Photons-Assisted Analog Wideband Self-Interference Cancellation for In-Band Full-Duplex MIMO Systems With Adaptive Digital Amplitude and Delay Pre-Matching

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Abstract—A photons-assisted analog wideband RF self-interference (SI) cancellation and frequency downconversion approach for in-band full-duplex (IBFD) multiple-input multiple-output (MIMO) systems with adaptive digital amplitude and delay pre-matching is proposed based on a dual-parallel Mach–Zehnder modulator (DP-MZM). In each MIMO receiving antenna, the received signal, including different SI signals from different transmitting antennas and the signal of interest, is applied to one arm of the upper dual-drive Mach–Zehnder modulator (DD-MZM) of the DP-MZM, the reference signal is applied to the other arm of the upper DD-MZM, and the local oscillator signal is applied to one arm of the lower DD-MZM. The SI signals are canceled in the optical domain in the upper DD-MZM and the frequency downconversion is achieved after photodetection. To cancel the SI signals, the analog reference signal is constructed in the digital domain, while the amplitude and delay of the constructed reference are adjusted digitally by upsampling with high accuracy. Experiments are performed when two different SI signals are employed. The genetic algorithm or least squares algorithm is combined with segmented search respectively for the SI signal reconstruction and amplitude and delay pre-matching. A cancellation depth of around 20 dB is achieved for the 1-Gbaud 16 quadrature-amplitude modulation orthogonal frequency-division multiplexing signal.

Index Terms—Adaptive control, in-band full-duplex, microwave photonics, MIMO systems, self-interference cancellation.

I. INTRODUCTION

As the application of RF technology becomes more and more widespread, the demand for spectrum resources has also increased dramatically. However, spectrum resources are limited. In-band full-duplex (IBFD) systems transmit and receive signals at the same time and same frequency band, which can greatly improve the spectrum efficiency [1], [2]. When the IBFD operation is employed, a very strong self-interference (SI) signal is inevitably introduced, which cannot be suppressed by a band-pass or notch filter. Thus, new ways for SI cancellation (SIC) are needed.

Since the SI signal is commonly very strong in power due to the very short distance between the transmitting and receiving antennas, approaches from the antenna domain, analog domain, and digital domain are always coupled to provide a significant amount of cancellation depth [3]. The digital domain SIC methods are low-cost and flexible. However, to avoid the saturation of the low-noise amplifier and analog-to-digital converter (ADC), the antenna domain SIC and the RF analog SIC are indispensable. There are lots of electrical-based analog SIC methods to cancel the SI signal by constructing a reference signal using the known transmitted signal. However, due to the inherent constraints of cutting-edge electronic technology, the electrical-based approaches have a restricted working frequency and bandwidth. Utilizing microwave photonic signal processing to implement SIC can get beyond these restrictions [4], [5].

In recent years, photons-assisted SIC has been widely studied [6], [7]. From the perspective of microwave photonic system architecture, the reported SIC systems can be roughly divided into two categories: 1) using one optical path; 2) using two separated optical paths. When two separated optical paths are used, two intensity modulators [8], [9], [10]/equivalent intensity modulators [11]/phase modulators [12] combined with a photodetector (PD), two modulators/modulated lasers combined with a balanced photodetector [13], [14], [15], [16], [17], [18], [19], [20], or a modulator with two orthogonal polarization states combined with a PD [21], are jointly used for the SIC. When one optical path is employed [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], a single modulator and a PD are used together to achieve the SIC. The system is more compact and may have better stability using a single optical path. Besides the SIC function, the photons-assisted SIC methods combining frequency downconversion [21], [24], [26], [27] and radio over fiber transmission [20], [22], [24], [26], [27], [28], [29] are also extensively studied.

For practical application, real-time adaptive control of the reference amplitude and delay is essential for the variable wireless channel, especially for multipath SI signals. Therefore, various
control methods are investigated based on photonics-assisted SIC methods. In [10] and [15], the amplitude and delay/phase of the reference signal were adaptively adjusted using the Nelder-Mead simplex algorithm with more than 60 iterations with the assistance of a semiconductor optical amplifier. To decrease the number of the iteration, the modified Hooke–Jeeves algorithm [16] and regular triangle (RT) algorithm [17] were applied to optimize the reference delay and amplitude via the tunable optical delay line (TODL) and variable attenuator. To achieve the SIC adaptive control with the signal of interest (SOI) [18], [19], the bit error rate of the SOI was used as the optimization parameter by using the RT algorithm. In [21], for adaptive control with more dimensions, the particle swarm optimization algorithm was applied to optimize the phase, amplitude, and time delay of the reference signal for the photonics-assisted SIC. In [33], photonic-enabled vector modulator architecture with 20 taps was adaptively tuned using a multidimensional gradient-descent algorithm to construct the reference signal for RF SIC.

Multiple-input multiple-output (MIMO) systems use antenna arrays to greatly increase the channel capacity or resist multipath fading [34], which can also be operated in the IBFD condition. When different antennas in the IBFD MIMO systems transmit different signals for increasing the capacity, the SI signals are much more complicated compared with conventional IBFD systems. Nevertheless, the reported SIC methods [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33] are not designed for this kind of IBFD MIMO system and cannot be applied to it directly. In [20], photonics-assisted SIC methods were proposed for IBFD MIMO systems. However, the adaptive control of time delay and amplitude is not investigated and the MIMO antennas transmit the same signal for resisting multipath fading but not different signals for increasing the capacity. Therefore, the implementation of SIC methods for IBFD MIMO systems with different antennas transmitting different signals is particularly desirable. Furthermore, most of the reported photonics-based SIC methods directly manipulate the amplitude and delay of the reference signals in the analog domain, which can be limited in efficiency due to the restricted tuning speed, for example, the motorized TODL. Therefore, it is worth studying the delay and amplitude adaptive search and adjustment method for the photonics-assisted SIC of IBFD MIMO systems without the limitation of the adjustment speed.

