# Wideband Optical Multipath Interference Cancellation Based on a Dispersive Element

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***Abstract*— A novel scheme is proposed for analog multipath interference cancellation based on two polarization modulators (PolMs) and a dispersive element. Multiple optical compensation branches are formed by an array of tunable lasers. By adjusting the wavelength and the optical power of each tunable laser, the delay and the magnitude of the known interference signal can be finely tuned, so that the multipath interference can be accurately reconstructed for counter-phase cancellation. The dispersion-induced RF power fading in a dispersive optical link can also be compensated because of the PolM-based intensity modulation scheme, so the best cancellation depth can be obtained at any desired frequency. Experimental result shows that the proposed system can achieve more than 44-dB cancellation depth for wideband signals.**

***Index Terms*— Co-site interference cancellation, dispersion, polarization modulator, RF photonics.**

## I. Introduction

IN WIRELESS communication systems, the receiver will take over a part of the transmitted signal directly from the transmitter if the transmit and receive antennas are close [1]. As a result, the signal-of-interest (SOI) for the receiver will be buried by the high power interference signal, which is hard to be filtered out by the filter since they are in the same frequency band. To remove the interference signal from the received signal, in the past few years electronic interference cancellation was developed, but this kind of method always suffers from narrow bandwidth, high loss and low precision time delay [1], [2]. To overcome these problems, optical interference cancellation has been proposed and becomes a very promising solution to deal with the co-site interference [3]–[6]. Generally, the optical interference cancellation is realized based on an analog incoherent subtraction method, in which the corrupted signal and the known interference signal are converted into two optical signals using either two Mach-Zehnder modulators (MZMs) [3], two electro-absorption modulators (EAMs) [7] or a dual-parallel polarization modulator (PolM) [8]. Then, after finely tuning the delay and amplitude by an optical tunable delay line (OTDL) and an optical variable attenuator (OVA), the interference signals carried by the two optical signals are made exactly out of phase with however identical magnitude. When the two optical signals are combined and detected by a photodetecor (PD), the interference signal will be removed from the corrupted signal, leaving only the SOI [3]–[9].

However, these methods have not taken into account that the interference signal might be reflected, scattered or diffracted by the surroundings in the realistic scenario, i.e. the receiver will receive multiple delayed and attenuated copies of the interference signal from the transmitter. To solve the multipath interference issue, one straight-forward and effective method is to produce multiple replicas of the interference signal with the same amount of delays and attenuations and then perform the counter-phase cancellation. Previously, Chang *et al.* proposed one such scheme with an array of OTDLs and OVAs [10]. Each set of OTDL and OVA is used to adjust the amplitude and delay of the interference signal in one path, and a single-mode to multi-mode combiner is inserted to avoid the severe beat noise which is not an easily-achievable device. On the other hand, all of the existing methods can only obtain the best cancellation depth at a certain frequency without considering the RF power fading issue caused by dispersion which is commonly existed in the optical intensity modulation systems.

In this letter, a novel scheme for optical analog multipath interference cancellation is proposed, which consists of an array of tunable lasers (TLs), two polarization modulators (PolMs), two polarizers, a dispersive element (DE) and a PD. Because of the DE, different delays can be realized by adjusting the wavelengths of the TLs, and different attenuations can be achieved by tuning the optical powers of the TLs. In addition, the dispersion-induced RF power fading in the system is removed by the PolM together with the polarizer [11], which can also provide the amplitude inversion for counter-phase cancellation.

## II. Operational Principle

Fig. 1 shows the schematic diagram of the proposed optical multipath RF interference cancellation system, which consists of $N+1$ TLs, two PolMs, two polarizers, a DE and a PD.

A wideband interference signal, represented by $n(t)$, is emitted by the transmit (Tx) antenna, which travels multiple transmission paths and received by the receive (Rx) antenna together with the SOI $s(t)$. Thus, the received RF signal at the Rx antenna can be written as $s(t) + n_0(t)$,

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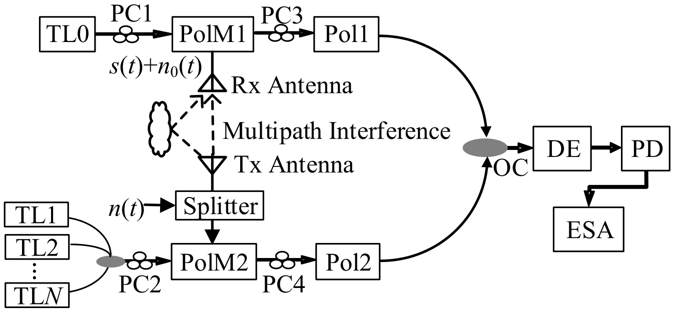


