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Zhenyang Shi

Nanjing University of Posts and Telecommunications

Yingchao Liao

Nanjing University of Posts and Telecommunications

Hao Xu

Nanjing University of Posts and Telecommunications

Enming Xu

enmingxu@njupt.edu.cn

Nanjing University of Posts and Telecommunications

Zuxing Zhang

Nanjing University of Posts and Telecommunications

Research Article

Keywords: Microwave photonics, Self-interference cancellation, Downconversion, Image rejection

Posted Date: October 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11306781/v1>

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Additional Declarations: No competing interests reported.

Multifunctional microwave photonic processor with multichannel self-interference cancellation

Zhenyang Shi¹ • Yingchao Liao¹ • Hao Xu¹ • Enming Xu¹ • Zuxing Zhang¹

Abstract

A photonic-assisted multifunctional microwave signal processor for in-band full-duplex system is proposed. It is based on dual-polarization dual-parallel Mach-Zehnder modulator (DPol-DPMZM) and can simultaneously realize multichannel self-interference cancellation (SIC), frequency downconversion and image rejection. The two-channel SIC can be simultaneously achieved in X-DPMZM and Y-DPMZM of the DPol-DPMZM in optical domain when the two DPMZM are biased at the minimum transmission point. After SIC, the two groups of optical orthogonal carrier-suppressed double-sideband signals generated from the two DPMZMs are sent into a fiber Bragg grating to obtain the single-sideband signal, overcoming the dispersion-induced power fading. Subsequently, the orthogonally combined optical signals are separated into two branches and detected by two photodetectors. Two quadrature IF outputs are generated through mixing a pair of quadrature local oscillator signals with the received signals. After combination using a 90° hybrid coupler, the frequency downconversion with image rejection is achieved. Both theoretical and experimental investigations are performed. The results show that the single-frequency SIC depth up to 49.1 dB and the image-rejection ratio (IRR) of 30.4 dB are independently achieved. The frequency downconversion with a broadband SIC depth of 18.8 dB within 150 MHz and an IRR of 21 dB for signal of interest at 6.4 GHz are simultaneously achieved.

Keywords Microwave photonics • Self-interference cancellation • Downconversion • Image rejection.

1 Introduction

Comparison to conventional frequency division duplex and time division duplex, in-band full-duplex (IBFD) system is capable of doubling the efficiency of RF spectrum and the data transmission rate due to simultaneously transmitting and receiving signals on the same frequency at the same time, and it is considered as one of the key technologies in the applications of future wireless communication [1]. However, some challenges existing in the IBFD should be solved. First, due to the close physical distance between the transmitting antennas and the receiving antennas, the signal emitted by the transmitting antenna will inevitably leak into the adjacent receiving antenna, resulting in a self-interference (SI) signal, which will cause interference to the signal of interest (SOI) and cannot be removed by an electrical filter. Second, when transmitting from remote antenna unit (RAU) to the central station (CS) in the uplink, the high-frequency received signal often needs to be downconverted to a lower intermediate frequency (IF) signal to relax the processing pressure of the analogue-to-digital conversion (ADC) [2]. However, the image (IM) signal along with the SOI is also converted to the same IF, since its frequency and the SOI frequency are symmetrical relative to the local oscillator (LO) frequency. Thus, the IF downconverted from the IM signal should be removed [3]. Besides, during the transmitting, the dispersion will induce power fading for the SOI signal which should also be overcome together [4]. Up to now, many photonic-assisted self-interference cancellation (SIC) methods have been proposed [5-8]. The key to achieving the photonic-assisted SIC lies in realizing the phase inversion between the reference signal and the interference signal, which can be implemented by many techniques, such as bias-controlled modulations [5], balanced photodetection [6], phase modulation [7], or using a microwave photonic phase shifter to adjust the phase of one signal [8].

As mentioned above, the frequency downconversion is a key function in IBFD system. To simplify the structure and reduce the cost of the system, the SIC and frequency downconversion should be realized simultaneously in a unified system. Some photonic-assisted approaches using dual-polarization dual-parallel Mach-Zehnder modulator (DPol-DPMZM) [5, 8] and dual-polarization dual-drive Mach-Zehnder (DPol-DDMZM) [9] have been proposed to achieve the SIC and frequency downconversion simultaneously. In addition, since the IM signal is another interference for the frequency downconverted signal, the image rejection should also be achieved when realizing the SIC and frequency downconversion. Up to now, several structures have been proposed to simultaneously realize the SIC, frequency downconversion and image

✉ Enming Xu
enmingxu@njupt.edu.cn

¹ College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing, 210023, China

rejection [10-14]. In [10], a photonics-based frequency downconversion with SIC and image rejection is realized through matching the proper power and time delay of the reference signal, which is based on the combining the specific phase shift channels provided by a polarization-multiplexed 90° optical hybrid. However, the use of the two separate modulators and four photodetectors (PDs) would increase the complexity of the system and lead to the instability of the system. In [11], the upper DPMZM of DPol-DPMZM is used to load the receiving signal and eliminate the SI signal in optical domain. The LO signal is applied to the lower DPMZM, and the quadrature IF signals is realized by adjusting the polarizer controller (PC). After combination using an electrical 90° hybrid coupler (HC), the frequency downconversion with image rejection is achieved. In [12], similar to [11], the upper DPMZM is used to achieve SIC in optical domain. With power splitting after the output of the DPol-DPMZM, the quadrature IF signals is obtained through a photonics-based continuously adjustable phase shifter, the photonic image rejection (IR) downconversion is achieved after a low-frequency electrical 90° HC. However, in [11] and [12], it is difficult to precisely achieve the desired phase shift and power matching simultaneously by adjusting the PC, which is insensitive to environmental perturbations. In [13, 14], the image rejection and SIC are simultaneously realized in IF band, reducing the requirement for precise delay control. However, two lasers and two separate modulators increase the complexity and instability of the system. In addition, in [14], the fiber dispersion cannot be overcome. Furthermore, the mentioned above multifunctional processors can only achieve one channel SIC. However, in the realistic scenario, multichannel radio-over-fiber (RoF) transmission system is usually required [15, 16].

