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RF Characterization of Self-Interference Cancellation Using Phase Modulation and Optical Sideband Filtering

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ABSTRACT

Full-Duplex scheme transmitting and receiving signals simultaneously in the same frequency band can significantly improve the throughput and the spectrum efficiency, and is considered as a candidate technology for the fifth generation (5G) wireless communication. However, the high power transmitted signal will interfere with the in-band weak received signal, which is called as RF self-interference. It cannot be simply removed by a notch filter or a narrow bandpass filter because the same frequency band is used for both transmitter and receiver. An optical approach to implement RF self-interference cancellation is proposed. Based on the inherent out-of-phase property between the left and right sidebands of phase-modulated signal and optical sideband filtering, the RF self-interference cancellation is achieved by tuning the delay time and amplitude in the optical domain. The cancellation depth of the system was measured for different frequencies and bandwidths. The cancellation performance affected by the time delay deviation, the amplitude deviation and phase response is analyzed according to experimental results. It gives the direction for the improvement of system performance. Finally, the full-duplex communication by using the optical SIC approach was also investigated. Signal of interest is recovered and the constellation diagram was also shown.

Keywords: full-duplex communication, RF self-interference cancellation, phase modulation, optical sideband filtering

1. INTRODUCTION

In the field of wireless communications, spectrum resources are the core resources for promoting industrial development and the basis for carrying wireless services. Each user enters the network and occupies a fixed spectrum or time slot. These are the well-known half-duplex communications, namely Frequency Division Duplex (FDD) and Time Division Duplex (TDD). However, in order to significantly improve the throughput and the spectrum efficiency, Full-Duplex communication which can transmit and receive signals simultaneously in the same frequency band is considered as a candidate technology for the fifth generation (5G) wireless communication [1]-[3]. However, due to problems such as array arrangement of receiving and transmitting antennas, the signal transmitted by the transmitting antenna will cause strong interference to the receiving antenna, which is called as the RF self-interference or co-location interference. In recent years, the electronic RF self-interference cancellation methods for full-duplex communication have been widely investigated [4], [5]. However, this kind of method suffers from narrow bandwidth, low precision time delay and vulnerable to electromagnetic interference.

Compared with electronic methods, photonic RF self-interference cancellation (SIC) approaches with the advantages of wider operational bandwidth, higher precision, and immunity to electromagnetic interference are being attracted more and more attentions[6]-[12]. In [6] two Mach-Zehnder modulators (MZMs) biased at inverted quadrature points are utilized to implement the electrical-to-optical (E/O) conversion of all the received signals, including the weak signal of interest (SOI) and the strong interference signal, and the tapped reference signal from the transmitter. After tuning the delay time and amplitude of the received signals in the optical domain by a tunable optical delay line (TODL) and a variable optical attenuator (VOA), the interference and reference signals cancel each other out upon a photo detector due to exact out of phase and however identical magnitude, and the SOI was recovered. A hybrid analog optical self-interference cancellation (OSIC) was proposed in [7], which is based on optical delay line, electro-absorption modulation lasers (EMLs) and balanced photodetector (BPD), and experimental results show about 10-dB more depth by digital SIC over 1GHz broad baseband. In [8] and [9] the integrated microwave photonic circuit for active, analog self-interference cancellation is designed and demonstrated experimentally. The cascaded semiconductor optical amplifiers (SOAs) simultaneously control the amplitude and phase, showing a compact sub-system and promising low power consumption. However, as the frequency increases that the independent amplitude and phase tunable range of the cascaded SOAs will be degraded. In [10], cancellation bandwidth and depth as two main performance indices of the optical self-interference cancellation (OSIC) system are theoretically analyzed. The directly modulated laser (DML)-based OSIC system verified experimentally in this paper. And the cancellation model is well demonstrated by the agreement between experimental cancellation results and predicted performance. In [11], the intensity-modulation direct-detection system is modified by adding a Mach-Zehnder modulator and an optical delay line in a single path. With a prior knowledge of the interferer, the optical carrier is pre-distorted before modulated by the received corrupted signal. In [12] a dual-parallel polarization modulator (DP-PolM) based RF SIC method is presented, where optical power control is achieved by tuning the polarization state of the input optical signal into the DP-PolM, avoiding the need of a VOA. However, the polarization state may be affected by the environmental conditions and the system stability degrades.

