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Real-time photonic sampling with improved signal-to-noise and distortion ratio using polarization-dependent modulators

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ABSTRACT

A real-time photonic sampling structure with effective nonlinearity suppression and excellent signal-to-noise ratio (SNR) performance is proposed. The key points of this scheme are the polarization-dependent modulators (P-DMZMs) and the sagnac loop structure. Thanks to the polarization sensitive characteristic of P-DMZMs, the differences between transfer functions of the fundamental signal and the distortion become visible. Meanwhile, the selection of specific biases in P-DMZMs is helpful to achieve a preferable linearized performance with a low noise level for real-time photonic sampling. Compared with the quadrature-biased scheme, the proposed scheme is capable of valid nonlinearity suppression and is able to provide a better SNR performance even in a large frequency range. The proposed scheme is proved to be effective and easily implemented for real time photonic applications.

1. Introduction

Analog-to-digital converters (ADCs) are essential building blocks in modern electronic systems, which form the critical link between front-end analog transducers and back-end digital signal processing (DSP). In the past decades, although great progress has been made in electronic ADCs, the ADC performance still cannot meet the rapidly increasing requirement of various applications such as military systems, software defined radio receivers, and broadband communication systems [1]. The dominant limitation of the electronic ADCs is the sharply-decreased resolution at high sampling rates, which is mainly restrained by aperture jitter and comparator ambiguity.

Photonic ADCs are recognized as the promising candidates to provide superior performance over its electronic counterparts. Especially, the photonic sampled ADC, which is composed of photonic sampling and electronic quantization, is able to achieve a broadband sampling with an ultra-low time jitter, and contributes to overcome the dominant limitation of the electronic ADCs [2]. Photonic sampling is generally achieved by employing a broadband Mach–Zehnder modulator (MZM) to modulate input analog signal onto ultra-short optical pulse train from an ultra-stable mode-locked laser. Its performance such as nonlinear distortion and signal-to-noise ratio (SNR) has a great influence on the effective number of bit (ENOB) of the ADC, which is generally characterized by signal-to-noise and distortion ratio (SINAD). In order to maximize the linearity of the photonic sampling, the MZM is usually biased at its quadrature point, which however is only effective for a small modulation depth. As is well known, a large modulation depth is favorable for increasing the SNR, but it will also deteriorate the linearity of the photonic sampling due to the increase of the third-order distortion. Hence, linearization technique is essential to increase the SINAD, and finally guarantees a large ENOB.

To date, various technologies have been proposed for the sake of linearization, which can be categorized into three types. The first one is based on pure digital signal processing (DSP), in which the undesired harmonic and intermodulation distortions introduced by a MZM are suppressed through digital pre- or post-distortion compensation [3–7]. The second type is realized via a dual output MZM, where the complementary outputs and the sine-shape transfer function nature of a MZM are exploited to restrain the distortion through differential and arcsine operation in the digital domain [8,9]. However, the aforementioned two types of technologies are both offline processing, which are not able to correct distortions in real time. The third type, which employs various electrooptic modulators to realize online linearization, attracts intensive interest in recent years.

Compared with the former two types, the third one is considered as a real-time processing. So far, various real-time linearization technologies

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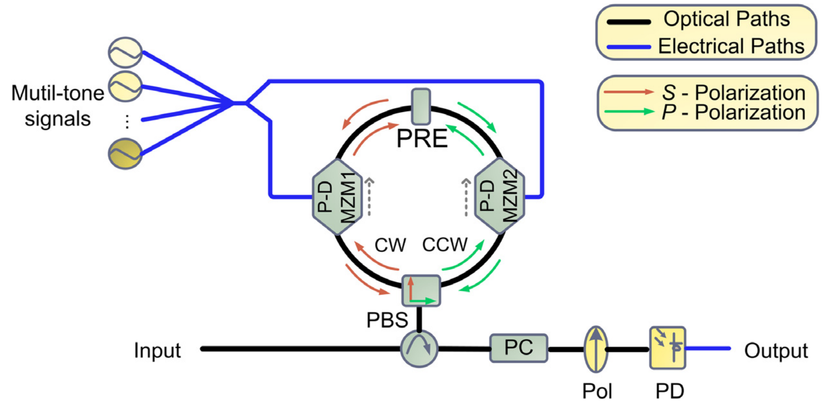

Fig. 1. The proposed photonic sampling structure based on a sagnac loop and two P-DMZMs. PC: polarization controller, PRE: Polarization rotation element. PBS: polarizing beam splitter. Pol: polarizer, PD: photo detector.

have been reported [10–16]. A typical scheme, in which electrical signals are symmetrically modulated on two sub-modulators, is exploited to suppress the third-order distortion for more than 30 dB [12]. In [13], for the purpose of linearization, a polarization-multiplexing dual-parallel Mach–Zehnder modulator is introduced, and the biases of modulators, together with the input RF power should be adjusted simultaneously. In [14] and [15], broadband linearization schemes based on dual-parallel Mach–Zehnder modulators are produced. In these schemes, the power splitter ratios in optical paths are different from those in the commodity-off-the-shelf. The differences will degrade the integration of the sampling structures. Moreover, in schemes, only linearization performance is demonstrated, while the SNR performance is rarely mentioned, and the degradation of SNR will definitely cause impact on the photonic sampling.