In this work, a multifunctional microwave signal processing system with multichannel SIC is proposed. To our knowledge, this is the first multifunctional microwave photonic processor capable of simultaneously achieving multichannel SIC, downconversion, image rejection, and eliminating the power fading induced by dispersion. Two groups of first-order optical sidebands of the SI, SOI, IM signals incorporated with the two LO signals with a 90° phase difference are generated by two sub-MZMs in two DPMZMs. Meanwhile, two first-order optical sidebands of the self-reference (SR) signals are generated in the other two sub-MZMs in the two DPMZMs. By adjusting the two main bias voltages of the two DPMZMs, a 180° phase difference is introduced between the SI and SR signals in each DPMZM. Consequently, SI signals in both channels are simultaneously cancelled in optical domain, achieving the two-channel SIC. The carrier-suppressed double-sideband (CS-DSB) signals generated from the two DPMZMs are orthogonally combined at the polarization beam combiner (PBC). The -1 st-order sidebands of the combined signal are suppressed by a fiber Bragg grating (FBG), and only $+1$ st-order sidebands of the SOI, IM and LO are selected, which has the advantage of achieving high mixing efficiency, reducing the mixing spurs [3], eliminating the power fading induced by dispersion and improving the spectrum efficiency [4]. After photodetection, a pair of quadrature downconverted IF signals are obtained. By combining them by a quadrature hybrid coupler, the image rejection is also achieved.

2 Operational Principle

The schematic diagram of the proposed system is illustrated as Fig. 1. A light wave from a tunable laser source (TLS) is injected into a DPol-DPMZM containing X-DPMZM and Y-DPMZM through PC1 that is used to reduce the polarization-dependence loss. The received signals include SI, SOI and IM signals, as well as two LO signals with a phase difference of 90° . This signal is divided into two parts, which are respectively applied to one sub-MZM (X1-MZM) of X-DPMZM and one sub-MZM (Y1-MZM) of Y-DPMZM. The SR signal is divided into two parts through an electrical coupler (EC), and then are applied to the other sub-MZM (X2-MZM) of X-DPMZM and the other sub-MZM (Y2-MZM) of Y-DPMZM, respectively. To match the time delay, two tunable electrical delay lines are inserted after the SR signals. All sub-MZMs of X-DPMZM and Y-DPMZM are operated at the minimum transmission point (MITP) to generate CS-DSB signals, achieving a high mixing efficiency [14]. Thus the CS-DSB of the SI, SOI, IM, SR and LO signals are obtained. The modulated optical signals from X- DPMZM and Y-DPMZM

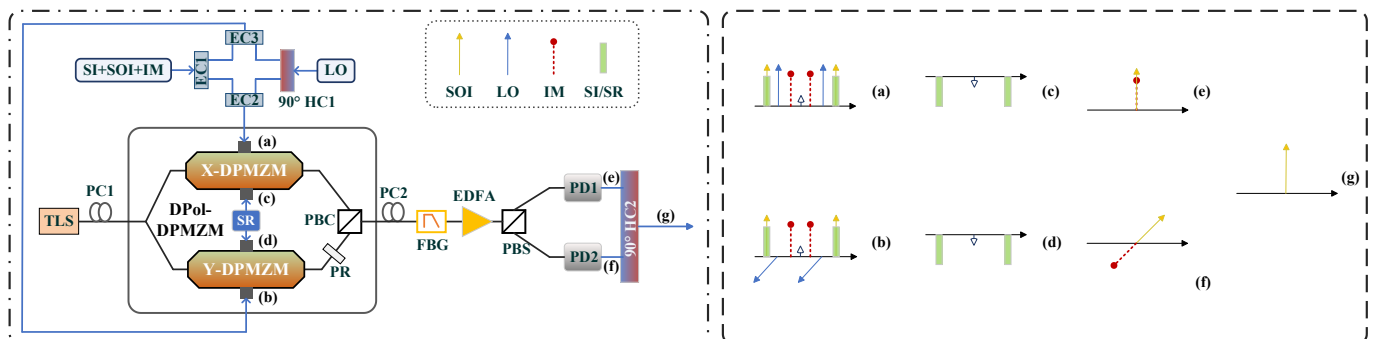


Fig. 1 Schematic diagram of the proposed multifunctional microwave photonic processor. TLS: tunable laser source; PC: polarization controller; DPol-DPMZM: dual-polarization dual-parallel Mach-Zehnder modulator; PR: polarization rotator; PBC: polarization beam combiner; EDFA: erbium-doped fiber amplifier; FBG: fiber Bragg grating; PBS: polarization beam splitter; PD: photodetector; EC: electrical coupler; 90° HC: 90° hybrid coupler; SI: self-interference; SOI: signal of interest; IM: image; SR: self-reference; LO: local oscillator.

