Photonic-enabled radio-frequency self-interference cancellation incorporated into an in-band full-duplex radio-over-fiber system

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Abstract. A photonic approach for radio-frequency (RF) self-interference cancellation (SIC) incorporated into an in-band full-duplex radio-over-fiber system is proposed. A dual-polarization binary phase-shift keying modulator is used for polarization multiplexing at the central office (CO). A local oscillator signal and an intermediate-frequency signal carrying the downlink data are single-sideband modulated on the two polarization directions of the modulator, respectively. The optical signal is then transmitted to the remote unit, where the optical signals in the two polarization directions are split into two parts. One part is detected to generate the up-converted downlink RF signal, and the other part is re-modulated by the uplink RF signal and the self-interference, which is then transmitted back to the CO for the signal down-conversion and SIC via the optical domain signal adjustment and balanced detection. The functions of SIC, frequency up-conversion, down-conversion, and fiber transmission with dispersion immunity are all incorporated into the system. An experiment is performed. Cancellation depths of more than 39 dB for the single-tone signal and more than 20 dB for the 20-Mbaud 16 quadrature amplitude modulation signal are achieved in the back-to-back case. The performance of the system does not have a significant decline when a section of 4.1-km optical fiber is incorporated. © 2022 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.61.3.034108]

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1 Introduction

In recent years, with the rapid development of mobile communication, artificial intelligence, internet of things, big data, and other industries, the number of wireless communication users and networking devices has increased dramatically. Various communication devices have higher requirements for communication traffic and speed. However, the spectrum resources are limited, so it is necessary to make reasonable and full use of the spectrum. In-band full-duplex (IBFD) systems can double the spectrum efficiency by employing the same frequency in the downlink and uplink, which is a promising solution to limited spectrum resources. Radio-over-fiber (ROF) systems directly transmit the radio-frequency (RF) analog signal in the optical fiber and have been extensively studied in combination with wireless communication systems. ROF systems greatly simplify the remote unit (RU) and are considered to be a promising solution for further wireless communication systems. ROF systems can also be operated in the IBFD condition. However, the IBFD operation introduces a strong self-interference (SI) from the transmitting antenna to the receiving antenna, and the SI cannot be filtered out because of the identical frequency in the downlink and uplink. Therefore, it is very important to eliminate the SI effectively.

In Ref. 7, Duarte and Sabharwal demonstrated the IBFD transmission of 2.4-GHz WiFi signals through experiments. Since then, many studies for self-interference cancellation (SIC) have...
been conducted. Because the power of the SI is much greater than that of the signal of interest (SOI), different kinds of methods should be combined to achieve a large cancellation depth for IBFD systems. The SIC can be implemented in the antenna domain,8 the analog domain,9 and the digital domain.10,11 The digital domain method is a low-cost solution to SIC. However, without the SIC in the antenna domain and the analog domain, the power of the SI will exceed the dynamic range of the analog to digital converter. Thus, many works have been conducted for analog SIC. In addition to implementing SIC using conventional electronic circuits, SIC can also be realized based on microwave photonics,12,13 which has unique advantages of large bandwidth, high frequency, good tunability, and immunity to electromagnetic interference. Furthermore, the photonic-based method can be seamlessly combined with ROF systems.

Some photonic-based SIC methods were proposed in the past decade. In Ref. 14, a method using two independent laser sources and two parallel Mach–Zehnder modulators (MZMs) biased at adjacent quadrature transmission points was proposed for SIC. To simplify the system structure, some simplified architectures were proposed. In Ref. 15, two electro-absorption modulated lasers and a balanced photodiode (BPD) were used in conjunction to realize the cancellation of the SI. A single laser, a single modulator, and a single photodetector (PD) were cascaded for SIC in Refs. 16 and 17, which simplifies the photonic-based SIC system structure greatly and avoids the instability caused by using two independent optical paths. However, the SIC methods mentioned above only focus on the function of SIC.

