

2×2 MIMO In-band Full Duplex Radio Front-End With 2-stage Passive Suppression and Four 3-tap RF Cancellers

Gisung Yang, *Student Member, IEEE*, Donghyun Lee and Byung-Wook Min, *Member, IEEE*

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 and 60-dB SIC targeting 100 MHz within entire 200-MHz bandwidth. A passive 30-dB suppression is achieved in two stages at the antenna board. Cross-talk suppression is achieved through antenna separation with a decoupling network, and self-talk suppression is achieved through a circulator with reflection coefficient controller. Additional active cancellation is achieved by using a RFSIC board composed of four RF cancellers for each channel. Each RF canceller should be composed of at least two taps taking into account for the 2-stage passive suppression and it needs one additional tap for reflected path from environment. Each tap of the RF canceller is composed of a variable attenuator, phase shifter, group delay controller and replaceable delay filter. To determine the required S-parameters of the RF canceller, a power delay profile analysis and gradient optimization are used, and to implement it on RF canceller, the bias voltages of each tap are determined by using proposed control method. The RF cancellers have the capability to adapt to the entire 200-MHz band as well as any channel band within the range of 3.6–3.8 GHz on the antenna board, leading to improved SIC. By adjusting the RF cancellers to the lower and upper 100-MHz bandwidth, it is possible to achieve active 30-dB cancellations and a total SIC of 60 dB.

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

I. INTRODUCTION

THE era of 5G and beyond 5G requires the higher data rate, resulting in frequency congestion. To solve this problem, the in-band full duplex radio (FDR) method has been used, which can transmit and receive signals simultaneously in the same frequency band in order to double the throughput compared to the half-duplex system [0], [0], [0], [0].

The biggest challenge to utilize FDR is to solve the self-interference (SI) problem, which the signal came out from transmitter (TX) is regarded as a noise at the receiver (RX). In general this SI signal is approximately 110-dB higher

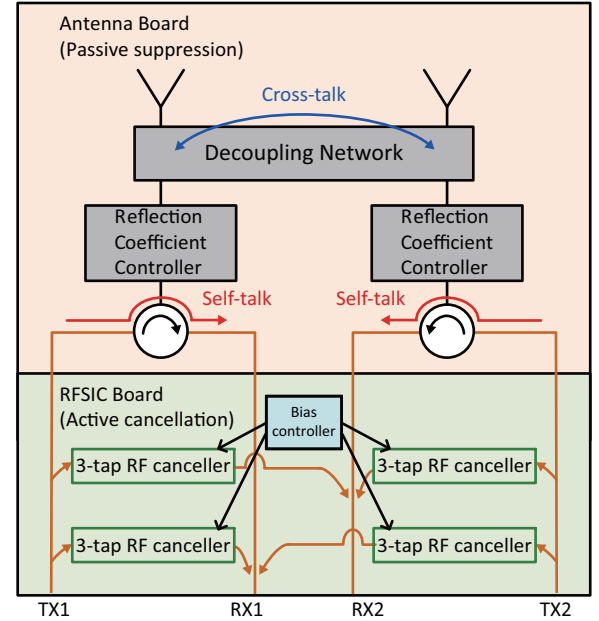


Fig. 1. 2×2 MIMO FDR front-end composed of an antenna board for a passive suppression and RFSIC board for an active cancellation.

than the RX noise floor. Therefore to configure FDR system, 110-dB SI cancellation (SIC) should be achieved not to fail communication [0], [0]. In digital domain, it is theoretically possible to achieve a large amount of SIC up to the dynamic range of the ADC, which is in general 60 dB [0], [0]. Therefore, considering 10-dB margin of OFDM PAPR, 60-dB analog SIC should be preceded in the RF front-end to prevent saturation of RX.

Analog SIC is mainly divided into two parts: passive suppression and active cancellation. Passive suppression aims to suppress a sufficient amount of SI at the antenna interface to avoid the saturation of the active cancellation. Therefore, it is important for passive suppression to restrain the dominant SI, which is the direct path originated from the antenna coupling and the antenna reflection [0]. Active cancellation achieves SIC by re-generating mimicked signal of the passively suppressed SI and subtracting each other [0]. The SI originated from dynamic environments after radiation needs to be cancelled by the active cancellation.

For SISO system using shared antenna, passive 15-dB suppression using circulator and 45-dB active cancellation using 16-tap RF canceller are conducted over 80-MHz bandwidth

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The authors are with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: bmin@yonsei.ac.kr).

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[0]. In this method, due to only passive 15-dB suppression, the RF canceller has to be limitedly designed considering saturation. In addition, due to the tap composed of an attenuator (ATT) and a fixed delay, performance is limited, resulting in a large number of taps being needed. To configure MISO system, rat race coupler is used for passive 30-dB suppression and 1-tap RF canceller for active 30-dB cancellation [0]. Due to the tap composed of ATT, group delay controller (GDC), and phase shifter (PS), sufficient amount of power can be cancelled with a small number of taps. As expanding this system, 2×2 MIMO system demonstrates 50-dB SIC over 80-MHz bandwidth [0], [0]. The 1-tap RF canceller is tried to cancel SI over the wider bandwidth than its capability, resulting in cancelling the smaller amount of SI. To expand bandwidth up to 100 MHz which is 5G communication bandwidth, 2×2 MIMO system using two antennas was demonstrated [0]. For passive 30-dB suppression, two-port decoupling network (DN) is used for SI suppression between two antennas, and circulator with reflection coefficient controller (RCC) for SI suppression of shared antenna. For four channels, four 3-tap RF cancellers is used for active 30-dB cancellation over 100-MHz bandwidth.

