RF Self-Interference Cancellation Circuits for Advanced Duplex Systems

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***Abstract*—Advanced duplex systems promise enhancing of spectral efficiency by enabling simultaneous uplink and downlink transmissions in the same band, but they suffer from severe self-interference (SI) that must be mitigated in the analog domain before digitization. This paper reviews the application of RF self-interference cancellation (SIC) circuits—active cancellation using multi-tap RF cancellers with tunable attenuators, phase shifters, and delay controllers—to realize advanced duplex operation at gNodeBs. From published RF circuit implementations, how to implement three-tap RF cancellation for active cancellation is introduced. Experimental validation confirms that 30-dB active RF cancellation meets the analog SIC requirement for advanced duplex operated in in-band full-duplex mode. These results demonstrate the feasibility of employing proven RF front-end techniques to enable advanced duplex in next-generation communications.**

***Index Terms*—Advanced duplex, in-band full duplex (IBFD), self-interference (SI), self-interference cancellation (SIC), spectrum shared full-duplex (SSFD), sub-band full duplex (SBFD).**

I. Introduction

As communication generations advance, the demand for higher data rates continues to grow. To meet this demand, extensive research has focused on improving spectral efficiency.

A. In-Band Full Duplex

Conventional duplexing methods are broadly categorized into time-division duplex (TDD) and frequency-division duplex (FDD). TDD alternates uplink (UL) and downlink (DL) transmissions in the same frequency band over different time slots, whereas FDD uses separate frequency bands to support UL and DL simultaneously.

In contrast, in-band full duplex (IBFD) doubles spectral efficiency by enabling concurrent UL and DL within the same band [1], [2]. However, IBFD faces the major challenge of self-interference (SI), where the signal from the transmitter (TX) appears as noise at the receiver (RX). Additionally, cross-link interference (CLI) between user equipments (UE) remains a critical issue.

B. Sub-Band Full Duplex and Advanced Duplex

Sub-band full duplex (SBFD) uses different frequency sub-bands for UL and DL at the gNodeB (gNB), as shown in Fig. 1 (b). Unlike FDD, SBFD does not employ a guard band, so it still experience SI; however, because DL and UL occupy separate sub-bands, SI is reduced by the power amplifier's (PA) adjacent channel leakage ratio (ACLR) compared to IBFD. Self-interference cancellation (SIC) techniques are still required to further mitigate residual SI.

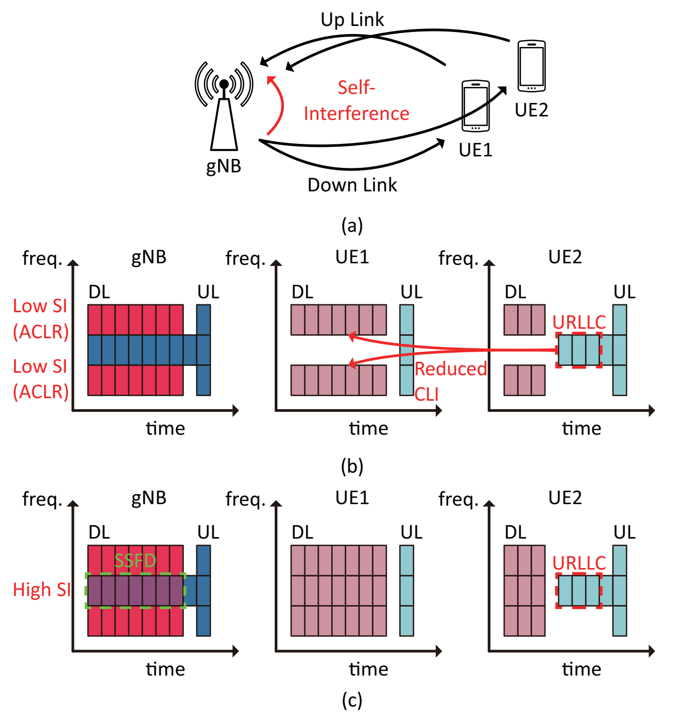

Fig. 1. Scenarios with SI in duplex communication systems: (a) communication environment with SI between gNB and UE, (b) time-frequency resource diagram for SBFD with reduced cross-link interference, and (c) for advanced duplex system with enhanced spectrum flexibility.