can be respectively expressed as

$$E_X(t) \propto E_0(t) \left\{ \begin{aligned} & \exp \left(j\beta_{SI} \cos \omega_{SI} t + j\beta_{SOI} \cos \omega_{SOI} t + j\beta_{IM} \cos \omega_{IM} t + j\beta_{LO} \cos \omega_{LO} t + j\frac{\theta_1}{2} \right) \\ & + \exp \left(-j\beta_{SI} \cos \omega_{SI} t - j\beta_{SOI} \cos \omega_{SOI} t - j\beta_{IM} \cos \omega_{IM} t - j\beta_{LO} \cos \omega_{LO} t - j\frac{\theta_1}{2} \right) \end{aligned} \right\} + \left[\exp \left(j\beta_{SR} \cos \omega_{SR} (t' + \tau) + j\frac{\theta_2}{2} \right) + \exp \left(-j\beta_{SR} \cos \omega_{SR} (t' + \tau) - j\frac{\theta_2}{2} \right) \right] \exp(j\theta_3) \quad (1)$$

$$E_Y(t) = \frac{E_0(t)}{2} \left\{ \begin{aligned} & \exp \left(j\beta_{SI} \cos \omega_{SI} t + j\beta_{SOI} \cos \omega_{SOI} t + j\beta_{IM} \cos \omega_{IM} t + j\beta_{LO} \cos \left(\omega_{LO} t + \frac{\pi}{2} \right) + j\frac{\theta_4}{2} \right) \\ & + \exp \left(-j\beta_{SI} \cos \omega_{SI} t - j\beta_{SOI} \cos \omega_{SOI} t - j\beta_{IM} \cos \omega_{IM} t - j\beta_{LO} \cos \left(\omega_{LO} t + \frac{\pi}{2} \right) - j\frac{\theta_4}{2} \right) \\ & + \left[\exp \left(j\beta_{SR} \cos \omega_{SR} (t' + \tau) + j\frac{\theta_5}{2} \right) + \exp \left(-j\beta_{SR} \cos \omega_{SR} (t' + \tau) - j\frac{\theta_5}{2} \right) \right] \exp(j\theta_6) \end{aligned} \right\} \quad (2)$$

where $E_0(t) = E_0 \exp(j\omega_0 t)$ denotes the optical field of the optical carrier, and E_0 and ω_0 are the corresponding amplitude and angular frequency. ω_{SI} , ω_{SOI} , ω_{IM} , ω_{LO} and ω_{SR} are the angular frequencies of the SI, SOI, IM, LO and SR signals, $\beta_i = \pi V_i / V_\pi$ ($i=SI, SOI, IM, LO, SR$) is the corresponding modulation depth. V_π is the half wave voltage of each sub-MZM, $\theta_n = \pi V_{bn} / V_\pi$ ($n=1,2,\dots,6$) represents the phase shift introduced by the corresponding DC bias voltage. t' represents the time delay difference between the SI and SR signals, and τ is the time delay introduced by the tunable electrical delay line. To simplify the analysis, it should be noted that the two parts of the SI, SOI, IM and LO signals, as well as the two parts of the SR signal, arrive at both X-DPMZM and Y-DPMZM simultaneously, and all the parameters of the sub-MZMs are the same. All the sub-MZMs and main MZMs are biased at the MITP, that is, $\theta_n = \pi$ ($n=1,2,3,4,5,6$). Thus, a 180° phase difference is introduced between the SI and SR signals. Under the condition of small signal modulation, using Jacobi-Anger, Eq. (1) and Eq. (2) can be expanded as

$$E_X(t) \propto E_0(t) \left\{ \begin{aligned} & -J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{IM})J_1(\beta_{LO})(e^{j\omega_{LO}t} + e^{-j\omega_{LO}t}) - J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{LO})J_1(\beta_{IM})(e^{j\omega_{IM}t} + e^{-j\omega_{IM}t}) \\ & - J_0(\beta_{SOI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SI})(e^{j\omega_{SI}t} + e^{-j\omega_{SI}t}) - J_0(\beta_{SI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SOI})(e^{j\omega_{SOI}t} + e^{-j\omega_{SOI}t}) \\ & + [J_1(\beta_{SR})(e^{j\omega_{SR}(t'+\tau)} + e^{-j\omega_{SR}(t'+\tau)})] \end{aligned} \right\} \quad (3)$$

$$E_Y(t) \propto E_0(t) \left\{ \begin{aligned} & -J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{IM})J_1(\beta_{LO}) \left(e^{j(\omega_{LO}t + \frac{\pi}{2})} + e^{-j(\omega_{LO}t + \frac{\pi}{2})} \right) - J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{LO})J_1(\beta_{IM})(e^{j\omega_{IM}t} + e^{-j\omega_{IM}t}) \\ & - J_0(\beta_{SOI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SI})(e^{j\omega_{SI}t} + e^{-j\omega_{SI}t}) - J_0(\beta_{SI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SOI})(e^{j\omega_{SOI}t} + e^{-j\omega_{SOI}t}) \\ & + [J_1(\beta_{SR})(e^{j\omega_{SR}(t'+\tau)} + e^{-j\omega_{SR}(t'+\tau)})] \end{aligned} \right\} \quad (4)$$

To realize the SIC in X-DPMZM and Y-DPMZM in optical domain, the following conditions should be satisfied.

$$J_0(\beta_{SOI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SI}) = J_1(\beta_{SR}) \quad (5)$$

$$t' + \tau = t \quad (6)$$

Thus, the SIC is achieved in optical domain before fiber transmission which can get rid of the influence of dispersion on the SIC [5]. After SIC in optical domain, the SOI, IM and LO modulated optical signals from the two DPMZMs are orthogonally combined by the PBC and fed into an FBG. After passing through the FBG, the carrier-suppressed single-sideband (CS-SSB) signals with +1st-order sidebands are obtained, which possesses the merit of reducing the mixing spurs [3], overcoming the dispersion-induced power fading and improving the spectrum efficiency [4]. The orthogonal CS-SSB signals after the FBG can be written as

$$E(t) \propto E_0(t) \left\{ \begin{aligned} & [-J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{IM})J_1(\beta_{LO})e^{j\omega_{LO}t} - J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{LO})J_1(\beta_{IM})e^{j\omega_{IM}t} - J_0(\beta_{SI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SOI})e^{j\omega_{SOI}t}] \vec{e}_x \\ & + [-J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{IM})J_1(\beta_{LO})e^{j(\omega_{LO}t + \frac{\pi}{2})} - J_0(\beta_{SOI})J_0(\beta_{SI})J_0(\beta_{LO})J_1(\beta_{IM})e^{j\omega_{IM}t} - J_0(\beta_{SI})J_0(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{SOI})e^{j\omega_{SOI}t}] \vec{e}_y \end{aligned} \right\} \quad (7)$$

