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RESEARCH ARTICLE

2 × 2 MIMO In-Band Full-Duplex Radio Front-End With Delay Shapable Single-Tap RF Cancellers

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ABSTRACT This paper presents the experimental results of self-interference cancellation for a 2×2 multiple input multiple output (MIMO) in-band full-duplex radio front-end. The proposed radio-frequency (RF) front-end consists of two rat-race couplers and a four antennas network for passive suppression, and four self-interference active cancellation. The canceller generates an identical signal to the residual self-interference signal, and then subtracts it from the received signal. The RF canceller has a single signal path(tap) composed of attenuator, phase shifter, and time delay circuit which all are variable. To broaden the bandwidth of active cancellation, the time delay circuit is developed to have a wide delay variation range and to control the shape of the delay over the frequency.

The experimental results demonstrate the 50-dB self-interference cancellation over the bandwidth of 90 MHz at the center frequency of 2.53 GHz.

INDEX TERMS Multiple input multiple output (MIMO), in-band full-duplex radios, self-interference cancellation (SIC), rat-race coupler, time delay circuit.

I. INTRODUCTION

In-Band full duplex radio systems enable communication using the same frequency band for transmitting and receiving, which doubles the throughput compared to time or frequency division duplex systems [1]. However, such systems suffer from high interference due to their own transmitting signals, whose power can, generally, exceed the dynamic range of the receiver. Thus, a key challenge in in-band full duplex radio systems is how to suppress such high self-interference (SI) at the front-end by about 50 dB, which is generally considered to be the required self-interference cancellation (SIC) level for the receiver and ADC to handle within their dynamic ranges [2]. Not only the SIC level, but also the SIC bandwidth is very important since the antennas and circuits for the front-end always have a limited bandwidth. The front-end for the full duplex system is even more complicated for multiple input and multiple output (MIMO)communication systems [14]. Recently, several research papers have reported how to implement the RF front-end for the MIMO full duplex systems, which consist of antennas with a high isolation and RF cancellation circuits [3], [4], [5], [6], [7], [8].

Thus far, the RF cancellation circuits has multiple delay taps to cover a wide bandwidth, which generally consist of a fixed time delay, variable attenuator and phase shifter. This multi-tap canceller is generally bulky, especially in MIMO systems, and requires a large power margin to divide the coupled transmitted power to the multiple taps [3]. A single-tap canceller is proposed with a variable time delay circuit for a MISO system [10] and MIMO system [11]. However, a simple variable delay circuit cannot mimic the SI in a wide bandwidth, and therefore, a novel variable delay circuit to generate a non-linear delay shape is required to imitate the SI with a combination of various delays in a wide bandwidth. Also, a control and adaptation mechanism of the delay shapable single-tap canceller needs to be invented to achieve

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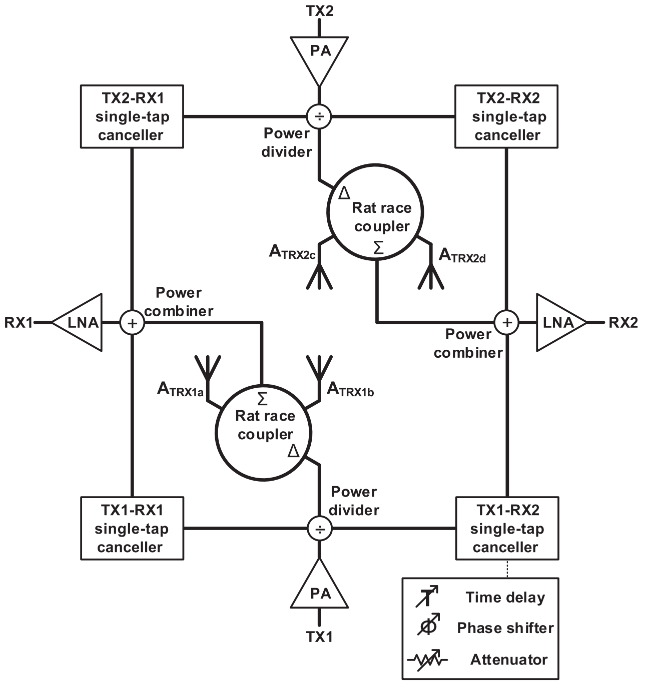

FIGURE 1. Proposed 2 × 2 MIMO RF front-end for a full duplex radio system.

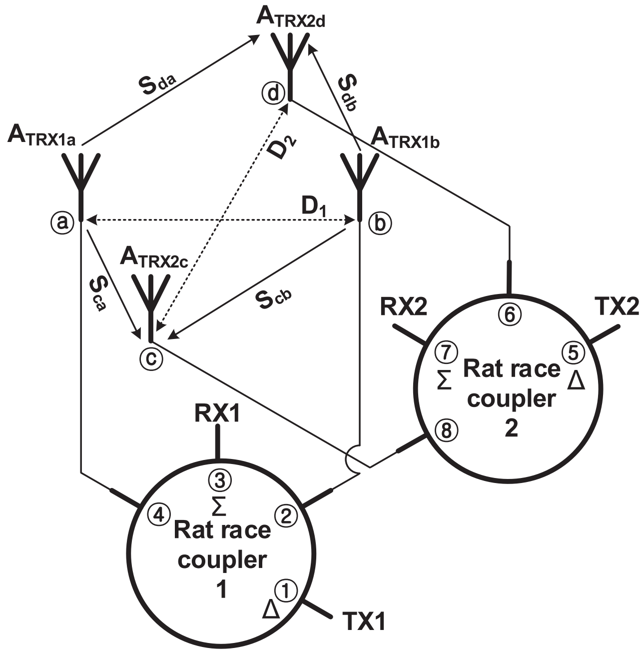

FIGURE 2. Proposed 2 × 2 MIMO antenna network followed by two rat-race couples. The rotation angle can be arbitrary, maintaining passive suppression.