In this paper, we propose and demonstrate experimentally a novel approach for optical RF SIC by using phase modulation and optical sideband filtering. After the signal is phase modulated onto the optical carrier, the left sideband of the interfered path and the right sideband of the reference path are filtered by the optical filter. The remaining two sidebands satisfy the opposite phase conditions. We adjust the time delay and the amplitude of the reference signal in the optical domain so that the interference signal is cancelled and the single of interest is recovered. Avoiding the complicated bias voltage control as used in intensity modulation [6], [13], the proposed scheme is greatly simplified. In addition the operational frequency range can be extended with the alignment of amplitude and delay time in the optical domain. The depth of RF self-interference cancellation at different bandwidths was measured and the factors affecting the cancellation depth were analyzed, including time delay deviation, amplitude deviation, and phase deviation. At last, the full-duplex communication by using the optical SIC approach was investigated.

2. SYSTEM STRUCTURE AND PRINCIPLE

The schematic of the proposed optical RF SIC system is shown in Figure 1. Two lasers with different wavelengths of λ1 and λ2 are sent to two phase modulators PM1 and PM2, respectively. The received RF signal s(t)+i(t) from the receiver antenna, where s(t) is signal of interest and i(t) is interference signal, is modulated on the light wave of λ1 via PM1. The tapped RF signal r(t) from the transmitter (Tx), as the reference signal, is modulated on the light wave of λ2 via PM2. The insets (A) and (B) in Figure 1 show the spectra of the phase-modulated optical signals output from PM1 and PM2. It can be seen that the sidebands of the phase-modulated optical signals have the inherent out of phase relationship, namely, there is a π phase difference between the right sideband and the left sideband. Through a VOA and a TODL, the phase-modulated signal in the lower path is combined with the phase-modulated signal in the upper path were fed to an OF. The left sidebands of the phase-modulated optical signals in the upper path and the right sideband of the phase-modulated optical signal are filtered out, generating the singles of the single sideband signal with carrier (SSB+C), as shown in the inset (C) in Figure 1. After being filtered by the OF, the optical signals are input to the PD, upon which the electrical signals are converted and the interference signal is cancelled by the reference signal.

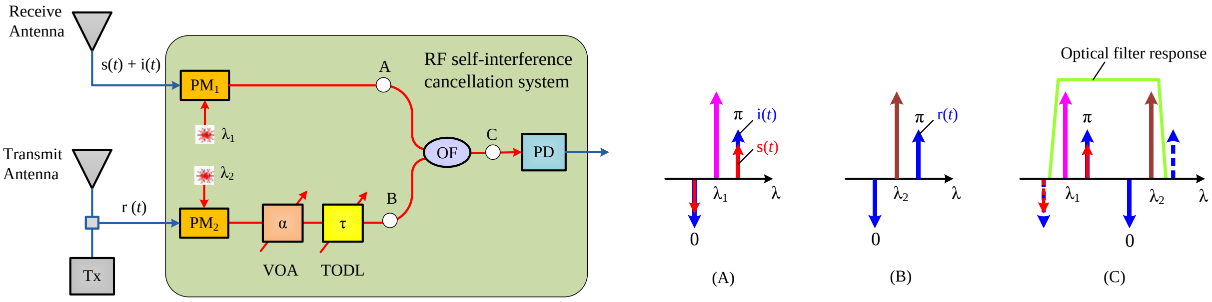

Figure 1. The schematic of the proposed optical RF SIC system. PM, phase modulator; VOA, variable optical attenuator; TODL, tunable optical delay line; OF, optical filter; PD, photodetector; Tx, transmitter. The insets show the spectra of the phase-modulated optical signals before (A and B) and after (C) the OF.

