2×2 MIMO In-band Full Duplex Radio Front-end with 55-dB/60-dB Self-interference Cancellation over 200-MHz/100-MHz Bandwidth

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***Abstract*— This paper presents a 2×2 MIMO in-band full duplex radio front-end with 55-dB self-interference cancellation (SIC) over 200-MHz bandwidth at 3.7 GHz. For 55-dB SIC, a passive 30-dB suppression is achieved by using an antenna board composed of a decoupling network and circulator with reflection coefficient controller. Additional active 25-dB cancellation is achieved by using a RFSIC board composed of four 3-tap RF cancellers between 2 transmitters and 2 receivers for the broadband operation. Each tap of the RF canceller is composed of a variable attenuator, phase shifter, group delay controller and replaceable delay filter. The RF cancellers can be adapted to not only entire 200-MHz band, but also any channel band between 3.6–3.8 GHz of the antenna board, resulting in a higher SIC. Active 30-dB cancellations and total 60-dB SIC can be achieved when the RF cancellers are adapted to lower and upper 100-MHz bandwidth.**

***Keywords*— Full duplex radio (FDR), MIMO, RF front-end, self-interference cancellation (SIC).**

I. Introduction

In-band full duplex radio (FDR) systems can transmit and receive signals simultaneously in the same frequency band in order to double the throughput comparing to half duplex systems. The FDR systems, however, suffer from high self-interference (SI) due to its own transmitting signals, which is 110–120 dB higher than the receiver noise floor. Therefore, the SI cancellation (SIC) is essential and the biggest challenge in FDR systems. SIC is generally required to >50 dB at the RF front-end considering the ADC dynamic range of 60–70 dB [1]–[5].

There are two ways to achieve enough SIC between transmitting (TX) and receiving (RX) ports; passive suppression and active cancellation. Since it is difficult to achieve SIC at once, it is common that passive suppressions are performed first before active cancellations [1]–[5]. For SISO systems using a single antenna, the circulator was used for passive 15-dB suppression and active 45-dB cancellation over 80-MHz bandwidth using a 16-tap RF canceller, in which each tap consisted of a variable attenuator (ATT) and fixed true time delay [1]. For MISO systems, a rat race coupler for passive 30-dB suppression and 1-tap RF cancellers composed of a variable ATT, phase shifter (PS) and group delay controller (GDC) for active 30-dB cancellations were used at 2.48 GHz over 60-MHz bandwidth [2]. This system was expanded to a MIMO system with a similar manner [3]. To minimize the number of antennas (TX and RX shared antenna), a single-stage decoupling network (DN) between antennas and circulators with reflection coefficient controller (RCC) were used in [4], but the SIC bandwidth was limited to 100 MHz due to the DN and a short delay of RF canceller. There is a real-time SIC with fast adaptation in spite of low power consumption over 20-MHz bandwidth in [5].

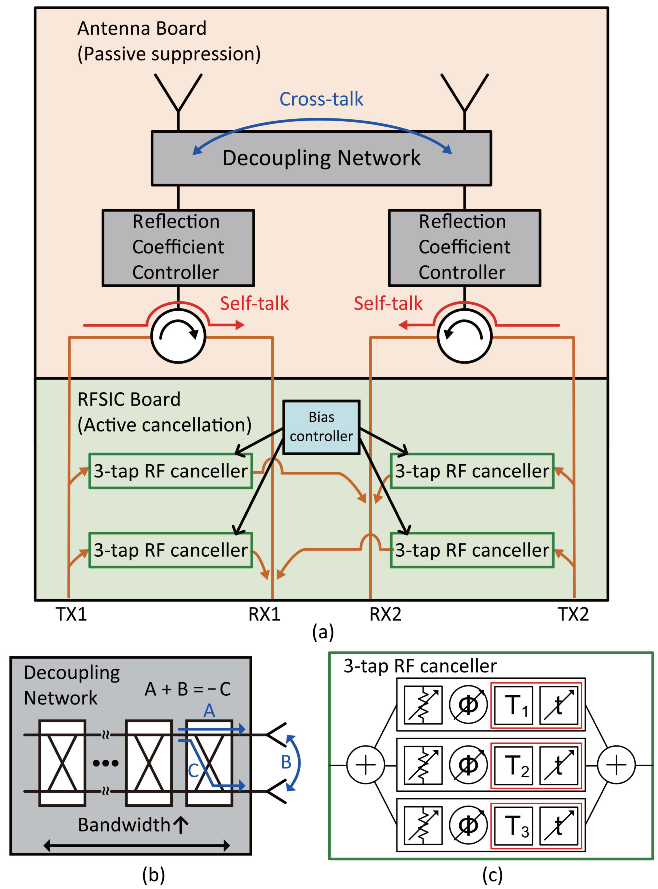

Fig. 1. Prototype for a 2×2 MIMO FDR front-end (a) composed of an antenna board and RFSIC board for a passive suppression and active cancellation respectively, (b) multi-stage decoupling network, and (c) 3-tap RF canceller with fixed delay filter for a wideband.

