Optical Analog Self-Interference Cancellation Using Electro-Absorption Modulators

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***Abstract*—An optical analog self-interference cancellation system for radio-frequency communications is proposed and experimentally demonstrated. The system uses two electro-absorption modulators, an optical attenuator and delay, and a balanced photodetector to subtract strong self-interference from a corrupted received signal and recover a weak signal of interest. The system achieves > 65 dB narrowband cancellation and > 30 dB broadband cancellation across more than 40 MHz bandwidth for interference in both the 900 MHz and 2.4GHz bands. Both narrowband and broadband cancellation are frequency tunable, and can be combined with other forms of interference cancellation to achieve even higher levels of cancellation.**

***Index Terms*—Electro-absorption modulators (EAMs), microwave photonics, self-interference cancellation (SIC).**

I. Introduction

SELF-interference, or co-site interference, occurs when a receiver cannot detect signals-of-interest (SOI) from other nodes because it is collocated with a strong transmitter. The high-power transmitter overwhelms any weaker SOI at the effectively disabled receiver [1]. When the interference is in-band, even notch filters cannot selectively remove the interference. Self-interference is an increasingly common problem because of the wide proliferation of wireless devices and sensor networks. The 900 MHz and 2.4 GHz bands are particularly vulnerable to self-interference because they contain the unregulated and thus crowded WiFi (IEEE 802.11) and Bluetooth (IEEE 802.15) bands [2]. Cancelling self-interference would enable full-duplex radios, opening the door to a variety of benefits like better spectral and power efficiency, and reduced network congestion [3].

RF interference cancellation schemes range from digital cancellation, such as the SIC algorithm [4], to analog cancellation, which generates a copy of the interfering signal and subtracts it from the received signal much like noise-cancelling headphones [2]. Some groups have combined the two techniques to compound their benefits. Jain *et al.* used analog balun cancellation to obtain ~ 45 dB cancellation over 10 MHz, and added another ~ 30 dB with digital cancellation. To make the analog cancellation adaptive, however, an RF circuit is used, which introduced nonlinearities. Unfortunately, the resulting system only achieved 30 dB analog interference cancellation at -60 dBm total input power. In addition, the nonlinearities reduce digital cancellation efficiency [3].

The Achilles' heel of RF interference cancellation lies in the limitations of RF components such as lack of precision, limited bandwidth, and nonlinearity. Optics provides a potential solution, because optical components have extremely broad bandwidth, high precision, and low loss [5]. Modulating RF signals onto optical carriers and processing signals in the optical domain can bypass the limitations of RF components. In this work, we build and demonstrate an optical self-interference cancellation system using a pair of Electro-Absorption Modulators (EAMs). EAMs are semiconductor optical devices, which intensity-modulate a light wave based on an RF input. Common in fiber-optics, commercial EAMs have bandwidths exceeding 10 GHz.

Suarez *et al.* used Mach-Zehnder Modulators (MZMs) to modulate an optical carrier for interference cancellation. They achieved $\sim$ 70 dB single-tone cancellation and $\sim$ 30 dB cancellation over 100 MHz [1], [6]. While impressive, lithium niobate, the compound that nearly all commercial MZMs are fabricated from, is not scalable or suitable in photonic integrated circuits. Unlike MZMs, EAMs can be integrated with a laser on the same semiconductor substrate, making them highly compact [7]. With integrated attenuators and delays, an entire optical interference cancellation system can potentially be realized on a single semiconductor substrate.