a robust SI cancellation with a wide bandwidth. Therefore, this paper focuses on the design of a delay shapable single-tap canceller and its adaptation mechanism for an active cancellation in full duplex radio systems. The antennas network of the proposed 2 × 2 MIMO RF front-end achieves the passive suppression by the symmetrical placement of four antennas, followed by two rat-race couplers. The experimental results demonstrate 25-dB passive suppression and 15 to 35-dB active cancellation depending on the type of adaptation mechanism used. In Section II, the design of the 2 × 2 MIMO RF front-end with the delay shapable single-tap SI canceller is explained, and the adaptation mechanism and measurement results are presented in Section III.

II. THE 2 x 2 MIMO RF FRONT-END ARCHITECTURE

Fig. 1 reveals the proposed 2 × 2 MIMO RF front-end for a full duplex radio system with a antenna network and cancellation circuits between 2 transmitters (TX) and 2 receivers (RX). The antenna network consists of two rat-race couplers and four antennas(A_{TRX1a}, A_{TRX1b}, A_{TRX2c} and A_{TRX2d}), and the cancellation circuits consist of the power combiners, power dividers and four cancellers. The power dividing and combining ratios are 1:4:1 for the signal path and two cancellation paths.

A. PASSIVE SUPPRESSION

Fig. 2 illustrates the proposed antenna network with four antennas and two rat-race couplers. These rat-race couplers are designed to achieve wideband performance [12]. The delta ports of couplers are used for the antenna TX ports, while the sigma ports are used for the RX ports. The isolation from TX1 to RX1 and RX2 is described by Equ. (1) and (2) using the S parameters of the antenna network and couplers of which the port number are shown in Fig. 2. The Equ. (1) and Equ. (2), with the s parameters associated with antennas a and b replaced by that of antennas c and d or vice versa, and the s parameters associated with rat race coupler1 replaced by that of rat race coupler2 or vice versa would be the isolation from TX2 to RX2 and TX2 to RX1.

$$S_{RX1TX1} = S_{31} + (S_{21}S_{bb}S_{32} + S_{41}S_{aa}S_{34}) + (S_{21}S_{ab}S_{34} + S_{41}S_{ba}S_{32}) \tag{1}$$

$$S_{RX2TX1} = (S_{21}S_{cb}S_{78} + S_{41}S_{ca}S_{78}) + (S_{21}S_{db}S_{76} + S_{41}S_{da}S_{76}) \tag{2}$$

In Equ.(1), S_{RX1TX1} can be zero if $S_{31} = 0$, and $S_{bb} = S_{aa}$ because $S_{21} = -S_{41}$ and $S_{32} = S_{34}$ in rat race couplers and $S_{ab} = S_{ba}$ from the reciprocity of passive network. Also, S_{RX2TX1} in Equ. (2) is zero if $S_{cb} = S_{ca}$ and $S_{db} = S_{ca}$ because $S_{21} = -S_{41}$. S_{RX2TX1} will be also zero if $S_{cb} = S_{da}$ and $S_{db} = S_{da}$ due to $S_{21} = -S_{41}$ and $S_{76} = S_{78}$. Therefore, the isolation of TXs and RXs are maximized when the four identical antennas are placed at the vertices of a rhombus as in Fig. 2. This isolation mechanism can be applied for any M×M MIMO system [15]. In an real antenna network, $S_{31} = 0$, $S_{bb} = S_{aa}$, $S_{21} = -S_{41}$, $S_{32} = S_{34}$, $S_{cb} = S_{da}$, and $S_{db} = S_{ca}$ cannot be guaranteed due to manufacturing imperfections and asymmetric environment around the antennas. Thus, a residual SI signal remains, which must be canceled by RF cancellers.

Each TX and RX signal is transmitted and received through two antennas, the radiation pattern will be a two-element array pattern. The desired signals from far-end transmitters

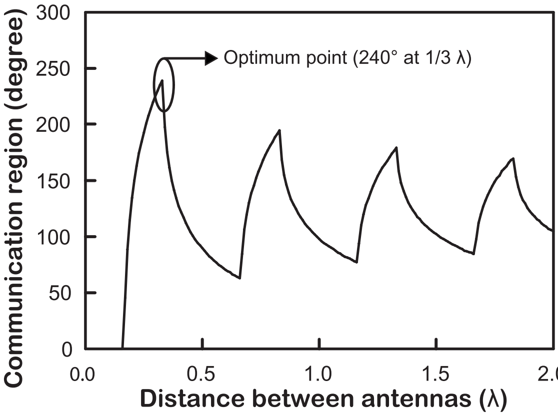

FIGURE 3. Region where both array factor of TX and RX are over 0 dB versus distance between antennas.

