Fast Dynamic In-band RF Self-Interference Cancellation for Enabling Efficient Spectral Usage

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Abstract: A photonic system capable of cancelling fast changing co-channel wideband RF self-interference is designed and demonstrated, providing a potential solution to RF spectral scarcity and full-duplex transmission in wideband emerging wireless systems.
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1. Introduction

"It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results." – Andrea Goldsmith, Wireless Communications [1]. The above quote well represents the long lasting issue in wireless system that the same frequency channel can only be operated in half duplex mode, where either transmit or receive can only be done at one time, but not simultaneously. Currently, LTE frequency-division duplex today uses two separate channels for full duplex, one for uplink and one for downlink. This is not an effective solution considering the over-crowding issue in RF spectrum and the dramatically increasing usage of wireless devices.

In-band full duplexing enables a single channel to be utilized for transmission and reception at the same time, essentially doubling the link capacity and spectral efficiency. Unfortunately, in-band duplexing is extremely challenging due to self-interference. When an antenna transmits a signal, part of the transmission signal is received by its own receiver, causing interference to the received signal of interest. Since the interfering signal is locally generated, the power is at least 100 times stronger than the remote signal of interest. Therefore, the signal of interest is completely masked by the local interfering signal in both temporal and spectral domain, even a RF bandpass filter will not be able to remove the in-band interference. This problem will continue to exist even for emerging 5G networks if the in-band interference issue is not solved.

In-band self-interference cancellation systems based on signal subtraction are very promising for removing self-interference, techniques based on RF electronics [2], digital signal processing [3], and photonics [4] are recently demonstrated. A copy of the transmission signal (interference signal) is delayed, weighted, and is subtracted from the received signal that consists of the signal of interest and the interference signal. The performance of self-interference cancellation is usually measured by two parameters: (i) cancellation bandwidth and (ii) cancellation depth. Cancellation bandwidth is determined by the matching of frequency response over a wide range of frequency, while cancellation depth is determined by the precision of the subtraction signal. A small mismatch will result in a significant degradation in cancellation performance. In self-interference, dynamic changes in channel loss and distance could be small but fast, which is unavoidable due to motion and vibration of the structure, i.e. a vehicle. In order to maintain good cancellation performance, a practical cancellation system should be dynamic and capable of fast adaptation to environmental changes.

With RF electronics and digital signal processing, it is challenging to achieve fast dynamic cancellation due to the speed and bandwidth limitation in RF electronics. One example of dynamic self-interference cancellation system is the use of both optical pump power control (fast) and current control (slow) of a semiconductor optical amplifier for signal matching and subtraction [5]. Photonics is a promising candidate for achieving fast and dynamic control of the interference cancellation system, due to its wide operation bandwidth and fast tunability. In this paper, we have designed and demonstrated a RF self-interference cancellation system that can support real time signal matching – both weight and delay, as well as signal subtraction at GHz speed.

2. Principle, Setups, and Results

The proposed dynamic in-band self-interference cancellation system is illustrated in Figure 1(a), which consists of a balan transformer for signal inversion, electroabsorption modulated laser (EML) for electrical to optical conversion, optical delay line and optical weight for time and amplitude matching, and a photodetector for converting the optical signal back into electrical domain. Our scheme utilizes a fast tunable delay based on the slow and fast light effect in semiconductor optical amplifier (SOA), while the tunable weight can be achieved using a GHz-speed $LiNbO_3$ electro-optics intensity modulator. Continuous tunable time delay up to 200 ps is obtained through controlling the optical pump power to the SOA, which is enough to compensate more than 4-cm change in RF path length due to vibration. The delay is rapidly tunable by a $LiNbO_3$ electro-optics intensity modulator with GHz modulation speed for controlling the optical pump power lauching into the SOA. In the SOA, time delay is achieved via coherent population oscillations (CPO) [6]. CPO effect is obtained through direct interference between the pump and probe light, which generates the coherent spectral hole in the SOA, resulting in a large change of refractive index and delaying/advancing of the probe signal.