where $\vec{e}_x$ and $\vec{e}_y$ refer to the two orthogonally polarization states. The two orthogonal CS-SSB signals generated by X-DPMZM and Y-DPMZM are separated into two branches at the PBS by adjusting PC2. The optical signals transmitting through the upper and lower branches are converted into electrical signals after PD1 and PD2, and they can be expressed as

$$i_{up}(t) \propto A \cos(\omega_{SOI} - \omega_{LO})t + B \cos(\omega_{LO} - \omega_{IM})t \quad (8)$$

$$i_{low}(t) \propto A \cos[(\omega_{SOI} - \omega_{LO})t - \pi/2] + B \cos[(\omega_{LO} - \omega_{IM})t + \pi/2] \quad (9)$$

where

$$A = E_0^2 J_0^2(\beta_{SI})J_0^2(\beta_{IM})J_0(\beta_{LO})J_1(\beta_{LO})J_0(\beta_{SOI})J_1(\beta_{SOI}) \quad (10)$$

$$B = E_0^2 J_0^2(\beta_{SOI})J_0^2(\beta_{SI})J_0(\beta_{LO})J_1(\beta_{LO})J_0(\beta_{IM})J_1(\beta_{IM}) \quad (11)$$

After combining i_{upper} and i_{lower} through an electrical 90° HC, the output signal can be expressed as

$$i(t) \propto 2A \cos(\omega_{LO} - \omega_{SOI})t \quad (12)$$

As can be seen from Eq. (12), the downconverted signal from the IM signal located at $|\omega_{LO} - \omega_{IM}|$ is eliminated, while the downconverted signal from SOI signal at $|\omega_{LO} - \omega_{SOI}|$ is enhanced. Consequently, two-channel SIC, downconversion, image rejection and overcoming the dispersion-induced power fading due to the SSB signal are simultaneously achieved.

3 Experimental Results and Discussion

The concept-of-proof experiment shown in Fig. 2 is carried out. A light wave with a tunable wavelength emitted from a TLS (YOKOGAWA, AQ4321D) is sent into a DPOL-DPMZM (Fujitsu, FTM7977HQA) with a bandwidth of 23 GHz via PC1. The RF signal from the output port of the vector network analyzer (VNA, Anritsu, N5230C) is denoted as microwave source 1 (MS1). The RF signal is divided into four parts by EC1, forming two pairs, and each pair serves as the SI and SR signals for each DPMZM. MS2 (Anapico, APSYN420) provides the SOI/IM signal that is divided into two parts by EC2 when testing the image cancellation performance. MS3 (DRO-5311-1) can only output a fixed frequency signal at 5.4 GHz and serves as the LO signal. The LO signal is divided into two parts through an electrical 90° HC (XBDQ-DA06, 1–18 GHz). Part of the LO signal combined with part of the SOI/IM and SI signals by EC3 is applied to X1-MZM in X-DPMZM, while the other part of the LO signal combined with the other part SOI/IM and SI signals by EC4 is injected into Y1-MZM in Y-DPMZM. One of the residual two parts divided by EC1 is applied to X2-MZM in X-DPMZM through an electrical phase shifter (EPS1, Anritsu A32-4xx0937-01) and an electrical attenuator (ATT1), and the other residual part is applied to Y2-MZM in Y-DPMZM through EPS2 (Anritsu A32-4xx0937-01) and ATT2. The EPS and ATT are used for adjusting the time delay and power of the SR signals to match that of the SI signals. All the sub-MZMs of X-DPMZM1 and Y-DPMZM work at the minimum points to obtain CS-DSB signals. The two main DC bias voltages of X-DPMZM and Y-DPMZM are also biased at the minimum point to achieve 180° phase difference. Thus, the SI signals applied to X-DPMZM and Y-DPMZM can be eliminated. Then the remaining CS-DSB signal is amplified by an erbium-doped fiber amplifier (EDFA, BA-GF-23-B) and then injected into a phase-shifted fiber Bragg grating (PS-FBG), and the +1st-order sidebands of the SOI/IM and LO signals are selected. The PS-FBG is used here since the conventional FBG with steep edge is absent in the experiment. Subsequently, the optical signal is divided into two channels through PC2 and a PBS. A pair of quadrature IF signals are obtained at two PDs (KG-PT-10G-A-FA) with a bandwidth of about 10 GHz. Finally, the image-rejection downconversion based on phase cancellation is realized after passing through an electrical 90° HC and measured by an electrical spectrum analyzer (ESA, R&SFSV30). It should be noted that since the frequency of the microwave signal generated by MS3 cannot be tuned, when testing single-frequency SIC at different frequency, MS2 is temporarily employed to serve as LO signal.

First, the performance of SIC for single-frequency signal is investigated in optical domain. In order to better test the SIC performance of the proposed structure, the SOI signal is not introduced when investigating the SIC performance. In the experiment, the RF signal at 6.2 GHz with a power of 4.63 dBm is generated from the output port of the VNA, then amplified by an electronic amplifier (EA) with a gain of 30 dB to compensate for the insertion loss of EC1. The RF signal is separated into four parts by EC1, two of these parts serving as the SI and SR signals are respectively applied to two sub-MZMs of X-DPMZM, while the residual two parts working as the SI and SR signals are respectively loaded on two sub-MZMs of Y-DPMZM. By properly adjusting the main DC bias voltages of the two DPMZMs, EPSs and ATTs, the CS-DSB signals produced by the SI and SR are made to have equal power and time delay for each DPMZM, thereby enabling a better SIC implementation for each channel in optical domain. To demonstrate it, the resulted CS-DSB signals before SIC (green dash lines and orange solid lines) in each DPMZM measured by an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370C) are shown in Fig. 3(a) and Fig. 3(b), respectively, which present quite similar spectra, indicating the consistency of the two spectra. The purple solid line is the transmission spectrum of the PS-FBG, which is used here to select the +1st-order optical sidebands of the SI and SR signals, as shown in red dashed and blue solid lines. As can be seen, the -1st-order optical sidebands are well suppressed. When the SR signals are connected, the SI signals are well cancelled, as shown by the black solid lines. As can be seen, after SIC, the optical

