Duplexer Design and Implementation for Self-Interference Cancellation in Full-Duplex Communications

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***Abstract*— The full-duplex (FD) based devices are capable of concurrently transmitting and receiving signals with a single frequency band. However, a severe self-interference (SI) due to the large difference between the power of the devices' own transmission and that of the signal of interest may be imposed on the FD based devices, thus significantly eroding the received signal-to-interference-plus-noise ratio (SINR). To implement the FD devices, the SI power must be sufficiently suppressed to provide a high-enough received SINR for satisfying the decoding requirement. In this paper, the design and implementation of the duplexer for facilitating SI cancellation in FD based devices are investigated, with a new type of duplexer (i.e. an improved directional coupler) designed and verified. It is shown that the SI suppression capability may be up to 36 dB by using the proposed design, which is much higher than that attainable in the commonly designed ferrite circulator.**

Keywords: Full-duplex Wireless Communications, Self-Interference Cancellation, Duplexer, Directional Coupler.

I. INTRODUCTION

As the rapid development of wireless communications technologies, it has drastically promoted the populations of traffic-consuming mobile applications [1], [2]. However, the exponentially increased mobile traffic makes the limited spectral resources no longer meet the ever increasing demands of the customers. Therefore, how to substantially improve the spectral efficiency of wireless communications systems has become one of the major concerns from both academia and industry [3].

A variety of studies have been carried out [4]–[6] to address the above-mentioned issues. In light of the fact that the conventional half-duplex (HD) based techniques may lead to an erosion in spectral efficiency, the full-duplex (FD) technique, which enables the devices to simultaneously transmitting and receiving using a single frequency band, has attracted a lot of concerns from both academia and industry. Since the FD technique is (in theory) capable of providing two times the spectral efficiency of the conventional HD mode, it has been regarded as one of potential key techniques in the fifth-generation (5G) wireless communications systems.

Despite of it, the FD based devices may still fail to implement unless the severe self-interference (SI) is sufficiently suppressed[1]. SI cancellation techniques have been widely studied [5], [6], with the existing techniques divided into two categories, including passive SI suppression (e.g. spatial suppression) and active SI cancellation (e.g. analog- and digital-domain cancellations):

- The basic principle of passive suppression techniques can be summarized as follows: *By adjusting the distance between the transmit and receive antennas of the same FD device, the SI power conceived at the receive antennas can be attenuated relying on the large-scale pass-loss effect [9].* Apart from it, the beamforming technology, which creates transmit and receive beams that point at orthogonal directions [10], can also be employed to enable the passive SI suppression. Furthermore, the other well-known techniques such as decoupling antenna, polarization decoupling and loop isolation, etc [11], [12], can also be classified in this category.
- Unlike the passive suppression, the active SI cancellation techniques mainly comprise the analog- and digital-domain cancellations [5]. In the former, a certain amount of SI power can be eliminated in the radio frequency (RF) domain. In the latter, on the other hand, digital-domain SI estimation and cancellation algorithms must be implemented to further reduce the residual SI. Since the analog-domain cancellation alone is usually insufficient for offering a enough-for-decoding SI-cancellation capability [6], a digital-domain cancellation must be successively implemented for further reducing the residual SI power. Evidently, the concatenation of analog- and digital-domain cancellations will be helpful to substantially improving the overall SI cancellation capability.

Despite of that, most of the existed FD-based designs employed the idea of transmit-receive antenna-sets separation, i.e. one set of antennas act as the transmit antennas, while the remainders act as the receive antennas. Note that the above-

[1]Unlike the conventional HD mode [7], the FD technique enables the concurrent transmission and reception at a single device with a single frequency band. Since the power of the FD-based devices' own transmission may be several orders of magnitude higher (e.g. 100 dB or more) than that of the useful signal comes from the remote transmitters, a severe SI power may significantly erode the performance of the FD devices or even make them fail to decode [8].

mentioned designs may lead to a significant loss in spatial diversity order due to the incapability of simultaneous transmission and reception in any individual antenna. To address the above-mentioned issue, a circulator-based FD radio design is proposed in [13] to enable the FD mode implementing on a single-antenna device. As a practical circulator design, the duplexer can be employed to achieve an isolation between transmitting and receiving circuits (i.e. to enable a spatial suppression of the SI signal). However, the existed isolator designs still suffer from a performance constraint in terms of the spatial suppression capability.