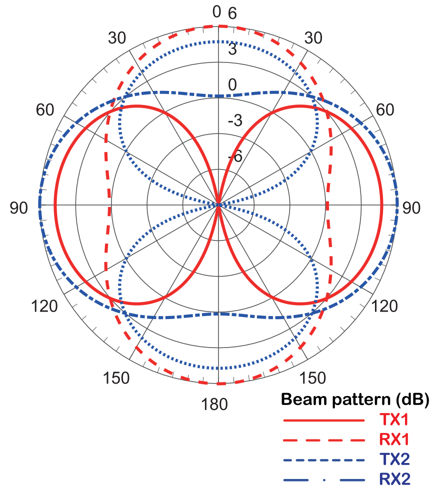

FIGURE 4. TX and RX beam patterns of four antennas in a square shape when D_1 and D_2 are $\lambda/3$ and the rotation angle is 90°.

arrive the four antennas, and are added at the sigma port of each rat-race coupler in phase. The TX signals are fed from the delta ports of each rat-race coupler, and radiate at the antennas out of phase. Thus, each TX and RX beam pattern is not the same, and a TX null region exists because the TX signals are radiated out of phase from two antennas. However, this problem can be eased by choosing the antenna distance, D_1 and D_2, so that the region where both the TX and RX array gains are over 0 dB (i.e., the communication region) can be maximized. Fig. 3 demonstrates the communication region and TX null region versus the distance between two antennas. As shown in Fig. 3 it is reasonable to choose D_1 and D_2 as $\lambda/3$, which is the point to maximize the communication region. The TX and RX beam patterns of the antenna network are shown in Fig. 4 when D_1 and D_2 are $\lambda/3$. The beam patterns of TX1(RX1) and TX2(RX2) are complimentary so that there is no shadow region.

B. THE RESIDUAL SELF-INTERFERENCE SIGNAL

Since the passive suppression of the antenna network is not perfect, there are residual SI signals remained in the RX ports.

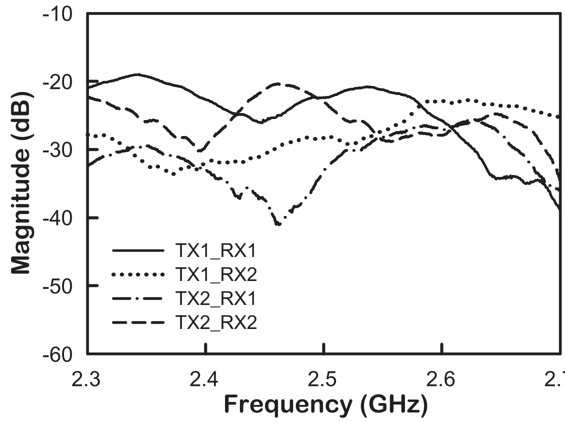

FIGURE 5. Magnitude of the measured s-parameters of the network in Fig. 2.

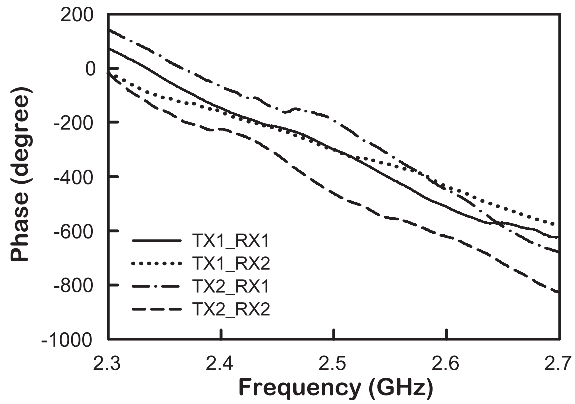

FIGURE 6. Phase of the measured s-parameters of the network in Fig. 2.

Figs. 5 and 6 illustrate the isolations (magnitude and phase) between TXs and RXs of the proposed antenna network where the four antennas are identical off-the-shelf monopole antennas for a WIFI access point, and have −10-dB matching from 2.4 GHz to 2.6 GHz. The self talk isolation between TX1(TX2) and RX1(RX2) is less than that of the cross talk isolation between TX1(TX2) and RX2(RX1). This is because the self talk is mainly affected by the difference between S_{aa} and S_{bb}, whose magnitudes are around −12 dB, while the cross talk is affected by the difference between S_{ca} and S_{cb}, whose magnitude are about −20 dB when D_1 and D_2 are $\lambda/3$.

One simple way to cancel out these residual SI signals is using a single tap canceller with a phase shifter, attenuator and true time delay to mimic SI signals. The level of cancellation that can be achieved with this single tap canceller over the frequency bands, can be mathematically simulated. The desired attenuation level of the canceller is chosen to the average power level of the SI signal in a target band of 2.49−2.57 GHz. The time delay, which is the slope of the phase of the isolation phase, is also set to be a average delay within the target band. Finally, the desired phase shift of the canceller is set to maximize the level of cancellation, resulting in 180o phase difference with the SI signal. Figs. 7

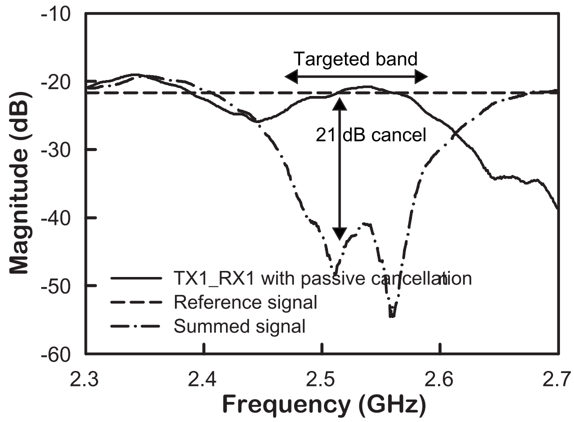

FIGURE 7. Magnitude of the measured TX1-RX1 s-parameters with passive cancellation, mathematical reference signal, and a summed signal in simulation.