In addition, there are several methods employed for active cancellation. One approach involves dual injection of cancellation signals in both RF and baseband domains to achieve SIC [0]. Another method utilizes a delay-generating N-path filter for down conversion, followed by the generation of cancellation signals in the baseband and subsequent up conversion for SIC in the RF domain [0]. For passive suppression, the hybrid couplers and non-reciprocal delay elements have been used to achieve SIC [0]. In the cases of [0] and [0], similar to [0], there is no component for controlling the phase, and in the case of [0], there is no component for controlling the delay. Therefore, more taps are needed for the canceller to achieve the same bandwidth compared to the canceller using GDC and PS together.

A 2×2 MIMO FDR front-end with 2-stage passive suppression and 3-tap RF cancellers is proposed with an experimental results achieving 55-dB SIC over a 200-MHz bandwidth and 60-dB SIC targeting 100 MHz [0]. In this paper, the detail design procedure and system analysis of the FDR front-end are reported. Since the FDR front-end are composed of many circuit components, this paper outlines the circuit requirements and details of each component. Especially for the active cancellation, the reason why each RF canceller needs to have 3 taps and the control method of RF canceller are explained. In section II, the design detail for the passive suppression over 200-MHz bandwidth is explained, composed of DN and RCC parts without tunability. The explanation for the active cancellation is followed in section III, composed of replaceable fixed delay filter, GDC, and PS parts with a discussion on the nonlinear distortion of the RF canceller. In section IV, the measurement results are shown with comparison table.

II. PASSIVE SUPPRESSION

To avoid saturation of RF cancellers employed for active cancellation, a passive 30-dB suppression must be preceded at

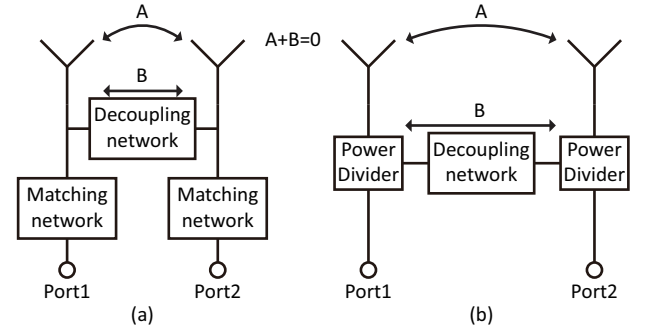


Fig. 2. Configuration of 2-port DN on the antenna interface using (a) matching network, or (b) power divider.

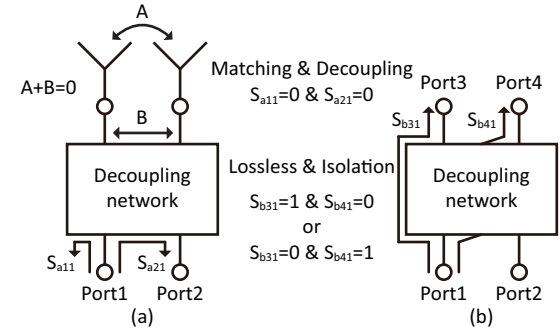


Fig. 3. Block diagram of 4-port DN (a) with antennas and (b) without antennas. Each diagram has horizontal symmetry.

the antenna board, as shown in Fig. . The design for the passive suppression depends on the antenna configurations [0]. For example, in a SISO system, there are two methods for antenna configurations. One method involves using separated antennas for TX and RX, while the other method utilizes a shared antenna for both TX and RX. In the configuration of separated antennas, dominant SI arise from a direct coupling between the antennas. Due to insufficient decoupling in the antenna separation, DN is proposed for another suppression stage [0], [0]. When using the shared antenna, it is necessary to use a circulator to separate TX and RX. SI in the shared antenna with the circulator is composed of an antenna reflection and a leakage signal arising from the low isolation of the commercial circulator. To alleviate this unwanted signal, RCC is used for another suppression stage by controlling the antenna reflection and cancel it with the leakage signal [0].

To expand 2×2 MIMO with two antennas by combining these two methods, two types of SI are present as shown in Fig. : cross-talk generated between the two separated antennas, and self-talk generated from the shared antenna with circulator. To suppress these SI, DN is used to suppress the cross-talk and RCC is used to suppress the self-talk resulting in 2-stage suppression respectively.

Although the SI originated from dynamic environments is resolved in the active cancellation, passive suppression can be designed with tunability to consider manufacturing tolerance, despite the loss it causes [0]. However, passive suppression can be implemented without any tunable components, if the dielectric constant variation of the PCB substrate and etching

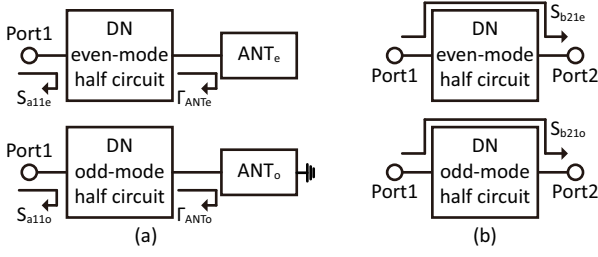


Fig. 4. Even- and odd-mode analysis for 4-port DN (a) with antennas, and (b) without antennas. ANT_e and ANT_o represent even- and odd-mode half circuit of the two separated antennas.

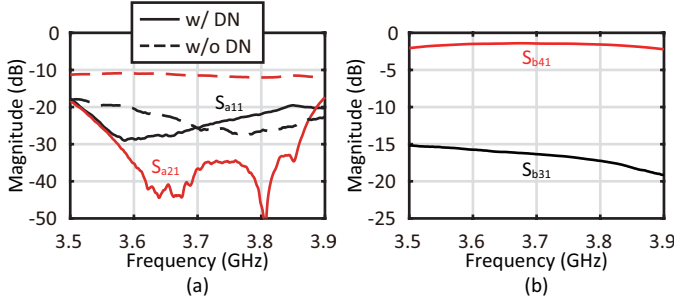


Fig. 5. Measured results of (a) return loss (S_{a11}) and coupling (S_{a21}) for 2 antennas with and without DN, and (b) insertion loss (S_{b41}) and isolation (S_{b31}) for DN.

tolerance are taken into account to achieve 30-dB suppression despite of the worst case. In this paper, it is considered that the dielectric constant variation of 3.6 to 3.7 and the etching tolerance of ± 5 μ m.

