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Ultrawideband optical cancellation of RF interference with phase change

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Abstract: This work proposes a novel approach to perform optical cancellation of RF interference with any constant phase change, based on polarization-modulator-based microwave photonic phase shifters. Preliminary results validate the proposed scheme and achieve a 30-dB cancellation depth over 9.5 GHz. The frequency independent microwave photonic phase shifters also allow for wide frequency range tunability towards 30 GHz, and recovery of a signal from a wideband interferer. The experimental results are limited by the imperfection of the electrical components. The proposed cancellation scheme might not only be applicable for WLANs based on standards such as IEEE 802.11ad and 802.11aj, but also provide a straight forward solution to the multipath effect.

OCIS codes: (350.4010) Microwaves; (050.5080) Phase shift; (120.5700) Reflection.

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1. Introduction

Self-interference cancellation (SIC) paves the road to full-duplexing, which doubles the efficiency of RF spectrum by simultaneously transmitting and receiving signals on the same frequency. Therefore it has been considered as one of the key technologies in the applications of 5G and future wireless communication [1]. In SIC, the received corrupted signal consists of intended signal of interest (SOI) and a known interferer, which is orders of magnitude stronger than the SOI and of the same frequency band. The recovery of the SOI can be achieved by introducing an inverted replica of the interferer.

The SIC technologies have been explored by means of both electronics and photonics approaches [2–6]. On one hand, both the approaches are on the same track of system integration to improve the practicability, effectiveness and reliability. On the other hand,

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photonics-based SIC solutions demonstrate an inherent figure of merit for promoting the working frequency as well as the bandwidth from MHz to GHz, which may result in a significant expansion of the potential applications.

However, these photonics-based techniques had only focused on the introduction of a fixed π-phase shift to the cancellation signal apart from keeping its amplitude and time delay matched to the interferer, therefore had not taken any phase change of the interference signal induced by reflections at the interfaces between different lossy materials into account. When a uniform plane wave is incident on a planar interface formed by lossy media, the reflection coefficients are given by the Fresnel equations, which results in a phase change depending on the material properties, incident angle and frequency. In reality, these phase changes could be any value between 0° and 180° but not equal to 0° or 180°, hence they are not able to be compensated by optical tunable delay line (OTDL) or modulation schemes for RF signals with certain bandwidth. An innovative phase insensitive approach based on the amplitude control of an interference signal has been reported, and the interference mitigation operating over 12 GHz of bandwidth with 32 dB of suppression has been demonstrated [7]. However, an automatic gain control stage is required to maintain the null condition and the tradeoff of an 8-dB degradation of the small signal response may not be acceptable in some applications. In addition to signal cancellation, photonics-based signal isolation scheme has also been used to achieve the ultrawideband suppression such that 30-dB over 17.5 GHz and 40-dB over 10 GHz has been obtained [8].

In this paper, we report a photonics-based interference cancellation scheme which employs microwave photonic phase shifters to compensate for the phase changes of the interference signals. A proof-of-concept experiment is carried out and 30-dB cancellation depth is achieved across 9.5 GHz. The tunability of frequency range towards 30 GHz is also demonstrated, limited only by the non-ideality of the electrical components employed in the system. The signal recovery capability of the proposed scheme is also verified, which otherwise is unable to be done with only amplitude and time delay control. In addition, the proposed scheme facilitates multipath interference cancellation by the implementation of a parallel set of microwave photonic phase shifters at the compensation branch with a shared laser source, a polarization modulator (PolM) and an optical bandpass filter (OBPF).

2. Operation principle

As mentioned above, the phase change at interference signal reflection will result in a phase mismatch deviated from 180° and severely degrade the cancellation performance such that a 30 dB degradation would be expected given a 2° phase error, based on [9]

$$D = -10\lg(1 + 10^{\frac{\Delta\alpha}{10}} - 2\cdot 10^{\frac{\Delta\alpha}{20}}\cdot\cos\Delta\varphi) \tag{1}$$

where D is the cancellation depth, $\Delta\alpha$ and $\Delta\varphi$ are the amplitude and phase error respectively.