3. EXPERIMENT RESULTS

An experiment based on the setup shown in Figure 2 is performed. The RF signal from a signal generator (SG1, Agilent E8257D) is used as the signal of interest $s(t)$. The RF signal from a second signal generator (SG2, Agilent E8267D) is split to two parts by an electronic 3dB splitter. One part is input to PM$_2$ (EO Space, V_π=4V, 40 GHz) as the reference signal $r(t)$ and the other part is used as the interference signal $i(t)$. The RF signal $s(t)$ from SG1 and the RF signal $i(t)$ split from SG2 are combined as the received signals $s(t)+i(t)$ via an electronic 3dB combiner, and are input to PM$_1$ (EO Space, V_π=4V, 40 GHz). A distributed feedback laser diode (DFB-LD, Emcore-1772) with a wavelength of λ_1=1549.9 nm and a output power of 13 dBm, and a tunable laser (NKT, DK-3460) with a wavelength of λ_2=1549.5 nm and a output power of 13 dBm are used as the light sources in the upper path and the lower path, respectively. Two phase modulators (PM1 and PM2) implement the E/O phase modulation of the received RF signal $s(t)+i(t)$ and the reference RF signal $r(t)$, respectively. After a VOA and a TODL, both of the phase-modulated optical signal in the lower path and the upper path were fed into the OF by which the left sideband of the received RF modulated optical signal and the right sideband of the reference RF modulated optical signal are filtered out. The spectra before and after filtering were measured with a spectrometer (ANDO AQ6317C) and the SSB+C signals are achieved by the OF. Therefore, the RF signals can be recovered by the O/E conversion from the SSB+C optical signals upon the PD (Miteq SCMR-10M18G). The detected RF signals are measured with an electrical spectrum analyzer (ESA, Agilent E4440A). A vector network analyzers (Keysight Technologies N5225B) was used to measure the cancellation performance and the response for each link.

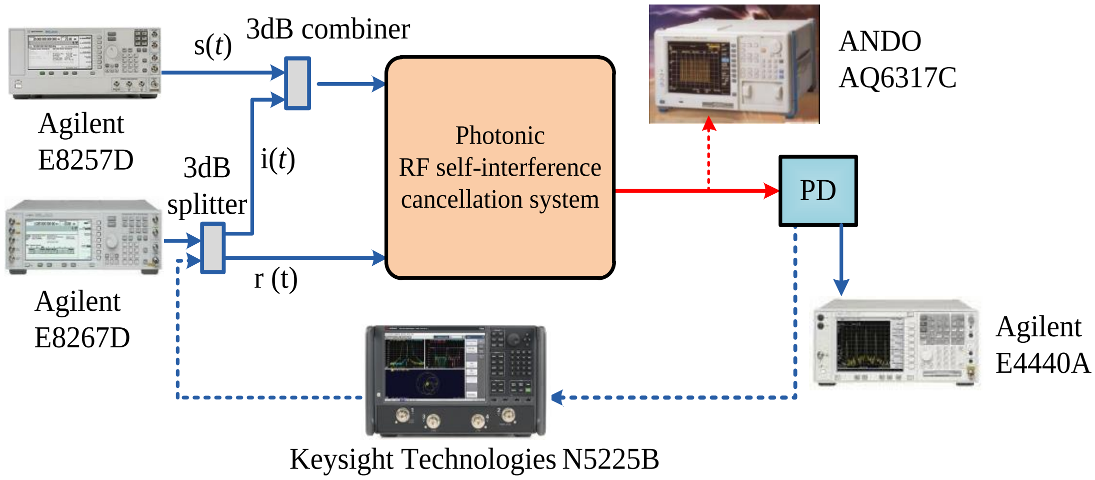

Figure 2. The experiment setup to demonstrate the photonic RF SIC.