A. Decoupling Network

A coupling and impedance matching between the same two off-the-shelf antennas, ANT1085 from TDK, relates to the physical distance between them. Considering MIMO system, 0.4λ distance is selected, with the 11-dB coupling and the return loss about 25 dB.

To suppress a strong coupling between antennas especially under $\lambda/2$, DN is required at the antenna interface. There are 4 requirements for DN: *decoupling*, *lossless*, *matching*, and *isolation*. *Decoupling* is a primary function of DN, which suppresses the cross talk arising from the coupling between the antennas. *Lossless* implies that the DN applied at the interface of the antennas should not cause a significant signal degradation. *Matching* should not be changed when DN is applied to the well-matched antenna interface. *Isolation* means the only one antenna should be excited by the each TX to prevent unwanted beam patterns.

In designing a DN as a 2-port network, when the DN is placed on the antenna interface as Fig. (a), the matching of the antenna is changed, requiring an additional matching network [0]. In consideration of matching and isolation, however, when designing a DN using a power divider as Fig. (b) there is a loss problem [0]. In the same antenna configuration, the DN must be designed as a 4-port network as Fig. rather than a 2-port network in order to satisfy all 4 requirements. These

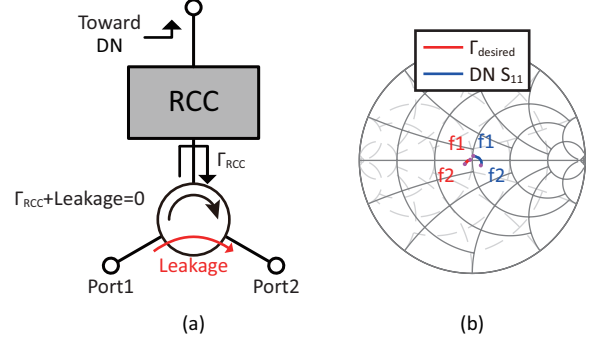


Fig. 6. (a) Circulator with RCC for self-talk suppression, and (b) $\Gamma_{desired}$ for the circulator and S_{11} looking into the DN on the Smith chart, where f_1 and f_2 is 3.6 GHz and 3.8 GHz respectively.

characteristics are analysed in () using even- and odd-mode analysis of Fig. , which is Fig. .

$$S_{a11} = \frac{S_{a11e} + S_{a11o}}{2} \quad (1a)$$

$$S_{a21} = \frac{S_{a11e} - S_{a11o}}{2} \quad (1b)$$

$$S_{b31} = \frac{S_{b21e} + S_{b21o}}{2} \quad (1c)$$

$$S_{b41} = \frac{S_{b21e} - S_{b21o}}{2} \quad (1d)$$

To satisfy the condition for *matching* and *decoupling*, S_{a11e} and S_{a11o} should be zero from () and (). In the case of the *isolation* condition, either () or () should be zero, which means $S_{b21e} = -S_{b21e}$ or $S_{b21e} = S_{b21e}$. Therefore the complex problem of designing DN with 4 conditions reduces to the simple problem of designing a lossless even- and odd-mode matching network in Fig. .

Measured DN with two antennas has 20-dB return loss and has 35-dB cross-talk isolation, showing well-matched and good decoupling characteristic over 200-MHz bandwidth as shown in Fig. (a). From Fig. (b), DN has 0.4-dB loss and 16.3-dB isolation showing low loss and good isolation characteristic.

B. Reflection Coefficient Controller

Using a shared antenna has the advantage of a small antenna footprint [0]. However, to separate TX and RX, a circulator is required. In this case, the SI is a composite signal of both the antenna reflection signal and the leakage signal from the circulator. Generally, due to commercial antennas have a 10-dB return loss and circulators have a 15-dB isolation, the SI is dominated by the antenna reflection signal.

In this paper, to reduce this SI, RCC in [0] is utilized between the circulator and DN as Fig. (a). It is designed to make the antenna reflection signal equal in magnitude but opposite in phase to the leakage signal of circulator. In [0], as RCC is designed for an arbitrary load impedance, bandwidth cannot be defined. Therefore, RCC is typically designed to operate at a single frequency with about 70-dB isolation as [0]. However, in this paper, the RCC is designed for the input impedance of the already manufactured DN as its load, and

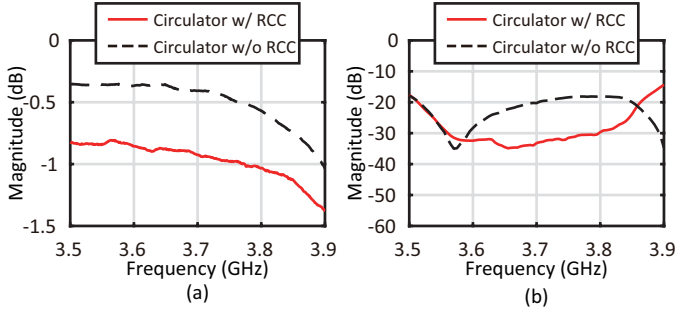


Fig. 7. Measured results of (a) insertion loss, and (b) isolation for circulator with and without RCC.

thus, its bandwidth can be defined. Therefore, RCC is designed to have more than 30-dB isolation over 200-MHz bandwidth.

In [0], a method was introduced to obtain $\Gamma_{desired}$ using the S-parameters of the circulator (1). This $\Gamma_{desired}$ corresponds to Γ_{RCC} , which ensures the perfect isolation.

$$\Gamma_{desired} = \frac{-S_{21}}{S_{31} \times S_{23} - S_{21} \times S_{33}}. \quad (2)$$

Although $\Gamma_{desired}$ in (1) is used to achieve perfect isolation, it is not clear how impedance matching and power delivery changed when RCC is inserted between the DN and port 3 of the circulator. Therefore, it is necessary to analyse the impedance matching and the transducer power gain.