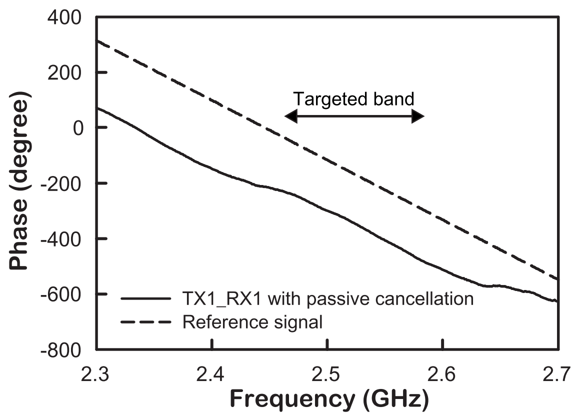

FIGURE 8. Phase of measured the TX1-RX1 s-parameters with passive cancellation, and a mathematical reference signal.

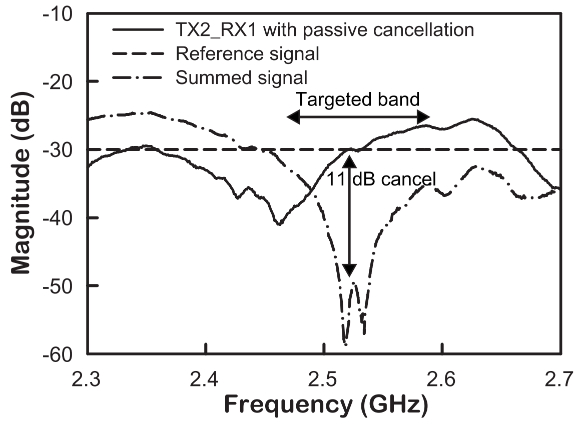

FIGURE 9. Magnitude of measured the TX2-RX1 s-parameters with passive cancellation, a mathematical reference signal, and a summed signal in simulation.

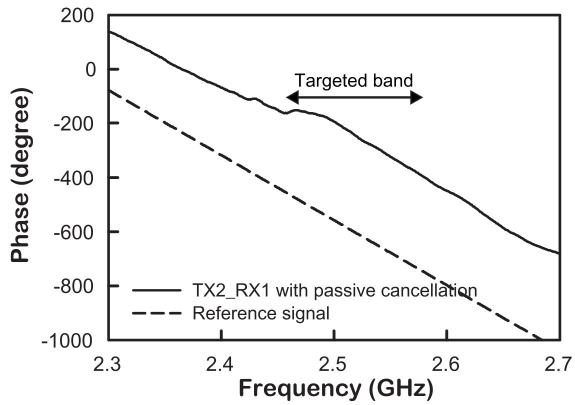

FIGURE 10. Phase of the measured TX2-RX1 s-parameters with passive cancellation, and a mathematical reference signal.

and 8 display the S-parameters of the self talk SI signal, canceller signal, and summation of them. The single tap canceller reduced the SI signal by 22 dB, achieving the total cancellation of 45 dB. For the cross talk in Fig. 9 and Fig. 10, a total of 43 dB cancellation is achieved,with the active cancellation of 13 dB. This simulation indicates that the use of the single tap canceller as a combination of the ideal true time delay, phase shifter and attenuator is unsuitable to accomplish the desired SIC level of 50 dB in 80-MHz bandwidth.

The residual SI is summation of multiple signal with different delays, and therefore a single tap canceller with a single time delay cannot generate a identical signal with the residual SI. The multi-tap canceller where each tap consists of a fixed time delay, phase shifter, and attenuator can provide a cancellation signal with non-linear group delay within a bandwidth. However, such multi-tap canceller is too bulky and has too many variables to control to mimic the residual SI signal, which makes the control system behind the RF front-end more complicated; therefore, single-tap canceller is needed for a MIMO system where many cancellers are required between all TXs and RXs.

C. DELAY SHAPABLE CANCELLER

To generate a non-lineary group delay with a signle tap canceller, a delay-shapable true time delay circuit is proposed in Fig. 11. The proposed circuit is a modified reflected type phase shifter based on resonances to achieve the high dynamic range of the variable time delay. Varactors C_1 and C_2 are used to change the quality factor of resonance and the resonance frequency. With cascaded identical circuit, quality factor and frequency of resonance points can be controlled independently, so that it can make any delay shape on the targeted center frequency. Each branch of the 3 dB coupler has one resonance point, and if the resonance frequencies are set to be the same, the variable delay is flat within a bandwidth. The measured dynamic range of the proposed circuit is 2 nsec at 2.5 GHz when it is used to create only a flat time delay. This measurement is aimed to compare the dynamic range of the true time delay to that of the typical variable time-delay circuit, such as the synthetic transmission line with a periodically loaded shunt varactor, with the variability of the quality factors of those two points and the resonance frequencies depending on the targeted frequency band. In [4], the synthetic transmission line with a periodically loaded shunt varactor is used as a variable true

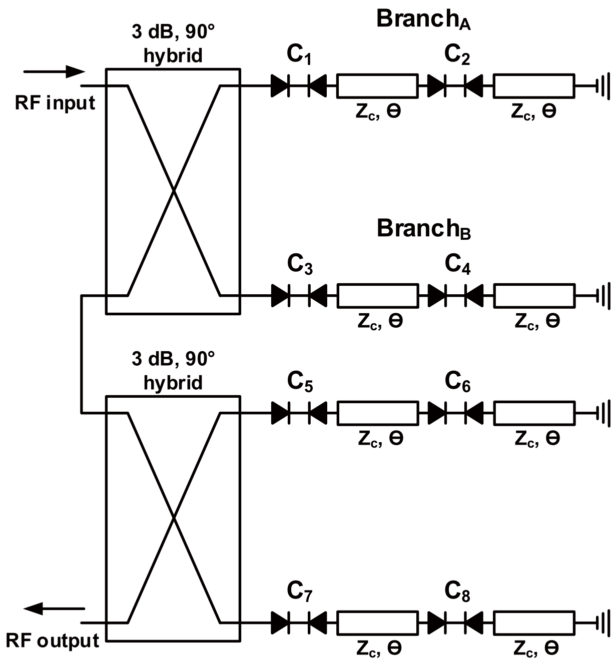

FIGURE 11. Schematic of the proposed true time delay circuit.