From the UE's perspective (Fig. 1(b)), UEs operate in TDD mode. Next-generation services demand ultra-reliable low-latency communication (URLLC), which prioritizes UL resources for emergency transmissions. As shown in Fig. 1(b), URLLC UL from UE2 can degrade UE1's DL performance due to CLI. SBFD mitigates this CLI performance degradation by separating DL and UL into different sub-bands.

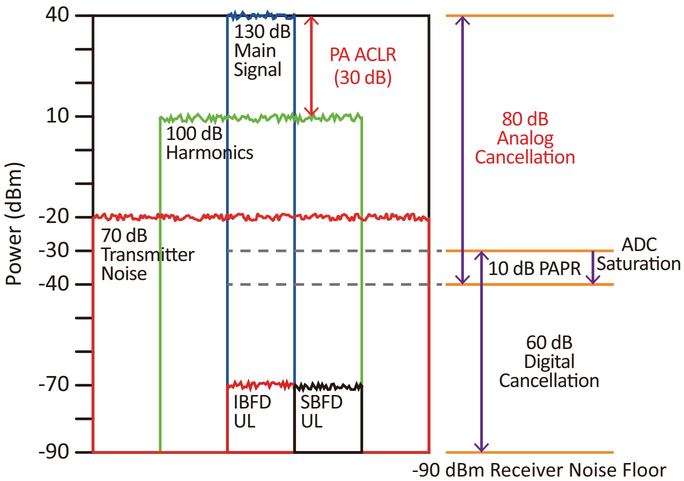

Fig. 2. gNB power budget for advance duplex.

As shown in Fig. 1(c), advanced duplex enhances SBFD's spectrum flexibility by dynamically allocates spectrum based on UL/DL congestion to maximize spectral efficiency. However, gNBs operating in spectrum shared full duplex (SSFD) mode must simultaneously support UL and DL transmissions in the same frequency band, similar to IBFD, necessitating advanced SIC capabilities to mitigate the strong SI.

C. *Self-Interference Cancellation for Advanced Duplex*

Fig. 2 depicts the gNB's TX power of 40 dBm and a RX noise floor of approximately –90 dBm. When advanced duplex operates in an IBFD configuration (ie., UL and DL share the same sub-band) the SI at the RX exceeds the noise floor by roughly 130 dB. In contrast, under SBFD operation, where UL and DL occupy distinct sub-bands, the PA's typical ACLR of 30 dB reduces SI to approximately 100 dB above the noise floor.

To address the worst-case scenario, SI removal must be examined for advanced duplex in its most extreme IBFD mode. In the digital domain, SIC is constrained by the analog-to-digital converter's (ADC) dynamic range. Consequently, digital SIC alone is insufficient, and a sufficiently high level of SIC must be performed in the analog domain before digitization. With a 12-bit ADC, approximately 60 dB of digital SIC is achievable; accounting for a 10 dB peak-to-average power ratio (PAPR) yields a requirement of 80 dB of analog SIC in IBFD operation.

Analog SIC encompasses two mechanisms: passive suppression and active cancellation [3]–[5]. Passive suppression enhances antenna or circulator isolation, whereas active cancellation mimics the suppressed SI and destructively combines it with the residual SI at the RX. When active cancellation is performed in the RF front-end, it is designated RF SIC; implementation in baseband (BB) is denoted BB SIC.

According to [6], [7], RF circuits for active cancellers suffer from severe bandwidth limitations due to fundamental constraints. In contrast, antenna isolation can support relatively wider bandwidths, providing significant advantages for passive suppression approaches.

In Fig. 2 when active cancellation targets the main signal, it may fail to adequately suppress harmonic components in adjacent channels due to its bandwidth constraints. This fundamental limitation necessitates that passive suppression, which can be implemented with broader bandwidth capability, must simultaneously suppress both the main signal and adjacent channel harmonics.

From a system design perspective, to prevent ADC saturation, the 10 dBm harmonic SI signal in adjacent channels must be suppressed to –40 dBm. This requires 50-dB SIC in the passive suppression stage. Following this passive suppression, the main signal exhibits a SI with 30 dB above the ADC saturation point.