In practical applications, the elimination of the SI needs to be combined with the system structure. Therefore, some photonic-based SIC methods were designed in combination with the characteristics of the IBFD ROF system. Since the IBFD ROF system with long-distance fiber transmission is influenced by the fiber dispersion, some methods were proposed in Refs. 18–20 to overcome the influence on the performance of SIC and the distortion of the SOI caused by the fiber dispersion. Furthermore, for an IBFD ROF system, it is highly desirable that the SIC can be implemented in conjunction with some other key functions of the system. Therefore, some methods that combine the function of SIC and frequency down-conversion were proposed in Refs. 18, 20, and 21. In Ref. 22, the SIC in an IBFD ROF system is further combined with the entire ROF system structure. In the system, the SI is transmitted back to the central office (CO), where the SIC is carried out. By moving the SIC from the RU to the CO, the complexity of the RU is reduced.

However, all of the photonic-based SIC methods mentioned above cannot simultaneously realize all functions, i.e., overcoming the influence on the performance of SIC and the distortion of the SOI caused by the fiber dispersion, realizing the SIC in conjunction with frequency conversion, and moving the SIC from the RU to the CO to simplify the RU. To solve this problem, in this paper, a photonic approach for SIC incorporated into an IBFD ROF system is proposed. In the system, a dual-polarization binary phase-shift keying (DP-BPSK) modulator is used for polarization multiplexing at the CO. A local oscillate (LO) signal and an intermediate-frequency (IF) signal carrying the downlink data are single-sideband (SSB) modulated on the two polarization directions of the modulator, respectively. The optical signal is then transmitted to the RU, where the optical signals in the two polarization directions are split into two parts. One part is detected to generate the up-converted downlink RF signal, and the other part is re-modulated by the uplink signal and the SI, which is then transmitted back to the CO for the signal down-conversion and SIC via optical domain signal adjustment and balanced detection. An experiment is performed. Cancellation depths of more than 39 dB for the single-tone signal and more than 20 dB for the 20-Mbaud 16 quadrature amplitude modulation (16-QAM) signal are achieved in the back-to-back case. The performance of the system does not have a significant decline when a section of 4.1-km optical fiber is incorporated.

2 Principle

Figure 1 shows the schematic diagram of the proposed photonic-based SIC system incorporated into an IBFD ROF system. A continuous-wave (CW) light wave from a laser diode (LD) is injected into a DP-BPSK modulator at the CO. The DP-BPSK modulator is composed of a 3-dB optical splitter (OS), two dual-drive Mach–Zehnder modulators (DD-MZMs), a 90 deg polarization rotator, and a polarization beam combiner (PBC1). In the system, the two
DD-MZMs are both biased as SSB modulators. The two RF ports of the X-polarization DD-MZM1 are driven by an IF signal carrying the downlink data via a 90 deg hybrid coupler (90 deg HC1), whereas those of the Y-polarization DD-MZM2 are driven by an LO signal via a second 90 deg hybrid coupler (90 deg HC2). The schematic of the optical spectrum from the DP-BPSK modulator is shown in Fig. 1(a). It is worth noting that the 1st-order optical sidebands generated by the LO signal and the IF signal are in the opposite directions. Then, the optical signal is amplified by an erbium-doped fiber amplifier (EDFA) before being transmitted to the RU via a section of single-mode fiber (SMF). An optical circulator (OC1) is inserted between the EDFA and the SMF to separate the uplink optical signal.

After the downlink fiber transmission, the downlink optical signal is received at the RU, which is first sent to OC2 and then split into two parts by an OS. One part of the optical signal is sent to a PD via PC2 and a polarizer. By properly tuning PC2, the optical signals in the two polarization directions are combined, which is shown in Fig. 1(b). By beating the combined optical signal in the PD, the original IF signal can be up-converted to an RF signal, which can be further filtered and then radiated from the transmitting antenna as the downlink RF signal. The other part of the optical signal from the OS is sent to a polarization beam splitter (PBS2) via PC3 to separate the optical signals at the two orthogonal polarization directions. The optical signal in the Y polarization is sent to DD-MZM3, where it is SSB modulated by the received signal consisting of the uplink RF signal and the SI from the transmitting antenna. The modulated optical signal in the Y polarization from DD-MZM3 and the optical signal in the X polarization is combined in PBC2 and transmitted back to the CO via OC2 and the SMF. The schematic of the uplink optical signal is shown in Fig. 1(c).