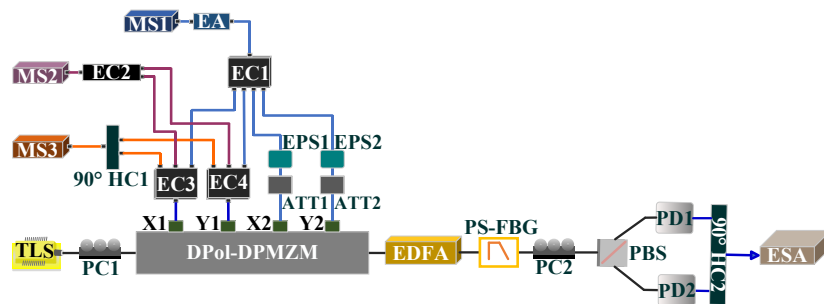


Fig. 2 Experimental setup of the proposed processor

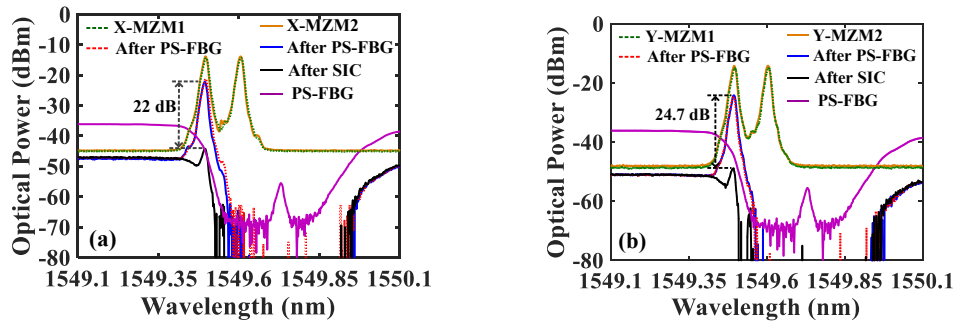


Fig. 3 Optical spectra of the CS-DSB signals before and after the PS-FBG, and before and after SIC for (a) X-DPMZM, (b) Y-DPMZM.

sideband suppression ratio larger than 22 dB is resulted. Thus, the SIC is successfully achieved in optical domain. The drawback of using the PS-FBG is that the transmission peak of the PS-FBG will deteriorate the SSB signal if the unwanted sideband follows within the bandwidth of the peak, which can be improved by using a steep-edge FBG to replace the PS-FBG.

Then, the SIC performance of the downconverted signal is then tested. During the testing process, the SOI signal is disconnected, only SI signal is connected to better test SIC performance. Since the SI signals of both X-DPMZM and Y-DPMZM are needed to be suppressed, the performances of the downconverted signals obtained from the two SI signals applied to the two DPMZMs are simultaneously tested. When the SI signal at 6.2 GHz with a power of -3.29 dBm and the LO signal at 5.2 GHz with a power of 7.49 dBm are applied to X-DPMZM, the electrical spectra of X-polarization state of the IF signal downconverted from the SI signal before and after SIC are shown in Fig. 4(a). As can be seen, the SI signal is downconverted to a frequency of 1 GHz. Noting that all the mentioned signal powers here and in the following text applied to the modulators are obtained at the RF ports of the modulators. Similarly, the frequencies of the SI and LO signals are kept unchanged, under the condition of the SI with a power of -3.17 dBm and LO with a power of 7.9 dBm, the electrical spectra of Y-polarization state of the IF signal downconverted from the SI signal before and after SIC are shown in Fig. 4(b). As can be seen from Fig. 4(a)

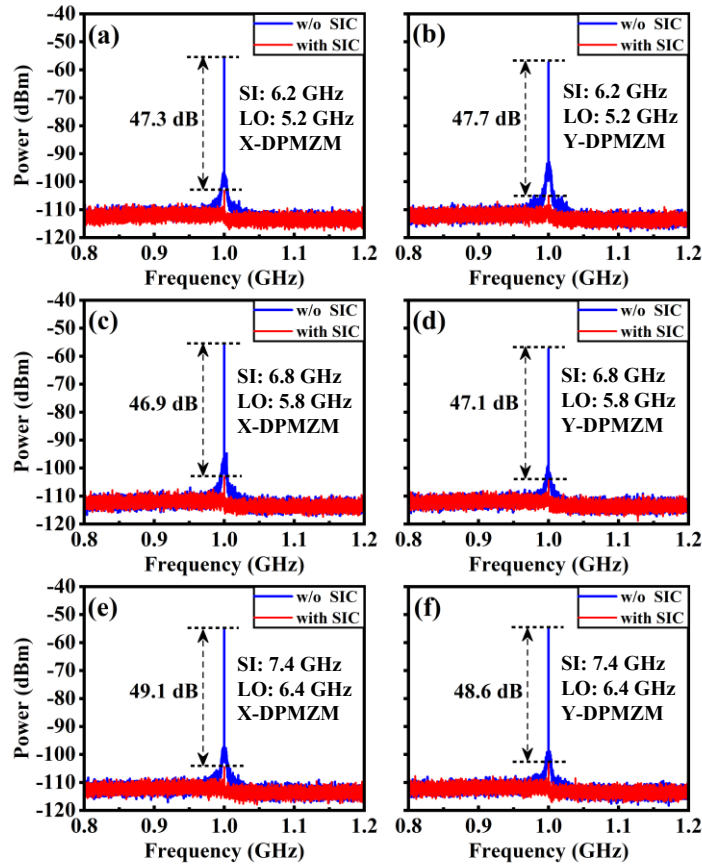


Fig. 4 Measured electrical spectra of the single-frequency signal before and after SIC at different frequency for different path. RBW: 5 kHz, VBW: 500 Hz.