In this paper, a photonics-assisted analog wideband RF SIC and frequency downconversion approach for IBFD MIMO systems with adaptive digital amplitude and delay pre-matching is proposed based on a dual-parallel Mach–Zehnder modulator (DP-MZM). The SI signals are canceled in the optical domain in a dual-drive Mach–Zehnder modulator (DD-MZM) of the DP-MZM and the frequency downconversion is achieved after photodetection. To the best of our knowledge, this is the first photonics-assisted SIC method with adaptive delay and amplitude control for IBFD MIMO systems whose transmitting antennas have different data streams. In comparison, our previous methods in [29] and [32] are invalid for this situation. The digital algorithms in [29] and [32] are mainly used for SIC in the digital domain after photonics-assisted analog SIC, while in this work, the algorithms are used to reconstruct the analog reference signals in the digital domain for the analog domain SIC, and the amplitude and delay of the constructed reference are adjusted in the digital domain by upsampling with high accuracy.

II. PRINCIPLE

A. Photonics-Assisted SIC

The schematic of the proposed photonics-assisted RF SIC and frequency downconversion system for IBFD MIMO systems is shown in Fig. 1. The continuous-wave (CW) optical signal emitted by a laser diode (LD) is sent to a DP-MZM via a polarization controller (PC). The received signal, including both the SI signals and the SOI, is applied to the lower arm of DD-MZM1 in the DP-MZM. The reference signal for SIC is constructed in the digital domain with pre-matched amplitude and delay, converted to an analog reference signal, and then applied to the upper arm of DD-MZM1. A local oscillator (LO) signal is sent to one RF port of DD-MZM2 for frequency downconversion. The two DD-MZMs are both biased at the minimum transmission point (MITP). Under these circumstances, the SI signals can be optically canceled in DD-MZM1, and the downconverted intermediate-frequency (IF) signal with SI suppressed can be obtained after photodetection. It should be emphasized that the SI scenario for an IBFD MIMO system is similar for each receiving antenna: The interference from every transmitting antenna is received. Thus, in this work, we only demonstrate the SIC after the signal is received by one of the receiving antennas. More specifically, we take two transmitting antennas as an example for subsequent analysis and experiments.

The SI signals (SI1 and SI2), the constructed reference signals (REF1 and REF2), the SOI, and the LO signal are expressed as

\[ V_{s1}(t) = A_{s1} \cos(\omega_s(t - \tau_{s1}) + \phi_1), \]

\[ V_{s2}(t) = A_{s2} \cos(\omega_s(t - \tau_{s2}) + \phi_2), \]

Fig. 1. Schematic of the proposed photonics-assisted SIC system. LD, laser diode; PC, polarization controller; DD-MZM, dual-parallel Mach–Zehnder modulator; DD-MZM, dual-drive Mach–Zehnder modulator; PD, photodetector; DAC, digital-to-analog converter; ADC, analog-to-digital converter; SI, self-interference; LO, local oscillator signal; SOI, signal of interest; LS, least squares. Case a, only considering direct-path SI signals; Case b, considering both direct-path and multipath SI signals. (c)-(f) are the schematic diagrams of the signals at different locations in the system diagram.
\[ V_{1}(t) = A_{1} \cos(\omega_{s}(t - \tau_{s1}) + \phi_{1}), \]  
(3) 
\[ V_{2}(t) = A_{2} \cos(\omega_{s}(t - \tau_{s2}) + \phi_{2}), \]  
(4) 
\[ V_{SOG}(t) = A_{3} \cos(\omega_{s}t + \phi_{3}), \]  
(5) 
\[ V_{L}(t) = A_{4} \cos(\omega_{L}t), \]  
(6)

where \( \omega_{s} \) is the angular frequency of the SI signals, reference signals, and the SOI, \( \omega_{L} \) is the angular frequency of the LO signal, \( A_{1}, A_{2}, A_{3}, A_{4} \), \( \phi_{1}, \phi_{2}, \phi_{3}, \tau_{s1}, \tau_{s2}, \tau_{s1}, \tau_{s2} \), and \( \tau_{s2} \) are the amplitudes, phases, and delays of the corresponding signals. To simplify the following analysis, it is assumed that \( \theta_{s1} = \omega_{s}(t - \tau_{s1}) + \phi_{1}, \theta_{s2} = \omega_{s}(t - \tau_{s2}) + \phi_{2}, \theta_{s1} = \omega_{s}(t - \tau_{s1}) + \phi_{1}, \theta_{s2} = \omega_{s}(t - \tau_{s2}) + \phi_{2}, \) \( \theta_{s1} = \omega_{s}t + \phi_{3}, \) and \( \theta_{s4} = \omega_{L}t. \) Thus, these signals can be expressed as \( A_{1}\cos(\theta_{s1}), A_{2}\cos(\theta_{s2}), A_{3}\cos(\theta_{s3}), \) and \( A_{4}\cos(\theta_{s4}) \), respectively. It is assumed that the optical signal from the LD is \( \exp(\text{j}\omega_{s} t) \). When DD-MZM1 and DD-MZM2 are biased at MITP, the optical signals from the lower and upper arms of DD-MZM1 and DD-MZM2 can be written as