In this paper, a new type of duplexer is developed by proposing an improved directional coupler. Experimental results show that the spatial suppression capability of the proposed design may be up to 36 dB, much higher than that attainable in the commonly designed ferrite circulator. The remainder of this paper is organized as follows. Section II presents the duplexer design and implementation for RF cancellation. After that, Section III presents the performance evaluation results of the proposed duplexers, followed by remaining challenges in duplexer design in Section IV. Finally, Section V concludes this paper.

II. New Duplexer Design for Radio Frequency Cancellation

In the high-efficiency FD systems, an individual antenna is capable of acting as both the transmission and reception roles simultaneously. However, in consideration of the impairments (e.g. the leakage of the duplexer, the antenna reflection, the multipath reflection, etc.) exist in practical FD systems, the transmitted signal will be partially leaked into the receive circuit of the same antenna, thus generating the non-zero SI signal. In order to relieve the SI induced by the power leakage from the transmit circuit to the receive circuit, a duplexer (or in other words, a coupler or circulator) should be employed.

The circulator or duplexer has been widely designed and employed [13]. In light of the fact that the SI suppression capability of the existed duplexer is not high enough, it would be promising to design a new duplexer with a higher SI-isolation capability. As shown in Fig. 1, a new duplexer with a higher isolation is designed based on the traditional parallel directional coupler featuring the characteristics of directional and coupling. This kind of coupler is capable of reflecting a part of cancellation signal[2] by exploiting the port-impedance-mismatching (PIM) effect in order to cancel out the leakage signal [14].

The architecture of the proposed duplexer is described as follows. As shown in Fig. 1, port 1 denotes the input port, and ports 2/3/4 represent the cut-through port, the isolated port and the coupling port, respectively. The transmitted signal is first impinge upon the duplexer from port 1, followed by transferring it to port 2, between which ports the insertion loss should be less than 1 dB. Note that port 2 is connected to an

[2]Note that the cancellation signal has the same amplitude as the leakage signal but with an opposite phase.

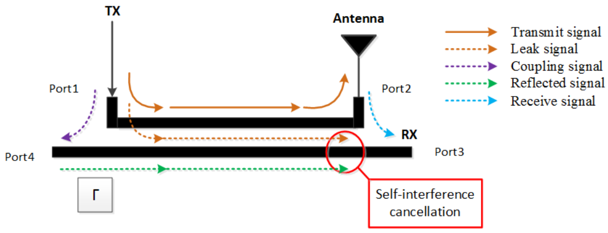

Fig. 1. Duplexer design and optimization by adjusting the reflection coefficient.

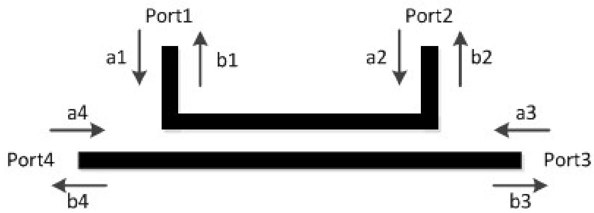

Fig. 2. Structure of the parallel directional coupler.

antenna, from which the transmit signal is radiated out and the received signal is detected simultaneously. After that, the received signal is transferred from port 2 to port 3, between which the insertion loss may be up to 10∼20 dB (i.e. due to the coupling effect between them). However, the performance erosion induced by this insertion loss can still be compensated for by employing a low-noise amplifier.

Under an ideal condition, port 1 should be completely isolated from port 3 (i.e. zero output is observed when a signal impinges into port 1). Unfortunately, a portion of the transmitted power will always be leaked from port 1 to port 3 in practical designs. To increase the isolation between these two ports (i.e. for reducing the SI power), the scheme of PIM can be employed. In the PIM scheme, we make port 4 produce the mismatching effect, followed by reflecting the port 1-to-port 4 coupling signal in port 4 and transferring it to port 3. If the reflected and leaked signals have an identical power but with an opposite phase, these two signals will cancel each other out. Evidently, the reflection coefficient Γ will play a critical role in determining the SI-isolation capability of the duplexer.

A. Technical Requirement and Designing Principle of the proposed Duplexer

In this subsection, the proposed duplexer is designed based on the theory of parallel directional coupler of microstrip line by employing the PIM effect, with a coupling degree of 15 dB considered. The designing principle of the proposed duplexer is described as follows: Based on the structure of *parallel directional coupler*, the duplexer with a high isolation can be designed. As shown in Fig. 2, a device comprising four ports is provided, in which the architectural feature can be represented as a characteristic matrix S, which is derived from the equation set (1).