The remaining 30 dB of interference can be effectively cancelled by the active cancellation stage. This multi-stage interference cancellation design provides an effective approach that optimizes overall system interference suppression performance while maintaining balanced implementation complexity across each stage.

This manuscript introduces an RF SIC circuit capable of 30-dB active cancellation. Section II details the RF SIC implementation in the presence of specified passive suppression. Section III presents the requisite circuit design. Section IV reports experimental results demonstrating active cancellation performance, and section V offers conclusions and prospects for future research.

II. Analog Cancellation

As shown in Fig. 2, a total of 80 dB of SIC is required in the analog domain. Analog cancellation proceeds by first performing passive suppression at the antenna stage, and then analysing the passively suppressed SI to apply active cancellation.

A. *Passive Suppression*

The antenna board in Fig. 3(a) was utilized for passive suppression, which was proposed in [6], [7]. This antenna board incorporates two antennas and two circulators to support 2×2 MIMO, resulting in two types of SI: cross-talk and self-talk. Cross-talk refers to interference between the two spatially separated antennas. Self-talk refers to interference caused by circulatory leakage within the shared antenna path.

A decoupling network (DN) was designed to enhance cross-talk isolation and a reflection coefficient controller (RCC) was designed to enhance circulator isolation. As illustrated in Fig. 3(b), over 30 dB of passive suppression was achieved.

To support advanced duplex systems, 50-dB passive suppression is required as demonstrated in Section I-B. While the antenna board in Fig. 3(a) achieves only 30-dB passive suppression, this is sufficient for demonstrating the RF SIC circuit proposed in this paper, which can achieve 30-dB active cancellation. Therefore, this paper demonstrates that the proposed RF SIC circuit can achieve 30-dB active cancellation with 30-dB passively suppressed SI. Future work will validate

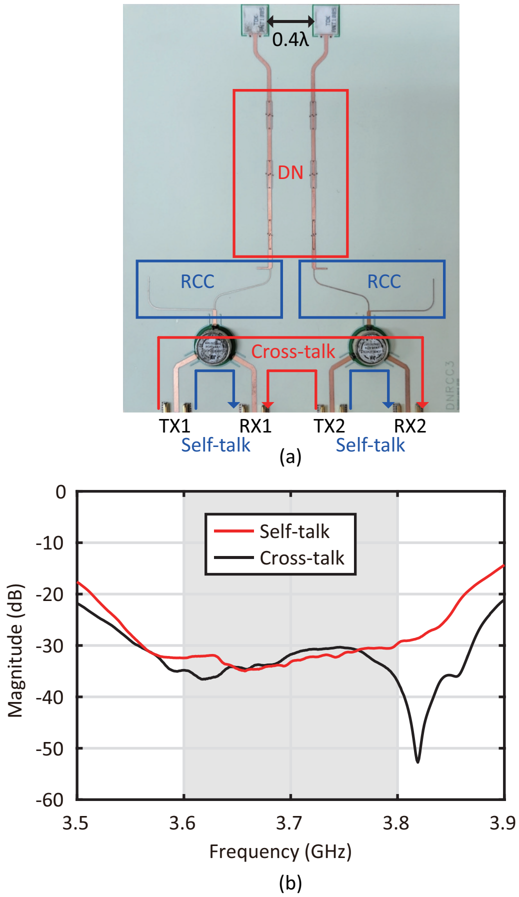

Fig. 3. Passive suppression for advanced duplex RF front-end: (a) antenna board supporting 2×2 MIMO with integrated decoupling network for cross-talk suppression and reflection coefficient controller for self-talk suppression, and (b) measured self-talk and cross-talk response for this antenna board.

that 30-dB active cancellation is achievable even with 50-dB passively suppressed SI.

B. Active Cancellation

Active RF cancellation is performed as illustrated in Figure 4. To achieve active cancellation, the RF canceller must accurately mimic the SI that has been suppressed passively. In order to mimic the nonlinearity of the PA, the signal coupled off from the PA's output is used.

The RF canceller is composed of multiple taps to mimic the SI. Each tap consists of a tunable attenuator (ATT) for adjusting signal magnitude, a tunable phase shifter (PS) for controlling phase, and a tunable delay circuit for setting delay.