\[ E_{1-1}(t) = \frac{1}{2} \exp[j\omega_{s}t] + jm_{s1}\cos(\theta_{s1}) + jm_{s2}\cos(\theta_{s2}) + jm_{s3}\cos(\theta_{s3}) \]
\[ \approx \frac{1}{2} \exp(j\omega_{s}t) [J_{0}(m_{s1})J_{0}(m_{s2})J_{0}(m_{s3}) + 2J_{1}(m_{s1})J_{0}(m_{s2})J_{0}(m_{s3})\cos(\theta_{s1}) + 2J_{0}(m_{s1})J_{1}(m_{s2})J_{0}(m_{s3})\cos(\theta_{s2}) + 2J_{0}(m_{s1})J_{0}(m_{s2})J_{1}(m_{s3})\cos(\theta_{s3})], \]
(7)
\[ E_{1-u}(t) = \frac{1}{2} \exp[j\omega_{s}t + jm_{r1}\cos(\theta_{r1}) + jm_{r2}\cos(\theta_{r2}) + jm_{r3}\cos(\theta_{r3})] \]
\[ \approx -\frac{1}{2} \exp(j\omega_{s}t) [J_{0}(m_{r1})J_{0}(m_{r2}) + 2J_{1}(m_{r1})J_{0}(m_{r2})\cos(\theta_{r1}) + 2J_{0}(m_{r1})J_{1}(m_{r2})\cos(\theta_{r2})], \]
(8)
\[ E_{2-1}(t) = \frac{1}{2} \exp[j\omega_{s}t] + jm_{s4}\cos(\theta_{s4}) \]
\[ \approx \frac{1}{2} \exp(j\omega_{s}t) [J_{0}(m_{s4}) + 2J_{1}(m_{s4})\cos(\theta_{s4})], \]
(9)
\[ E_{2-u}(t) = \frac{1}{2} \exp(j\omega_{s}t + jm_{s4}, \cos(\theta_{s4})], \]
(10)

where \( J_{n}(\cdot) \) is the \( n \)-th order Bessel function of the first kind, \( m_{i} = \pi A_{i}/V_{s} \) \((i = s1, s2, r1, r2, 3, 4)\) are the modulation indices, and \( V_{s} \) is the half-wave voltage of the DP-MZM. When small-signal modulation \( (m_{i} << 1, J_{0}(m_{i}) \approx 1, J_{1}(m_{i}) << J_{0}(m_{i})) \) is employed, only the first-order optical sidebands are taken into account in the derivation, and the optical signal from the DP-MZM can be written as

\[ E_{DLP-MZM}(t) \]
\[ \approx \frac{j}{2} \exp(j\omega_{s}t) [J_{1}(m_{s1})\cos(\theta_{s1}) + J_{1}(m_{s2})\cos(\theta_{s2}) - J_{1}(m_{r1})\cos(\theta_{r1}) - J_{1}(m_{r2})\cos(\theta_{r2}) + J_{1}(m_{s4})\cos(\theta_{s4}) + J_{1}(m_{s4})\cos(\theta_{s4})]. \]
(11)

In this article, the reference is pre-matched in the digital domain, so \( \tau_{s1} = \tau_{r1}, \tau_{s2} = \tau_{r2}, A_{s1} = A_{r1}, \) and \( A_{s2} = A_{r2} \) are valid, and the SI signals can be canceled in the optical domain. The SI-free optical signal from the DP-MZM can be derived as

\[ E_{DLP-MZM}(t) \]
\[ = \frac{j}{2} \exp(j\omega_{s}t) [J_{1}(m_{s1})\cos(\theta_{s1}) + J_{1}(m_{s2})\cos(\theta_{s2}) - J_{1}(m_{r1})\cos(\theta_{r1}) - J_{1}(m_{r2})\ cos(\theta_{r2}) + J_{1}(m_{s4})\cos(\theta_{s4}) + J_{1}(m_{s4})\cos(\theta_{s4})]. \]
(12)

Then, the optical signal from the DP-MZM is detected by the PD with a responsivity of \( R \), and the downconverted IF signal from the PD can be expressed as

\[ i_{PD-IF}(t) = \frac{R}{4} J_{1}(m_{s}) J_{1}(m_{r}) \cos[(\omega_{s} - \omega_{L})t + \phi_{3}]. \]
(13)

As can be seen, the SI signals are canceled and the SI-free SOI is downconverted to the IF band.

In the above analysis, SI1 and SI2 represent two different SI signals from two different MIMO antennas, so we only consider the two direct-path SI signals, and the multipath SI signals from the two antennas are not taken into consideration. Indeed, when more direct-path SI or multipath SI signals are also considered, the conclusion of the above analysis is still valid, but the derivation process is more complex.

To realize good cancellation performance, the optimal time delay and amplitude of the constructed reference should be found. The amplitude attenuation factor of the reference signal can be determined by the power ratio of the SI signal and the reference signal without attenuation [32], whereas a rough estimation of the proper time delay of the reference signal can be obtained by a cross-correlation process. In the cross-correlation process, both the received signal and the reference signal without delay adjustment are applied to DD-MZM1. After the cross-correlation of the transmitted signal and the signal from the ADC, a rough estimation of the proper time delay can be acquired according to the two correlation peaks corresponding to the SI signal and reference signal in the cross-correlation curve. However, the accuracy and efficiency of the search are limited inherently, and a more accurate and efficient amplitude and time delay search of the reference signal is needed. In this article, the segmented search method is used for amplitude and time delay search, and the genetic algorithm is also introduced to estimate the amplitude and time delay of the reference signal.

**B. Segmented Search in the Digital Domain**

One of the advantages of the delay and amplitude adjustment in the digital domain is that the reference signal can be segmented for searching, which can greatly reduce the difficulty and improve the efficiency of the delay and amplitude search. As shown in Fig. 2, a reference signal with a time length of \( T \) is divided into \( U \) segments, and each segment can be set with a different amplitude and/or time delay. Therefore, the SIC performance of lots of different settings can be easily achieved for one search iteration by measuring each corresponding segment residual power of the IF signal from the PD. Using segmented search, it is very easy to find the optimal time delay and amplitude via a very small number of iterations. In addition, compared with the conventional methods which optimize the reference delay via the TODL, the segmented search method in the digital domain...
Fitness assignment: Calculate the SIC depth of each solution according to (14). If the predefined SIC depth is achieved, terminate the procedure of the genetic algorithm for SIC optimal parameters search. The designed procedure of the genetic algorithm for SIC optimal parameters search is given as follows:

**Step 1:** Set \( g = 1 \). Create the first population \( G_1 \) by randomly generating \( N_p \) group solutions, and apply \( G_1 \) to the segmented reference. Evaluate the SIC performance in \( G_1 \) according to each corresponding segment IF signal power from the PD.