When each port achieves an impedance matching, it leads to the following equation:

$$\begin{cases} b_1 = Ta_2 + Ia_3 + Ca_4 \\ b_2 = Ta_1 + Ca_3 + Ia_4 \\ b_3 = Ia_1 + Ca_2 + Ta_4 \\ b_4 = Ca_1 + Ia_2 + Ta_3 \end{cases} \tag{1}$$

where a_n and b_n represent the input and output signals of port n, respectively, parameters T, I and C represent the cut-through coefficient, the isolation coefficient and the coupling coefficient of the proposed coupler, respectively. When each port of the coupler achieves an *impedance matching* condition, all the diagonal elements of S will become 0. If, on the other hand, an impedance mismatching state is imposed on port 4, a signal reflection will happen in this port. Assuming the reflection coefficient is Γ, without consideration of direction, we have

$$a_4 = \Gamma b_4 = \Gamma(Ca_1 + Ia_2 + Ta_3) \tag{2}$$

Let us bring the above-mentioned result into the equation (1), followed by transforming the equation as:

$$\begin{cases} b_1 = C^2\Gamma a_1 + (T + C\Gamma I)a_2 + (I + C\Gamma T)a_3 \\ b_2 = (T + C\Gamma I)a_1 + I^2\Gamma a_2 + (C + T\Gamma I)a_3 \\ b_3 = (I + C\Gamma T)a_1 + (C + T\Gamma I)a_2 + T^2\Gamma a_3 \end{cases} \tag{3}$$

When we perform SI cancellation, the input signal can be observed only in port 1, with the other three ports having no signal. The solution of b_n can thus be given by:

$$\begin{cases} b_1 = C^2\Gamma a_1 \\ b_2 = (T + C\Gamma I)a_1 \\ b_3 = (I + C\Gamma T)a_1 \end{cases} \tag{4}$$

Note that the main functionality of the proposed duplexer is to isolate the received signal of interest from the transmitted SI signal. By representing the input of port 1 as a_1, the output of port 3 will be 0, implying that $b_3 = (I + C\Gamma T)a_1 = 0$. Furthermore, assuming that $I + C\Gamma T = 0$ is always satisfied, the optimal reflection coefficient of the impedance mismatching is given by

$$\Gamma = -\frac{I}{CT}. \tag{5}$$

B. Advanced Design System based Simulation

In this paper, the Advanced Design System (ADS) as well as its performance evaluation is carried out via simulation. We first design and simulate the traditional parallel directional coupler of microstrip line with a coupling degree of 15 dB for obtaining the reference sizes and parameters of the main structure of ADS. After that, based on the traditional theory of parallel directional coupler, we artificially make impedance of port 4 stay in the *mismatching* state by adding an open-circuit line at the end of this port. The length of the open-circuit line can thus be initialized according to both the optimal reflection coefficient[3] Γ and the result of electromagnetic simulation.

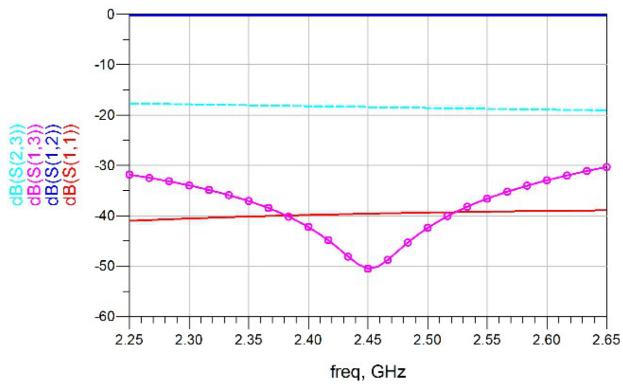

Fig. 3. Isolation between two ports of the proposed duplexer in the electromagnetic simulation.

When we perform the software simulation, the RF circuit simulation software ADS2011 can be employed, with the critical parameters of the proposed design given out as follows:

- Relative dielectric constant of the microstrip line is given by $Er = 4.3$;
- Relative permeability of the microstrip line is given by $Mur = 1$;
- Thickness of the circuit board is assumed to be $H = 0.5$mm;
- Width of microstrip line is W = 0.939mm;
- Thickness of microstrip line is T = 0.05mm;
- Gap between two microstrip lines is S = 0.305mm;
- Electrical conductivity of microstrip line is given by $Cond$ = 4.1e+7;
- The loss tangent of the microstrip line is defined as $TanD = 0.003$;
- Surface roughness of microstrip line is assumed to be $Rough = 0$.