III. Microwave Circuits for RF Canceller

A. Attenuator

An ATT is a circuit that controls the magnitude of a signal, as depicted in Fig. 5(a). Achieving 30 dB of SIC requires a 30-dB attenuation range. By pre-analysing the passively suppressed SI and determining the power required for each tap, the power divider and combiner in the RF canceller can be optimized to reduce the burden of the ATT.

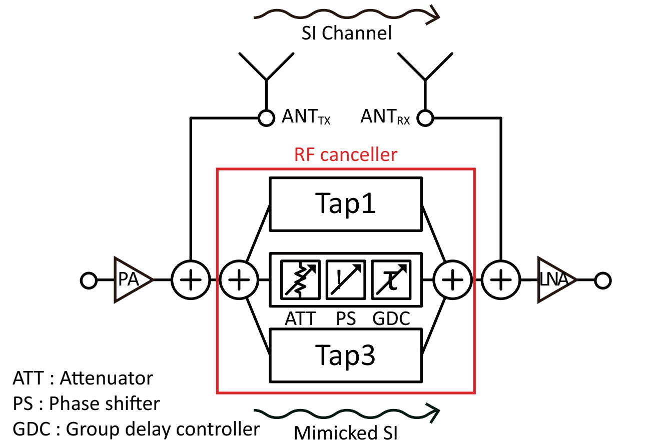

Fig. 4. Multi-tap RF canceller for active cancellation: Each tap consists of variable attenuator, phase shifter, and group delay controller to mimic SI channel characteristics.

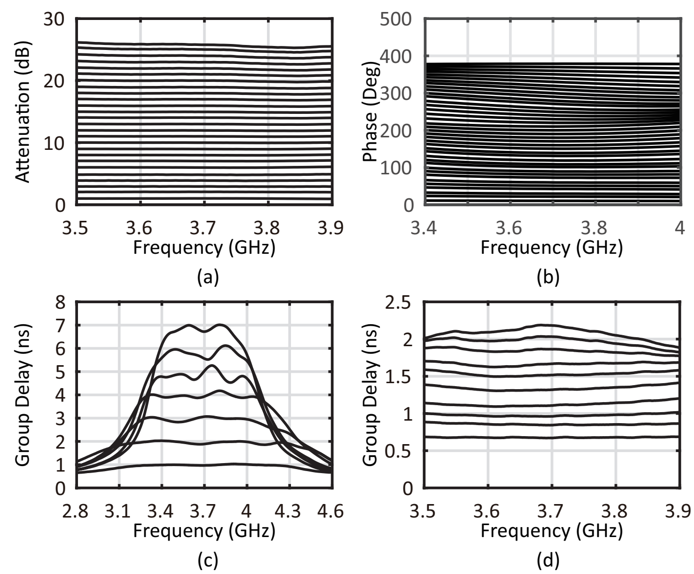

Fig. 5. Measured responses of the RF circuits to be employed in the RF canceller: (a) magnitude variation of attenuator, (b) phase variation of the phase shifter, (c) multiple fixed-delay filters implemented with various delays, and (d) delay variation of group delay controller.

The ATT employed in this study is Qorvo's RFSA2033, offering a 25-dB variable attenuation range. The measured attenuation response is shown in Fig. 5(a).

Considering RF canceller linearity, the attenuator must be placed at the front end of each tap. As mentioned in Section II-A, this paper conducts experimental validation with 30-dB passively suppressed SI; however, for practical gNB applications, validation should be performed with at least 50-dB passively suppressed SI. Under these conditions, the maximum input to the RF canceller is –10 dBm. Since the selected IP_{1dB} of the ATT is 24 dBm, a –10 dBm input does not introduce additional nonlinearity.

Changing the bias state of the ATT affects signal magnitude as well as phase and delay. Measurements reveal approxi-

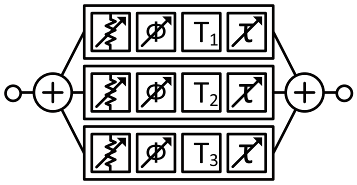

Fig. 6. Proposed RF canceller with each tap comprising an attenuator, phase shifter, group delay controller, and fixed-delay filter.

mately 40° of phase variation and 100-ps of delay variation, which increases RF canceller operation complexity.