**Step 2:** Crossover: Choose the best solution for SIC and the other half of the top solutions from \( G_g \) for SIC and generate \( N_p \) offspring by using a crossover operator, and add the generated offspring to \( Q_g \).

**Step 3:** Mutation: Each solution in \( Q_g \) is mutated with a predetermined mutation rate of \( P_m \).

**Step 4:** Fitness assignment: Calculate the SIC depth of each solution in \( Q_g \).

**Step 5:** Selection: Based on their SIC depths, the top \( N_p \) solutions from \( Q_g \) and \( G_g \) are copied to \( G_{g+1} \).

**Step 6:** If the predefined SIC depth is achieved, terminate the search and apply the best solutions to the SIC system, else, set \( g = g+1 \) and go to Step 2.

### C. Delay and Amplitude Search by Genetic Algorithm

In this work, different antennas in the IBFD MIMO system transmit different signals for increasing the capacity. First, a simpler case is considered: Only the direct-path SI signals from different transmitting antennas are considered. Therefore, the optimal values of \( A_{r1}, A_{r2}, \tau_{r1}, \) and \( \tau_{r2} \) should be found. In this case, intelligent optimization algorithms, such as the genetic algorithm, are suitable to solve this kind of multidimensional optimization problem. Before using the genetic algorithm, the rough time delays and amplitudes are first determined by the cross-correlation and the SI signal power. The search range is set according to the obtained rough time delays and amplitudes. Thus, the multidimensional SIC problem is defined as follows

**Step 1:** Set \( g = 1 \). Create the first population \( G_1 \) by randomly generating \( N_p \) group solutions, and apply \( G_1 \) to the segmented reference. Evaluate the SIC performance in \( G_1 \) according to each corresponding segment IF signal power from the PD.

**Step 2:** Crossover: Choose the best solution for SIC and the other half of the top solutions from \( G_g \) for SIC and generate \( N_p \) offspring by using a crossover operator, and add the generated offspring to \( Q_g \).

**Step 3:** Mutation: Each solution in \( Q_g \) is mutated with a predetermined mutation rate of \( P_m \).

**Step 4:** Fitness assignment: Calculate the SIC depth of each solution in \( Q_g \).

**Step 5:** Selection: Based on their SIC depths, the top \( N_p \) solutions from \( Q_g \) and \( G_g \) are copied to \( G_{g+1} \).

**Step 6:** If the predefined SIC depth is achieved, terminate the search and apply the best solutions to the SIC system, else, set \( g = g+1 \) and go to Step 2.

### D. Constructing the Reference Signal Using LS Estimation

When both the direct-path and multipath SI signals are considered for IBFD MIMO systems, the problem is more complicated and the intelligent optimization algorithms discussed above require much more iterations, resulting in an exponential increase in the algorithm complexity. Under these circumstances, the reference signal for SIC can be more efficiently constructed in the digital domain via the least squares (LS) algorithm.

The vector representation of the received IF signal in one receiving antenna can be expressed as

\[
y = V_s + V_{SOI},
\]

where \( V_s \) is the IF SI signal, and \( V_{SOI} \) is the IF SOI signal. For the channel estimation of the SI signal, the received signals with upampling. Thanks to the introduction of DSP, in the case of a limited DAC sampling rate, high-accurate delay matching can be achieved by upampling. In practical applications, the rough time delay can be first found through cross-correlation, and then a more precise time delay can be searched through segmentation combined with upampling.
$N$ samples are needed and can be written as

$$y = [y(n) \ y(n+1) \ \cdots \ y(n+N-1)]. \quad (15)$$

The channel estimation $\hat{h}$ by the LS algorithm can be estimated as

$$\hat{h} = (\Psi^H \Psi)^{-1} \Psi^H y,$$  

where

$$\Psi = [\Psi_1 \ \Psi_2 \ \cdots \ \Psi_{NT}], \quad (17)$$

$$\Psi_j = \begin{bmatrix} x_j(n) & x_j(n-1) & \cdots & x_j(n-M) \\ x_j(n+1) & x_j(n) & \cdots & x_j(n-M+1) \\ \vdots & \vdots & \ddots & \vdots \\ x_j(n+N-1) & x_j(n+N-2) & \cdots & x_j(n-M+N-1) \end{bmatrix}, \quad (18)$$

where $j = 1, 2, \ldots, NT$, $NT$ is the number of transmitting antennas, $x_j(n)$ corresponds to the IF signal of the $j$-th transmitting antenna, and $M$ is the order of the LS algorithm. Thus, the total reference includes all the SI information for analog SIC can be constructed as

$$\hat{r} = \Psi \hat{h}. \quad (19)$$

After the reference construction, the amplitude and time delay information of the constructed reference is required. The amplitude of the constructed reference via the LS algorithm can be determined by the SI signal power. The rough time delay of the total reference can be first found through cross-correlation, and then a more precise time delay can be searched through segmentation combined with upsampling. It should be noted that the reference signal constructed by the LS algorithm contains all the SI information and has the relative amplitude and delay information of all the SI paths. Therefore, there is no need to find the delay and amplitude of each SI path and only a single delay and amplitude of the constructed reference needs to be found.