In this paper, an FDR front-end for a 2×2 MIMO with 2 TX and RX shared antennas is proposed for a more wide bandwidth. The proposed RF front-end achieves the SIC with a broadband passive suppression and active cancellation. For the wide band, the design methods of passive suppression in antenna board and active cancellation in RFSIC board are explained in section II and III. In section IV, the experiment result shows the passive 30-dB suppression over 200-MHz bandwidth. Then, it is followed by the active 25-dB and 30-dB cancellation over 200-MHz and 100-MHz band, respectively, between 3.6–3.8 GHz of the passive suppression bandwidth.

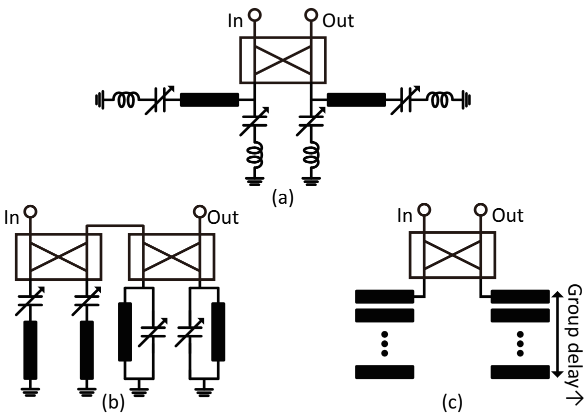

Fig. 2. Single stage 360° RTPSs (a), cascaded GDCs (b) and replaceable delay filter (c) used for the RF canceller.

II. Passive Suppression in Antenna Board

Fig. 1(a) shows the proposed 2×2 MIMO RF front-end for a FDR system with passive antenna board and active RF SIC board with cancellers. To meet the power budget and linearity of canceller, a passive 30-dB suppression is required at the antenna board of two MIMO antennas. Between the two antennas, a 10-dB isolation can be achieved by 0.4-λ physical separation. For the 30-dB suppression, a DN is introduced between the antennas. The proposed DN is shown in Fig. 1(b), which is multiple stages of asymmetric couplers to have the divided power cancelled at the antennas. The multiple stages of couplers helps to increase the isolation bandwidth comparing to the single-stage DN in [4].

A circulator is used for separating TX and RX ports from a single antenna. A commercial circulator has 15–20-dB isolation, which is insufficient for the passive suppression. Since the isolation of circulator depends on impedance matching of the antenna port, the RCC controlling reflection coefficient of the antenna is used for increasing isolation exchanged for a loss less than 0.1 dB [6].

There are two kinds of SI called cross-talk and self-talk. The cross-talk is an SI between two separated antennas isolated by the multi-stage DN, and the self-talk is an SI between TX and RX ports of one antenna isolated by the circulator with RCC as shown in Fig. 1(a). With the proposed antenna board, the passive 30-dB suppression over 200-MHz bandwidth is achieved as black line in Fig. 3.

III. Active Cancellation in RFSIC Board

In order to cancel the passive suppressed SI, the signal identical with the passive suppressed SI (mimicking SI) should be subtracted from the received signal. To generate the mimicking SI, the transmitting signal is coupled and fed to the RF canceller composed of a variable ATT, PS and GDC [2]. The variable ATT used is RFSA2033 from Qorvo, which is commercially available. For the PS, a reflection type PS (RTPS) [7] is designed as shown in Fig. 2(a). The RTPS uses reflective loads based on two $\lambda/2$-separated resonators with varactors, and the varactors are independently controlled for a low loss and delay variation. The proposed RTPS can cover a full 360° phase shift in a single stage, even though conventional RTPSs need to be a multiple stages as a 3-stage RTPS in [4].