Fig. 1. Schematic diagram of the proposed optical multipath interference cancellation system. TL: Tunable Laser; PolM: Polarization Modulator; PC: Polarization Controller; Pol: Polarizer; OC: Optical Coupler; DE: Dispersion Element; PD: Photodiode; ESA: Electrical Spectrum Analyzer.

where $n_0(t) = \Sigma\alpha_i \cdot n(t-\tau_i)$, and $\alpha_i$ and $\tau_i$ $(i = 1, 2, \cdots, N)$ are the attenuation and delay related to the $i$th multipath.

The received RF signal is converted into an optical signal using a TL, a PolM and a polarizer. The PolM together with the polarizer can work as an intensity modulator [11]. To cancel the multipath interference $n_0(t)$ in the received RF signal, the interference signal $n(t)$ from the Tx antenna, which is known to the user, is tapped out and modulated on the optical carriers from $N$ TLs at a second intensity modulator formed by PolM2 and Pol2. By adjusting the DC bias of the PolMs, the two equivalent intensity modulators can be biased at the opposite quadrature transmission points [8]. The Rx branch and the compensation branch are then combined, followed by the DE and the PD. Assuming the dispersion value of the DE is $D$ (ps/nm), the relative time delay for the $i$th compensation channel can be expressed by $\tau_i' = D \cdot \Delta\lambda_i$, where $\Delta\lambda_i$ is the relative wavelength of TL$i$. In addition, the attenuation $\alpha_i$ in the $i$th compensation channel can be adjusted by tuning the output powers of TL$i$. As a result, if the wavelengths and the optical powers of the TLs are adjusted to let $\tau_i' = \tau_i$ and $\alpha_i' = \alpha_i$ $(i = 1, 2, \cdots, N)$, the multipath interference signal can be removed, leaving only the SOI.

Because a dispersive element is applied in the proposed system, the dispersion-induced RF power fading, which is a serious problem in the intensity-modulation direct-detection analog optical system, should be removed. This can be implemented by adjusting the angle between the polarization axes of the PolM and the polarizer. According to [11], the output RF power of the PolM-based dispersive link is proportional to $\eta = sin(2\alpha + 1/2(D_\omega\omega_m^2))$, where $\alpha$ is the angle between the polarization axes of the PolM and the polarizer, $D_\omega$ is the dispersion value, and $\omega_m$ is the angular frequency of the RF signal. By tuning the PC placed between the PolM and the polarizer, to let $2\alpha + 1/2(D_\omega\omega_m^2) = (2k+1)\pi/2$, the output power of the RF signal at $\omega_m$ reaches its maximal value.

Compared with the existing optical multipath interference cancellation scheme in [10], the required amplitude balance and time alignment for cancelling the interference in each multipath in the proposed scheme can be realized by adjusting the parameters of the TLs. Besides, without the need of OTDL and OVA, the proposed system is easier to be integrated, which can ensure the system's compactness.

## III. Experiment Results and Discussion

A proof-of-concept experiment based on the setup shown in Fig. 1 is performed. For simplicity, we only consider a two-path interference case. A digital phase-modulated RF signal with a bandwidth of 50 MHz centered at 3 GHz is generated by a vector signal generator (Agilent 8267D) and split into three paths with different path lengths. Two of them are combined to simulate $n_0(t)$, and the other one serves as $n(t)$. The SOI $s(t)$ is a very weak 3-GHz single-frequency signal generated by a RF signal generator (Agilent 8257D). A multichannel TL (Agilent N7714A) is used to generate three optical carriers. One of them carries the corrupted signal $s(t) + n_0(t)$, and the other two carry the known interference signal $n(t)$. The two PolMs have a bandwidth of 50 GHz and a half-wave voltage of ~3.1 V. A dispersion compensation module (TeraXion TDCMX) based on a chirped fiber Bragg grating (FBG) is used to introduce the delay. The dispersion value is fixed at 400 ps/nm, and the maximum wavelength range is about 0.4 nm, so the maximum delay variation is 160 ps, which is larger than 83 ps provided by the tunable delay line in [10]. A PD with a bandwidth of 50 GHz and a responsivity of 0.65A/W is used to perform optical-to-electrical conversion. The spectra of the output signals from the PD are observed by an electrical spectrum analyzer (ESA, Agilent E4447A).