II. System Description

The EAM interference cancellation system subtracts the known self-interference signal from the corrupted received signal. The system accepts two RF inputs: x_0, the received signal, which consists of the coupled SOI and self-interference, and x_1, a tap from the transmitting antennae (the known self-interference signal)

$$x_0(t) = s(t) + n_0(t) \quad (1)$$
$$x_1(t) = n_1(t) \quad (2)$$

where s is the SOI, n_0 is the actual interference coupled with the SOI, and n_1 is the copy of the self-interference from the transmitting antennae tap. Initially in the electrical domain, the RF signals are first modulated into the optical domain through their respective EAMs. The now-optical signals, x_0 and x_1, then

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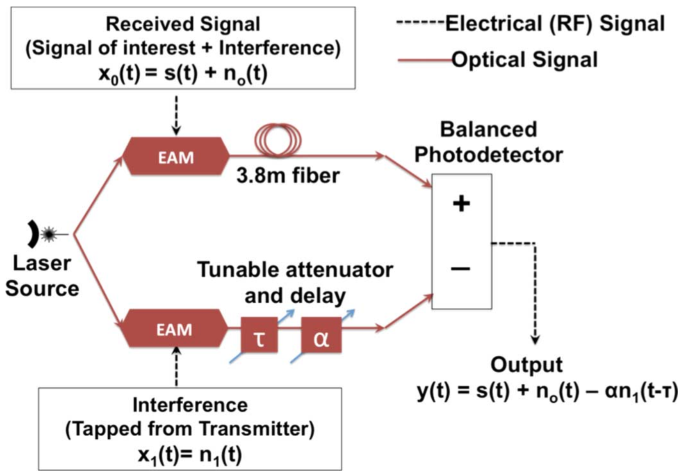

Fig. 1. Schematic of the EAM interference cancellation system.

propagate through the upper and lower branches of the system, respectively, as shown in Fig. 1.

Despite the fact that n_1 is tapped from the transmitting antennae, it does not perfectly replicate the interference at the receiver, n_0, because of channel effects; while propagating from transmitter to receiver, the interference will be, among other things, attenuated and delayed by the channel (more complex channel effects are discussed later). To replicate these effects, a voltage-controlled MEMS optical attenuator and a manually tuned optical delay line with sub-picosecond resolution are inserted into the lower branch, which processes n_1. To optimize cancellation, the attenuator and delay are manually tuned to amplitude and phase match n_1 with n_0. An additional 3.8 meters of optical fiber is spliced to the upper branch to account for coarse delays between the two branches.

After matching n_1 and n_0, x_1 is subtracted from x_0 via a balanced photodetector. A balanced photodetector converts two input optical signals into electrical signals and outputs their difference, effectively subtracting one from another. The bandwidth of this method is only limited by the photodetector bandwidth, which in this case exceeds 10 GHz. The output

$$y(t) = s(t) + (n_0(t) - \alpha n_1(t - \tau)) \tag{3}$$

where α is the applied attenuation and τ is the applied delay, has a much weaker residual interference, given by the second term in (3). The amount of cancellation depends on how well α and τ can model the channel effects. Uncompensated channel effects can be measured and the cancellation achieved by the system can be predicted by taking the Fourier transform of the second term in (3). This is shown together with the experimental results in Section III.

III. Experimental Results

To demonstrate the system's ability to cancel only the interferer while recovering the SOI, a weak, single-tone SOI 10–15 dB above the noise floor and an in-band interferer were generated by separate signal generators and coupled together for use as the received signal (x_0). This was done in both the 900 MHz and 2.4 GHz bands. The coupled interferer and SOI were injected into the upper branch EAM via an RF cable to simulate the channel, while the tapped interferer was input to the lower branch EAM. A 1551.72 nm wavelength laser was used as the optical source; each branch received 10 dBm optical power. System performance was characterized in terms of broadband and narrowband cancellation.

A. Narrowband Cancellation

For narrowband cancellation, a 0 dBm, 10 kHz bandwidth interferer with center frequency of either 915.5 MHz or 2.4 GHz was input into the EAM interference cancellation system along with a weak SOI in the same band. The optical attenuator and delay were tuned until the residual interferer power at the output of the system was at a minimum. The output of the system with and without interference cancellation is shown in Fig. 2(a) and (b) for the 900 MHz and 2.4 GHz bands, respectively. In both cases, the system reduced the interferer by > 65 dB over the entire 10 kHz bandwidth, uncovering the SOI. Only weak remnants of the interferer are visible above the noise floor after cancellation.