To mitigate the degradation of cancellation depth as the result of phase errors induced by phase changes at signal reflections, we propose a novel RF interference cancellation scheme based on microwave photonic phase shifters. Figure 1 shows the schematic diagram of the proposed optical RF interference cancellation system. A broadband interference signal $n(t)$, which is already known to the users, as well as its multipath responses are received by a PolM in the upper branch. The responses represent not only time delayed and attenuated, but also phase shifted replicas of $n(t)$. The PolM, together with two polarization controllers (PCs) and a polarizer (Pol), is equivalent to an intensity modulator [6]. The cancellation branches consist of a PolM, an OBPF, a coupler, and a set of attention and delay components. The compensation of phase shifts at multipath reflections of the upper branch is implemented by a set of tunable and wideband microwave photonic phase shifters based on shared optical single-sideband (OSSB) polarization modulation along with PCs and Pols [10]. Besides, a single-mode-to-multimode (SM-MM) combiner is employed before a photodetector (PD) to avoid the optical interference noise at the output. In order to achieve destructive interference, the π-phase mismatch must be introduced between the upper interference branch and the lower compensation branches. This can be realized by adjusting PCs of the microwave phase shifters.

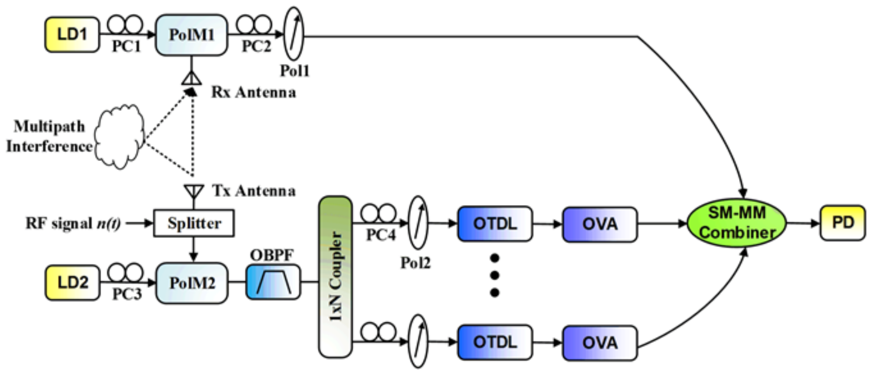

Fig. 1. Schematic diagram of the proposed photonics-based RF cancellation system. LD: laser diode; PC: polarization controller; PolM: polarization modulator; EPS: electrical phase shifter; OBPF: optical bandpass filter; Pol: polarizer; OTDL: optical tunable delay line; OVA: optical variable attenuator; PD: photodetector.

3. Experiment and results

A proof-of-concept experiment is carried out and the result is shown in Fig. 2. Simplifications are made, including a 90° electrical hybrid to induce a constant wideband RF phase change at the upper interference branch, and a single-tap cancellation branch to compensate for the wideband 90° phase change and achieve wideband cancellation.

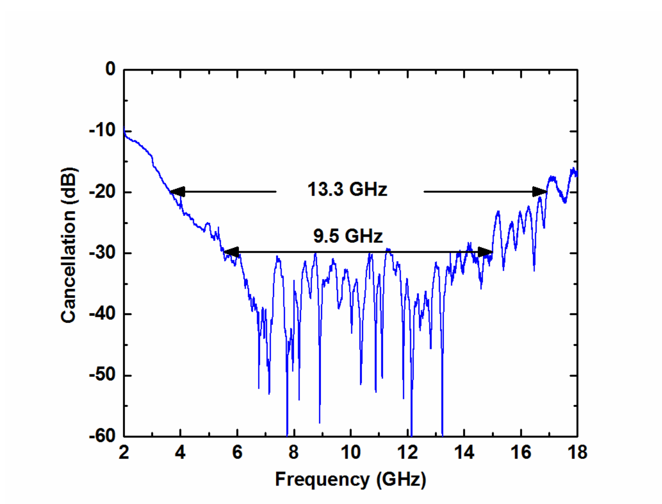

Fig. 2. The measured wideband cancellation based on microwave photonic phase shifter. The lines with arrows mark the 20-dB and 30-dB cancellation bandwidth.

Two optical carriers at 1550 nm and 1552 nm are modulated by a RF signal (2-18 GHz), which is determined by the bandwidth of the hybrid. A tunable OBPF (Yenista XTM-50) with an edge slope of more than 500 dB/nm and a top flatness of 0.2 dB is incorporated to achieve the OSSB modulation. The spectra of output signals from the PD which has a bandwidth of 57 GHz are observed by a vector network analyzer (VNA). The measured optimal

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cancellation exhibits a 20-dB cancellation over 13.3 GHz and a 30-dB cancellation over 9.5 GHz.