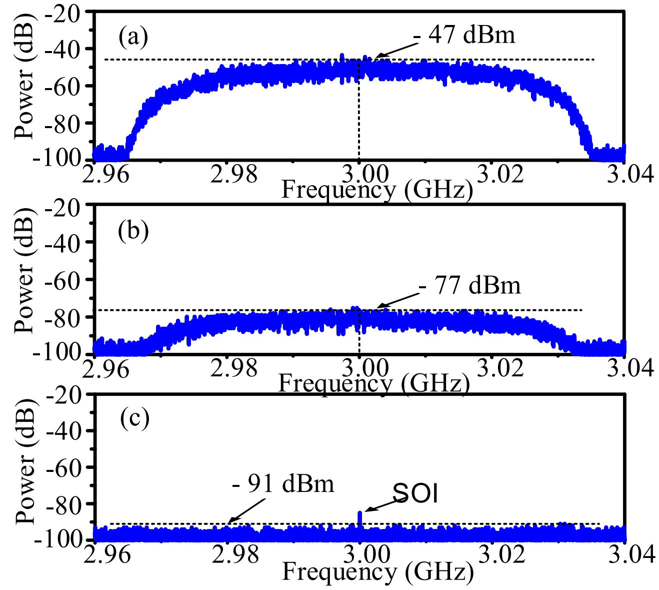


Fig. 2. Cancellation of 50-MHz multipath interference signal centered at 3 GHz (a) before cancellation, (b) single path cancellation, and (c) multipath cancellation. Resolution bandwidth of the ESA is 5.1 kHz.

Fig. 2(a) shows electrical spectrum of the output signal when the compensation branch is disconnected. As can be seen, the peak power of the output wideband corrupted signal is about −47 dBm. The SOI cannot be seen since it is totally buried by the strong multipath interference signals. Then, one TL in the compensation branch is enabled to suppress the interference signal. By carefully adjusting the attenuation and delay of $n(t)$, which is implemented by tuning the output power and wavelength of the TL, the power level of the multipath interference signal is dramatically dropped. However, as shown in Fig. 2(b), the 3-GHz SOI component is also unobservable because the residual interference signal still has a peak power of −77 dBm. In order to remove all of the interference signals, both TLs in the compensation branch are enabled. After adjusting the optical powers and wavelengths of the TLs, the power level of the multipath interference

TABLE I
PERFORMANCE COMPARISON BETWEEN DIFFERENT METHODS FOR INTERFERENCE CANCELLATION

| | Single frequency cancellation | Wideband cancellation |
|---|---|---|
| [3] | >70 dB | >30 dB@100MHz |
| [6] | 78 dB | 35 dB@25MHz |
| [7] | 65 dB | 30 dB@40MHz |
| [10] | / | 40 dB@200MHz |
| This work | >70 dB | >44 dB@50MHz |

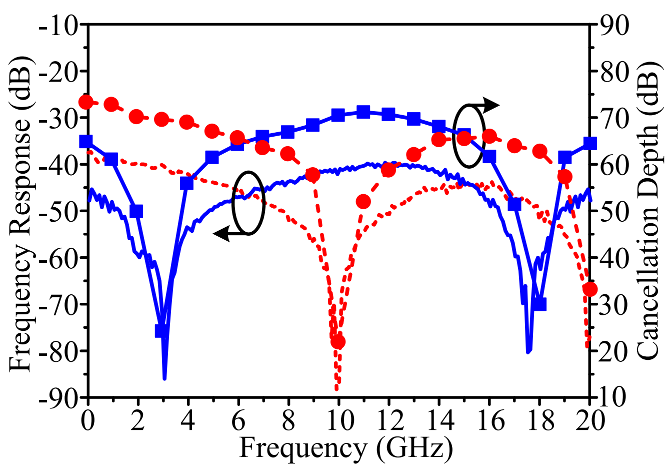


Fig. 3. Frequency responses and cancellation depths of the PolM-based links when their RF power fading points are set at 3 GHz (solid lines) and 10 GHz (dashed lines).

signal is lower than the noise floor and the SOI which has a power of about −84 dBm can be clearly observed, as shown in Fig. 2(c). Wideband multipath cancellation is therefore implemented. The cancellation depth of the wideband signal is 44 dB. Since the SOI is now above the interference signal, a narrow RF bandpass filter can be applied to further filter out the residual interference signal, making the aggregate power of the wideband interference much lower than the SOI. Table I gives the performance comparison between this work and other reported methods for interference cancellation.