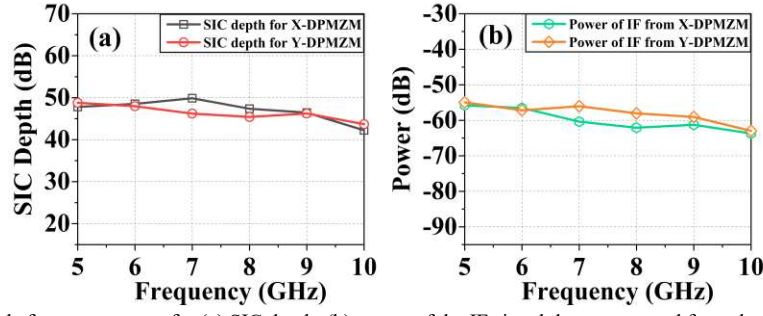


Fig. 5 Measured results over a wide frequency range for (a) SIC depth, (b) power of the IF signal downconverted from the SI signal.

and (b), the SIC depth of 47.3 dB and 47.7 dB are successfully achieved, respectively. Next, the SI signal is changed to 6.8 GHz, while the LO is changed to 5.8 GHz, the corresponding measured electrical spectra for X-DPMZM and Y-DPMZM are shown in Fig. 4(c) and (d). The SIC depths of 46.9 dB and 47.1 dB are obtained, respectively. Finally, the SIC for the SI signal of 7.4 GHz and the LO signal of 6.4 GHz is investigated. As shown in Fig. 4 (e) and (f), the SIC depths of 49.1 dB and 48.6 dB for X-DPMZM and Y-DPMZM are achieved, respectively. It can be seen from Fig. 4 that the SI signal has been effectively suppressed, and the power of SI drops to below -100 dBm after SIC, which almost reaches the noise level of the SI under the condition of resolution bandwidth (RBW) 5 kHz and video bandwidth (VBW) of 500 Hz. It should be noted that SIC depth monitored by the ESA is larger than the optical sideband suppression ratio observed by the OSA because the resolution bandwidth of the ESA is higher than that of the OSA.

To further test the SIC performance at different frequencies, the SI frequency is increased from 5 to 10 GHz at a step of 1 GHz, and the corresponding LO frequency is increased from 4 to 9 GHz at the same step, thus all the downconverted signals are ensured to be 1 GHz. Fig. 5(a) shows the measured SIC depths from X-DPMZM and Y-DPMZM at different SI frequencies. It can be seen that the SIC depth higher than 40 dB is maintained over a wideband SI frequency range. The SIC depth has slight decline with the frequency shifted to high frequency, which is mainly caused by the inherent power response reduction of the RF devices as signal frequency increases. To further demonstrate the result, the power levels of the IF signals downconverted from SI signals at different frequencies from X-DPMZM and Y-DPMZM are shown in Fig. 5(b). It can be observed that the power of the downconverted IF signal indeed has a slight decrease to a small extent with the frequency shifted to high frequency.

Subsequently, the performance of the IM signal rejection for single-frequency signal is investigated. To better test the performance of the IM signal rejection, the SI and SR signals are disconnected from the system. First, for X-DPMZM, as the frequency of SOI signal is set as 6.5 GHz with a power of 7.33 dBm, while the LO signal is set as 5.4 GHz with a power of -6.95 dBm, the measured IF signal at 0.9 GHz downconverted from the SOI signal is shown in Fig. 6(a). Similarly, the measured IF signal from Y-DPMZM is shown in Fig. 6(b). As can be seen, the power of the IF signal is approximately -50 dBm. Then, the SOI signal is disconnected and switched to the corresponding IM signal at 4.5 GHz, the two powers of the two IM signals applied to X-DPMZM and Y-DPMZM are 8.39 dBm and 8.38 dBm, the measured result after passing through the 90° HC is shown in Fig. 6(c). It can be seen that the IF signal downconverted from the IM signal is suppressed well, and the image-rejection ratio (IRR) reaches about 30.4 dB.

Next, to investigate the image-rejection performance at other frequency, the IM signal is changed to 4.4 GHz, while the LO

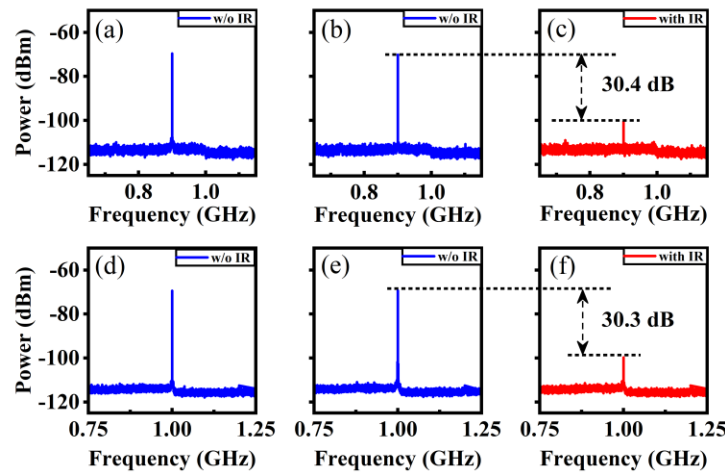


Fig. 6 Measured electrical spectra of IR for the single-frequency signal with IM set as 4.5 GHz for (a) & (b) & (c), and 4.4 GHz for (d) & (e) & (f). RBW: 5 kHz, VBW: 500 Hz.