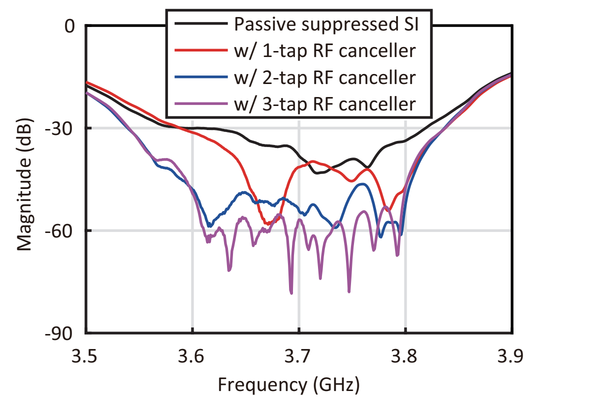

Fig. 3. Measured passive suppressed SI of the antenna board and simulated active cancelled SI in terms of different number of taps.

The group delay of SI should be mimicked and therefore, GDCs are required for the canceller. GDCs are small and low loss, but have a bandwidth limitation comparing to a true time delay circuit. To increase the bandwidth, the GDC in Fig. 2(b) are based on a two stage of RTPSs which give a delay variation rather than a phase shift [8]. However, the delay control range is about 1.5 ns, which is not long enough to cover various SI, because there can be a static reflector around antennas, resulting in a long delay. Therefore, a replaceable delay filter is used for a long group delay as shown in Fig. 2(c). The delay filter can be replaced to optimize the FDR front-end to reduce the required dynamic range of GDC. For example, if a 4.7-ns group delay is required, the 4-ns replaceable delay filter is used and the GDC is dynamically adjusted to have 0.7 ns.

The magnitude and group delay of the passive suppressed SI vary over the bandwidth. This is because there can be many different paths between TX and RX ports such as circulator, DN, antennas and reflectors. Since a single-tap RF canceller can not cancel the passive suppressed SI within a wide bandwidth, several number of delay taps are required to mimic SI. In the proposed front-end, the RF canceller are composed of 3 taps to have the active cancellation over 200-MHz bandwidth as shown in Fig. 3.

IV. Demonstration of 2×2 MIMO FDR

The RF front-end prototype in Fig. 4(a) consists of the antenna board for the passive suppression, the RFSIC board for the active cancellation, and a bias controller to control RF cancellers. The antenna board consists of two antennas, DN for the cross-talk isolation and circulator with RCC for the self-talk isolation. The 3-tap RF canceller is used for the active cancellation, which include a variable ATT, RTPS, cascaded GDC and replaceable delay filter (connector only) as shown in Fig. 4(b). Since the 2×2 MIMO requires 4 RF cancellers between 2 TX and 2 RX for the self-talk and cross-talk in Fig. 1(a), the proposed RFSIC board composed of 4 RF cancellers, which are on the front and back sides of the RFSIC board.

Since the antenna board are designed symmetrically, the passive suppressed SIs of two cross-talk paths (TX 1,2 – RX

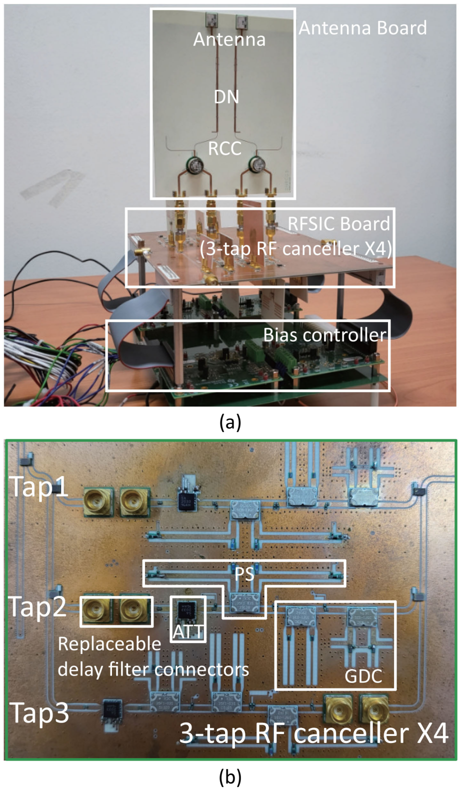

Fig. 4. Photograph of (a) the proposed 2×2 MIMO FDR front-end (b) with 3-tap RF cancellers.