B. Phase Shifter

The PS is a circuit that adjusts the phase of each tap, as shown in Fig. 5(b). The PS must support the full 360° range, and variations in loss and delay with bias state should be kept to a minimum.

Accordingly, the phase shifter from [8] was employed in this paper. It provides continuous tunability over 360°, with a loss variation of 1.3 dB and a delay variation of only 250 ps.

C. Delay Circuit

True time delay (TTD) and group delay controller (GDC) are the two primary types of tunable delay circuits. The TTD, based on a transmission line, operates over an extremely wide bandwidth but requires substantial physical size and incurs significant loss when a broad delay range is needed.

The GDC, utilizing a resonator structure, overcomes the drawbacks of the TTD. Resonator integration enables a compact form factor while providing a wide tunable delay range; however, the achievable bandwidth is inherently narrower than that of the TTD.

Mimicking SI in an RF canceller requires taps with diverse delay values. Satisfying this demand necessitates a circuit with an extensive tunable delay range. Consequently, a combined architecture employing a fixed-delay filter fabricated at 1-ns intervals and a GDC has been adopted to realize multiple discrete delay settings.

The fixed-delay filter from [7] was fabricated at 1-ns spacing; its response is presented in Fig. 5(c). The GDC, based on [9], exhibits the response shown in Fig. 5(d).

To ensure compatibility with the fixed-delay filter's 1-ns step size, the GDC was designed to provide up to 1.5 ns of tunability. The GDC was designed to minimize magnitude and phase fluctuations across bias states. It exhibits a phase variation of 31.4° and a loss variation of 2.6 dB.

D. Three-Tap RF Canceller

As shown in Fig. 6, the RF canceller was implemented using the RF circuits described above. The key point here is that a fixed delay filter and GDC were employed to cover a wide range of delay variations. As mentioned earlier, each RF circuit exhibits unwanted parameter variations when the bias voltage changes. Therefore, as in [6], [7], a lookup table must be constructed in advance based on measured data for each tap.

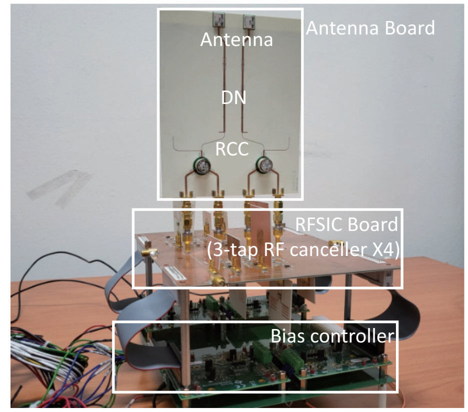

Fig. 7. Experimental setup of the three-tap RF canceller with the antenna board.

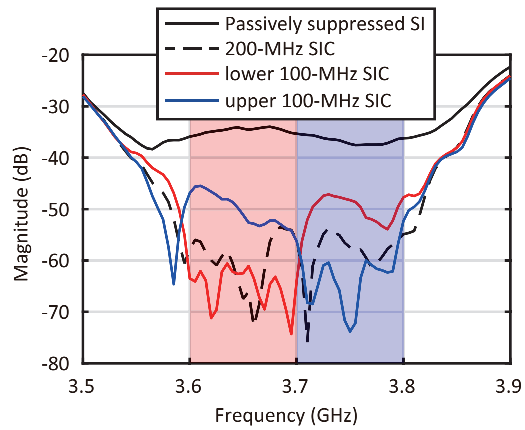

Fig. 8. Measured RF SIC result implemented by three-tap RF canceller using sequential SIC removal method proposed in [6], [7].

IV. Active Cancellation Result

The active cancellation experiment was conducted using the setup shown in Fig. 7. The antenna board and RFSIC board used are identical to those described in [6], [7].

A. Sequential SIC Removal of the Highest-Power Residual SI Component

In [6], [7], the passively suppressed SI was analysed via power delay profile (PDP), and the component with the highest power was implemented as the first tap. After performing single-tap SIC, the residual SI was reanalysed via PDP, and the component with the highest remaining power was implemented as the second tap. This process was repeated to design an RF canceller comprising three taps.