In this paper, a real-time photonic sampling structure composed by a sagnac loop and two polarization-dependent modulators (P-DMZMs) is proposed and demonstrated. By separating the linearly polarized lightwave into two orthogonal polarizations, different modulation depths are exploited in sagnac loop. Furthermore, the selection of specific biases in P-DMZMs is helpful to achieve a preferable linearized performance with a low noise level for real-time photonic sampling. Compared with the quadrature-biased sampling scheme, the experimental results prove that the proposed scheme has a superior performance in nonlinearity suppression and SNR.

2. Theoretical description

The sampling structure in this work is exhibited in Fig. 1. The input lightwave passes through a circulator and divides into S- and P-polarizations at the polarizing beam splitter (PBS) with the splitting ratio of 50:50. The S- polarizations lightwave transmits along clockwise (CW) direction of the sagnac loop, while P- polarizations lightwave transmits along counter-clockwise (CCW) direction. In addition, P-DMZMs driven by the multi-tone RF signals are located in the CW and CCW directions of the sagnac loop. In comparison with the commercial MZM, the P-DMZM is a special one without the polarizer. Benefited by this feature, different modulation depths can be achieved along the x-axes and y-axes of P-DMZM. In the CW direction, the S-polarization lightwave is aligned at an angle of 0° to the x-axis (the principal axis) of the $LiNbO_3$ crystal. Therefore, high modulation depth is achieved in P-DMZM1. Furthermore, the lightwave passes through the Polarization rotation element (PRE), and the polarization is converted from S- to P-. Due to the velocity mismatch of the modulator, the lightwave in CW direction will not be modulated in P-DMZM2 [17]. As for the CCW direction, the P-polarization lightwave is aligned at the angle of 0° to the y-axis, so that lower modulation depth is achieved in P-DMZM2 comparing with the modulation depth in P-DMZM1. In this situation, the lightwave passes through the PRE, and the P-polarization is converted to S-polarization.

Attributing to the sagnac loop, the insertion loss and optical phase delay in two directions are able to match with each other. In the following analysis, the theoretical design principle of the sampling processing will be indicated in detail and the parameters can be optimized to implement a sampling processing with a high linearization and the outstanding SNR performance. The ultrafast optical pulses are transform-limited with a hyperbolic secant envelope, which is represented as

$$\boldsymbol{S_{MLL}}(t) = \boldsymbol{F}_0 \sum_{n=-\infty}^{+\infty} \boldsymbol{p}(t - n\Delta t) \tag{1}$$

where $\boldsymbol{F}_0$ is the pulse amplitude and $\boldsymbol{\Delta t}$ denotes the time interval. As displayed in Fig. 1, optical pulses are split into two paths. The output lightwave along the CW and CCW directions are shown as

$$\begin{aligned} S_{SAM-cw}(t) &= \frac{\sqrt{2}}{2}\alpha_{loss-cw}\exp\left(j\phi_{cw}\right)\mathrm{S_{MLL}}(t) \\ &\quad\cdot\left[\exp\left(j\Delta_1 + jm_1\cdot\sum_{i=1}\sin\omega_i t\right)\right. \\ &\quad\left.+\exp\left(-j\Delta_1 - jm_1\cdot\sum_{i=1}\sin\omega_i t\right)\right] \\ S_{SAM-ccw}(t) &= \frac{\sqrt{2}}{2}\alpha_{loss-ccw}\exp\left(j\phi_{ccw}\right)\mathrm{S_{MLL}}(t) \\ &\quad\cdot\left[\exp\left(j\Delta_2 + jm_2\cdot\sum_{i=1}\sin\omega_i t\right)\right. \\ &\quad\left.+\exp\left(-j\Delta_2 - jm_2\cdot\sum_{i=1}\sin\omega_i t\right)\right] \end{aligned} \tag{2}$$

where $\alpha_{loss-cw}$ and ϕ_{cw} represent the values of insertion loss and phase shift along the CW direction of the sagnac loop. As for $\alpha_{loss-ccw}$ and ϕ_{ccw}, they stand for the values of insertion loss and phase shift along the CCW direction. $\omega_i (i = 1, 2, 3, 4, 5.....)$ are frequencies of multi-tone signals. m_1, m_2 and Δ_1, Δ_2 are the modulation indexes and biases of two P-DMZMs, respectively.

Then, the two orthogonal optical signals with a 180° phase difference produced by a polarization controller (PC) are combined together in a polarizer. In the sagnac loop, both the difference of insertion loss and the difference of phase shift in CW and CCW directions can be neglected, so we have $\alpha_{loss-cw} = \alpha_{loss-ccw} = \alpha_{loss}$ and $\phi_{cw} = \phi_{ccw} = \phi$. The combined lightwave is represented as

$$\begin{aligned} S_{SAM}(t) &= \frac{1}{2}\alpha_{loss}\exp(j\phi)\,\mathrm{S_{MLL}}(t) \\ &\quad\cdot\left[\cos\left(\Delta_1 + m_1\cdot\sum_{i=1}\sin\omega_i t\right) - \cos\left(\Delta_2 + m_2\cdot\sum_{i=1}\sin\omega_i t\right)\right] \end{aligned} \tag{3}$$