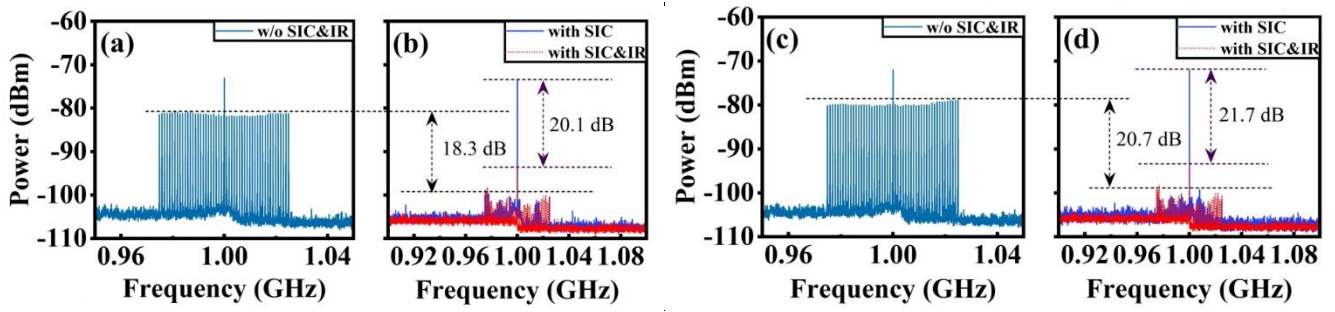


Fig. 7 Measured electrical spectra of the downconverted signal before and after SIC & IR with the center and bandwidth of the SI set as 6.4 GHz and 50 MHz for different path (a) & (b) for X-DPMZM, (c) & (d) for Y-DPMZM. RBW: 10 kHz, VBW: 2 kHz.

is kept at 5.4 GHz. The measured result is shown in Fig. 6(f), and the IRR of 30.3 dB is achieved. As can be seen that the IM signal is not suppressed completely. The main reason lies in the fact that the quadrature phases of the two IM signals failed to be precisely matched, which is induced by the uneven power distribution and the different lengths of the optical fiber pigtails at two ports of the PBS, as well as the non-ideal 90° phase difference of the 90° HC device. Fortunately, there are two possible methods to improve the exact matching. One method is an optical tunable attenuator and an optical tunable delay line are used in one path before one PD. The other method is an electrical tunable attenuator and an electrical tunable phase shifter are inserted in one path after one PD. The two methods can enable the powers and the quadrature phases of the two IM signals to be precisely matched, thereby enhancing the suppression depth of the IM signal.

After that, the simultaneous SIC and IR performances of the broadband signal are studied. Fig. 7 shows the measured electrical spectra without and with SIC and IR. The frequencies of the single-frequency SOI generated from MS2 and the LO signals generated from MS3 are 6.4 GHz and 5.4 GHz, and corresponding powers are 7.08 dBm and -5.36 dBm, respectively. The broadband SI signal is generated from the output port of the VNA with the center frequency of 6.4 GHz and the bandwidth of 50 MHz, and the output power is -3.26 dBm. That is, the SI signal sweeps from 6.375 to 6.425 GHz with a step of 1 MHz. When the reference branch is disconnected, the measured electrical spectra from X-DPMZM and Y-DPMZM with neither SIC nor IR are shown in Fig. 7(a) and (c), respectively. The results indicate that both the SOI and SI signals are downconverted to the IF signals with a center frequency of 1 GHz. After connecting the reference branch, the output electrical spectra with SIC from X-DPMZM and Y-DPMZM are shown as blue solid lines in Fig. 7(b) and (d), respectively. It can be observed that the SIC depths of 18.3 dB and 20.7 dB over 50 MHz bandwidth are achieved, whereas the IF downconverted from the SOI signal does not show significant power degradation. When the SOI is disconnected and switched to the IM signal at the frequency of 4.4 GHz with a power of 8.19 dBm, the electrical spectra with both SIC and IR is shown as red dotted line in Fig. 7(b) and Fig. 7(d). As can be seen, the IRR of larger than 20 dB has been achieved. It should be noted that the red dotted lines in Fig. 7(b) and (d) represent the same curve, so as to facilitate a better comparison for the purpose of observing the IRR.

Afterwards, the performances of SIC and IR at different bandwidths are also investigated. As the bandwidth of the broadband SI signal is increased to 100 MHz, the downconverted SOI and SI signals from X-DPMZM with neither SIC nor IR is shown in Fig. 8(a). When the SR is connected to achieve the SIC function, the electrical spectrum with SIC is shown as blue solid line in Fig. 8(b). As can be seen, a SIC depth of 18.7 dB over 100 MHz bandwidth is obtained. Similarly, for Y-DPMZM, the signal before SIC is shown in Fig. 8(c), and the signal after SIC is shown as the blue solid line in Fig. 8(d). As can be seen, when SIC is enabled, the SIC depth reaches 21.3 dB over 100 MHz bandwidth.

After the SIC is realized in X-DPMZM and Y-DPMZM, the image rejection is studied. To do it, the signals from X-DPMZM and Y-DPMZM after the SIC are combined through a 90° HC, and the SOI signal is disconnected and switched to the IM signal at the frequency of 4.4 GHz with a power of 7.92 dBm. For same reason, to better illustrate the IRR, the measured curves drawn with red dotted lines in Figures 8(b) and 8(d) are the same spectrum. As can be seen, the IRR of larger than 20 dB has been