At the CO, the uplink optical signal is sent to PBS1 via OC1 and PC4, where the optical signals at the two orthogonal polarization directions are separated and then sent to a BPD. When considering only the optical sideband close to the optical carrier, as shown in the dotted box in Fig. 1(c), the beating product of the X polarization can be used as an IF reference, and that of the Y polarization consists of not only a down-converted uplink IF signal but also an SI. To cancel the SI, an optical attenuator (ATT) and a tunable optical delay line (TODL) are set on one optical path to the BPD to match the delay and amplitude of the reference and the SI.
Assume that the IF signal and the LO signal are

\[ V_1(t) = A_1 \cos(\omega_{\text{IF}} t + \varphi_1), \]

\[ V_2(t) = A_2 \cos(\omega_{\text{LO}} t + \varphi_2), \]

where \(A_1\) and \(A_2\) are the amplitudes, \(\omega_{\text{IF}}\) and \(\omega_{\text{LO}}\) are the angular frequencies, and \(\varphi_1\) and \(\varphi_2\) are the phases of the IF signal and the LO signal, respectively.

Since the IF signal and the LO signal are applied to the \(X\)-polarization DD-MZM1 and \(Y\)-polarization DD-MZM2 of the DP-BPSK modulator, respectively, the optical signal from the DP-BPSK modulator is expressed as

\[
E_{\text{DP-BPSK}}(t) = \begin{bmatrix}
E_X(t) \\
E_Y(t)
\end{bmatrix}
= \frac{\sqrt{2}}{2} \sqrt{\frac{\pi}{2}} J_0(m_1) \exp\left(j \omega_c t + j \frac{1}{4} \pi \right) + J_1(m_1) \exp\left(j \omega_c t - j \omega_{\text{IF}} t - j \varphi_1 + j \pi \right) \]
\[ + \frac{\sqrt{2}}{2} J_0(m_2) \exp\left(j \omega_c t + j \frac{1}{4} \pi \right) + J_1(m_2) \exp\left(j \omega_c t + j \omega_{\text{LO}} t + j \varphi_2 + j \pi \right), \]

(3)

where \(E_X(t)\) and \(E_Y(t)\) represent the optical signals from the two DD-MZMs, \(m_i = \pi V_i/V_x (i = 1, 2)\) is the modulation index, and \(\omega_c\) is the angular frequency of the input optical signal. In Eq. (3), only the optical carrier and the 1st-order optical sideband are considered.

The polarization multiplexed optical signal is transmitted to the RU via a section of SMF. It is noted that, due to the SSB operation, the system is immune to the power fading effect caused by the fiber dispersion. Then, the optical signal is split into two parts at the RU, which are respectively used for the generation of the downlink RF signal and the cancellation of the SI. The former part is applied to a polarizer via PC2 with its principal axis oriented at an angle of 45 deg to one principle axis of the DP-BPSK modulator and then detected in the PD to obtain the downlink signal. The signal in the RF band that we are interested in is expressed as

\[ V_{\text{Trans}}(t) \propto J_1(m_1) J_1(m_2) \cos(\omega_{\text{IF}} t + \omega_{\text{LO}} t + \varphi_1 + \varphi_2). \]

(4)

Because of the crosstalk from the transmitting antenna to the receiving antenna, the SI at the receiving antenna is expressed as

\[ V_{\text{SI}}(t) = A_{\text{SI}} \cos[\omega_s (t - \tau_1) + \varphi_1 + \varphi_2], \]

(5)

where \(A_{\text{SI}}\) is the amplitude of the SI, \(\tau_1\) is the time delay of the SI, and \(\omega_s = \omega_{\text{IF}} + \omega_{\text{LO}}\), representing the angular frequency of the SI and the SOI.