In order to investigate the cancellation performance for RF signal with a certain bandwidth, the additive white Gaussian noise (AWGN) with a bandwidth of 50 MHz and a power of 10 dBm is modulated on the RF signal at 6 GHz, from SG2. A 6 GHz signal with the same bandwidth from SG1 is used as the signal of interest. With the laser source of λ_2 being turned off, a strong interference signal is observed in the electrical spectrum as shown the red curve in Figure 3. Then, by tuning on the laser source of λ_2, the 50MHz bandwidth interference signal is suppressed greatly with a cancellation depth as high as 32 dB and the desired 6 GHz signal is maintained, as shown the black curve in Figure 3. The cancellation performance for 16 GHz RF signal with 50 MHz bandwidth is also investigated and the cancellation depth of 28 dB is obtained.

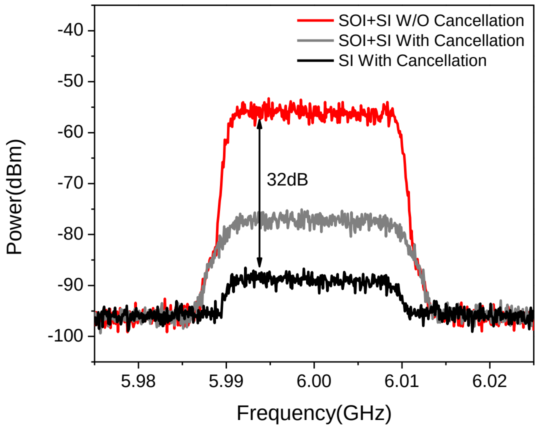

Figure 3. The measured RF spectra with and without SIC at bandwidth of 50MHz (f_{RF}=6 GHz).

To further characterize the performance of the RF SIC, a vector network analyzer was used to test the cancellation depth of the system at a larger bandwidth. The measured results over a bandwidth of 200 MHz are shown in Figure 4. The measured amplitude response before and after the interference cancellation are indicated by a red and black lines, respectively. From Figure 4, it can be seen that the cancellation depth of about 20.2 dB over a bandwidth of 200MHz is achieved. There are some ripples of the amplitude after the interference cancellation. It is due to the different phase mismatch values and amplitude mismatch values over a wide bandwidth and will be discussed in the next section.

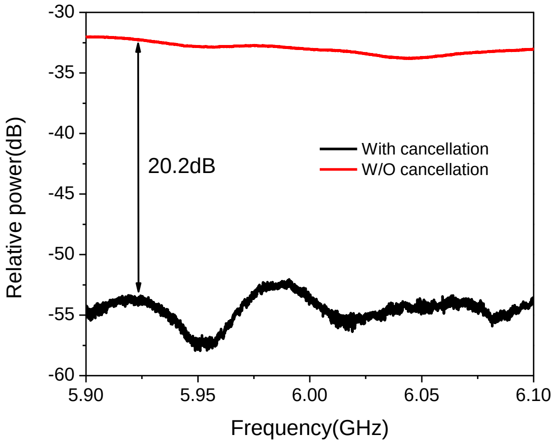

Figure 4. The measured RF spectra with and without photonic RF SIC over a bandwidth of 200 MHz.

4. ANALYSIS AND DISCUSSION

Here we give an analysis and explanation of the above experimental results. There are three main factors affecting the cancellation depth of the photonic RF SIC, which are the time delay matching, amplitude matching and phase matching between the upper and lower channels. The phase response of the two channels is scanned over a range of 1 GHz at the central frequency of 6 GHz by a vector network analyzer. The phase difference between the two phase-modulated optical signal paths is given in Figure 5, which floats up and down around 180 degrees. It is proven that out of phase relationship between the upper and lower paths is realized. It can be seen that there is a phase deviation of 3° over the bandwidth of 200MHz at the central frequency of 6 GHz. Therefore, it can be understood that there are some ripples of the amplitude after the interference cancellation as shown in Figure 4.

The amplitude response of the upper and lower paths was also measured. The amplitude difference between the upper and lower paths is shown in Figure 6. It can be seen that there is about of 2 dB amplitude difference over the bandwidth of 200 MHz. The amplitude response difference is an important factor affecting the cancellation performance of the photonic RF SIC system.

