# Differentially Encoded Photonic Analog-to-Digital Conversion Based on Phase Modulation and Interferometric Demodulation

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***Abstract*—We propose a novel approach to realizing photonic analog-to-digital conversion in a system with a phase modulator (PM) and a delay-line interferometer (DLI). The phase modulation and interferometric demodulation techniques are employed to realize quantization and encoding. In the system, the phase-modulated signal is optically sampled by a multiwavelength pulsed source and the phase-shifted transfer functions of the DLI under different wavelengths are used for encoding. In the approach, the differential signal, but not the original analog signal, is encoded, which increases the equivalent number of bits. In addition, the balanced detection technique can be incorporated into the system to alleviate the influences of amplitude and timing jitter.**

***Index Terms*—Balanced detection, delay-line interferometer (DLI), differential encoding, photonic analog-to-digital conversion (ADC).**

## I. Introduction

PHOTONIC analog-to-digital conversion (ADC) technologies are considered to be potential solutions for digitalization of wideband signals in a wide range of modern applications such as wideband radar, electronic monitor, spread spectrum communication, and electronic countermeasure. One of the major advantages of photonic ADC lies in that mode-locked lasers with high repetition rate and low timing-jitter are available as high performance sampling source [1]. By now, a variety of techniques for optical quantization and encoding have been proposed. One category of optical quantization and encoding techniques is the approaches based on optical nonlinearity [2]–[4]. Another important category is those based on optical external modulator, initially proposed by Taylor in [5]. The Mach–Zehnder modulators (MZMs) applied in the Taylor's scheme should be geometrically scaled in half-wave voltage ($V_\pi$), which is hard to realize even under the state-of-the-art photonic integrated circuit technology. To overcome this problem, some techniques have been proposed, which include the approaches to realizing equivalent $V_\pi$ scaling based on cascading MZMs or phase modulators (PMs) [6], [7] and the approaches avoiding $V_\pi$ scaling based on phase shift in modulation transfer function, initially proposed by Stigwall and Galt [8]–[11]. Recently, a technique to realize photonic quantization with differential encoding using a phase modulator and an array of delay line interferometers (DLIs) is proposed in [12]. The differential encoding is advantageous for improving the number of bits of the ADC system. However, the use of $2^{N-1}$ ($N$ is the number of bits) DLIs with precise phase control in the system makes the system complicated and therefore difficult to realize.

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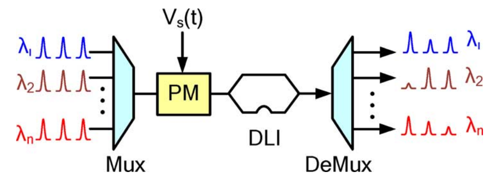


Fig. 1. Schematic illustration of the proposed photonic ADC with differential encoding (PM: phase modulator; DLI: delay-line interferometer).

In this letter, we propose a novel approach to realizing photonic ADC using a single PM and a single DLI. With the help of multiwavelength pulsed source and interferometric demodulation technique, the photonic quantization and differential encoding can be achieved. Operation principle and discussions on practical realization of the approach are presented. We show that the balanced detection technique can be incorporated into the system to alleviate the influences of the amplitude and timing jitter of the pulsed source.

## II. Principle of Operation

The schematic illustration of the proposed ADC approach is shown in Fig. 1. $n$ synchronized high-repetition-rate ultrashort pulsed lasers with different central wavelengths combined by a multiplexer are used as an optical sampling source. The analog signal $V_s(t)$ to be digitized is modulated upon the multiwavelength optical pulses via a phase modulator. Then the phase-modulated sampled signals pass through a DLI followed by a demultiplexer. At the output of the demultiplexer, the pulsed signals are detected by a photodetector and then sent to a comparator in each wavelength channel. According to the electrical level of the detected signal, the corresponding bit of "1" or "0" is obtained at the output of the comparator.

The electrical field of the optical pulses with central angular frequency $\omega_i$ can be expressed as $E^i_{in}(t) = g(t)\exp(j\omega_i t)$, where $g(t)$ represents the pulse train with a repetition period

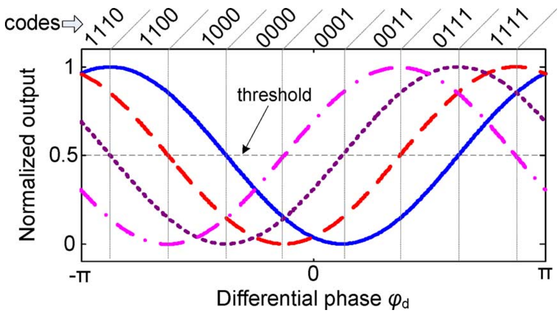


Fig. 2. Output optical power versus differential phase transfer functions of a four-channel system (output codes are also shown).