The corresponding frequency dependent responses of both amplitude and phase mismatches are illustrated in Fig. 3. In order to achieve an ideal destructive interference, the 0-dB amplitude mismatch and the π-phase mismatch are required for each frequency. As can be seen, the amplitude mismatch exceeds 0.5 dB below 5.5 GHz, which is due to the insufficient sideband suppression in the OBPF, and gives rise to < 30 dB cancellation below 5.5 GHz in Fig. 2. On the other hand, microwave photonic phase shifters exhibit a much flatter phase response within 10-40 GHz [10], therefore, the cancellation degradation at higher frequencies (> 15GHz) can be attributed not only to a larger amplitude mismatch, but also to a deteriorated phase match induced by the non-ideal phase shift of the 90° electrical hybrid, as illustrated in the inset of Fig. 3.

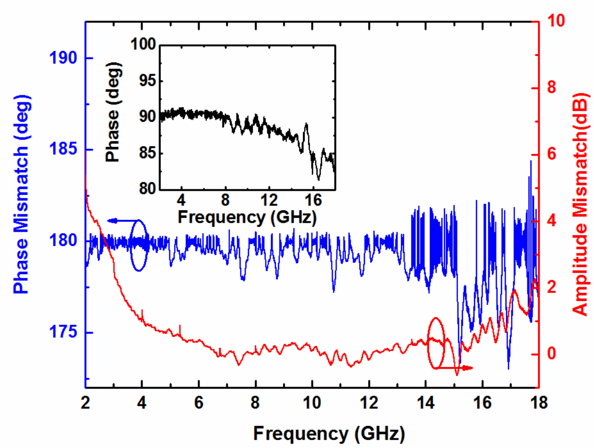

Fig. 3. The measured amplitude and phase mismatches between interference branch and the compensation branch. Inset shows the phase response of the 90° electrical hybrid which is used to imitate the environment introduced phase change.

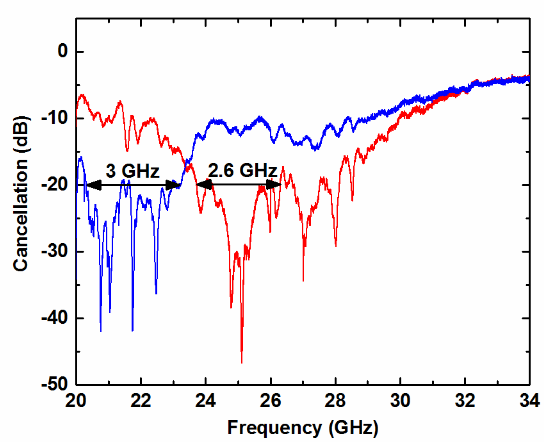

Fig. 4. RF cancellation at different central frequencies, manipulated by the microwave photonic phase shifter.

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To further explore the tunability of the system over a wide frequency range, another 90° electrical hybrid (20-34 GHz) is employed in the setup with an even worse phase response stability (particularly at frequencies above 30 GHz). A frequency tunable cancellation is performed with smaller bandwidth by simply adjusting the PC of the microwave phase shifter thanks to its flat and tunable phase control ability. With proper manual control of the microwave photonic phase shifter, a 20-dB cancellation can be achieved either at the central frequency of 22 GHz with a bandwidth of 3 GHz or at 25 GHz with 2.6 GHz bandwidth, as shown in Fig. 4.