Because a dispersive element is applied in the proposed system, the influence of dispersion-induced RF power fading should be investigated. To do so, we first measure the frequency response of the PolM-based link by a vector network analyzer (VNA) with a power of −5 dBm, and then adjust the parameters of the TLs to obtain the best cancellation depth at every frequency. According to [11], when adjusting the angle between the polarization axes of the PolM and the polarizer, the peak of the frequency response of the PolM-based link would be shifted. For instance, the solid line in Fig. 3 shows a typical frequency response of the PolM-based link. In that case, even we carefully adjust the parameters of the TLs, the cancellation depth at 3 GHz is lower than 25 dB (solid circle line in Fig. 3) because the SOI at 3 GHz is largely suppressed by the dispersion-induced RF power fading. To overcome this problem, one effective method is to adjust the angle between the polarization axes of the PolM and the polarizer, to shift the transmission peak of the PolM-based link to the desired frequency. The dashed line in Fig. 3 is the frequency response after the optimization of the angle between the polarization axes of the PolM and the polarizer. In this case, the cancellation depth around 3 GHz is larger than 70 dB. It should be noted that the optimization of the setting of the link is always allowed in practice because a wireless system has its pre-defined frequency.

It should be noted that only a static case of multi-path interference is considered in the experiment. In practice, the multi-path interference may be dynamically varied. To match all delays and attenuations automatically, an adaptive feedback circuit should be incorporated. In addition, just like other existing methods, the scheme in the current form cannot be used for multi-band applications, either, but multi-band interference cancellation is possible if more cancellation links with independent electro-optic modulators are added.

## IV. CONCLUSION

A novel approach for optical multipath interference cancellation was proposed and experimentally demonstrated. Experimental result shows that the cancellation depth is 44 dB for signals with a bandwidth of 50 MHz. In the proposed system, only the parameters of TLs are needed to tune both the attenuations and delays of the signals, so the multipath effect can be eliminated by adding laser sources instead of adding sets of OTDLs and OVAs with two types of controlling interfaces, which leads to a more compact scheme. In addition, the dispersion-induced RF power fading in the system can be easily compensated by adjusting the parameters of the PolM-based link. This scheme may find applications in modern radars and wireless communications.

## REFERENCES

[1] A. Raghavan, E. Gebara, E. M. Tentzeris, and J. Laskar, "Analysis and design of an interference canceller for collocated radios," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 11, pp. 3498–3508, Nov. 2005.

[2] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Commun. Mag.*, vol. 47, no. 4, pp. 74–81, Apr. 2009.

[3] J. Suarez, K. Kravtsov, and P. R. Prucnal, "Incoherent method of optical interference cancellation for radio-frequency communications," *IEEE J. Quantum Electron.*, vol. 45, no. 4, pp. 402–408, Apr. 2009.

[4] M. Alemohammad, D. Novak, and R. Waterhouse, "Photonic signal cancellation for co-site interference mitigation," in *Proc. Military Commun. Conf.*, Nov. 2011, pp. 2142–2146.

[5] E. J. Adles, T. R. Clark, M. L. Dennis, A. M. Karim, and T. P. McKenna, "Interferer cancellation in coherent optical RF receivers via optical phase modulation," in *Proc. IEEE Photon. Conf.*, Sep. 2012, pp. 218–219.

[6] V. J. Urick, J. F. Diehl, C. E. Sunderman, J. D. McKinney, and K. J. Williams, "An optical technique for radio frequency interference mitigation," *IEEE Photon. Technol. Lett.*, vol. 27, no. 12, pp. 1333–1336, Jun. 15, 2015.

[7] M. P. Chang, M. Fok, A. Hofmaier, and P. R. Prucnal, "Optical analog self-interference cancellation using electro-absorption modulators," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 2, pp. 99–101, Feb. 2013.

[8] M. Huang, D. Zhu, and S. Pan, "Optical RF interference cancellation based on a dual-parallel polarization modulator," in *Proc. Asia Commun. Photon. Conf.*, 2014, paper ATh1F.6.

[9] J. Suarez and P. R. Prucnal, "Instantaneous bandwidth of counter-phase optical interference cancellation for RF communications," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 9, pp. 507–509, Sep. 2011.

[10] J. Chang and P. R. Prucnal, "A novel analog photonic method for broadband multipath interference cancellation," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 7, pp. 377–379, Jul. 2013.

[11] H. Zhang, S. Pan, M. Huang, and X. Chen, "Polarization-modulated analog photonic link with compensation of the dispersion-induced power fading," *Opt. Lett.*, vol. 37, no. 5, pp. 866–868, Mar. 2012.