of $\tau$ which satisfies $g(t) = g(t-\tau)$. Then the phase-modulated pulses can be expressed as $E_m^i(t) = g(t)\exp[j(\omega_i t + \varphi_s(t))]$, where $\varphi_s(t) = (\pi/V_\pi)V_s(t)$ is the phase signal induced by the input analog signal and $V_\pi$ is the half-wave voltage of the PM. After passing through the DLI (with a delay $\tau'$), the optical signal can be expressed as

$$\begin{aligned} E_D^i(t) &= \left(\frac{1}{2}\right)[E_m^i(t) + E_m^i(t-\tau')] \\ &= \left(\frac{1}{2}\right)\exp(j\omega_i t)\{g(t)\exp[j\varphi_s(t)] \\ &\quad + g(t-\tau')\exp[j\varphi_s(t-\tau') - j\omega_i\tau']\}, \end{aligned} \tag{1}$$

Therefore, by square-law detection, the photocurrent is given by

$$\begin{aligned} i(t) \propto |E_D^i(t)|^2 = \left(\frac{1}{2}\right)\Bigg\{&\frac{[|g(t)|^2 + |g(t-\tau')|^2]}{2} \\ &+ g(t)\cdot g(t-\tau')\cos[\varphi_s(t) - \varphi_s(t-\tau') + \omega_i\tau']\Bigg\}. \end{aligned} \tag{2}$$

In this system, the DLI delay $\tau'$ is set to be identical to the repetition period $\tau$. Therefore the detected current can be simplified as $i(t) = (1/2)\,|g(t)|^2\{1 + \cos[\varphi_d(t) + \varphi_i]\}$, where $\varphi_d(t) = \varphi_s(t) - \varphi_s(t-\tau')$ is the differential phase signal and $\varphi_i = \omega_i\tau' = 2\pi c\tau'/\lambda_i$ is the phase shift ($c$ and $\lambda_i$ are speed of light in vacuum and central wavelength of the pulse train, respectively). Based on the encoding scheme of the phase-shift-based photonic ADC [9]–[12], quantization of the differential signal can be achieved. In order to do this, the phase shift difference $\Delta\varphi = \varphi_{i+1} - \varphi_i$ between adjacent channels should be set as $\pi/n + 2\pi M$, where $n$ is the channel number and $M$ is any integer. The central wavelengths of the multiwavelength pulsed source should satisfy

$$\frac{1}{\lambda_{i+1}} - \frac{1}{\lambda_i} = \frac{1}{2nc\tau'} + \frac{M}{c\tau'}. \tag{3}$$

Fig. 2 shows the transfer functions (output optical power versus differential phase) of a four-channel system with $\Delta\varphi = \pi/4$. The corresponding output codes are also shown in the figure. The quantization and encoding process is similar to that of the phase-shift-based photonic ADC approaches [9]–[12] except that the differential signal $V_s(t) - V_s(t-\tau')$ (or $\varphi_s(t) - \varphi_s(t-\tau')$) but not the original signal $V_s(t)$ (or $\varphi_s(t)$) is quantized and encoded here.

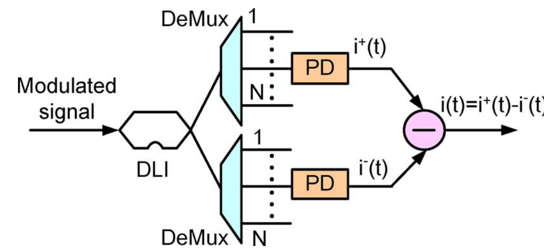


Fig. 3. Balanced detection technique to overcome amplitude jitter.

## III. Discussion

### A. Balanced Detection

The amplitude jitter of the pulsed laser source or the power fluctuation induced by the environmental turbulence would lead to output power variation and therefore the thresholding error in the comparators, which is a major impairment that results in performance degradation. To overcome this, the single-ended receivers can be replaced by balanced detectors, as shown in Fig. 3 [13]. In this scheme, the detected signal is expressed as

$$i(t) \propto \left(\frac{1}{2}\right)|g(t)g(t-\tau')|\cos[\varphi_d(t) + \varphi_i]. \tag{4}$$

It is shown that the dc value of the output signals is kept as zero. In other words, the threshold can be kept as zero even if there is amplitude jitter or power fluctuations (i.e., $g(t) \neq g(t-\tau')$).

Timing jitter of the sampling source may create different effects compared with previous approaches [9]–[12]. It can be seen from (4) that the misalignment in time of the pulses $g(t)$ and $g(t-\tau')$ induced by the timing jitter would lead to not only the sampling time error but also the reduction of the peak power of the sampling pulses. However, the latter factor is equivalent to the amplitude jitter, which can be alleviated by the balanced detection technique.