For the convenience of analysis, the SOI is ignored and only the SI in the received signal is considered. The SI is applied to DD-MZM3, which also functions as an SSB modulator. The optical signal from DD-MZM3 is expressed as

\[
E_{Y-\text{SSB}}(t) \propto \frac{1}{2} J_0(m_2) J_0(m_3) \exp\left(j \omega_c t + j \frac{1}{2} \pi \right) + \frac{1}{2} J_1(m_2) J_0(m_3) \exp\left(j \omega_c t + j \omega_{\text{LO}} t + j \varphi_2 + j \frac{5}{4} \pi \right) + \frac{1}{2} J_0(m_2) J_1(m_3) \exp\left(j \omega_c t - j \omega_c t + j \omega_c \tau_1 + j \frac{5}{4} \pi - j \varphi_1 - j \varphi_2 \right) + J_1(m_2) J_1(m_3) \exp\left(j \omega_c t + j \omega_{\text{LO}} t - j \omega_c t - j \omega_c \tau_1 - j \varphi_1 \right),
\]

(6)

where \(m_3 = \pi A_{\text{SI}}/V_x\).

Then the optical signal in the \(X\) polarization and the modulated optical signal in the \(Y\) polarization are transmitted back to the CO. At the CO, the optical signals in the two polarizations are separated by PBS1, which are injected into the two optical ports of the BPD, respectively. Between PBS1 and the BPD, an ATT and a TODL are employed to adjust the amplitude and
the delay of the optical signal in the X polarization while the optical signal in the Y polarization is unchanged. The two optical signals applied to the BPD are expressed as

\[ E_{\text{BPD}-X}(t) = \frac{\sqrt{2}}{2} \sqrt{a} E_X(t - \tau_2) \]

\[ \propto \frac{\sqrt{2}}{2} \sqrt{a} J_0(m_1) \exp \left( j \omega_c(t - \tau_2) + j \frac{1}{4} \pi \right) \]

\[ + \sqrt{a} J_1(m_1) \exp(j \omega_c(t - \tau_2) - j \omega_{\text{LO}}(t - \tau_2) - j \varphi_1 + j \pi), \]  

(7)

\[ E_{\text{BPD}-Y}(t) = E_{Y-\text{SSB}}(t), \]  

(8)

where \( a \) is the power attenuation coefficient introduced by the ATT and \( \tau_2 \) is the delay introduced by the TODL.

The photocurrent in the IF band from the BPD is

\[ i(t) = i_X(t) - i_Y(t) \]

\[ \propto \sqrt{2} a J_0(m_1) J_1(m_1) \cos \left( \omega_{\text{IF}} t - \omega_{\text{LO}} \tau_2 + \varphi_1 - \frac{3}{4} \pi \right) \]

\[ - J_0(m_2) J_0(m_3) J_1(m_2) J_1(m_3) \cos \left( \omega_{\text{IF}} t - \omega_{\text{LO}} \tau_1 + \varphi_1 + \frac{1}{2} \pi \right). \]  

(9)

To cancel the SI, a basic condition that must be satisfied is that the time delays of the SI and the TODL must match. Under this premise, the amplitudes and phases of the two terms in Eq. (9) should also match. Therefore, the time delay \( \tau_2 \) of the TODL is adjusted to the same as the time delay \( \tau_1 \) of the SI, the power attenuation coefficient \( a \) is adjusted to

\[ J_0(m_2) J_0(m_3) J_1(m_2) J_1(m_3) / \sqrt{2 J_0(m_1) J_1(m_1)}, \]

and a phase \( \theta \) must be compensated by a phase shifter. The compensated phase \( \theta \) is the remainder of \( \omega_{\text{LO}} \tau_1 - \omega_{\text{IF}} \tau_1 = 5 \pi / 4 \) divided by \( 2 \pi \).

The phase compensation can be done together with the matching of attenuation and delay after the uplink signal is received at the CO. If the phase \( \theta \) is compensated, the SIC can be achieved for a wideband system. For narrowband systems, in which the carrier frequency is far greater than the signal bandwidth, the phase compensation can also be implemented by slightly tuning the TODL. In this case, the time delay of the TODL should be \( \tau_2 = \tau_1 + \theta/\omega_{\text{IF}} \). It is worth noting that, for narrowband systems, \( \theta/\omega_{\text{IF}} \) is much smaller than the width of the transmitted symbol, resulting in little influence on the SIC.

