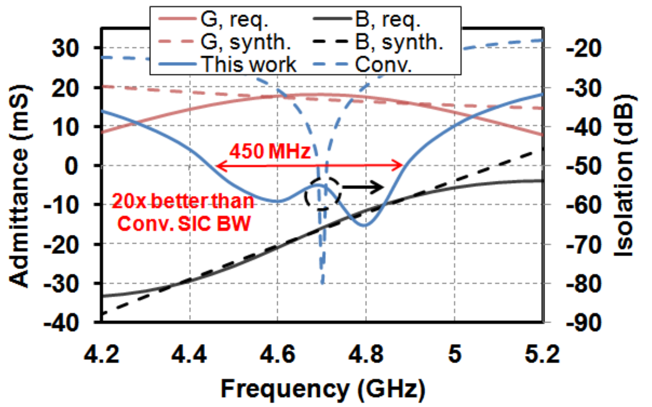

Fig. 2. Required conductance and susceptance for the reflective termination across frequency to achieve perfect SIC. Reflective termination synthesizes the required G_{req} and B_{req} values across frequency to accomplish wideband SIC. T/R isolation better than 50 dB over 450 MHz is seen in the simulation.

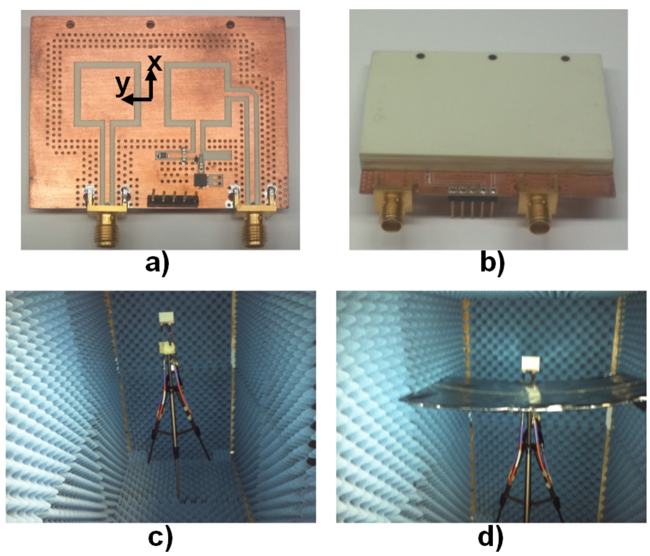

Fig. 3. Antenna pair prototype: a) top view, b) bottom view, and measurement setup in the anechoic chamber c) without reflector, and d) with reflector.

cancellation. Treating the antenna pair as a 3-port microwave network, the total SI leakage from transmit to receive port is

$$b_2 = \left(S_{21} + \frac{S_{23}S_{31}\Gamma_L}{1 - S_{33}\Gamma_L} \right) a_1 \tag{1}$$

where S_{21}, S_{31} and S_{32} are the S-parameters of the 3-port antenna core (ports 1, 2 and 3 are TX, RX and auxiliary ports, respectively), Γ_L is the reflection coefficient of the variable termination at the auxiliary port, a_1 is the incident wave variable at the TX port and b_2 is the outgoing wave variable at the RX port. The first and second terms on the right hand side of (1) correspond to direct and indirect path couplings, respectively. Perfect cancellation, $b_2 = 0$, can be achieved when these two coupling terms are 180° out of phase with the same magnitude.

It should be noted that all the parameters in (1) are frequency dependent. Previously reported techniques mimic the magnitude and phase of the direct path in the cancellation path at a single frequency [4] or slightly separated frequencies [5]. *Our technique is based on mimicking the direct path's magnitude and phase as well as their slopes to achieve wide band cancellation.* To this end, first, the T/R antenna pair is designed and simulated in Mentor Graphics IE3D EM solver. Thus, all the parameters in (1) except Γ_L are fixed and accomplishing SIC simplifies to setting the phase and magnitude of Γ_L. Then we calculate the required reflection coefficient for cancellation across frequency ($\Gamma_{L,req} \approx -S_{21}/S_{23}S_{31}$, assuming $S_{33} \approx 0$). The required reflection coefficient is mapped to more meaningful physical design parameters; conductance and susceptance. Fig. 2 shows the simulated required conductance (G_{req}) and susceptance (B_{req}) across frequency to achieve perfect SIC. It is desirable to synthesize G, B *and their slopes a a given frequency* in the reflective termination to achieve wideband cancellation. Having variable L, C and R in a parallel RLC would allow us 3 degrees of freedom to control the G, B and the slope of B at a given frequency but not the slope of G, which is approximately zero. Variable L can be implemented using switches that change the location of the short on a shorted stub but has not been pursued here. In this work, L is set to achieve the slope of B dictated by EM simulation of the direct coupling between T/R ports without considering environmental reflections. Our measurements with a metallic close-in reflector show that we can still recover the cancellation by just changing the R and C values. Switches can be included to vary L in case a strong reflection necessitates changing B and its slope independently. Fig. 2 shows the synthesized G and B to achieve wideband cancellation. A T/R isolation better than 50 dB over 450 MHz is seen in simulation.