In Fig. (a), when employing a conjugated matching network for maximum power transfer instead of RCC, the signal inserted at port 1 is fully directed towards the DN, excluding leakage signal. Otherwise, when using RCC, in the same situation, the signal is directed towards the DN, excluding leakage signal and $\Gamma_{desired}$. Since the magnitude of $\Gamma_{desired}$ is comparable to the magnitude of the leakage signal, the transducer power gain of RCC does not differ significantly from that of maximum power transfer when a high-isolation circulator is used. Similarly, in the case of impedance matching, for the signal incident on port 1 to be reflected back towards port 1 after encountering the RCC, it must go through the isolation of the circulator. Therefore, impedance matching can lead to favorable results.

Now, the method of passively self-talk suppression by increasing the isolation of the circulator is simplified by designing RCC, which is a straightforward matching network that moves S_{11} of the DN to the $\Gamma_{desired}$ of the off-the-shelf circulator, JCM3600T4200VM3R from JQL, as shown in Fig. (b). Differ from [0], the isolation of the circulator must be good for a wide bandwidth rather than a single frequency, so a matching network must be designed for several frequencies. In this paper, an RCC is designed for three frequencies, including f_1 (3.6 GHz) and f_2 (3.8 GHz), which are both ends of the target bandwidth, as well as the center frequency of 3.7 GHz. As a result of designing the RCC, Fig. (a) indicates that the intrinsic loss of the RCC is approximately 0.4 dB, and including the circulator's loss of 0.5 dB, the total combined loss amounts to 0.9 dB. Without the use of RCC, the self-talk will exhibit an approximately 20-dB isolation as the black line in Fig. (b), which is not sufficient for passive suppression. By

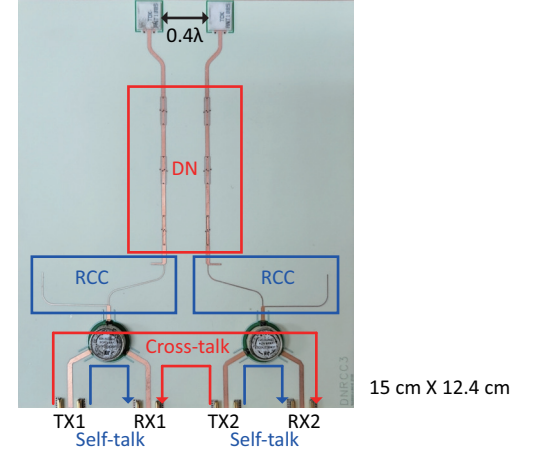


Fig. 8. Photograph of antenna board for 2×2 MIMO composed of 2 separated antennas with DN for cross-talk 30-dB suppression, and circulator with RCC for self-talk 30-dB suppression. Each SI is passively suppressed by 2 stages respectively.

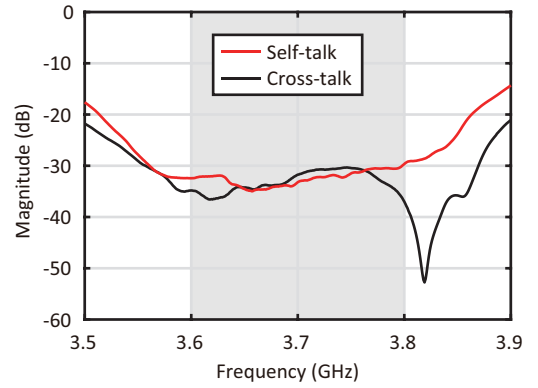


Fig. 9. Measured result for the cross-talk and self-talk of the antenna board.

using RCC, the self-talk has 30-dB isolation as shown in the red line of Fig. (b).

C. Measurement of the Proposed Antenna Board

So far, all efforts for passive 30-dB suppression including DN, circulator with RCC have been put into the antenna board of Fig. . The antenna board was manufactured on a substrate of Ro4350B with a thickness of 0.762 mm. The metal lines are wide enough, with a minimum width of 0.1 mm, considering general PCB manufacturing process. The antenna board shows more than 30-dB passive suppression in Fig. . Since the antenna board is horizontally symmetric, the response is the same for each of cross-talks and self-talks. Therefore, only one graph is plotted for each in Fig. .

III. ACTIVE CANCELLATION

To remove the 2-stage passively suppressed SI achieved by the antenna board, active cancellation is performed by subtracting the residual SI from the signal regenerated by the RF canceller. As shown in Fig. , the RF canceller uses the coupled-off signal from the TX, which includes both linear

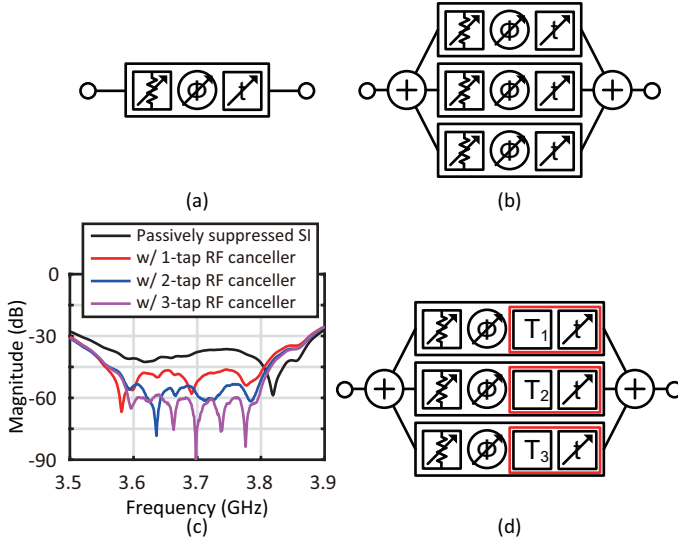


Fig. 10. RF canceller for mimicking passively suppressed SI : (a) a single tap, (b) multiple taps. (c) Simulated active cancellation for passively suppressed cross-talk, in terms of different number of taps, considering 3-dB power dividing/combining loss, and (d) RF canceller with three taps including fixed delays.

and non-linear components, to remove not only the linear but also the non-linear components at the active cancellation [0].