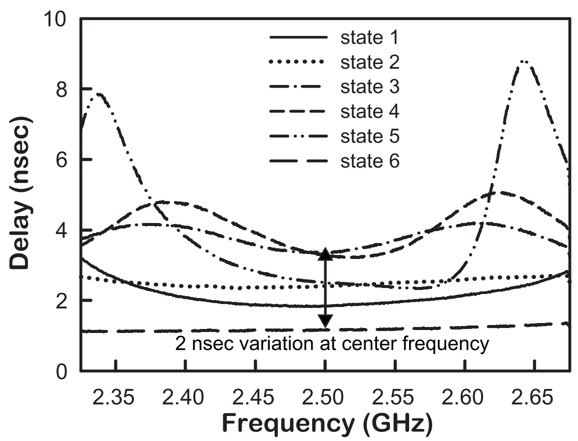

FIGURE 12. Measured delay variation of the proposed true time delay circuit.

time delay circuit, but its dynamic range of variable time delay is too small to cancel out the residual SI whose time delay is unknown and varies depending on what antennas are used and the environment around the antenna network. Moreover, it is a low-pass filter and can only imitate a flat channel. Regarding insertion loss, if the branches of 90° hybrid couplers are electrically identical and the internal resistance of varactors is zero, no loss would occur; however, due to the imperfection in the board-level design, the insertion loss varies from 2 to 6 dB, depending on the control of the quality factor of the resonance, as illustrated in Fig. 13.

Thus far, the usefulness of this circuit has been explained regarding the high dynamic range as the ideal true time delay circuit over the relatively narrow bandwidth. However, the true advantage is that it can mimic any frequency selective channel, such as a residual SI signal, as shown above over

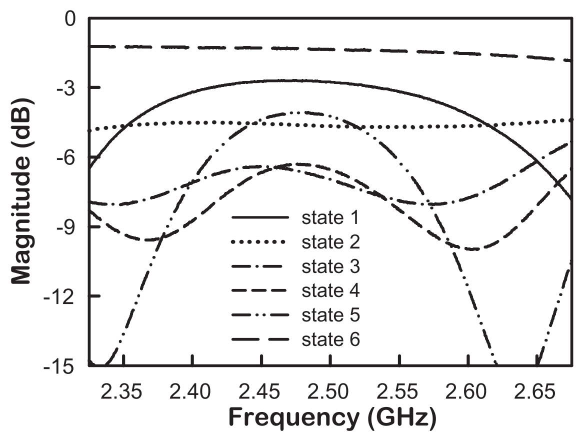

FIGURE 13. Measured magnitude variation of the proposed true time delay circuit.

the large bandwidth. As explained, the delay of the residual SI signal has a local minimum or maximum at the frequency where its magnitude has a local minimum. If those bias voltages of $Branch_A$ and $Branch_B$ are free to be chosen, instead of $Branch_A$ and that of $Branch_B$ being compulsorily the same, the transmission s-parameter can be understood as the summation of the different reflection coefficients of each branch. For example, when the bias voltages of C_3 and C_4 are set to some fixed value such that the varactor is an open circuit and the variability is given as that of C_1 and C_2, the reflection coefficient of $Branch_B$ has a short delay and high magnitude compared to that of $Branch_A$ where C_1 and C_2 are used to make some resonance points. Consequently, the local minimum of group delay is expected at the local minimum of the magnitude of the s-parameter, similar to the measurement results of various states in Figs. 14 and 15.

Simulated SIC results with the SI reference generator as a combination of the proposed reflected type true time delay, phase shifter, and attenuator are shown in Figs. 16, 17, 18, and 19, and the performance is much better than that of the ideal true time delay in Figs. 7, 8, 9, and 10. The anti-series varactor configuration is used for high linearity [13] and the varactor used in this simulation and measurement is BB833, which is made by Infineon, whose series resistance, series inductance, and parasitic capacitance are 1.8 ohm, 1.8 nH and 0.2 pF, respectively.

D. POWER MARGIN FOR ACTIVE CANCELLATION AND TX-RX LOSS

The SI reference signal can be made by taking some power from the power divider followed by the PA. Then, it is fed to a canceller that consists of a variable attenuator, phase shifter, and true-time delay circuits. The power budget for SIC and TX-RX loss of the proposed 2 × 2 MIMO full duplex RF front-end is shown in Fig. 20. The 1:4:1 three way power divider and combiner to send TX power to a SI reference generator circuit to make a signal identical to an SI signal and to subtract it from the received signal lead to a 2 dB TX power loss and a 2 dB RX SNR degradation. As shown in

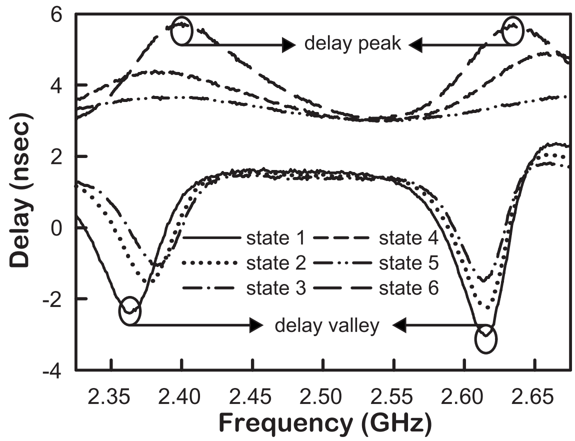

FIGURE 14. Measured delay variation of the proposed true time delay circuit.