However, this method suffers from inter-tap disturbance due to nonuniform delay intervals between taps, which degrades the performance of the initially implemented tap. To address this issue, the parameters obtained by this approach were used as initial values in a gradient-based optimization to determine the optimal components for RF canceller.

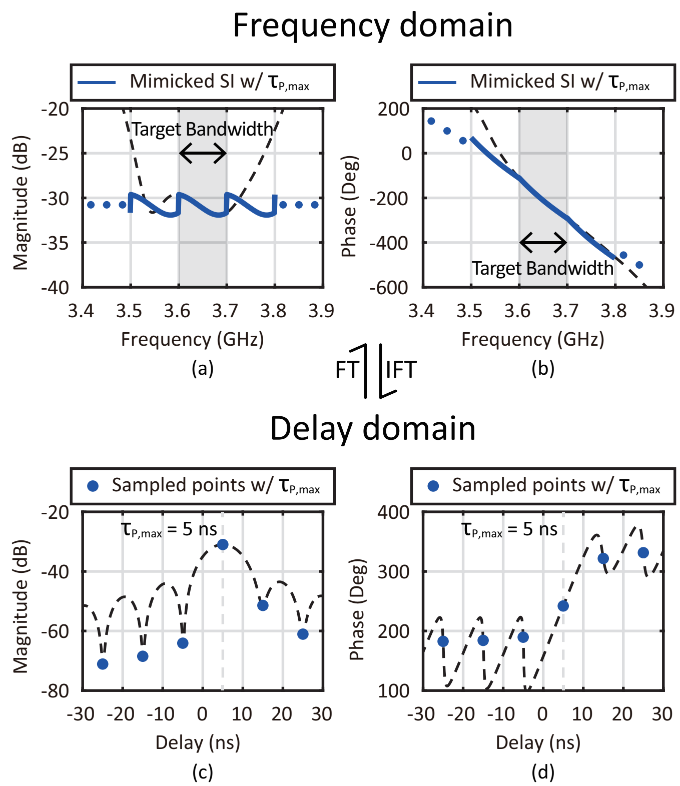

Fig. 9. Self-interference analysis using the inverse Fourier transform: frequency-domain (a) magnitude, (b) phase responses,and delay-domain (c) magnitude, (d) phase responses.

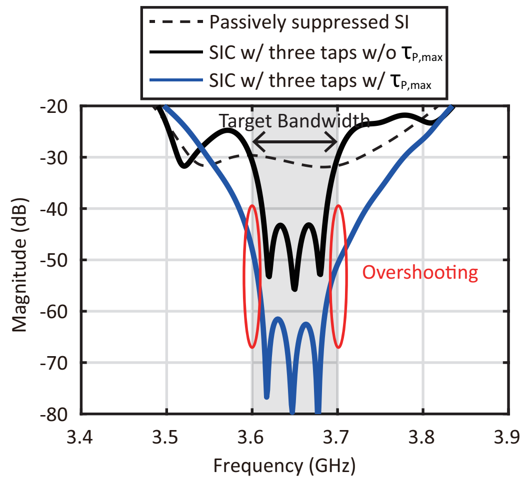

Fig. 10. Measured RF SIC results implemented by three-tap RF canceller using sampling uniform delay intervals proposed in [10].

The measured results, shown in Fig. 8, confirm that, under self-talk conditions, SIC achieves 55-dB cancellation over a 200-MHz bandwidth and 60-dB cancellation over a 100-MHz bandwidth.

B. Fourier-Based RF Self-Interference Cancellation

To mitigate the inter-tap disturbance reported in [6], [7], [10] realizes SI by sampling the SI signal at uniform delay intervals.

In Fig. 9(a), (b), the black dashed lines represent the measured SI. The response within the target bandwidth is transformed into the delay domain via an inverse Fourier transform (IFT); the resulting responses are plotted as black dashed lines in Fig. 9(c) and (d).

As shown in Fig. 9(c), the delay-domain SI exhibits its maximum power at $\tau_{P,max} = 5$ ns. The SI in the delay domain is then sampled, including the point at $\tau_{P,max}$, with a period equal to the reciprocal of the target bandwidth; the sampled values appear as blue points in Fig. 9(c), (d). When these samples are implemented as taps in the RF canceller, the blue solid curves in Fig. 9(a), (b) confirm that the SI can be reconstructed without aliasing.