In addition, the influence of the fiber dispersion on the SIC capability of the system is also analyzed. In the downlink, different phase shifts are introduced to different optical wavelengths of the transmitted signal due to the fiber dispersion, as shown in Fig. 2(a). Here, we only consider the influence from the fiber dispersion, so only the additional phases that are not considered in the deduction above are shown in the figure. The optical signal received at the RU is written as

\[ E_{\text{downlink}}(t) = \begin{bmatrix} E'_X(t) \\ E'_Y(t) \end{bmatrix} \]

\[ \propto \begin{bmatrix} \frac{\sqrt{2}}{2} J_0(m_1) \exp \left( j \omega_c t + j \frac{1}{2} \pi + \Phi_0 \right) + J_1(m_1) \exp(j \omega_c t - j \omega_{\text{LO}} t - j \varphi_1 + j \pi + \Phi_1) \\ \frac{\sqrt{2}}{2} J_0(m_2) \exp \left( j \omega_c t + j \frac{1}{2} \pi + \Phi_0 \right) + J_1(m_2) \exp(j \omega_c t + j \omega_{\text{LO}} t + j \varphi_2 + j \pi + \Phi_2) \end{bmatrix}, \]  

(10)

where \( \Phi_0, \Phi_1, \) and \( \Phi_2 \) are the phase shifts introduced by the fiber dispersion to the optical carrier, the 1st-order optical sideband of the IF signal, and the opposite 1st-order optical sideband of the LO signal, respectively.

When the phase shifts introduced by the fiber dispersion is considered, an additional phase shift of \( \Phi_2 - \Phi_1 \) is introduced to the downlink RF signal, which is also the SI and is rewritten as

\[ V_{\text{SI-fiber}}(t) = A_{\text{SI}} \cos(\omega_c(t - \tau_1) + \varphi_1 + \varphi_2 + \Phi_2 - \Phi_1). \]  

(11)
In the uplink, the optical signal is SSB modulated by the SI at DD-MZM3, obtaining two optical sidebands as shown in Fig. 2(c). The optical carriers and the optical sidebands that we are concerned about in the two dash boxes are expressed as

$$E_{\text{uplink}}(t) = \begin{bmatrix} E_{X1}^+(t) \\ E_{Y1}^+(t) \end{bmatrix}$$

$$= \sqrt{2} J_0(m_1) \exp \left( j\omega_c t + j\frac{1}{2} \pi + \Phi_0 \right) + J_1(m_1) \exp \left( j\omega_c t - j\omega_{\text{IF}} t - j\phi_1 + j\pi + \Phi_1 \right)$$

$$J_0(m_2)J_0(m_3) \exp \left( j\omega_c t + j\frac{1}{2} \pi + \Phi_0 \right) + J_1(m_2)J_1(m_3)$$

$$\exp \left( j\omega_c t + j\omega_{\text{LO}} t - j\omega_{\text{IF}} t + j\omega_{\text{RF}} t - j\phi_1 + j\pi + \Phi_1 \right)$$

(12)

Then the optical signal is sent back to the CO via the SMF. Additional phase shifts of $\Phi'_0$ and $\Phi'_1$ are introduced to the optical carriers and the IF optical sidebands. Since the optical reference signal and the optical SI are located at the same wavelength, they experience the same phase shift as shown in Fig. 2(d). The SI can still be canceled at the output of the BPD when the matching condition of delay, phase, and amplitude are met. Therefore, the optical fiber dispersion in uplink and downlink will not affect the SIC performance of the ROF system.