### III. EXPERIMENT AND RESULTS

#### A. Experimental Setup

An experiment is carried out to verify the proposed method based on the setup shown in Fig. 4. The CW optical signal from an LD (ID Photonics CoBriteDX1-1-C-H01-FA) with a wavelength of 1550.053 nm and a power of 15.5 dBm is sent to a DP-MZM (Fujitsu FTM7960EX301). An arbitrary waveform generator (AWG, Keysight M8195A, 64 GSa/s) is used to simulate and generate the signals in the real-world IBFD MIMO system. In the experiment, two SI signals with different data streams from two transmitting antennas and their multipath components are considered to simulate the SI signals, while in the receiving end, only the SIC following one receiving antenna is investigated because other receiving ends have the same SIC system structure and principle. The SI signals from the two transmitting antennas are generated from two different channels of the AWG, while the digitally constructed reference signal is generated from the third channel of the AWG, all with an output peak-to-peak amplitude of 1 V. One direct-path SI signal and its multipath SI signals are denoted as SI1, while the other direct-path SI signal and its multipath SI signals are denoted as SI2. In addition, the SOI is generated along with the SI signals in one channel. The LO signal is generated by a microwave signal generator (MSG, Agilent 83630B) with a power of 20 dBm. The SI signals and SOI from the AWG are combined at an electrical coupler (EC, Narda 4456-2) and applied to the lower arm of DD-MZM1 in the DP-MZM, whereas the digital pre-matched reference is applied to the upper arm of DD-MZM1. The LO signal is sent to one RF port of DD-MZM2. Both DD-MZM1 and DD-MZM2 are biased at MITP, and the SI signals are canceled in the optical domain. Then, the optical signal from the DP-MZM is injected into a PD (Nortel Networks PP-10G), and the IF electrical signal from the PD is captured by an oscilloscope (OSC, R&S RTO2032, 10 GSa/s). The digitized IF signal from the OSC is processed in a computer using Matlab and then the constructed digital reference signal from Matlab is downloaded to the AWG to generate the analog reference signals for SIC.

#### B. Delay Search Accuracy Improvement by Upsampling

Because the amplitude of the constructed reference can be adjusted according to the SI signal power and the accuracy is high enough to guarantee good cancellation performance, the segmented search method proposed in Fig. 2 is only used to obtain the accurate reference delay in conjunction with cross-correlation in the experiment.

First, the time delay search with higher accuracy by upsampling in the digital domain is investigated. In this study, the experiment is performed based on Fig. 4 but only employs the direct-path SI signal from one transmitting antenna, which is a 16-QAM OFDM signal with a center frequency of 9 GHz and a baud rate of 1 Gbaud, respectively. The LO frequency is set to 8 GHz. The amplitude attenuation factor is calculated to be around 0.51 according to the SI signal power. Fig. 5(a) shows that the cross-correlation delay difference between the transmitted signal and the signal from the ADC is 4.9 ns when an unadjusted reference signal is used. For a more accurate time delay search of the reference signal, the segmented search method with upsampling to 1000 GSa/s in the digital domain is employed, and Fig. 5(b) and (c) show the corresponding results. When the 4-μs reference signal is divided into 200 segments with different delays from 4800 to 4999 ps, a better delay is found to be 4880 ps which is actually not the optimal delay value. As
shown in Fig. 5(c-ii), only a 13.7-dB SIC depth is obtained in this case. Thus, the search range is enlarged to 4700∼5099 ps, and the 4-μs reference signal is divided into 400 segments. Fig. 5(c-i) shows that the optimal delay value is 4768 ps and the SIC depth is greatly improved to 27.3 dB. Fig. 5(d) shows the comparison of the SIC performance with and without upsampling in the delay search. It can be seen that the best SIC depth is around 27.3 dB when upsampling (1000 GSa/s) is employed, whereas the best SIC depth is around 14 dB when the delay is adjusted under the sampling rate of the AWG (64 GSa/s). When the center frequency of the SI signals is changed to 10 GHz and the LO frequency is changed to 9 GHz, a result similar to that in Fig. 5(d) is obtained, as shown in Fig. 5(e).

There are some interferences in the spectra of Fig. 5(c-e). To more clearly distinguish these interferences from the residual SI signals after SIC, the output of the AWG is enabled without downloading any signal. It can be observed that the frequencies of the interferences caused by the AWG are mainly at 2, 1, 2, and 3 GHz, respectively, when the frequency of the LO signal is changed from 8 to 11 GHz with a step of 1 GHz, as shown in Fig. 6. Thus, these interferences should not be considered when calculating the SIC depth from the spectra.

C. SIC for IBFD MIMO Systems Considering Only Direct-Path SI Signals

For IBFD MIMO systems, if only the direct-path SI signals are taken into account, in general, it can be considered that the SI signals from the direct-path are fixed and without variation when the beams of the transmitting antennas are not scanned and the transmitting power is not changed. Under these circumstances, the amplitudes and delays of the direct-path SI signals are also fixed and unchanged, so these parameters can be obtained in advance by sequentially transmitting signals on each transmitting antenna and measuring the amplitude and delay from each transmitting antenna to each receiving antenna.

In our experiment, two direct-path SI signals from two channels of the AWG are sequentially sent to the SIC system. One SI signal is the same as used in Section III-B, and the other SI signal has a completely different data stream with a new set of delay and amplitude. The time delays and amplitudes of the two direct-path SI signals are searched using the methods discussed in Section III-B, which are 4768 ps and 0.51, and 3828 ps and 0.53, respectively. Fig. 7(a) and (b) show the spectra of the two SI signals with and without SIC. For both SI signals, an SIC depth of around 27.5 dB can be achieved. After getting the amplitudes and delays of the direct-path SI signals in advance, the SIC system can still work when all the transmitting antennas transmit signals simultaneously, as long as the transmitting power is fixed and the beams of the transmitting antennas are not scanned. Fig. 7(c) shows the spectra of the SI signals with and without SIC when the two direct-path SI signals are enabled simultaneously. An SIC depth of about 23.5 dB is obtained.