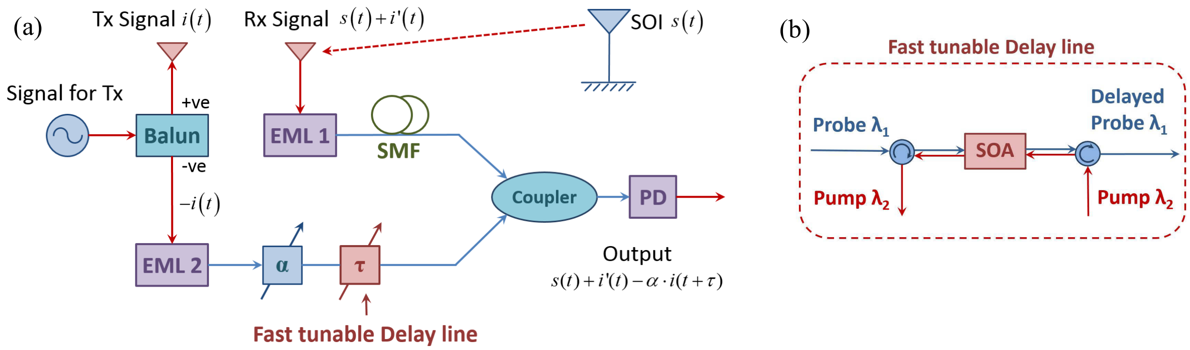

Fig. 1. (a) Schematic illustration of the fast dynamic in-band self-interference cancellation system. (b) zoom in view of the fast tunable delay line using CPO effect in a semiconductor optical amplifier.

Figure 1(a) illustrates the experimental setup of the dynamic in-band self-interference cancellation system that consists of the fast tunable optical delay as shown in Figure 1(b) on the right. The goal of the proposed cancellation system is to subtract the in-band co-site interferer i(t) from the received signal s(t)+i'(t) and recover the weak signal of interest s(t). First, the transmission signal i(t) is launched into a Balun transformer such that both inverted –i(t) and non-inverted i(t) copies of the transmission signal are obtained. The non-inverted copy of the transmission signal is launched to an antenna for transmission, while the inverted copy –i(t) is modulated onto an electro-absorption modulated laser (EML2) with an optical carrier wavelength at 1553.7 nm (subtraction branch). The modulated optical signal is then launched into the fast tunable delay line, with its architecture shown in Figure 1(b). The optical signal –i(t) is a probe signal to the SOA, that is entering the SOA via an optical circulator for temporally delay. An unmodulated CW light is launched into the SOA from the other end, which is used as the optical pump for controlling the amount of time delay. The pump and probe light are counter-propagating through the SOA to improve the isolation between pump and probe at the output. Based on CPO effect, a decrease in group velocity is resulted, i.e., a delay of the probe light is obtained. The stronger the pump power, the larger time delay is resulted in the probe signal. Upon exiting the SOA, the delayed probe is extracted via an optical circulator. The delayed probe signal is then weighted by an optical attenuator, which can be a $LiNbO_3$ electro-optics intensity modulator operating at GHz speed. On the other branch of the cancellation system (signal branch), the received signal that consists of the weak signal of interest s(t) and the strong interfering signal i(t) are converted to optical domain using an EML. The delayed and weighted signal –i(t) is combined with the optical version of the received signal s(t) + i'(t) at the optical coupler, resulting in a subtraction between the signal branch and subtraction branch, i.e. $s(t) + i'(t) - \alpha\cdot i(t-\tau)$. The combined signal is then converted back to electrical domain using a photodetector. Best cancellation can be obtained if the amplitude and phase of subtraction branch matches with that of the signal branch, i.e., $i'(t) = \alpha\cdot i(t-\tau)$ resulting in just s(t).

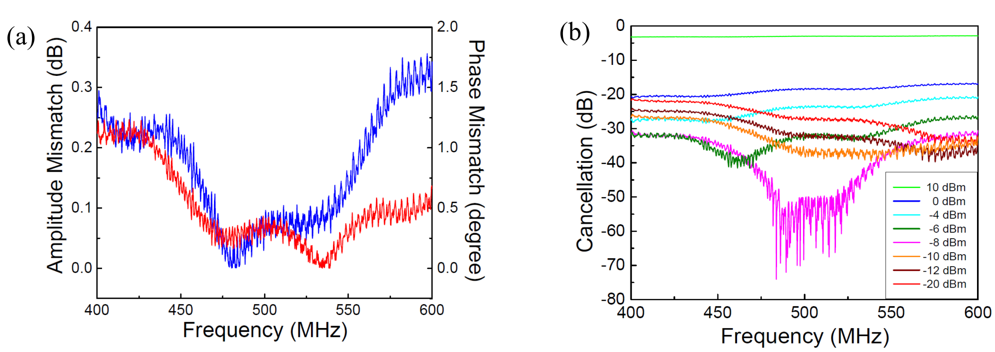

Fig. 2. (a) Phase and amplitude mismatch between the signal branch and subtraction branch. (b) Progression of the dynamic cancellation system using SOA based fast tunable delay through the control of optical pump power.