Conventional cancellation involves using a TX-side coupler, variable-gain amplifier, phase shifter and a RX-side coupler to mimic the direct path. The SIC bandwidth achieved by a conventional canceler with flat amplitude and phase response versus frequency is simulated to be 20 MHz at 50 dB isolation (Fig. 2). *Our work improves the SIC bandwidth by 20x compared to a conventional canceler in simulation*. Our work can be seen as a cancellation path with a tunable resonator with amplitude and phase scaling that is embedded within the antenna element. The introduction of the co-polarized port on the RX antenna allows us to embed the coupler functionalities within the antenna pair. This allows the couplers to track the antenna's inherent isolation across frequency, resulting in wide cancellation bandwidth in conjunction with the additional degree of freedom in the reflective termination.

III. Implementation

The transmit and receive antennas are implemented as rectangular slot loop antennas with orthogonal linear polarizations. Slot antennas are chosen for their wide impedance bandwidth. Using them also allows this work to be readily integrated on Si at millimeter/sub-millimeter wave frequencies as they allow satisfaction of stringent metal density rules. The antenna dimensions and cross-section of the PCB board are shown in Fig. 1. The antenna pair is built on Rogers 4350B material with 20 mils thickness. A 240 mils superstrate layer is employed

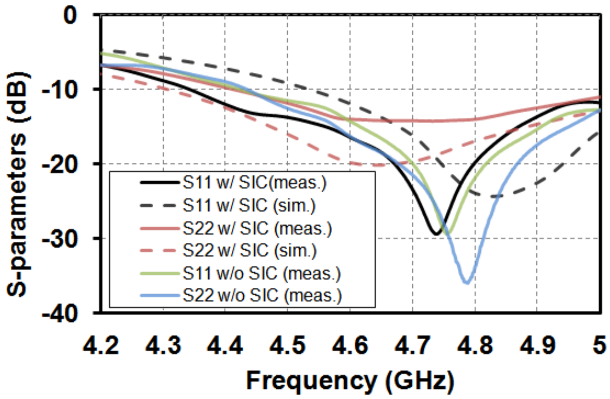

Fig. 4. Measured and simulated S_{11} and S_{22} of the antenna pair.

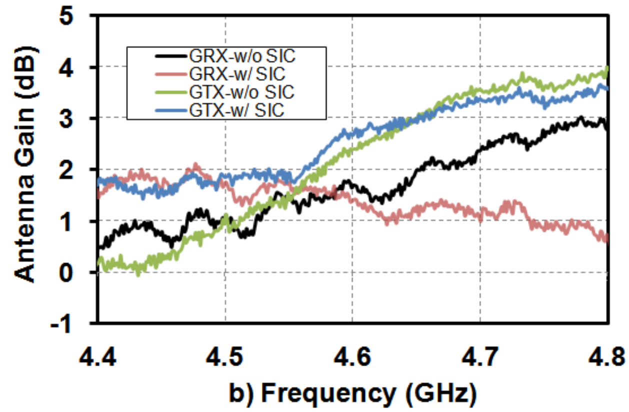

Fig. 6. Effect of SIC on broadside TX and RX antenna gain.