3 Experimental Results

An experiment based on the setup shown in Fig. 3 is performed. A CW light wave from an LD (ID Photonics CoBriteDX1-1-C-H01-FA) is injected into a DP-BPSK modulator (Fujitsu FTM7980EDA) via PC1. The downlink IF signal generated from a vector signal generator (VSG, Agilent N5182A) is sent to the two RF ports of the X-SSB modulator of the DP-BPSK modulator via 90 deg HC1 (Tamagawa Electronics UPD-3025 1.7 to 2.3 GHz). The LO signal generated from a microwave signal generator (MSG1, Agilent 83630B) is applied to the two RF ports of the Y-SSB modulator of the DP-BPSK modulator via 90 deg HC2 (Macon Omni-Spectra FSC 16179 4 to 8 GHz). The optical signal from the DP-BPSK modulator is sent to the RU via a section of SMF. At the RU, the optical signal is amplified by an EDFA (Amonics AEDFA-PKT-DWDM-15-B-FA) and split into two paths via a 3-dB OS. One output from the OS is sent to a polarizer via PC2 and then applied to a PD (Discovery Semiconductors DSC-40S) to generate the downlink RF signal. The other output from the OS is demultiplexed into two orthogonally polarized branches ($X$ and $Y$ polarizations) by a PBS and PC3. The SSB-modulated optical signal is then detected by a PD and converted to an IF signal.
The signal in the $Y$ polarization is applied to a DD-MZM (Y-SSB2, Fujitsu FTM 7937EZ) as the optical carrier. The SOI is generated from MSG2 (HP 83752B), whereas the SI is simulated by the up-converted RF signal from the PD, which is filtered by a bandpass filter (BPF, 6.45 to 8.55 GHz) and amplified by an electrical amplifier (EA, CTT CLM/145-7039-293B, 5.85 to 14.85 GHz). The SOI and the SI are combined by an electrical coupler (EC, Narda 4456) and then applied to the Y-SSB2 modulator via 90 deg HC3 (Narda 4065 7.5 to 16 GHz). The output of the Y-SSB2 modulator is sent to one input port of the BPD (U2T BPRV2025), and the optical signal with its power attenuated and time delayed by an ATT and a TODL in the $X$ polarization is sent to the other input port of the BPD. The generated electrical signal from the BPD is then filtered by a lowpass filter (LPF, 3-GHz bandwidth) and then monitored by an electrical spectrum analyzer (ESA, Keysight N9020B). Due to the limited number of PBCs, PBSs, and PCs in our laboratory, the two optical signals in the two orthogonal polarization directions are not combined, transmitted back in the SMF, and split into two paths as shown in Fig. 1. Although the uplink transmission is omitted in the experiment, all functions shown in Fig. 1 except the uplink transmission are implemented in the experiment setup.

In the experiment, the wavelength and power of the CW light wave from the LD are set to 1567 nm and 10 dBm, respectively. The frequency and power of the IF signal are set to 2 GHz and 20 dBm, respectively, whereas those of the LO signal are set to 6 GHz and 20 dBm, respectively. The corresponding optical spectra at the X-SSB modulator and the Y-SSB modulator observed by the optical spectrum analyzer (OSA, ANDO AQ6317B) with a resolution of 0.01 nm are shown in Fig. 4(a). The optical signal in the $X$ polarization is modulated by the IF signal, which contains the optical carrier and the $-1$st-order optical sideband as shown by the red dash line. The green solid line shows the optical signal in the $Y$ polarization modulated by the LO signal, which contains the optical carrier and the $+1$st-order optical sideband. Due to the limited resolution of the OSA, the optical carrier and the optical sideband cannot be clearly distinguished in the $X$ polarization because the frequency spacing between them is only 2 GHz. Figure 4(b) shows the spectrum of the polarization multiplexed optical signal at the output of the DP-BPSK modulator. The optical signal is then split into two parts. The part for the generation of the up-converted downlink RF signal is combined at the polarizer, with its optical spectrum shown in Fig. 4(c). The other part of the optical signal is demultiplexed into two orthogonally polarized branches, which are respectively used as the reference optical signal for SIC and the optical carrier for the uplink modulation and frequency down-conversion. The reference optical signal in the $X$ polarization is adjusted by the TODL and the ATT to match the delay and amplitude of the SI. Because a narrowband system is employed in the experiment, no RF phase shifter is used. Therefore, the TODL should be adjusted to compensate for not only the time delay but also the phase shift $\theta$. The optical spectrum after the TODL is shown by the red dash line in Fig. 4(d). The optical signal in the $Y$ polarization is SSB-modulated by the received signal, and two optical sidebands are generated at frequencies of $f_c - f_B$ and $f_c - f_s$, which is shown by the green solid line in Fig. 4(d).