A. Structure of the Proposed RF Canceller

In general, a tap composed of ATT, PS, GDC as Fig. (a) can model one delayed path. To regenerate a signal that is equal in magnitude but opposite in phase to the residual SI, the RF canceller should be composed of multiple taps [0]. Regarding cross-talk, there are two types of residual SI : one comes from the direct path and the other from antenna reflections. As for self-talk, there are also two types of residual SI : one from antenna reflections and the other from circulator leakage. For this reason, each RF canceller should consist of at least two taps, taking into account the two-stage passively suppressed SI, and it needs additional taps for the SI from the dynamic environment.

The required S-parameters of the taps for achieving active cancellation after passively suppressed SI are determined by analyzing the power delay profile (PDP) and gradient optimization [0]. To achieve 30-dB active cancellation, the RF canceller should be composed of three taps, as illustrated in Fig. (b), (c). It implies that the RF canceller needs one additional tap for SI originated from the dynamic environment. To apply it for the 2×2 MIMO system, a total of 4 RF cancellers are required considering the number of channels as shown in Fig. .

Considering the trade-off between the bandwidth and delay variation range, the GDC inherently has a narrower delay variation range to operate over a wide bandwidth. For compensation, replaceable fixed delays are required as shown in Fig. (d).

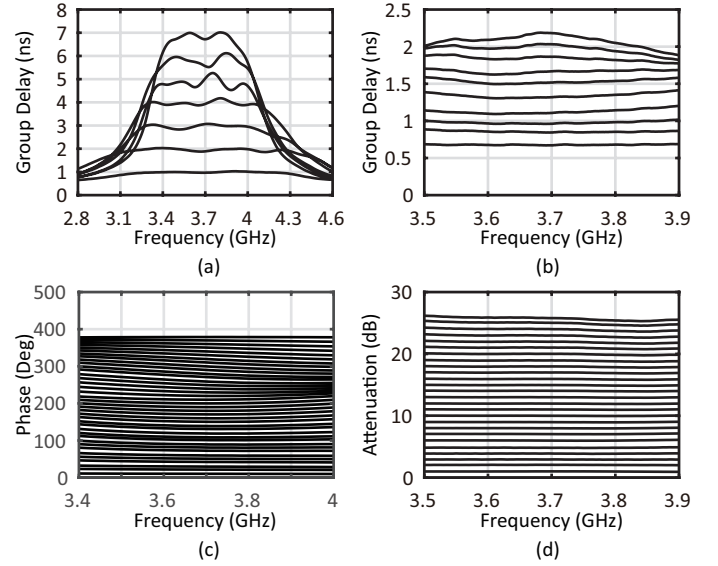


Fig. 11. Measured results of (a) fixed delay filter, (b) group delay controller, (c) phase shifter, and (d) off-the-shelf attenuator.

B. Replaceable Delay Filter

The most common way to implement large delays is to use coaxial cable [0], but it has a bulky size with a length of 25 cm/1 ns. To solve this problem, a method was published, using a band pass filters to have a long delay with a small size by using the principal of the reflection-type phase shifter (RTPS) [0]. This filter, however, has a maximally flat delay, so it has narrow bandwidth, and to use for a wider bandwidth, multiple delay filters should be cascaded. In this paper, a delay filter is proposed to achieve a flat delay over a wide bandwidth by allowing a certain amount of ripple.

Proposed delay filters were manufactured using the off-the-shelf hybrid coupler of X3C35F1-03S by Anaren and implemented on a 0.762-mm thick Ro4350B substrate by Rogers. Delay filters were manufactured with delay values ranging from 1 ns to 7 ns by 1 ns steps, normalized with reference delay of 0-ns bypass as shown in Fig. (a).

C. Group Delay Controller

To be utilize in the RF canceller, the GDC needs to have a delay variation range of more than 1 ns, which corresponds to the resolution of the replaceable fixed delay filter. Additionally, for the sake of control simplicity in the RF canceller, it is necessary for the GDC to exhibit low insertion loss and phase variation at the center frequency of 3.7 GHz. In this paper, the GDC from [0] is used to implement the RF canceller.

The group delay of the GDC of [0] varies from 0.67 to 2.18 ns at 3.7 GHz, which is a 1.51-ns group delay variation corresponding to a 5.6-fold wavelength at 3.7 GHz as shown in Fig. (b). The insertion phase variation shows a 31.4° at 3.7 GHz. The insertion loss is 2.1 ± 1.3 dB, indicating that the larger the delay, the larger the loss. The impedance of the GDC is well matched, with more than 18-dB return loss over the bandwidth for all delay states.

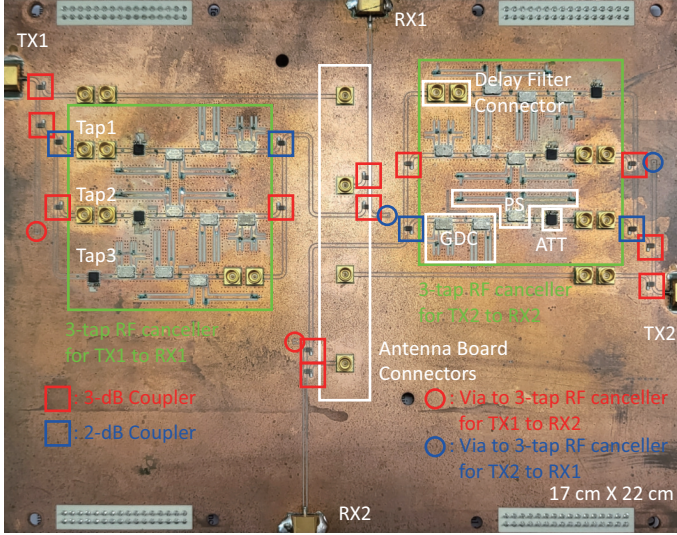


Fig. 12. Photograph of RFSIC board composed of four 3-tap RF cancellers.