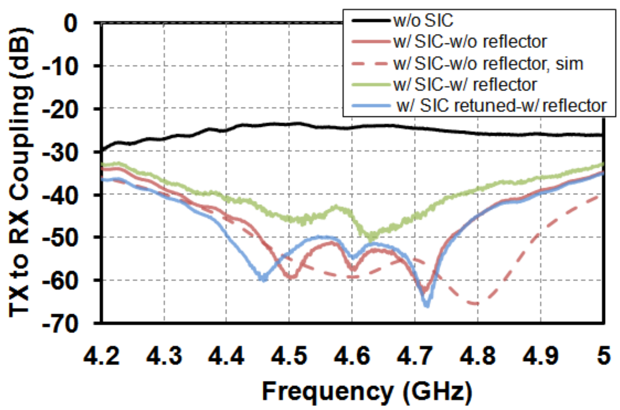

Fig. 5. Measured S_{21} with and without SIC in anechoic chamber. Bringing an aluminum reflector close to antenna degrades the cancellation, but it can be recovered by reconfiguring the canceller settings.

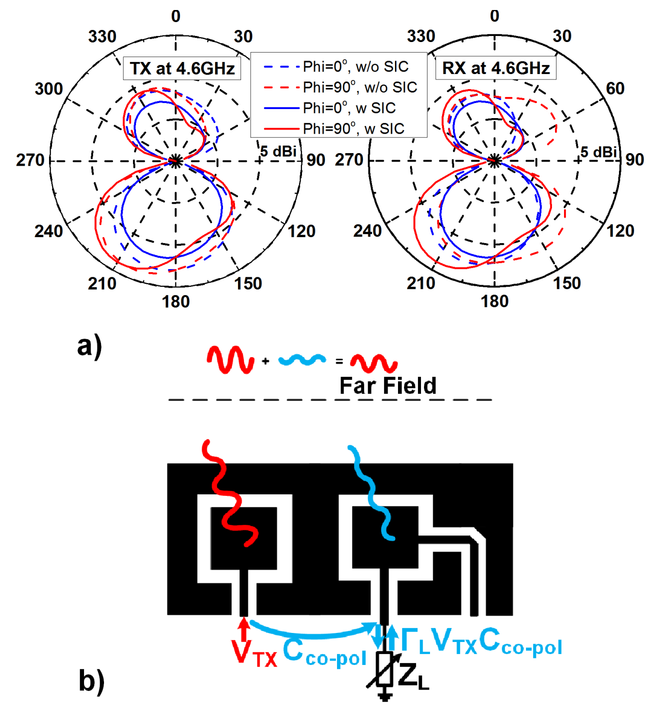

Fig. 7. a) TX and RX patterns with and without SIC (simulation). b) TX pattern degradation mechanism.

under the antenna to increase the directivity in this direction. It is built by sticking four 60 mils Rogers 4350B layers to each other using epoxy. Fig. 3(a) and Fig. 3(b) show the top and backside view of the PCB, respectively.

The cancellation termination is implemented using a 3.5 mm shorted stub with 50 Ω characteristic impedance, Skyworks SMV1430-079LF varactor diode and Hittite Microwave HMC973LP3E voltage controlled attenuator as the variable resistor. The varactor is tunable from 0.31 pF to 1.24 pF and it is reverse biased through a 10 $k\Omega$ resistance. The attenuator is DC isolated using AVX GX03 ultra broadband capacitor.

IV. Measurements

S-parameters of the antenna pair are measured in a mini-anechoic chamber from 4.2 GHz to 5 GHz using a DC$-$67 GHz Anritsu 37397E Lightning VNA. Fig. 3(c) shows the measurement setup in the anechoic chamber. Measured return loss at TX and RX ports is higher than 10 dB from 4.4 GHz to 5 GHz with and without SIC (Fig. 4). Measured TX to RX isolation is shown in Fig. 5. First a reference antenna pair which consists of only cross-polarized T/R antennas is measured and its isolation is 24 ± 1 dB from 4.4 GHz to 4.8 GHz. Measurements with SIC are compared to this curve to determine the improvement in T/R isolation. When there is no nearby object, the T/R isolation of the antenna pair with SIC is higher than 50 dB from 4.45 GHz to 4.75 GHz. The cancellation (i.e. improvement in isolation) is higher than 20 dB from 4.4 GHz to 4.8 GHz. The diode and attenuator voltages (V_{CV} and V_{CA}) are set to 7 V and 1.5 V, respectively. The measured T/R isolation with SIC compares well with the simulation.