B. Broadband Cancellation

To measure broadband cancellation, a network analyzer was first used to measure the system frequency response before and after applying cancellation. The difference in dB was defined as cancellation. Here, no SOI was used. The experimental results, shown by the thick red curve in Fig. 3, demonstrate the extremely broadband cancellation of the system. Cancellation of about 30 dB and 25 dB was achieved across a 400 MHz bandwidth in the 900 MHz and 2.4 GHz bands, respectively. The thinner blue curve shows the simulated cancellation, which was obtained by measuring the S21 differences between the two individual branches (uncompensated channel effects) and using them in the Fourier transform of (3). As shown in Fig. 3, simulation matches the experiment well. Most applications do not span across 400 MHz, however. For example, channel bandwidth in IEEE 802.11n (WiFi) is 40 MHz. Focusing on this more relevant bandwidth, a 0 dBm signal was swept through a bandwidth of 50 MHz or 40 MHz with either a 915.5 MHz or a 2.4 GHz center frequency respectively, and used as the broadband interferer. Coupled with a weak SOI, this interferer was input into the interference cancellation system. After tuning, the results with and without applying cancellation are shown in Fig. 2(c) and (d). For the 900 MHz interferer, the system achieved ~ 55 dB cancellation over 10 MHz. Cancellation degraded as bandwidth increased, but the system still achieved ~ 40 dB cancellation over 50 MHz. For the 2.4 GHz interferer, the system achieved ~ 45 dBm cancellation over 10 MHz and ~ 30 dB over 40 MHz. In both cases, the SOI could be recovered from the interference. Additionally, thanks to the broad bandwidth of optics, only a small adjustment of attenuation and delay was required to reconfigure the system for operation between the 900 MHz and 2.4 GHz bands.

Broadband cancellation decreased with increasing bandwidth because of the inability of a single optical attenuator and delay to emulate the channel, which in this case was a set of RF cables, splitters, and combiners used to send the coupled interferer/SOI to the cancellation system. Reflections within the channel caused the ripples shown in Fig. 3, and can be considered a form of multipath. Nontrivial and dynamic channel effects can be compensated with adaptive filters, digital