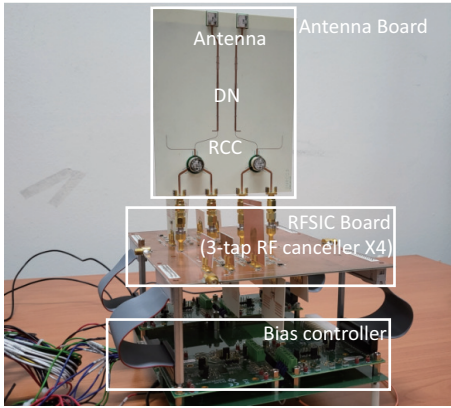


Fig. 13. Photograph of the proposed 2×2 MIMO FDR front-end composed of the antenna board, RFSIC board, and bias controller.

D. Phase shifter

To be used as a block of the RF canceller, PS should perform a 360° phase shift, and have a high resolution to minimize the quantization error. Additionally, when mimicking a high power signal, it is important to have a good linearity characteristic. Since it is a part of the RF canceller, along with ATT and GDC, the loss and delay variation of the PS should be low, regardless of the phase states to avoid unnecessary iterations. In this paper, RTPS proposed by [0] is utilized to achieve a low delay and loss variation according to phase states, in addition to satisfying the aforementioned conditions.

The RTPS described in [0] exhibits continuous 360° phase shifting as shown in Fig. (c). The delay variation is 250 ps, and the loss variation is 1.3 dB respectively. Furthermore, the RTPS demonstrates a return loss of over 15 dB, indicating good impedance matching.

E. Discussion on Nonlinear Distortion

Unlike the antenna board, the RFSIC board has tunable components. Therefore, it is important to check whether these tunable components create additional nonlinear distortion from

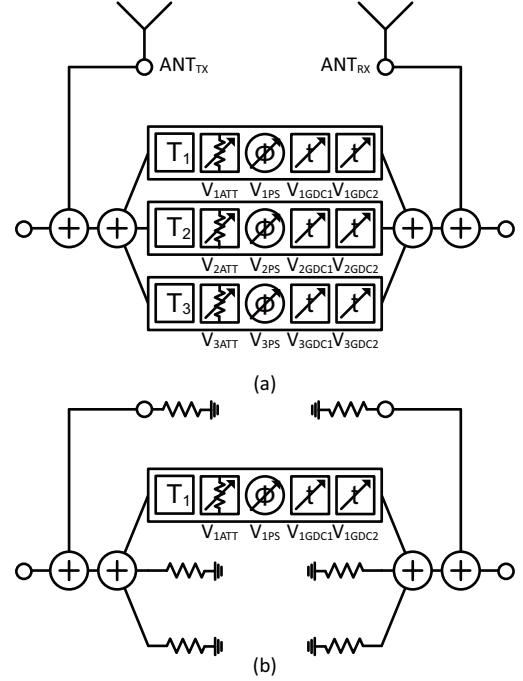


Fig. 14. (a) Proposed RF canceller, assuming a SISO system. (b) To model the first-tap S-parameters, ports of the antennas, and the second, third taps are terminated by 50Ω .

the modulated signal or high power signal. Therefore, as shown in Fig. (d), given that the attenuator is positioned ahead of the other tunable components, it is important to check the nonlinear distortion of the attenuator, where the highest power is reached.

To know the input power of the attenuator, the power dividing/combining loss of the RFSIC board should be calculated. As shown in Fig. , once a signal is input to the TX port of the RFSIC board, it is evenly split between the antenna board and RF cancellers using a 3-dB coupler designed as a power divider. The signal input to the RF cancellers is further evenly split between the RF canceller designed for self-talk SIC and the one designed for cross-talk SIC. Since each RF canceller is composed of 3 taps, a power divider is designed using 2-dB and 3-dB couplers to evenly split the input signal.

In MIMO wireless communication standard, the TX power should be 23 dBm at the antenna. Considering the 1.3-dB loss of antenna board and the 3-dB power dividing loss of RFSIC board, the TX port of Fig. should receive a input power of 27.3 dBm. This TX signal of 27.3 dBm undergoes power dividing loss of 11 dB before reaching the RF canceller, resulting in a power of about 16.3 dBm at the RF canceller. Since the IP_{1dB} of the off-the-shelf attenuator RFS2033 from QORVO, with the performance in Fig. (d), is 24 dBm, which is significantly higher than its input power, the attenuator and canceller do not introduce a serious nonlinear distortion. If there is a small amount of nonlinear distortion in the RFSIC board, it can be sufficiently removed in the digital domain [0].

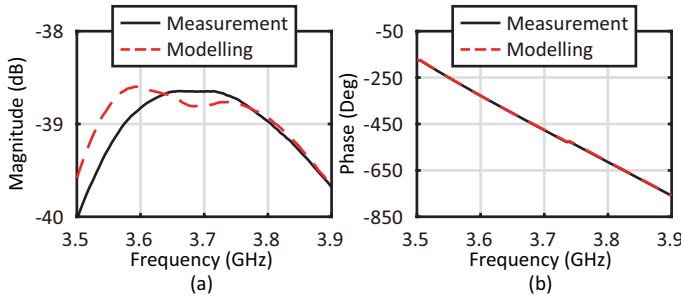


Fig. 15. Comparison between the measurement and the modeling of the S-parameters using the proposed control method by using randomly selected bias voltages.

IV. DEMONSTRATION OF 2×2 MIMO FDR FRONT-END

By combining the previously mentioned antenna board and RFSIC board, a 2×2 MIMO FDR front-end is designed, as shown in Fig. . To control each RF canceller, a DAC81416 from Texas Instruments is utilized for each RF canceller.