Fig. 3(d) shows the setup used for testing the effect of nearby objects on the SIC. When SIC is active with 7 V and 1.5 V diode and attenuator control voltages, respectively, an aluminum reflector was brought 5 cm below the antennas. As can be seen in Fig. 5(a), this increases the self-interference by 4-16 dB in the 4.4-4.8 GHz range. The reflector changes the required Γ_L for SIC but we can recover the degradation in SIC by reconfiguring the diode and attenuator control voltages

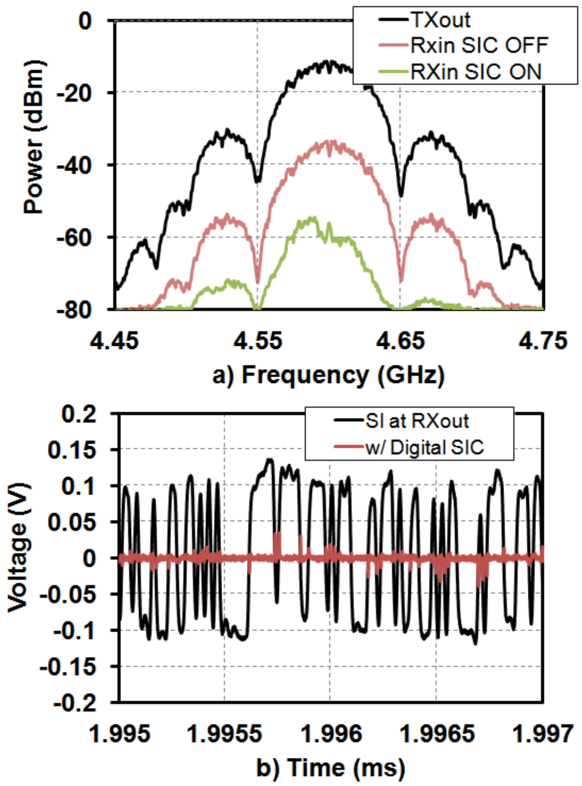

Fig. 8. a) Cancellation of a 50 Mbps BPSK signal in a lab environment using a transceiver employing the proposed antenna pair and b) digital SIC is studied on the remaining SI in Matlab.

to $V_{CV} = 8\,\text{V}$ and $V_{CA} = 1.25\,\text{V}$, respectively.

The effect of antenna cancellation on broadside antenna gains is given in Fig. 6. The change in RX antenna gain is ± 1 dB from 4.4 to 4.7 GHz. The reduction in the RX antenna gain can be considered similar to the noise figure penalty of conventional RF cancellers. TX gain does not change from 4.5 GHz to 4.8 GHz. The TX and RX patterns are simulated with and without SIC (Fig. 7(a)). SIC affects the pattern along the coupling axis by $\pm$ 2 dBi (around Phi=$\pm 90°$). Fig. 7(b) depicts the main reason of the degredation of the TX pattern. Due to the close proximity of the antennas, there is a strong coupling between the TX and the co-polarized auxiliary port. The coupled signal to the auxiliary port also radiates from the RX antenna and eventually interferes with the radiation from the TX antenna in the far-field. Increasing the isolation, avoiding close proximity of the antennas, reduces this penalty. The measured axial ratio of TX is better than 11.6 dB over 4.4-4.8 GHz. RX axial ratio with SIC is better than 5.2 dB in the same frequency range.

The antenna pair is incorporated in a transceiver which is built using off the shelf components. Fig. 8 (a) shows the cancellation of 50 Mbps BPSK signal in a lab environment. The remaining SI at the receiver output (digitized using an Agilent InfiniiVision MS07054A oscilloscope, essentially an 8-bit 2GSPS ADC) is plotted in Fig. 8 and its cancellation in the digital domain using an adaptive digital FIR filter is studied in Matlab. An average of 24 dB digital SIC is achieved. This brings total SIC to approximately 70 dB. For a transmitted power of 14 dBm, an additional 25 dB cancellation is needed to suppress the SI below the receiver noise floor (P_n=$-174\,dBm$+$10log(BW)$+NF=-174+$10log(300\,MHz)$+8 dB≈-81 dBm), which can be achieved through RF or analog baseband cancellation.

V. Conclusion

A T/R antenna pair with a novel wideband SIC cancellation technique is demonstrated. It achieves 50 dB isolation in 300 MHz bandwidth centered at 4.6GHz when SIC is activated. The SIC is reconfigurable and recovers cancellation quality as the environment changes. It can easily be implemented at mmwave frequencies either on chip or on PCB.

Acknowledgment

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