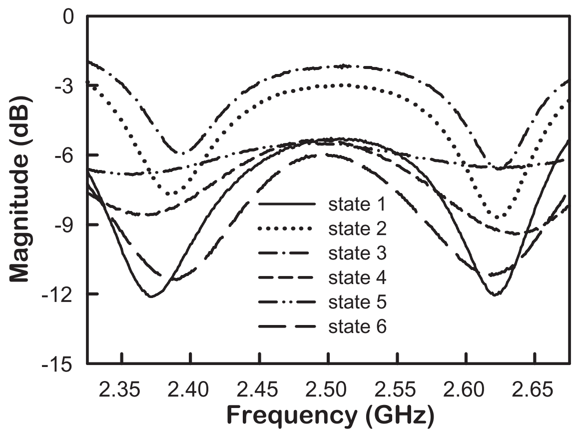

FIGURE 15. Measured magnitude variation of the proposed true time delay circuit.

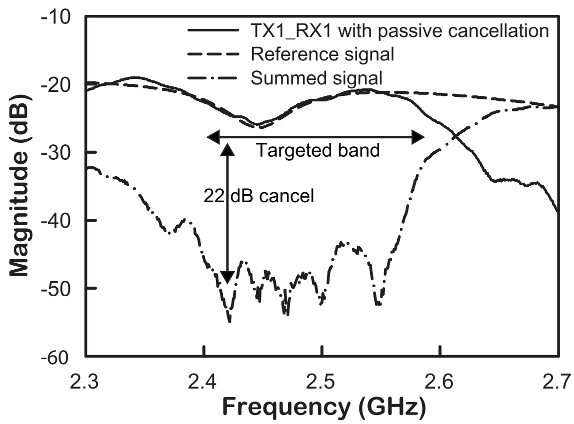

FIGURE 16. Magnitude of the measured TX1-RX1 s-parameters with passive cancellation, a simulated reference signal and a summed signal in simulation.

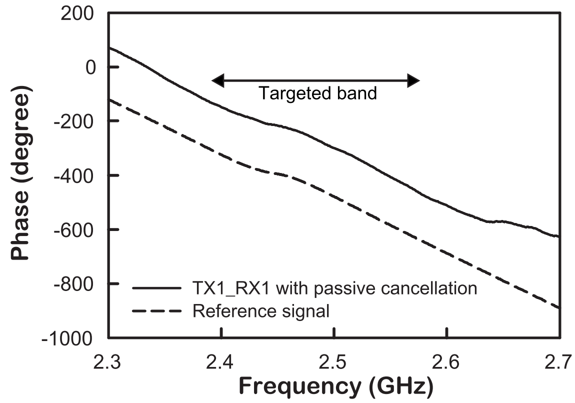

FIGURE 17. Phase of the measured TX1-RX1 s-parameters with passive cancellation and a simulated reference signal.

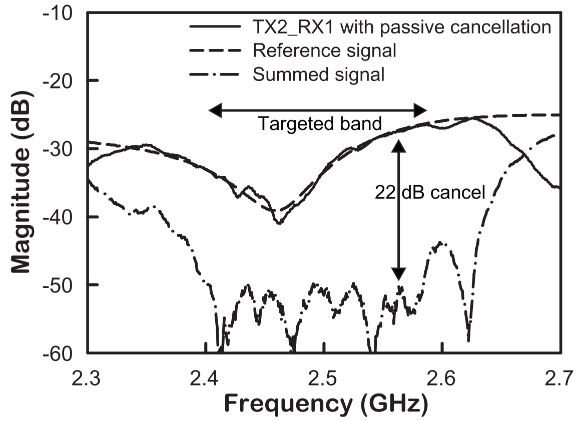

FIGURE 18. Magnitude of the measured TX2-RX1 s-parameters with passive cancellation, a simulated reference signal, and a summed signal in simulation.

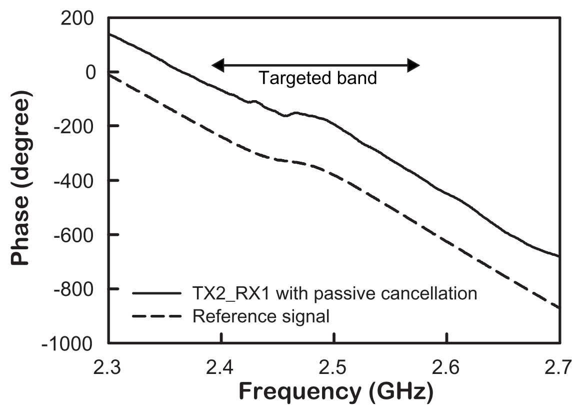

FIGURE 19. Phase of the measured TX2-RX1 s-parameters with passive cancellation and a simulated reference signal.

Fig. 5, assuming that passive suppression is performed by about 25 dB and the TX power is 23 dBm, 20 dB remains for the reference signal generator circuit. Regarding the insertion loss of the off-the-shelf variable attenuator and phase shifter, which are about 2 dB and 3 dB, the room for a time-delay circuit and control margin of the variable attenuator is 15 dB.