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**Fig. 3** Experimental setup of the proposed system. VSG, vector signal generator; MSG, microwave signal generator; BPF, bandpass filter; EA, electrical amplifier; EC, electrical coupler; LPF, lowpass filter; ESA, electrical spectrum analyzer.
Then, the downlink signal generation is experimentally verified. Due to the limitation of the operating bandwidth of the 90 deg HCs, the BPF, and the LPF that are available in our laboratory, the frequencies of the IF signal, the LO signal, and the RF signal must be carefully selected to verify the experimental setup in Fig. 3. In this experiment, the center frequencies of the IF signal and the LO signal are set to 2.1 and 5 GHz, respectively, and the power of the two signals is set to 10 dBm. The generated up-converted downlink RF signals at the output of the BPF are shown in Fig. 5. When a single-tone signal is employed as the IF signal, a single-tone RF signal at 7.1 GHz is observed as shown in Fig.5(a). When the IF signal is replaced by a 20-Mbaud 16-QAM signal, the generated downlink RF signal centered at 7.1 GHz is shown in Fig.5(b). It can be seen that the power of the up-converted RF signal from the BPF is very low, so it is amplified by the EA with 39-dB gain and then used as the SI in the following experiment.

Then, the downlink signal generation is experimentally verified. Due to the limitation of the operating bandwidth of the 90 deg HCs, the BPF, and the LPF that are available in our laboratory, the frequencies of the IF signal, the LO signal, and the RF signal must be carefully selected to verify the experimental setup in Fig. 3. In this experiment, the center frequencies of the IF signal and the LO signal are set to 2.1 and 5 GHz, respectively, and the power of the two signals is set to 10 dBm. The generated up-converted downlink RF signals at the output of the BPF are shown in Fig. 5. When a single-tone signal is employed as the IF signal, a single-tone RF signal at 7.1 GHz is observed as shown in Fig. 5(a). When the IF signal is replaced by a 20-Mbaud 16-QAM signal, the generated downlink RF signal centered at 7.1 GHz is shown in Fig. 5(b). It can be seen that the power of the up-converted RF signal from the BPF is very low, so it is amplified by the EA with 39-dB gain and then used as the SI in the following experiment.

The ability of SIC and frequency down-conversion in the uplink is then demonstrated. A 6-dBm single-tone signal centered at 2 GHz is used as the IF signal, and it is up-converted to 7 GHz by an LO signal with a frequency of 5 GHz and a power of 17.3 dBm. The 7-GHz signal at the output of the EA is used as the SI and applied to Y-SSB2 via 90 deg HC3. The SOI is not considered in this case. Under these circumstances, the electrical spectrum at the output of

![Fig. 4](image)

**Fig. 4** Optical spectra of the optical signals from (a) the X-SSB modulator and the Y-SSB modulator; (b) the DP-BPSK modulator; (c) the polarizer; and (d) the TODL and the Y-SSB2 modulator.

![Fig. 5](image)

**Fig. 5** Electrical spectra of the downlink RF signals at the output of the BPF when the IF signal is (a) a single-tone signal and (b) a 20-Mbaud 16-QAM signal.
the BPD without SIC is shown by the red dash line in Fig. 6(a), where the SI at 2 GHz after frequency down-conversion is observed. When the SIC is enabled, the electrical spectrum at the output of the BPD is shown by the green solid line in Fig. 6(a). It can be seen that the SI is well canceled with a cancellation depth of more than 40 dB. Furthermore, the frequency tunability of the system is also verified by changing the frequencies of the IF signal and the LO signal. Figures 6(b)–6(d) show the electrical spectra at the output of the BPD with and without SIC under different conditions. The frequency of the IF signal is 2 or 2.1 GHz, and the frequency of the LO is 5 or 6 GHz. It can be seen that the cancellation depths are all around 40 dB.