According to the above analysis results, in the case of consistent time delay matching, the cancellation depth at the bandwidth of 200MHz was 11.1dB higher than that at 1GHz, which is mainly caused by amplitude mismatch and phase mismatch. Therefore, the narrower the bandwidth, the smaller the amplitude mismatch value and the phase mismatch value under a certain bandwidth, and the greater the cancellation depth.

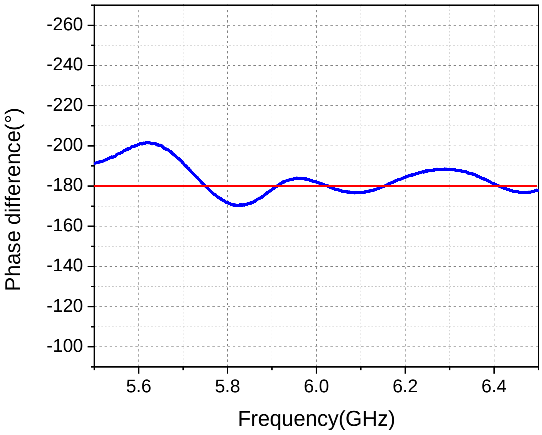

Figure 5. Phase response difference between the lower path and the upper paths.

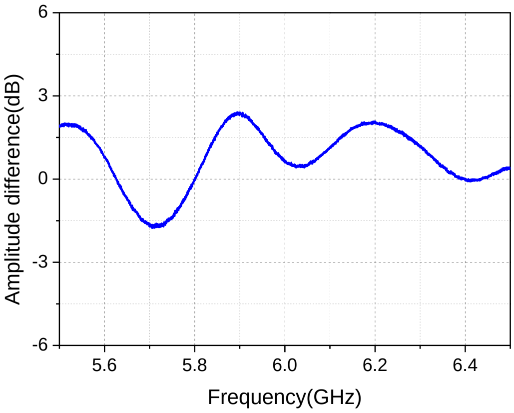

Figure 6. Amplitude response difference between the lower path and the upper paths

Finally, the full-duplex communication based on the photonic RF SIC system was investigated. The signal of interest is digitally modulated by 16QAM. The carrier frequency of 6 GHz is utilized in the full-duplex communication experiment due to current signal generator in our lab. The 6 GHz signal with a bandwidth of 20MHz and a power of -14 dBm from SG1 is used as the signal of interest. The AWGN signal with a bandwidth of 20MHz is modulated on the RF signal (10 dBm) from SG2, which is used as the interference signal. The constellation diagrams of the recovered signal without and with the photonic enabled RF SIC system are measured. In the absence of photonic RF SIC, the signal of interest is buried by the interference noise and the constellation is chaotic. By using the photonic RF SIC system, the single of interest is recovered well with EVM of 11.58%. The experimental result demonstrates the feasibility of the photonic enabled RF SIC scheme for full-duplex communication.

5. CONCLUSION

The method of photonic self-interference cancellation based on phase modulation and optical single sideband filtering has been presented. It avoids the bias voltage control as required in intensity modulation and greatly simplifies the photonic RF SIC system. The depth of self-interference cancellation over different bandwidths was measured, and the experimental results were discussed. The factors affecting the cancellation depth of the photonic RF SIC system were analyzed, which gives the direction for further improving the system performance. Finally, the performance of full-duplex communication based on the photonic RF SIC system was investigated for RF signals with certain bandwidth.

In the following work, it is necessary to achieve more ideal matching conditions between the amplitude response and the phase response of the upper and lower channels, which can substantially improve the self-interference cancellation depth of the system. In addition, the adaptive controlling method is essential to tune the reference signal for the real application scenario. Furthermore, in order to increase the integration capacity of the proposed photonic RF self-interference cancellation scheme, the silicon photonic integrated chip is being designed and fabricated, and the result will be reported in future.

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