The method discussed above is applicable, but with restrictions: The transmitting beam and power cannot be changed, which means the delays and amplitudes measured in advance will not be applicable in future advanced IBFD MIMO systems, that is, it is necessary to track the delay and amplitude changes of the direct-paths in real-time adaptively.
D. Adaptive Tracking of the SI Signal Delay and Amplitude Variation Based on Genetic Algorithm

To solve the problem mentioned above, the genetic algorithm as discussed in Section II-C is used to adaptively track the SI signal delay and amplitude variation. Specifically, two direct-path SI signals with different data streams are considered in this study as a 4-dimensional optimization problem. The center frequency and baud rate of the SI signal are first set to 9 GHz and 1 Gbaud, respectively, the LO frequency is set to 8 GHz, and the SOI is still not applied.

In order to reduce the search complexity of the genetic algorithm, an extra stage (Stage 1) is used to estimate the search ranges of time delays and amplitude attenuation factors of two reference signals, which can also be implemented by using the cross-correlation method and SI signal power. As shown in Fig. 8, when an unadjusted reference signal is used and the signal from the PD is cross-correlated with the corresponding transmitted signal of SI1 and SI2, respectively, the rough SI signal delays with respect to the unadjusted reference signal are around 4.9 and 4.0 ns. Therefore, the ranges of the time delays of the two reference signals are set to 4700 ∼ 5100 ps and 3800 ∼ 4200 ps, respectively. The amplitudes of the two reference signals can be searched from 0 to 1. However, because the delay difference between the two SI signals from two transmitting antennas is not very large, the power difference between the two SI signals is also not very large. Although the amplitude attenuation factor obtained using the total SI power is not accurate due to the mixing of the SI signals, the value can still be used as a reference value to search the two amplitudes of the SI signals in a smaller range rather than from 0 to 1. In this experiment, the range of the amplitude attenuation factors of REF1 and REF2 are set to 0.24 ∼ 0.74 with a resolution of 0.01.

After determining the search ranges, genetic algorithm search Stage 2 for large range search is further employed. In this stage, both the 4-μs REF1 and 4-μs REF2 are divided into 160 segments. 152 segments of them are used for genetic algorithm search and the other 8 segments are used for experimental synchronization convenience, so the population number $N_p$ is 152. The mutation rate $P_m$ is set to 0.1. The search range determined in Stage 1 is used in Stage 2, and eleven iterations are performed to search for the optimal time delays and amplitude attenuation factors. Fig. 9(a) shows the distribution of the time delays and amplitude attenuation factors of 152 individuals in the population of the first and eleventh iterations. It can be seen that these parameters are uniformly distributed throughout the search area owing to the random generation in the first iteration. However, in the eleventh iteration, most of the parameters converge to some specific value due to heredity, and some parameters are not converged owing to the crossover and mutation operation. Fig. 9(b) shows that the optimal time delays and amplitude attenuation factors change with eleven iterations in five searches. It can be seen that the converge ranges of the time delay and the amplitude attenuation factor of REF1 and REF2 are 4766 ∼ 4771 ps, 3827 ∼ 3831 ps, 0.42 ∼ 0.56, and 0.46 ∼ 0.57, respectively. Fig. 9(c) shows the SIC depth is increased with the iterations in both five searches. Fig. 9(d) shows the electrical spectra of the downconverted IF signal from the PD captured by the OSC when using the optimal delay and amplitude setting of some specific iterations in five searches. It can be seen that at least 16.11 dB SIC depth can be achieved after eleven iterations.

For a more accurate search, the genetic algorithm search is executed once again in Stage 3. In this stage, the search range
Fig. 10. Genetic algorithm search Stage 3. (a) Optimal delay and amplitude setting of eleven iterations in five searches. (b) SIC depth versus the iterations in five searches. (c) Electrical spectra of the downconverted IF signal from the PD in five searches.

...is reduced based on the converged values in Stage 2. Fig. 10(a) shows that the optimal time delays and amplitude attenuation factors change with eleven iterations in five searches in Stage 3. It can be seen that the converge ranges of the time delays of REF1 and REF2 are $4767 \sim 4769$ ps and $3828 \sim 3829$ ps. The amplitude attenuation factors converge to $0.46 \sim 0.51$ and $0.44 \sim 0.49$, and the range of the convergence distribution is reduced by half compared to the genetic algorithm search Stage 2. Fig. 10(b) shows that the SIC depth is increased with the iterations in both five searches. Fig. 10(c) shows the electrical spectra of the downconverted IF signal from the PD when using the optimal delay and amplitude setting of some specific iterations in five searches. It can be seen that an SIC depth of more than $12.34$ dB can be obtained in the first iteration. After eleven iterations, a minimum SIC depth of $20.74$ dB is obtained in the third search, whereas a maximum SIC depth of $26.63$ dB is obtained in the fourth search. Compared with the result in Stage 2, the SIC depth can be increased by at least $7.1$ dB from Stage 2 to Stage 3 when the baud rate of the SI signals is $500$ Mbaud.