Then, the SIC performance of the system is further verified by employing vector signals as the SI. First, a 16-QAM signal centered at 2 GHz with a symbol rate of 10 Mbaud and a power of 6 dBm is used as the input IF signal for the downlink. The frequency and power of the LO signal are set to 6 GHz and 17.3 dBm, respectively. A 22-dBm single-tone sinusoidal signal at 2 GHz is employed as the SOI in this case. The electrical spectrum at the output of the BPD with and without SIC is shown in Fig. 7(a). It can be seen that, when the SI is enabled, the SOI is completely submerged by the SI. After SIC, the SI is suppressed by more than 26 dB, and the SOI can be clearly observed. Then, the center frequency of the IF signal is changed to 2.1 GHz, and a cancellation depth of 23.9 dB is obtained as shown in Fig. 7(b). The SIC performance of the system is further studied by increasing the symbol rate of the SI to 20 Mbaud. As shown in Figs. 7(c) and 7(d), the cancellation depths are about 23.5 or 22 dB, respectively, when the center frequency of SI is 2 or 2.1 GHz. Compared with the results in Figs. 7(a) and 7(b), it can be seen that the cancellation depth slightly deteriorates when the symbol rate of the SI increases. The reason is that a TODL is used in the experiment to compensate for the phase shift $\theta$ in the system instead of a phase shifter. As the bandwidth increases, the phase compensation by the TOLD will be more inaccurate, which leads to the decrease of the cancellation depth.

Finally, a section of 4.1-km SMF is inserted in the system to further verify the SIC performance. In the experiment, the frequency of the LO signal is fixed at 6 GHz while the frequency and the symbol rate of the IF signal are changed. The electrical spectra at the output of the BPD are shown in Fig. 8. When the center frequency of the IF signal is set to 2 GHz and the symbol
Fig. 7 Electrical spectra of the down-converted IF signals in the uplink with and without SIC when the IF symbol rate, the center frequencies of the IF signal, and the LO signal are (a) 10 Mbaud, 2 GHz, 6 GHz; (b) 10 Mbaud, 2.1 GHz, 6 GHz; (c) 20 Mbaud, 2 GHz, 6 GHz; and (d) 20 Mbaud, 2.1 GHz, 6 GHz. No SMF is inserted.

Fig. 8 Electrical spectra of the down-converted IF signals in the uplink with and without SIC when the IF symbol rate, the center frequencies of the IF signal, and the LO signal are (a) 10 Mbaud, 2 GHz, 6 GHz; (b) 20 Mbaud, 2 GHz, 6 GHz; (c) 10 Mbaud, 2.2 GHz, 6 GHz; and (d) 20 Mbaud, 2.2 GHz, 6 GHz. A section of 4.1-km SMF is inserted.
rates of the input IF signals are 10 and 20 Mbaud, the cancellation depths are 23.6 and 20.9 dB, respectively. Then, the center frequency of the IF signal is adjusted to 2.2 GHz, the cancellation depths are 24.2 and 22 dB, respectively. Compared with the results without fiber transmission, no significant performance degradation is observed.

In the experiment, the operating bandwidths of the three 90 deg HCs need to have a certain relationship. Due to the limitation of such electrical devices available in our laboratory, the system is only demonstrated by employing an IF signal at around 2 GHz and an RF signal at around 7 to 8 GHz. In fact, these frequencies can be adjusted in a wider range if three 90 deg HCs with better matched bandwidths are employed. As discussed in the previous section, a phase shift $\theta$ needs to be compensated to make the system suitable for wideband systems. Because the electrical phase shifter in our laboratory is all based on the time delay, we only demonstrate the SIC performance of a narrowband system.

4 Conclusion

We have proposed and experimentally demonstrated a photonic approach for SIC incorporated into an IBFD ROF system. All functions, including overcoming the influence on the SIC and the distortion of the SOI caused by the fiber dispersion, realizing SIC in conjunction with frequency conversion, and moving the SIC from the RU to CO to simplify the RU, are simultaneously realized in the system, which provides a feasible solution for the SIC in IBFD ROF systems. An experiment is carried out. The SIC performance of the proposed approach is studied by employing a single-tone signal and a vector signal as the SI. The cancellation depth is around 40 dB for the single-tone SI and around 22 dB for the 20-Mbaud 16-QAM modulated SI.

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