As shown in Fig. , it is a prototype to show that a 60-dB SIC is possible in the front-end with the proposed method for 2×2 MIMO FDR, resulting in a large size. To reduce the size of the proposed FDR front-end, the whole circuit components needs to be integrated in a module which can have a small form factor using LTCC or MMIC technology.

A. Control Method for RF Canceller

To achieve SIC through active cancellation, after passive suppression in the antenna board, the required S-parameters for each taps in the RF canceller are determined by using PDP analysis and gradient optimization, which is the same method in Fig. (c). The proposed RF canceller in Fig. can be briefly depicted assuming a SISO system, as shown in Fig. (a). To measure the S-parameters of the first tap of the RF canceller, the ports of the antennas, as well as the second and third taps, should be terminated with a $50\text{-}\Omega$ load as shown in Fig. (b). However, implementing the required S-parameters in the RF canceller is challenging due to interdependencies between the RF blocks. For instance, when the state of an attenuator changes, it not only affects the loss but also affects other factors, including phase and delay. Therefore, to implement the required S-parameters in the RF canceller considering its interdependencies, the S-parameters for the taps need to be measured for all bias states. However, due to the large number of bias voltages involved in the taps, the number of measurement cases increases exponentially. For instance, considering that a tap includes 4 different types of bias: one for ATT, one for PS, and two for GDC, if N bias states are measured for each bias voltage, the total number of bias states to be measured would be N^4 . In this paper, a method will be introduced to infer the S-parameters across all bias states by measuring only a few representative bias states out of the many available.

If the RF blocks have good impedance matching and the coupling between taps can be ignored, the S_{21} of a tap can be obtained by multiplying the S_{21} of each RF block. However, in the case of measurement as shown in Fig. (b), the S_{21}

of each RF block cannot be obtained. Instead, in this case, the variation in the S_{21} of the tap from the reference state is equivalent to the multiplication of the variations in the S_{21} of each RF block from reference state. Let the S_{21} of the tap be $S_{21}(V_{ATT}, V_{PS}, V_{GDC1}, V_{GDC2})$, where V_{ATT} , V_{PS} , V_{GDC1} , and V_{GDC2} are the bias voltages of each RF block. The variation in S_{21} of the tap from the reference state can be expressed as

$$\begin{aligned} & \left[\frac{S_{21}(V_{ATT}, V_{PS}, V_{GDC1}, V_{GDC2})}{S_{21}(0, 0, 0, 0)} \right] \\ &= \left[\frac{S_{21}(V_{ATT}, 0, 0, 0)}{S_{21}(0, 0, 0, 0)} \right] \times \left[\frac{S_{21}(0, V_{PS}, 0, 0)}{S_{21}(0, 0, 0, 0)} \right] \\ & \quad \times \left[\frac{S_{21}(0, 0, V_{GDC1}, 0)}{S_{21}(0, 0, 0, 0)} \right] \times \left[\frac{S_{21}(0, 0, 0, V_{GDC2})}{S_{21}(0, 0, 0, 0)} \right]. \quad (3) \end{aligned}$$

To verify the proposed method, a comparison is made between the measurements obtained from arbitrary bias voltages and the modeled S-parameters using the proposed method. The results, as shown in Fig. , exhibit a remarkable similarity, indicating the equation's effectiveness. Using the proposed method, the S_{21} for all bias states can be inferred by measuring only $S_{21}(V_{ATT}, 0, 0, 0)$, $S_{21}(0, V_{PS}, 0, 0)$, $S_{21}(0, 0, V_{GDC1}, 0)$, and $S_{21}(0, 0, 0, V_{GDC2})$ where each bias voltage $V_{RF \text{ block}}$ varies from 0 to $V_{RF \text{ block}, \max}$. This method saves a significant amount of time compared to measuring N^4 S-parameters, as it only requires measuring $4N$ S-parameters.

B. Measurement

As shown in Fig. , the antenna board exhibits horizontal symmetry, resulting in similar suppression of self-talk between TX 1,2 and RX 1,2, and cross-talk between TX 1,2 and RX 2,1 respectively. Similarly, the RFSIC board, shown in Fig. , is designed to be nearly symmetric, utilizing the same RF canceller for each SI. Consequently, each self-talk between TX 1,2 and RX 1,2, and cross-talk between TX 1,2 and RX 2,1 components exhibit similar SIC performance respectively. To illustrate this, Fig. exhibits one representative example each for self-talk and cross-talk performance. It shows that 55-dB SIC is achieved over 200-MHz bandwidth for both cross-talk and self-talk. To evaluate the SIC performance within the targeted 100-MHz bandwidth, the SIC performance reaches 60 dB, as also depicted in Fig. .

The comparison with other FDR front-ends is shown in Table . Generally, in the sub-6G frequency band, FDR front-end designs that satisfy the 5G bandwidth of 100 MHz are rare [0]. However, the proposed FDR front-end achieves passive suppression of 30-dB SIC over a 200-MHz bandwidth without any tunable components for low loss and active cancellation of 25-dB SIC, resulting in a total of 55-dB SIC over 200 MHz without any power dissipation. For the higher SIC performance, specifically targeting 100 MHz within a 200-MHz bandwidth, the 60-dB SIC is achieved. This work demonstrates the best performance among the compared works listed in Table .