E. SIC for IBFD MIMO Systems by LS Estimation for Both Direct-Path and Multipath SI Signals

When both the direct-path and multipath SI signals are considered in IBFD MIMO systems, the problem is more complicated. To avoid too many iterations and too much algorithm complexity in intelligent optimization algorithms, the reference signal for SIC can be constructed digitally via the LS algorithm as discussed in Section II-D. To achieve SIC via the LS estimation, the optimal time delay and amplitude attenuation factor also need to be found for the reference signal after the SI signals, including the direct-path SI signals from different antennas and their multipath SI signals, are estimated and the corresponding reference signal is constructed. The amplitude attenuation factor of the reference signal can also be determined according to the SI signal power, and the optimal time delay can be found by the cross-correlation and segmented search combining upsampling, as discussed in Section III-B. It should be pointed out here that the reference signal constructed by the LS algorithm contains all information of all the SI paths and only a single delay and amplitude of the constructed reference needs to be found. The difference between this study and that in Section III-B is the reference: The reference in this study is constructed by taking all the direct-path SI signals and multipath SI signals into consideration, while that in Section III-B is constructed by only considering one direct-path SI signal.
Sowing to the relatively small multipath SI signals. The (f) and kept unchanged in the following study. No obvious

An example of a time delay search for the constructed reference signal is shown in Fig. 12(a) and (b). Fig. 12(a) shows that the correlation delay difference between the SI signals and the unadjusted reference signal is 3.8 ns when the center frequencies of the SI signals and LO signal is 9 and 8 GHz and the baud rate of the 16-QAM OFDM SI signals is 1 Gbaud. For a more accurate time delay search, the segmented search method with upsampling to 1000 GSa/s is used. The 4-μs constructed reference signal is divided into 400 segments, and the optimal delay is found to be 3815 ps, as shown in Fig. 12(b).

Then, various cases are further studied when using LS-constructed reference for the analog SIC of IBFD MIMO systems. The center frequencies of the LO signal and the SI signals are 8 and 9 GHz and the baud rate of the SI signals is 0.5 or 1 Gbaud. When the received signal includes only direct-path SI signals with (c) 1 and (d) 0.5 Gbaud are employed, and when direct-path and multipath SI signals with (e) 1 and (f) 0.5 Gbaud are employed. Electrical spectra and constellation diagrams when the SOI, the direct-path SI signals, and multipath SI signals with (g) 1 and (h) 0.5 Gbaud are employed.

| Multipath relative to direct-path | SI1 | SI2 |
|----------------------------------|-----|-----|
| Delay                            | 8/13/15 ns | 7/15/17 ns |
| Gain                             | –10/–12/–15 dB | –10/–12/–15 dB |

is set to be a quadrature phase-shift keying (QPSK) signal, the center frequency of the SOI is the same as that of the SI signals, and the baud rate of the SOI is set to half that of the SI signals for convenience of observation. These settings are also not changed in the subsequent investigation. Fig. 12(g) and (h) show that the SOI is submerged in the spectrum by the SI signals and the constellation diagrams of the SOI are chaotic when the SIC is not employed. When the SIC is enabled, the SOI is no longer submerged by the SI signals, and the SIC depths of 1- and 0.5-Gbaud SI signals are 19.2 dB and 24.0 dB, respectively. The constellation diagrams of the SOI can be distinguished and the corresponding error vector magnitudes (EVMs) of the SOI are 26.36% and 24.39%. As can be seen, when the SOI is added, the SIC performance decreases a little but can still effectively suppress the complex SI signals.

Then, the SOI is still included in the following experiments. Fig. 13 shows the performance of the IBFD MIMO analog SIC by LS estimation in different signal-to-interference ratio (SIR) conditions. With the decrease of the SIR, SIC depths of around 20 dB are achieved. Nevertheless, the EVMs of the SOI become worse and the constellation diagrams of the SOI tend to be chaotic with the decrease of the SIR. This phenomenon is mainly because that the power of the SOI decreases with the SIR decrease, and the influence of noise and residual SI signals is more obvious when the power of the SOI decreases.

Afterward, the frequency tunability of the IBFD MIMO analog SIC system using LS estimation is also demonstrated with the results shown in Fig. 14. As can be seen, the SIC depth, the EVM of the SOI, and the constellation diagrams of the SOI after SIC are very similar at different LO and RF frequencies.

When antenna remoting is used in the IBFD MIMO system, it is highly desirable that the signal received in the antenna can be transmitted back to the central office for further signal processing [24]. Therefore, the performance of the IBFD MIMO analog SIC system is further studied by inserting a section of 25.2 km single-mode fiber (SMF) for antenna remoting applications. The center frequency of the SI signals and SOI is set to 10 or 11 GHz, the center frequency of the LO signal is set to 9 or 10 GHz, and the baud rate of the SI signals is set to 1 or 0.5 Gbaud. Experimental results are shown in Fig. 15. The SIC performance and the EVMs and constellation diagrams of the SOI after SIC are very similar to that without inserting the 25.2-km SMF. It should be noted that since the power attenuation of the used 25.2-km SMF is measured to be around 4.6 dB, there is also a power
attenuation of the downconverted IF signal which is measured to be around 8.8 dB. Furthermore, thanks to the benefits of the IF fiber transmission and optical domain SIC [24] used in the proposed system, the SIC is not influenced by the fiber dispersion and the reception of the SOI is also not influenced by the fiber dispersion-induced fading effect.

IV. DISCUSSION

A. Cross-Correlation and Segmented Search

To ensure the accuracy of the delay search process, i.e., the cross-correlation and segmented search, some settings should be considered. For a rough estimation of the time delay by the cross-correlation process, the baud rate of the signals determines the width of the correlation peaks (the time resolution of the estimation is determined by the reciprocal of the baud rate) while the IF center frequency determines the internal variation of the envelope of the correlation peaks. Fig. 16 shows the cross-correlation results when the center frequencies and baud rates of the IF signals are 1, 1, 1, 1, 0.5, 0.25 GHz and 1, 0.5, 0.25, 0.1, 0.5, 0.25 Gbaud, respectively. The set time delay is around 4.768 ns. It can be seen that when the baud rate of the IF signal is higher, it is much easier to get a more accurate delay value. If the reciprocal of the baud rate is greater than the delay value, as shown in Fig. 16(d), the delay estimation via cross-correlation will have much worse accuracy. Nevertheless, the IF center frequency is also very important for the delay estimation, especially when the set time delay is very close to the reciprocal of the baud rate because when the time delay approaches the width of the correlation peak, the low IF frequency will cause the two correlation peaks to overlap with each other as shown in Fig. 16(f).