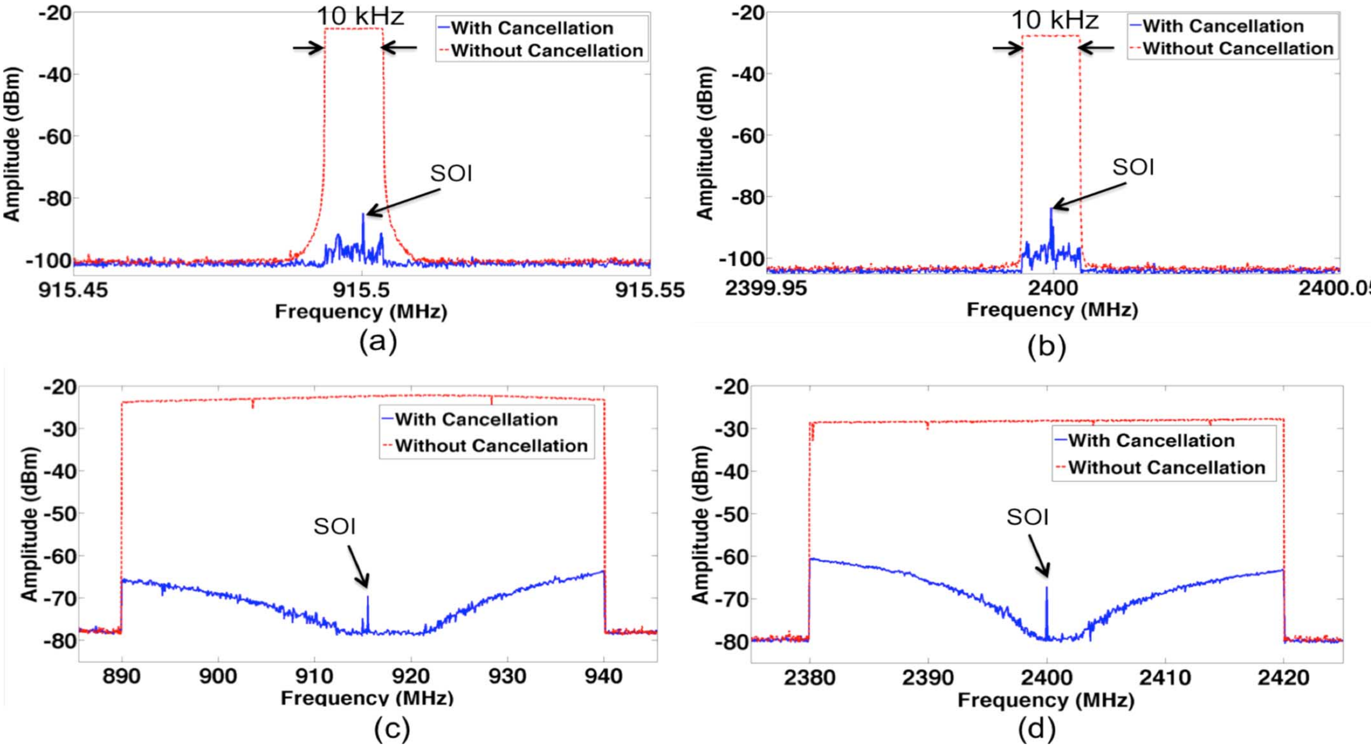

Fig. 2. Spectrum of the received signal before (dotted line) and after (solid line) applying the EAM interference cancellation system for a (a) 900 MHz narrowband interferer, (b) 2.4 GHz narrowband interferer, (c) 900 MHz broadband interferer, and (d) 2.4 GHz broadband interferer. SOI = signal of interest.

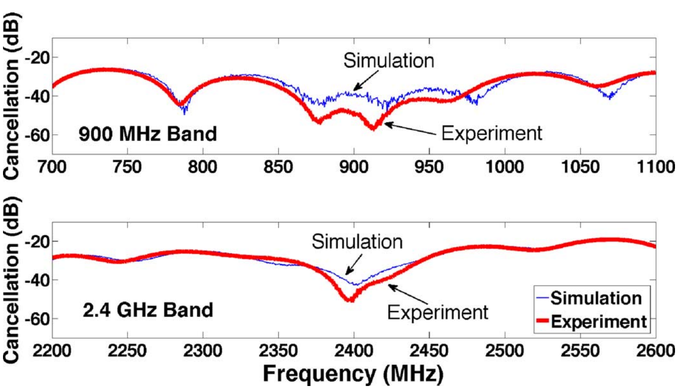

Fig. 3. Cancellation profile across 400 MHz bandwidth in both the 900 MHz and 2.4 GHz bands. Experimental results are given by the thick, red line while simulation is given by the thinner blue line.

signal processing, and RF equalization [8]. Such techniques are already being investigated in the optical domain. For example, Chang *et al.* have demonstrated broadband photonic multipath cancellation by cancelling the first few, and therefore strongest, multipath reflections [9]. Our group is currently investigating dynamic interference cancellation using an adaptive optical matched filter to match the frequency response of the channel. In field tests, the system has already successfully enabled communication on a self-jammed vehicle communication system. Future tests will be planned as improvements to the system are implemented.

IV. Conclusion

An optical system using two EAMs and a balanced photodetector was used to remove self-interference from a corrupted received signal. The system can be used to eliminate self-interference between collocated receivers and transmitters, as well as increase the receiver dynamic range over a broad bandwidth. One system can be used in both the 900 MHz and 2.4 GHz bands, and can also cancel in-band, broadband interference. The system is scalable and has potential to be integrated on a single semiconductor substrate.

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