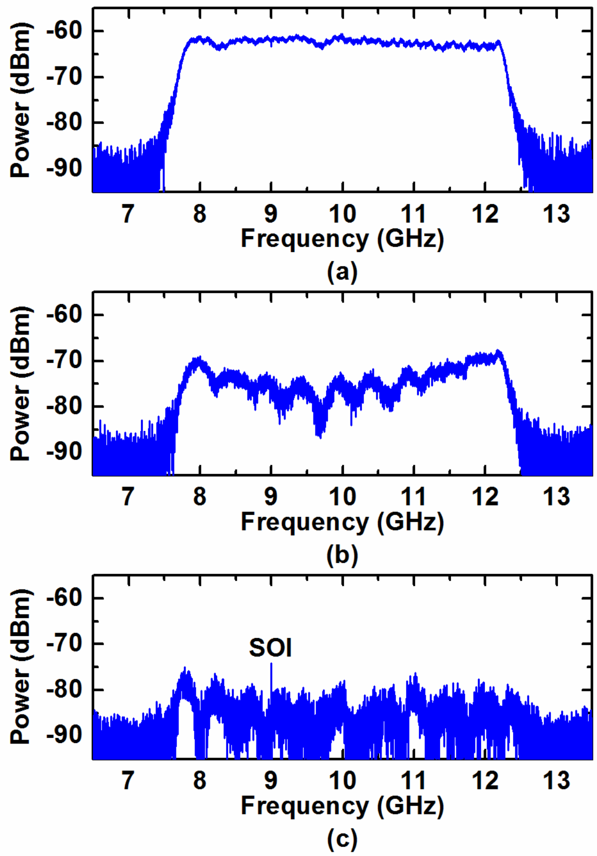

Fig. 5. Measured RF spectra of the received signal (a) before cancellation, (b) after amplitude and delay-controlled cancellation and (c) after complete cancellation including phase control.

Figure 5 shows the in-band signal of interest (SOI) recovery performance of the proposed RF cancellation system. In a co-site interference scenario, an unknown receiving signal as the weak SOI, is typically masked by a strong wideband interference signal. In the case of our experimental demonstration, a 9 GHz single-tone signal with a receiving power of −75 dBm is implemented as the weak SOI, and a 15-dB stronger interferer across a bandwidth of 4 GHz centered at 10 GHz serves as the interfering signal, which is imitated by the swept source of a VNA. As can be seen in Fig. 5(a), the SOI is completely buried in the interfering signal and is unable to be filtered out without any cancellation implementation. By optimizing the amplitude and delay mismatches between the interference and compensation branches, a RF cancellation is achieved as shown in Fig. 5(b). However, the SOI is still unable to be recovered in the corrupted signal after cancellation due to the wideband constant phase change of 90°. In fact, a similar cancellation performance can be obtained for any constant

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phase change larger than 30°. The resultant signal after a complete cancellation enabling a wideband microwave photonic phase shift in addition to the amplitude and delay control is presented in Fig. 5(c), inside which the SOI is now recovered and clearly seen in the RF spectrum.

4. Discussion and conclusion

The experimental demonstration represents a rather simple scenario of the proposed conceptual scheme as shown in Fig. 1, e.g., a single path and electrical hybrids are employed to imitate the reflection induced phase changes, the power fading effect has not taken into consideration which the realistic wireless channels may suffer from. Our point still stands given the fact that the real wireless environments do more than just attenuate and delay a signal, only a complete signal manipulation of amplitude, time delay as well as phase gives access to the ultimate cancellation performance. The implementation of PolM-based microwave photonic phase shifters offers a way to frequency independent phase control to achieve the destructive interference with an enormous frequency tunable range, and makes the proposed scheme useful for applications such as WLAN system operating at 45 GHz band (IEEE 802.11aj) or 60 GHz band (IEEE 802.11ad).

As already mentioned, the reflection induced phase change varies as function of material properties, working frequency and incident angle. In the proposed cancellation scheme, we make the assumption of a constant phase change over a certain bandwidth, but it is only true for certain incident angle range within limited bandwidth determined by the Fresnel equations. Therefore, the cancellation performance would be limited by these more complex frequency and/or incident angle responses. This is actually imitated by the imperfection of the electrical hybrids, the fluctuations of whose phase responses result in the degradation of the cancellation performance, as manifested in both Figs. 2 and 3.

In conclusion, we have reported a photonics-based RF cancellation scheme to compensate for wideband phase changes by using frequency independent microwave photonic phase shifters. Preliminary results exhibit a 30-dB cancellation depth over a bandwidth of 9.5 GHz. The tunability of frequency range towards 30 GHz is also demonstrated, limited only by the characteristics of the electrical components employed in the system. The signal recovery capability of the proposed scheme is also verified, which is otherwise unachievable by controlling the amplitude and time delay match only. The photonics-based cancellation scheme allows for a straight forward solution to the multipath effect with a laser source, a PolM and an OBPF shared by a parallel set of microwave photonic phase shifters.

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