C. Practical Duplexer Design

According to the above-mentioned schematic analysis, the proposed duplexer circuit can be designed based on the theory of *parallel directional coupler*. Despite of it, we still need to perform the electromagnetic simulation for further validating the proposed design. As shown in Fig. 3, the isolation between port 1 and port 3 can be up to 50 dB[4].

In theory, the practical PCB board design can be implemented for a given size of the parallel directional coupler with impedance mismatching (i.e. based on the simulation results). However, a constrained performance in the duplexer with fixed reflection coefficient will be observed due to the limited precision in the practical design. To address the above-mentioned problem, new schemes may be employed to enable the reflection coefficient of port 4 to be fine-tuned.

[3]We may adjust the length of the open-circuit line in order to achieve the optimal reflection effect (i.e. the optimal SI-isolation effect).

[4]Considering the insertion loss of 18 dB, this corresponds to an isolation capability of 32 dB.

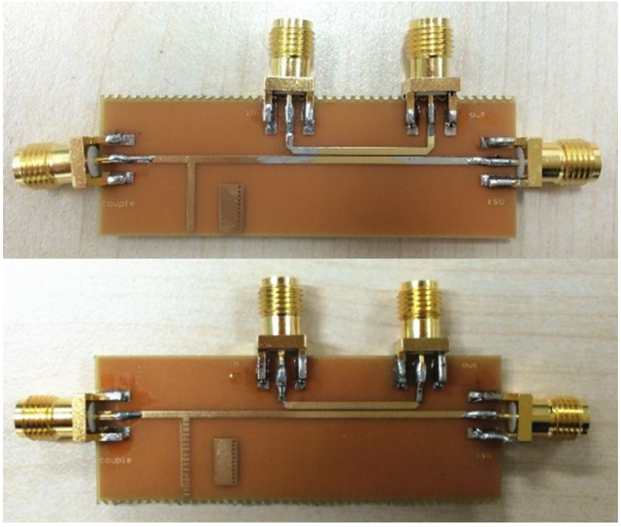

Fig. 4. The designed duplexers with capabilities of capacitor and/or length adjustment.

In this section, two fine-tune schemes are proposed. The two types of duplexers are adjustable though they are not as flexible and dynamic as the duplexers raised in [15]. The first scheme is called "capacitor adjustment (CA)", in which the reflection coefficient can be optimized by changing the values of the capacitors as well as the welding positions of the capacitors between the open-circuit line and the ground plane (GND). The second one, on the other hand, is referred to as "length adjustment (LA)", in which the open-circuit line is divided into several small sections. The LA enables the reflection coefficient to be optimized according to the actual situation by simultaneously welding different capacitors and filling the gaps with tin solder (i.e. to adjust the length of the open-circuit line). The improved duplexers based on the above-mentioned two schemes are shown in Fig. 4.

III. Performance Evaluation

According to the above-mentioned theory, the practical duplexer design with SI-isolation capabilities can be implemented. Without loss of generality, the 16-ordered Quadrature Amplitude Modulation (16QAM) constellations are considered, with a transmit power of 0 dBm assumed. Furthermore, the central frequency is assumed to be 2.45 GHz. By performing the experimental tests for the bandwidth of 4 MHz and 8 MHz, it is shown that the SI-isolation capability of the proposed duplexer is higher than that (i.e. about 25 dB) attainable in the commonly designed ferrite circulator.

A. Experimental Test for Bandwidth of 4 MHz

Before implementing the SI isolation, the initial power of the transmit signal with bandwidth of 4 MHz is observed to be -0.26 dBm. After enabling the SI isolation by employing the duplexer with a capacitor adjustment capability, the signal spectral characteristics changes, as shown in Fig. 5(a), illustrating that the signal power decreases from -0.26 dBm to -36.94 dBm. It corresponds to an SI-suppression capability of 36.68 dB offered by the proposed duplexer. After that, a different spectral characteristic can be observed, as shown in Fig. 5(b). It is shown that the SI signal power decreases to -31.37 dBm, corresponding to an SI-suppression capability of 31.11 dB.

B. Experimental Test for Bandwidth of 8 MHz

Similar to the 4 MHz case, the (prier-isolation) transmit power of 8 MHz is shown to be -0.24 dBm. After performing SI isolation relying on duplexer with capacitor adjustment capability, the signal power decreases from -0.24 dBm to -36.63 dBm, corresponding to an SI-suppression capability of 36.39 dB, as shown in Fig. 5(c). Furthermore, by employing duplexer with length adjustment capability, the SI-suppression can be up to 31.71 dB, as shown in Fig. 5(d).