V. CONCLUSION

This paper presents a 2×2 MIMO FDR front-end for achieving 55-dB SIC over 200-MHz bandwidth and 60-dB SIC over

TABLE I
PERFORMANCE COMPARISON WITH OTHER FDR FRONT-ENDS

Reference	f_c^* (GHz)	Bandwidth (MHz / %)	Passive suppression	$SIC_{ANT}^\dagger$ (dB)	Active cancellation (number of taps / RF blocks for tap)	$SIC_{ANT+RF}^\ddagger$ (dB)	Power (mW)
This MIMO	3.7 3.65–3.75	200 / 5.4 100 / 2.7	Ant. Sep. ¹ with fixed DN, Circ. ² with fixed RCC	30	3 taps / Fixed delay, ATT, GDC, PS	55 60	$\times^*$
[0] SISO	2.45	80 / 3.3	Circ. ²	15	16 taps / Fixed delay, ATT	60	$\times^*$
[0] SISO	2.2	40 / 1.8	Ant. Sep. ¹ or Circ. ²	30	5 taps / Fixed delay, VGA ^{††}	60	11.5
[0] SISO	26	400 / 1.5	Hybrid coupler, non-reciprocal delay	20	1 tap / PS, VGA ^{††}	53	23.5
[0] MISO	2.48	60 / 2.4	Rat race coupler	30	1 tap / ATT, GDC, PS	60	$\times^*$
[0] MIMO	2.53	80 / 3.2	Rat race coupler	25	1 tap / ATT, GDC, PS	50	$\times^*$
[0] MIMO	3.55	100 / 2.8	Ant. Sep. ¹ with tunable DN, Circ. ² with tunable RCC	30	3 taps / ATT, GDC, PS	60	$\times^*$
[0] MIMO	2.5	20 / 0.8	Circ. ²	24	2 taps / Fixed delay, VGA ^{††}	48	32–104

f_c^* : Center frequency of the bandwidth, $SIC_{ANT}^\dagger$: Passive suppression, $SIC_{ANT+RF}^\ddagger$: Active cancellation, VGA^{††} : Variable gain amplifier, Ant. Sep.¹ : Antenna separation, Circ.² : Circulator, $\times^*$: Implemented on PCB without power consuming components

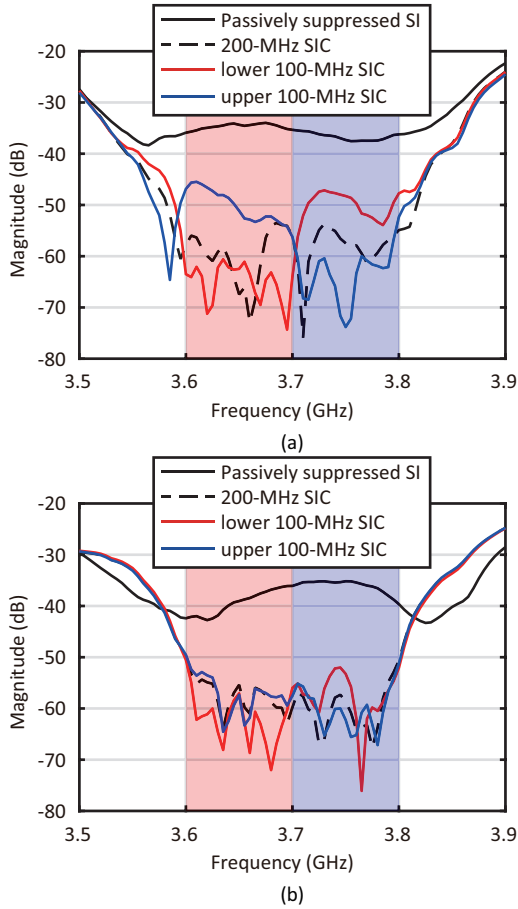


Fig. 16. Measured result of the proposed 2×2 MIMO FDR front-end with (a) self-talk between TX 1 and RX 1, (b) cross-talk between TX 1 and RX 2.

a targeting 100 MHz within a 200-MHz overall bandwidth. In the proposed 2×2 MIMO system, both cross-talk and self-talk are present as two types of SI, and effective cancellation techniques are employed to mitigate their impact. The

antenna board achieves a passive 30-dB suppression, while the RFSIC board achieves an additional active cancellation. To achieve the passive suppression in two stages over the entire 200-MHz bandwidth without any tunable components for low loss, the antenna board incorporates antenna separation with DN for cross-talk and circulator with RCC for self-talk. On the other hand, the RFSIC board incorporates four 3-tap RF cancellers, with two taps dedicated to supporting the 2-stage passively suppressed SI and one tap for the SI originated from dynamic environment. Configuring each tap presents for GDC a significant challenge due to the narrow delay variation range when achieving the wide bandwidth. To address this issue, a replaceable delay filter is introduced to compensate the problem of the GDC. Therefore, each tap consists of a replaceable delay filter, ATT, PS, and GDC. The proposed RF canceller is designed without an amplifier, offering the advantage of high linearity and not consuming power. The required S-parameters of the RF canceller for active cancellation are determined through a combination of PDP analysis and gradient optimization techniques. To implement the required S-parameter into the RF canceller, a number of bias voltages should be controlled. An efficient control method is proposed to determine the appropriate bias voltages for each tap. Through experimentation, the proposed front-end is demonstrated to achieve 60-dB self-interference cancellation over a 100-MHz bandwidth within the overall 200-MHz range. To highlight the performance of proposed front-end, a comparison with other existing FDR front-ends is provided in Table .

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Gisung Yang received the B.S. degree in electrical and electronic engineering from Yonsei University, Seoul, South Korea, in 2020, where he is currently pursuing the Ph.D. degree in electrical and electronic engineering. His current topics of study include optimization techniques for tuning RF canceller in in-band full duplex RF front-end by a machine learning.



Donghyun Lee was born in Suwon, Korea, in 1988. He received the Ph.D. degree in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2022. He started a company that makes components for in-band full duplex radios, such as delay filters.



Byung-Wook Min (S'03-M'08) received the B.S. degree from Seoul National University, Seoul, Korea, in 2002, and the M.S. and Ph.D. degrees from The University of Michigan at Ann Arbor, in 2004 and 2007, respectively. In 2006-2007 and 2019, he was a Visiting Scholar with the University of California at San Diego, La Jolla.

He is currently an Professor with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea. In 2008-2010. He was a senior engineer at Qualcomm Inc., Santa Clara, CA and Austin, TX. His research interests include Si/SiGe RFIC and communication systems for microwave and millimeter-wave applications. He was a recipient of the Samsung Scholarship in 2002-2007.