III. EXPERIMENTAL VERIFICATION

A. EXPERIMENT SETUP AND ADAPTIVE CONTROL

In the proposed canceller, six control voltages make identical signal to the SI signal: two voltages for the variable attenuator and phase shifter and four voltages for the time-delay circuit. Controlling such an SI reference generator manually is impossible because too many degrees of freedom are in the proposed tunable RF circuit. Therefore, some automatic

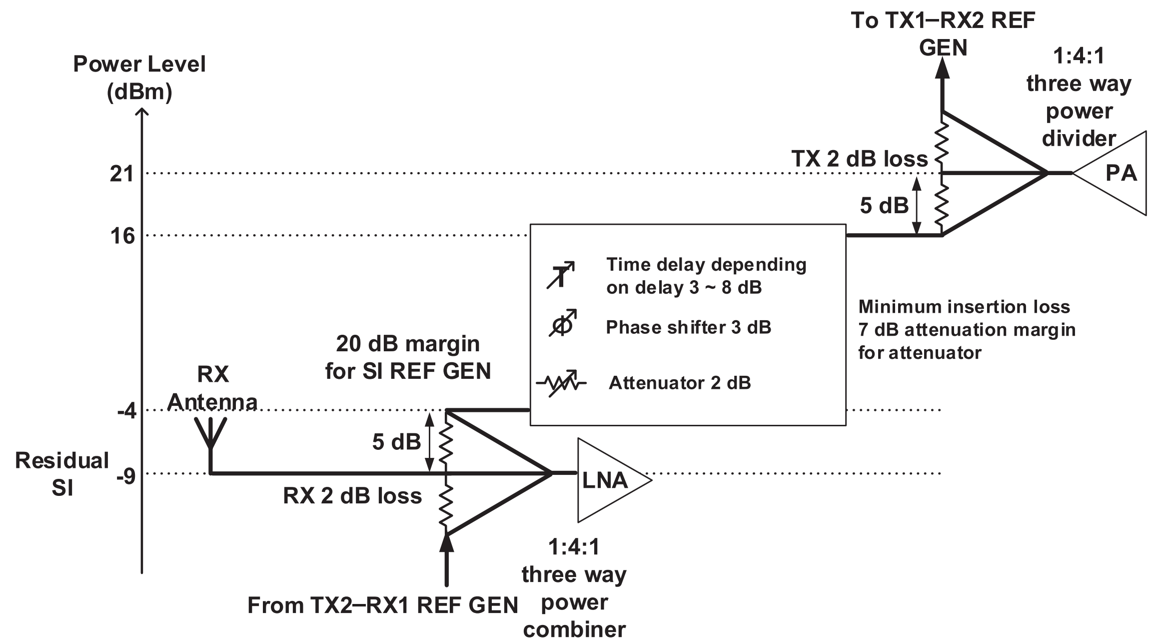

FIGURE 20. Power margin map for SIC and TX-RX loss.

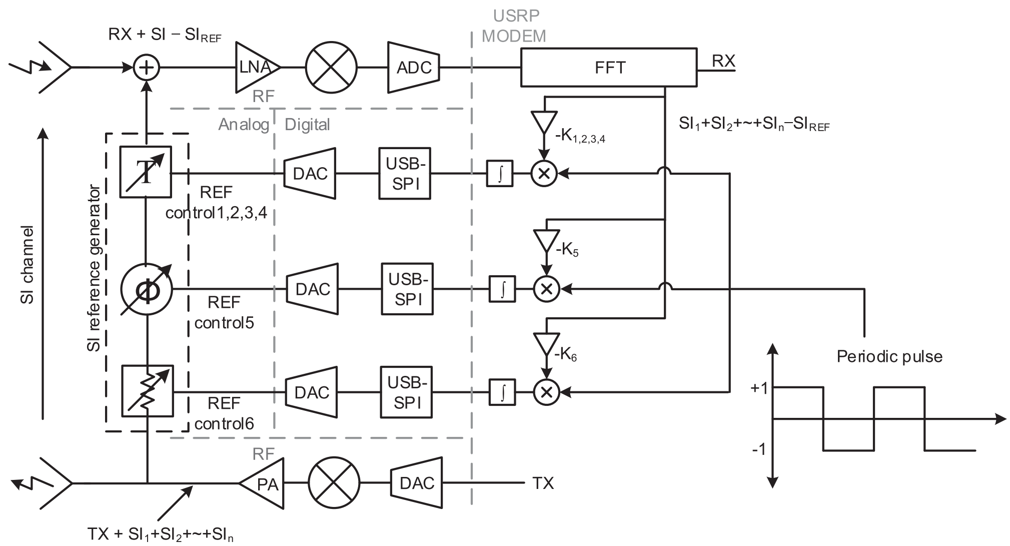

FIGURE 21. Overall experimental setup with a negative feedback loop to minimize the received power at the test-tone frequencies by automatically adjusting the bias voltages of the SI reference generator circuit. A software-defined radio, NI-USRP RIO, was used to create the test tones and measure the received power at the test-tone frequencies.