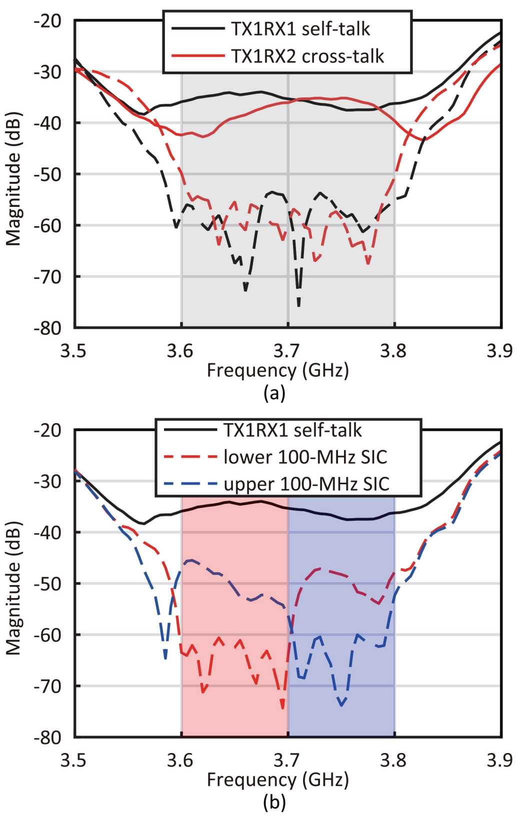

Fig. 5. Measured SI of the proposed RF front-end with the RF canceller adapted for (a) 200-MHz bandwidth (55-dB SIC) and (b) 100-MHz bandwidth (60-dB SIC). The solid line is for passive suppressed SI and the dotted line is for residual SI after the active cancellation.

Table 1. Performance Comparison with Other FDR systems

Reference	$f_c^\star$ (GHz)	Bandwidth (MHz)	$SIC^{\dagger}_{ANT}$ (dB)	$SIC^{\ddagger}_{ANT+RF}$ (dB)	RF canceller (number)
This MIMO	3.7	200	30	55	3 taps
		100	30	60	3 taps
[1] SISO	2.45	80	15	60	16 taps
[2] MISO	2.48	60	30	60	1 taps
[3] MIMO	2.53	80	25	50	1 taps
[4] MIMO	3.55	100	30	60	3 taps

$f_c^\star$: Center frequency of the bandwidth, $SIC^{\dagger}_{ANT}$: Antenna board SIC, $SIC^{\ddagger}_{ANT+RF}$: Antenna board and RFSIC board SIC.

2,1) and two self-talk paths (TX 1,2 – RX 1,2) are very similar, respectively. Furthermore, since RFSIC board is also designed symmetrically and use identical 3-tap RF cancellers, the total SIs after active SIC are similar. Therefore, only one SI result are shown for each cross and self talk. In Fig. 5(a), it can be seen that the total 55-dB SIC is performed using the active 25-dB cancellation after the 30-dB passive suppression over 200-MHz bandwidth for both cross and self talks. For the bandwidth of 5G communication of 100 MHz, if the active cancellation is adapted for an upper and lower 100-MHz bandwidth, the SIC up to 60 dB (active 30-dB cancellation) is achieved as shown in Fig. 5(b). This result shows that the RFSIC board adapt to active 30-dB cancellation (60-dB SIC) over 100-MHz bandwidth for anywhere between 3.6–3.8 GHz of the antenna board. Performance comparison with other FDR front-end is shown in Table 1. Comparing to the other works, the proposed RF front-ends can support up to 200-MHz bandwidth and 60-dB SIC.

V. Conclusion

This paper presents a method for the 55-dB SIC over 200-MHz bandwidth for a 2×2 MIMO FDR front-end. To achieve 55-dB SIC, passive 30-dB suppression is preceded before the active 25-dB cancellation. The antenna board composed of a DN and circulator with RCC shows 30-dB isolation over 200-MHz bandwidth. The RFSIC board with four 3-tap RF cancellers is introduced for the active cancellation. Each tap of RF canceller consists of a variable ATT, RTPS, cascaded GDC and replaceable delay filter. By using a proposed RFSIC board with antenna board, the measured results show the RFSIC board can adapt to not only entire 200-MHz band, but also any channel band between 3.6–3.8GHz of the antenna board, resulting in a higher SIC. Total 60-dB SIC can be achieved when the RF cancellers are adapted to lower and upper 100-MHz bandwidth.

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