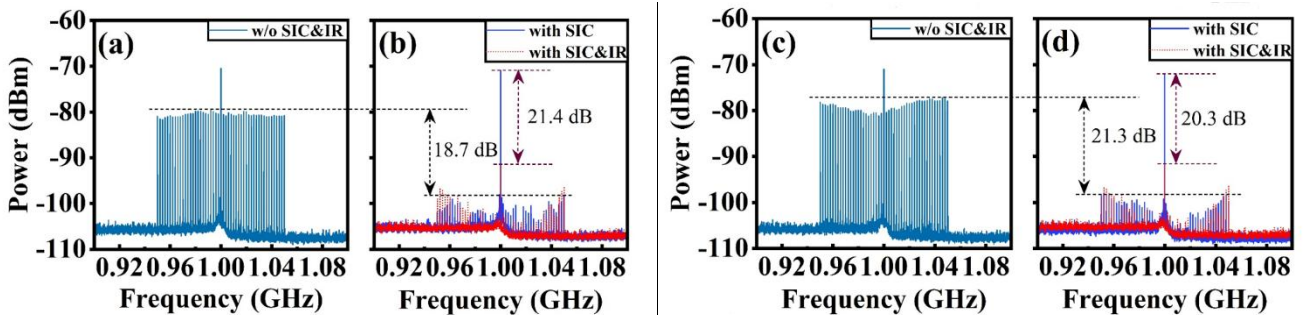


Fig. 8 Fig. 7 Measured electrical spectra of the downconverted signal before and after SIC & IR with the center and bandwidth of the SI set as 6.4 GHz and 100 MHz for different path (a) & (b) for X-DPMZM, (c) & (d) for Y-DPMZM. RBW: 10 kHz, and VBW: 2 kHz.

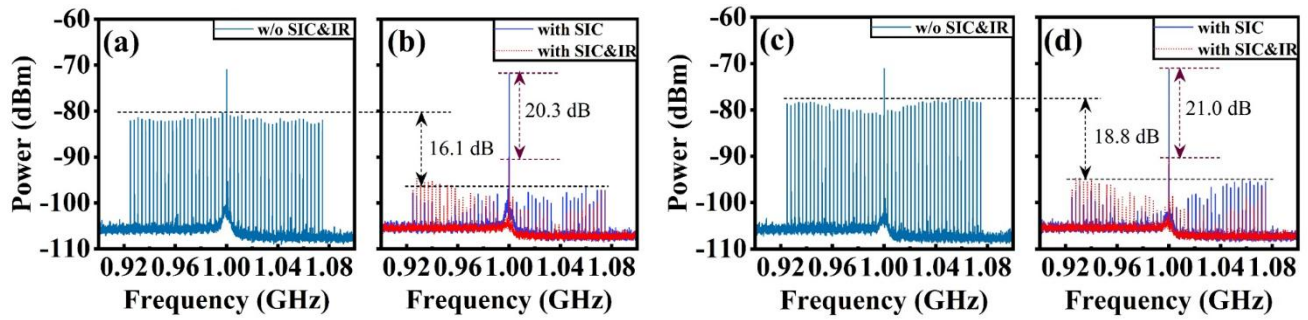


Fig. 9 Measured output electrical spectra of the downconverted signal before and after SIC & IR with the center and bandwidth of the SI set as 6.4 GHz and 150 MHz for different path (a) & (b) for X-DPMZM, (c) & (d) for Y-DPMZM. RBW: 10 kHz, RBW: 10 kHz, and VBW: 2 kHz.

reached. When SIC is enabled, the SIC depth over 100 MHz bandwidth reaches 21.3 dB.

Finally, the bandwidth of the SI signal is further increased to 150 MHz, and the measured results are shown in Fig. 9(a)-(d). As can be seen that a SIC depth of 16.1 dB from X-DPMZM and a SIC depth of 18.8 dB from Y-DPMZM over 150 MHz bandwidth are realized. The maximum IRR of up to 21 dB has been obtained. It can be seen that the power of the SOI signal is nearly kept unchanged after SIC, confirming that the SIC process has no effect on the SOI. In addition, by comparing the IRR of the single-frequency signal, it is found that in the presence of the SI signal, the IRR is slightly deteriorated. One reason is the residual downconverted SI signal is superimposed with the downconverted IM signal, resulting in the deterioration. The other reason is that when achieving the power matching for signal interference (SI) and radio frequency (SR) to achieve the maximum SIC depth, the power matching of the quadrature IF signals will be affected. It should be noted that the performance of broadband image rejection is not investigated when performing the broadband SIC due to the lack of an additional microwave source capable of generating broadband signals.

The SIC depth are mainly limited by the phase and power matching between the SI and the SR. As can be seen from Fig. 7- Fig. 9, the SI signal at the center is suppressed well, while the SIC depth becomes deteriorated with the frequency deviated from the center frequency, which can be attributed to that the phase shift introduced by the phase shifter is different at different frequency. The IRR is mainly constrained by the phase accuracy of the electrical 90° HC and power accuracy of the ATTs. If the accuracy of phase and power can be improved, the SIC depth and IRR of this method can be further enhanced. In addition, in this paper, only two-channel SIC is realized for verification. In practical application, the proposed scheme can be extended to realize two more channels SIC if two more DPol-DPMZMs are used, which can be applied in MIMO RoF transmission system.

4 Conclusion

A photonic-assisted multifunctional microwave signal processor with multichannel SIC based on the DPol-DPMZM for in-band full-duplex system has been proposed and experimentally demonstrated. It can simultaneously realize multichannel SIC, downconversion, image rejection, and eliminating the power fading induced by dispersion. The two-channel SIC is achieved in two DPMZMs. An electrical 90° HC is used to generate a 90° phase difference for the LO signal to generate a pair of quadrature IF signals, the image signal can be eliminated effectively after combination by an additional 90° HC. The SIC and image rejection in this frequency downconverter are demonstrated both in single frequency and wideband frequency range. The experimental results show that the single-frequency SIC depth up to 49.1 dB and the IRR of 30.4 dB are independently achieved. The frequency downconversion with a broadband SIC depth of 18.8 dB within 150 MHz and an IRR of 21 dB for SOI at 6.4 GHz are simultaneously achieved. The proposed approach has potential applications in IBFD-based MIMO RoF transmission systems.

Acknowledgments This work was partly supported by the National Natural Science Foundation of China (62675171).

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