Fig. 9(c), (d) indicate that selecting the three blue points with the highest power and implementing a three-tap RF canceller yields the SIC performance as the blue line in Fig. 10. This improvement results from including $\tau_{P,max}$ among the RF-canceller taps. In contrast, excluding $\tau_{P,max}$ causes SIC performance to degrade significantly, as shown by the black line in Fig. 10.

Even with $\tau_{P,max}$ included, the blue line in Fig. 10 exhibits overshooting problem. This overshoot effectively reduces the effective bandwidth, causing performance degradation of the OFDM subcarriers within the affected frequency region.

C. Future Work—SIC Without Overshooting Problem

The overshooting observed in Fig. 10 is caused by the discontinuities at the band edges, as shown in Fig. 9(a), (b). To eliminate these band-edge discontinuities, a fill-in function is introduced, as illustrated in Fig. 11(a). The corresponding SIC result, depicted in Fig. 11(b), shows that the overshooting is effectively resolved. Research on further methods to address this overshooting issue is currently ongoing and will be explored in depth in future work.

V. Conclusion

This paper confirms that proven RF front-end techniques can readily enable advanced duplex operation in next-generation communications.

The first approach implements a three-tap RF canceller by iteratively identifying and cancelling the strongest SI component via PDP analysis. Using this method, 55-dB SIC over 200-MH bandwidth, and 60-dB SIC over 100-MHz bandwidth were achieved. However, nonuniform delay spacing between taps induces inter-tap disturbance, requiring optimization algorithm.

To address inter-tap disturbance, the second method uniformly samples the passively suppressed SI in delay domain using Fourier analysis. This yields improved and simple reconstruction of the SI channel but exhibit band-edge overshooting issue.

The third approach introduces a fill-in function to smooth the SI discontinuities at the band edges, effectively eliminating overshooting and achieving SIC across entire target bandwidth.

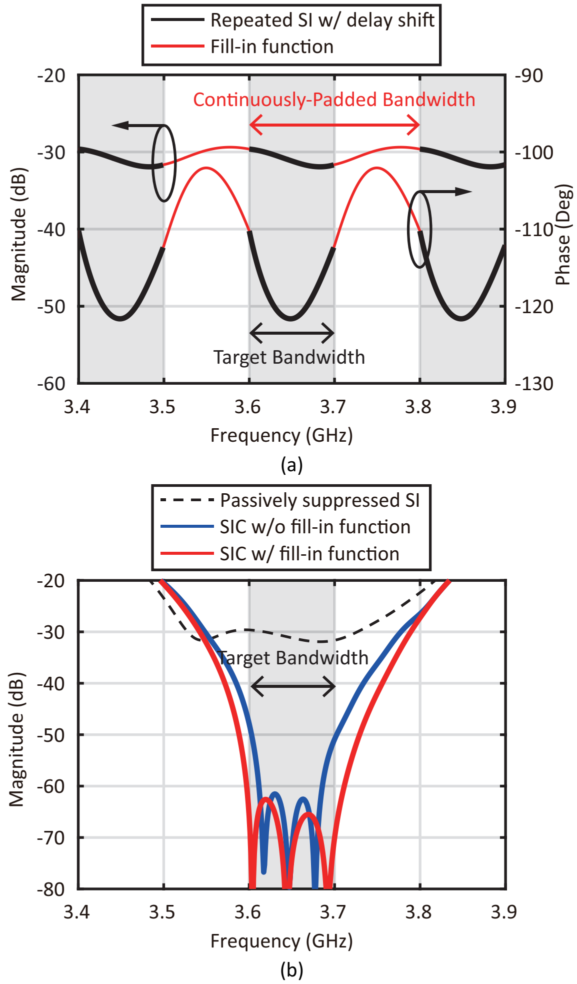

Fig. 11. Solution to overshooting problem: (a) SI without discontinuity using the fill-in function, and (b) corresponding SIC result showing the elimination of the overshooting issue.

Detailed implementation of this technique are ongoing and will be explored in future work.

Consequently, the proposed RF SIC circuits provide a practical, scalable solution for realizing advanced duplex for enhancing spectral efficiency in 6G deployments.

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