### B. Mismatch Between the DLI Delay and the Repetition Period of the Pulsed Source

Mismatch between the DLI delay $\tau'$ and the repetition period $\tau$ of the pulsed source would lead to pulse misalignment at the output of the DLI and thus the peak power reduction, just as the case of timing jitter. To quantitatively analyze the performance degradation induced by this mismatch, a Monte-Carlo simulation on a 4-bit system was implemented to give the dependence of the effective number of bits (ENOB) on the signal-to-noise ratio (SNR) of the detector current [8]. In the simulation, the repetition rate and the full width at half maximum (FWHM) of the pulsed source are set to be 20 GHz and 5 ps, respectively. Three cases of mismatch, i.e., 0, $0.6\times$ FWHM and $0.8\times$ FWHM, are studied. Results are shown in Fig. 4. Based on the model and the typical parameters given in [8], it is estimated that the SNR of the photo-current is around 17 dB if the detector bandwidth is 60 GHz and the average optical power to each detector is $-10$ dBm.

### C. Benefit From Differential Encoding

Unlike the previous phase-shift-based photonic ADC approaches, the difference of the adjacent samples of the input

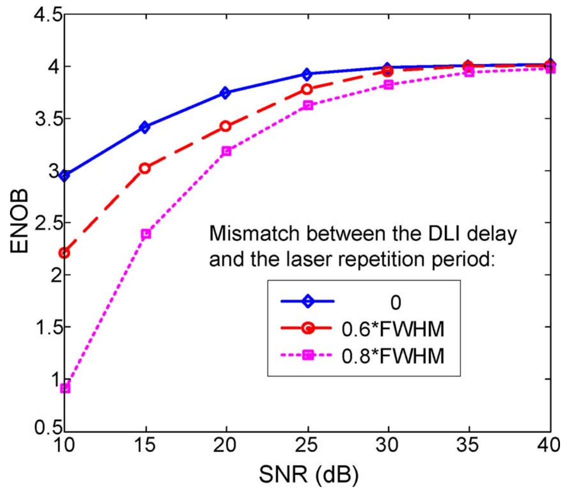


Fig. 4. ENOB as a function of the SNR of the detector current under different cases of mismatch between the DLI delay and the laser repetition period.

analog signal is quantized and encoded in the given scheme. Since the peak-to-peak amplitude of a differential signal is usually smaller than that of its original analog signal, especially at high sampling rate, the quantization noise of the differentially encoded digital signal is smaller than that of the directly encoded digital signal under the same number of bits. In other words, the differential encoding improves the equivalent number of bits of the ADC system. For example, for a sinusoidal signal with full scale voltage $V_{fs}$ and angular frequency $\omega_0$, the full scale voltage $V'_{fs}$ of its differential signal is given by $V'_{fs} = 2V_{fs}\sin(\pi\omega_0/\omega_s)$, where $\omega_s$ is the sampling rate. It is estimated that if $\omega_s = 10\omega_0$ the number of bits can be improved by around 0.7 bit and $\omega_s = 20\omega_0$ corresponds to a number of bits improvement of around 1.7.

### D. Experimental Considerations

Semiconductor-amplifier-based fiber ring lasers that can be applied in the proposed system as the synchronized multiwavelength pulsed source have been reported in [14], [15]. For a four-channel system, a pulsed source with repetition rate of 20 GHz and FWHM of 5 ps can be employed. Note that the wavelength spacing of the pulsed source in [14], [15] have some tunability and therefore the (3) can be satisfied. According to (3), the channel spacing is around 400 GHz if $M$ is 20, and the central wavelengths can be 1548.5, 1551.7, 1554.9 and 1558.1 nm. The required wavelength division multiplexing components are commercially available. Also note that the number of bits $N$ is decided by the wavelength channel number $n$ as $n = 2^{N-1}$. Despite of the limitation of currently available multiwavelength pulsed source in wavelength count, we believe the approach can find applications where a high sampling rate but a relatively low number of bits is required.

DLI with stable performance as well as balanced detectors are mature and commercially available as they have been widely used for the demodulation of DPSK signal in high-speed optical communications nowadays. To reduce the thermal and acoustic disturbances, a control loop can be added to the system [16].

## IV. Summary

We have proposed a novel approach to realizing photonic ADC with differential encoding employing phase modulation and interferometric demodulation technique as well as multi-wavelength pulsed laser. Compared with the approaches using MZMs or PMs with orthogonal polarizations, the given architecture is much simpler since a conventional PM is applied. The use of PM and DLI also reduces the power loss of the system and thus helps to improve the performance in term of signal-to-noise ratio. The differential encoding is another advantage which increases the equivalent number of bits. It is shown that the balanced detection technique can be applied in the system to overcome the performance degradation induced by the amplitude and timing jitter of the sampling source.

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