IV. Remaining Challenges in Duplexer Design

Although the proposed duplexer is capable of meeting the SI-suppression requirements in practical systems, there still exist several challenges to address. For example, since the coupling degree of the parallel directional coupler is shown to be 15 dB, the receive signal delivered from port 2 to port 3 will go through an attenuation of 15 dB, which amount of attenuation must be compensated for by employing a low noise amplifier. After all, the design is so simple and low-cost that a few problems, such as insertion loss, remain with it. Furthermore, more works are needed to reduce the insertion loss in verifying the effect of the above-mentioned LNA. In addition, it requires the performance of the proposed design to be further verified by considering a larger bandwidth.

V. Conclusion

A novel duplexer design is proposed based on the theory of parallel directional coupler by making an impedance mismatching at the ports of the duplexer, which is capable of isolating the received signal from the transmitted signal effectively. The reflection coefficient Γ of the coupler can be adjusted in two ways, i.e. by adjusting the capacitor or by changing the length of the open-circuit line. Experimental results showed that the coupler of capacitor adjustment outperforms the coupler of length adjustment in terms of SI-isolation capability due to the fact that the relative dielectric constant of the circuit will change by adjusting the length of the open-circuit line. It was shown in experimental results that the proposed duplexers are capable of outperforming the commonly used ferrite circulator in terms of SI-suppression capability.

Acknowledgement

This work was supported by the key project of the National Natural Science Foundation of China (No. 61431001), Key Laboratory of Cognitive Radio and Information Processing, Ministry of Education (Guilin University of Electronic Technology), and the Foundation of Beijing Engineering and Technology Center for Convergence Networks and Ubiquitous

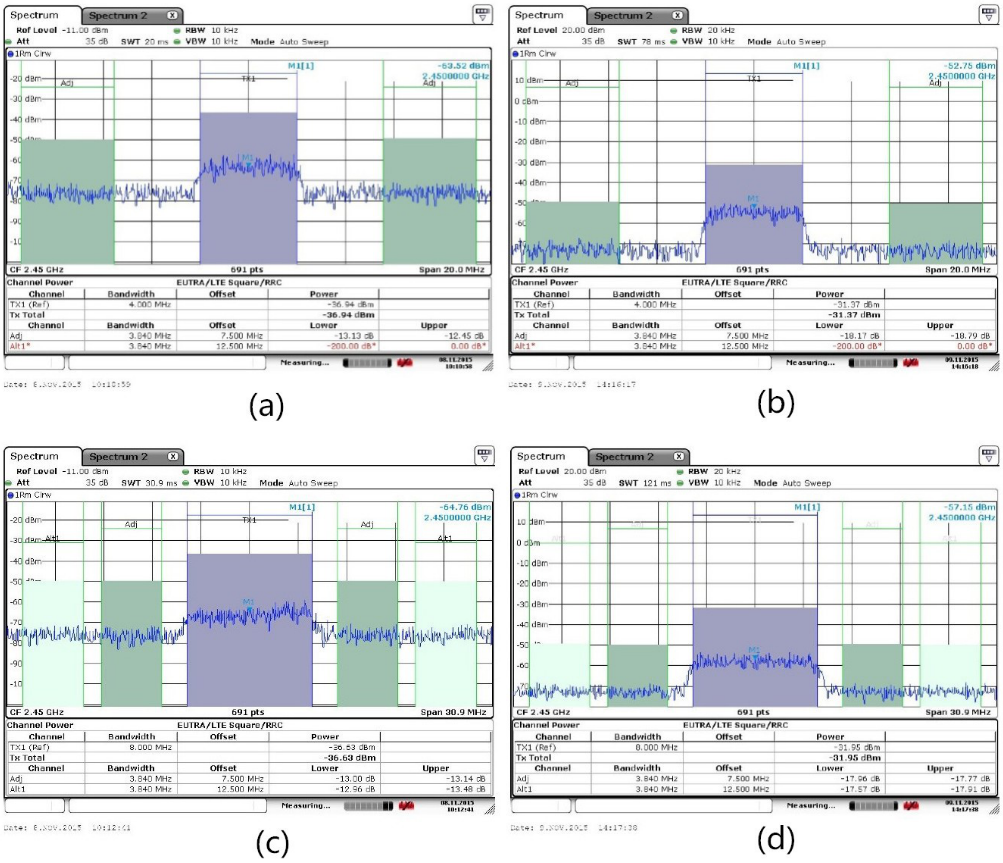

Fig. 5. Spectrum of the test signal after performing SI isolation by using duplexers.

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