mechanism to control them must be used and the overall performance of SIC is expected to vary depending on what control mechanism is used. In this paper, some test tones were sent in the targeted band of SIC to adjust the SI reference generators so that the sum of the power of these test tones can be minimized. Then, the automatic control mechanism was achieved by constructing a negative feedback loop between the sum of the power of these test tones and the bias voltages for the SI reference generator. Overall, the experimental setup is shown in Fig. 21. The negative feedback loop to minimize the received power at the test-tone frequencies consists of an integrator and multiplier whose inputs are the received power at the test-tone frequencies and a periodic pulse, which determines the sign of the increment of the bias voltages of the SI reference generator. Moreover, this mechanism to adaptively adjust the reference generator to varying SI channel does not disturb the communication if the modulation data are not sent to the positions of the test tones, which is a standalone method that can be worked independently from communication. However, when more test tones are introduced, the throughput/hertz decreases, so the number of test tones is also a critical design factor to use this mechanism

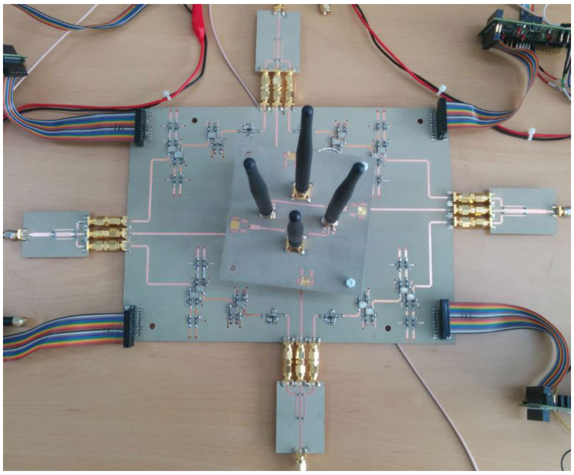

FIGURE 22. Photograph of the proposed full-duplex RF front-end.

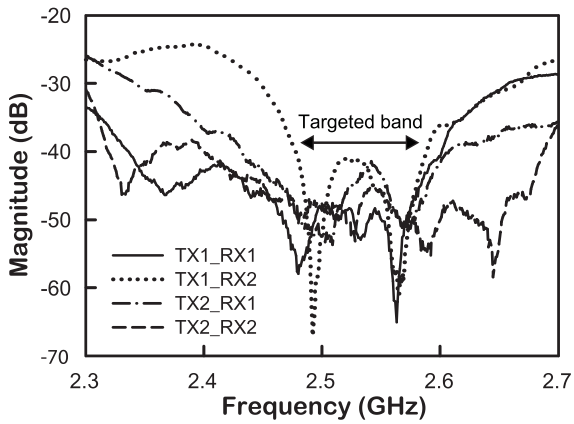

FIGURE 23. Total self-interference cancellation when two test tones are used at the band edge. The targeted center frequency is 2.53 GHz, and bandwidth is 80 MHz.

without severe loss of throughput/hertz. Therefore, two test tones and then four test tones were sent to find the maximum spacing between the test tones to achieve SIC over the targeted frequency band, which leads to using the minimum test tones.

B. RESULTS OF THE EXPERIMENTAL IMPLEMENTATION

The photograph of the proposed RF front-end board is shown in Fig. 22. The power divider, power combiner, and antenna network board can be detached from the SI reference generator board to measure the passive suppression and active cancellation, respectively. The targeted bandwidth of the SIC is 80 MHz at 2.53 GHz. Two test tones were sent to the edge of the band, and four test tones were sent over the band with equal spacing, at 20 MHz.

When the control mechanism of the SI reference generator was driven by two test tones, Fig. 23 reveals that the total SIC level was greater than 40 dB over 110 MHz, at 2.48 to −2.59 GHz, indicating only 15 dB of cancellation by the tunable RF circuit, considering that 25 dB of passive cancellation is shown in Section II Fig. 5. However, in Fig. 24, when four test tones were used, the total SIC level was greater than 50 dB over 90 MHz, at 2.49 to 2.58 GHz, indicating that active cancellation is performed by 25 dB. Experimental results indicate a trade-off between the SIC level and SIC bandwidth depending on different control mechanisms, and 20 MHz of spacing between the test tones is sufficient to achieve the overall 50 dB SIC in the proposed architecture.

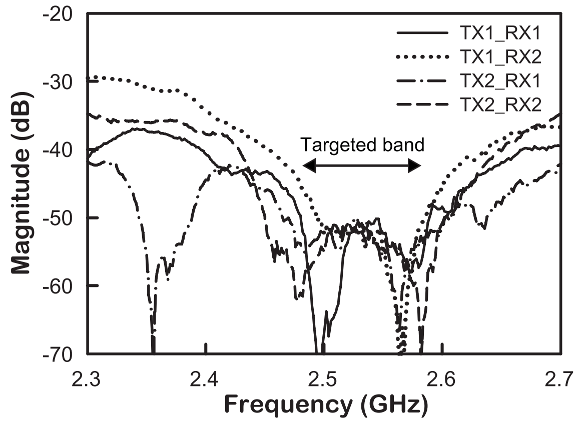

FIGURE 24. Total self-interference cancellation when four test tones are used over the bandwidth. The targeted center frequency is 2.53 GHz and bandwidth is 90 MHz.

IV. CONCLUSION

The 2 × 2 MIMO full duplex RF front-end using two rat-race couplers and four antennas was designed and four SI paths were canceled using passive suppression and active cancellation. Due to the method of passive suppression, an issue is that the TX and RX beam pattern are different, which is eased by the displacement of the antennas. The experimental results demonstrate a total SIC of 50 dB in 90 MHz at 2.53 GHz with a standalone active cancellation by tunable RF circuit to adaptively work independently from communication. Further study is required to investigate the automatic control mechanism of the SI reference generator and to achieve more wideband SIC, and a higher SIC level is required.

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