In our experiment, the Balun has a well matched frequency response between the inverted and non-inverted outputs, while both the fast tunable optical delay and the fast tunable weight have very high tuning precision for matching the received signal and subtraction signal. To characterize the ability of matching the signal branch and subtraction branch, amplitude mismatch and phase mismatch are measured using a vector network analyzer. In the experiment, we are focusing on center frequency at 500 MHz, the amplitude and phase mismatch between the two branches are shown in Figure 2(a), indicating amplitude mismatch of less than 0.2 dB and phase mismatch of less than 1.75° over a 200 MHz bandwidth is obtained. The smaller the mismatch, the better is the cancellation performance. We then study the cancellation performance using the vector network analyzer output as the "transmission signal" – for launching into the cancellation system through the Balun. By taking the difference between S21 response with and without the dynamic cancellation system, cancellation performance is characterized. Figure 2(b) shows the cancellation performance of the dynamic cancellation system, depicting how the fast tunable delay is used to dynamically converge the residual interference to its minimum. In this figure, the cancellation system is optimized at center frequency of ~500 MHz (for land mobile communication in vehicles) with a 400 MHz bandwidth, while the optical pump power is tunable between -20 dBm to 10 dBm, providing 0 – 200 ps of delay. As the time delay is tuned across the delay range, the dynamic self-interference cancellation system reaches a maximum of 50-dB cancellation depth over a 40 MHz bandwidth when pump power is at -8 dBm.

To investigate the ability of the proposed interference cancellation system for recovering the weak signal of interest from a strong in-band self-interference, a 200-MHz sweeping signal is used as the interfering signal, while a weak single tone sinusoidal signal at 500 MHz is used as the signal of interest (SOI). The interfering signal has a much wider bandwidth and is at least 20 dB stronger than the signal of interest at the SOI frequency. An RF spectrum analyzer operating at max-hold is used for the measurement. The red curve in Fig. 3 is the measured corrupted received signal, which consists of both the strong interfering signal and the weak SOI. As shown, the weak SOI is completely buried under the in-band interfering signal. To cancel out the 200-MHz wideband strong interfering signal and recover the weak SOI, the dynamic interference cancellation system is enabled. By adjusting the fast tunable delay and weight, the wideband interfering signal is significantly suppressed with residual interference at its minimum. The blue curve shows the resultant signal after cancellation, where the weak SOI is successfully recovered and is clearly shown in the RF spectrum. The out-of-band interference can now be removed using an RF bandpass filter.

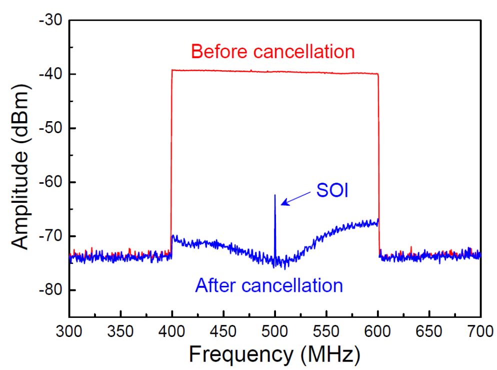

Figure 3: Measured RF spectrum of the received signal before interference cancellation (red curve) and after interference cancellation with dynamic in-band RF self-interference cancellation system (blue curve) at 500 MHz band.

3. Discussion and Conclusion

We demonstrate a fast dynamic in-band self-interference cancellation system that enables real-time response to fast channel changes between the interfering antenna and the receiving antenna. The proposed interference cancellation system could enable full-duplex communication and facilitate efficient RF spectrum usage. In our scheme, temporal matching is achieved through optical pump power control of CPO effect in SOA, while amplitude matching can be achieved using a GHz $LiNbO_3$ intensity modulator, enabling GHz-speed tuning and adaptation.

Acknowledgements

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