In the segmented search process, the search accuracy is influenced by the length of zero-padding of the OFDM SI signals. An experiment is further conducted by using SI signals with different lengths of zero-padding, the results are shown in Fig. 17. In the segmented search, the reference signal is divided into 400 and 800 segments. It can be seen that with the increase of the zero-padding percentage in the OFDM SI signals, the search curve turns noisier and the search accuracy will be degraded. When the percentage of zero-padding is high, if the optimal value found by the segmented search method cannot get a good SIC performance, we can do a small-scale search near this value to approach a better result.

B. Comparison of SIC by Genetic Algorithm and LS Algorithm

The adaptive control of the amplitudes and delays of the reference signals is a multidimensional optimization problem in the IBFD MIMO systems whose transmitting antennas have different data streams at the same center frequency. To solve this problem, the genetic algorithm and LS algorithm are used, and both two methods achieve similar SIC performance.

Using the genetic algorithm combining the segmented search method can directly solve the multidimensional optimization
problem. In our experiment, the 4-dimensional optimization is implemented by the genetic algorithm. The experiment is carried out by combining the online Matlab-based signal processing, waveform generation from the AWG, and the analog optoelectronic system. Only 4-dimensional optimization is realized because the efficiency of the experiment is highly limited by the data transmission and processing speed in Matlab and the waveform download time. The efficiency and number of dimensions can be increased by implementing the genetic algorithm and signal generation on hardware [37].

By using the LS estimation to first estimate the SI channel response, this multidimensional problem is reduced to a 2-dimensional problem. Thus, compared to the SIC method using the genetic algorithm, the complexity of that using the LS algorithm is much reduced. However, to track the SI channel variations, we need to re-capture the SI signals and re-estimate the channel every once in a while, which interrupts the analog SIC. Thus, compared to the SIC method using the LS algorithm, the genetic algorithm is easier to track the best parameters for SIC without interruption to the analog SIC when the search of the genetic algorithm is converged to a small search range.

C. Noise and Dynamic Range Consideration

To cancel the SI signals in the IBFD systems, noise introduced by the SIC operation needs to be minimized. In this work, the analog reference signal is constructed in the digital domain and converted to the analog domain via a DAC. Therefore, the quantization noise, as well as the dynamic range, of the DAC will be a key factor that limits the performance of the system. A DAC with a large effective number of bits (ENOB) is needed to decrease the quantization noise and improve the system’s dynamic range. Limited by the equipment in the laboratory, the ENOB of the wideband DAC (AWG, Keysight M8195A) is only 8 bits. Thus, a DAC with lower bandwidth but larger ENOB, combining an upconversion module, can be used in the system for performance improvement. Besides the influences from the DAC, other components in the microwave photonic link also influence the system’s dynamic range. Laser sources with high power and low relative intensity noise, low loss optical devices, modulators with low half-wave voltage, and high-responsivity PDs can be used to achieve a better system dynamic range [38].

Furthermore, although the noise from the power amplifier in the transmit link cannot be canceled by the digital-assisted analog SIC method in this work, compared to the analog SIC method whose reference is constructed based on the coupled signal from the power amplifier of the transmit link, the digitally-assisted analog SIC method used in this work is more suitable for complicated SI signals in the IBFD MIMO systems due to the simple system structure and easy control.

D. Complexity of Digital Algorithm Implementation

To achieve a higher time delay adjustment accuracy in the digital domain for analog SIC, the digital upsampling of 1000 GSa/s is employed in the experiment, which results in a huge amount of data processing if the digital algorithm discussed in this paper needs to be implemented on all the upsampled signals. First, in the experiments in this work, center frequencies at around 10 GHz are used, so the upsampling is carried out at 1000 GSa/s to ensure a good SIC depth. As discussed in Fig. 3(c), if the center frequency of the signal sent to the SIC system is reduced, a lower sampling rate can be used to achieve similar SIC depth. In this case, the received signal needs to be first downconverted to the low-frequency band and then the system can be used to achieve a good SIC depth at a much lower sampling rate. In this case, the amount of data needed to be processed by the algorithm in this paper can be greatly reduced.

Second, limited by the sample memory of the AWG, signals with a time length of 4 µs are used in the work. In practical applications, the signals are much longer, but not all of them need to be processed by the algorithm in this paper after upsampling. This is because the delays and amplitudes of the SI signals vary with the variation of the wireless channel, and variations in wireless channels are usually much slower than the time required to obtain an accurate delay through the algorithm. Therefore, although we need to upsample and delay all signals, we only need to use the algorithm in this paper to process signals within a relatively short time every once in a while, which can also greatly reduce the resources needed to implement the algorithm.

V. Conclusion

In summary, we have demonstrated a photonics-assisted analog wideband RF SIC and frequency downconversion approach for IBFD MIMO systems with adaptive digital amplitude and delay pre-matching. To the best of our knowledge, this is the first photonics-assisted SIC method with adaptive delay and amplitude control for IBFD MIMO systems whose transmitting antennas have different data streams. The time delay and amplitude were searched and adjusted in the digital domain by segmented search and upsampling with improved accuracy. When only the direct-path SI signals were considered, the genetic algorithm was used for amplitude and delay search, and an SIC depth of more than 20 dB was achieved for the 1-Gbaud 16-QAM OFDM signal. When both the direct-path and multipath SI signals were considered, the LS algorithm was used to estimate the SI signal for constructing the reference signal, the delay was found by segmented search, and the amplitude of the reference was determined according to the SI signal power. An SIC depth of more than 19 dB was achieved for the 1-Gbaud 16-QAM OFDM signal. The approach proposed in this paper is a pioneering photonic exploration of SIC in IBFD MIMO systems and is expected to be a solution for complex SI problems in future IBFD MIMO systems.

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