Proposal for photonic quantization with differential encoding using a phase modulator and delay-line interferometers

H. Chi,[1,*] Z. Li,[1,2] X. Zhang,[1] S. Zheng,[1] X. Jin,[1] and J. P. Yao[2]

[1]*Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China*

[2]*Microwave Photonics Research Laboratory, School of Information Technology and Engineering,*
University of Ottawa, Ottawa, Ontario K1N 6N5, Canada
*Corresponding author: chihao@zju.edu.cn

A photonic quantization approach to implementing analog-to-digital conversion (ADC) in the optical domain with differential encoding employing a phase modulator and delay-line interferometers (DLIs) is proposed and demonstrated. In the proposed ADC system, the phase-modulated signal is sent to an array of DLIs that have identical time delay difference, but different phase shifts, which are employed to achieve quantization with differential encoding. A proof-of-concept experiment is performed. The quantization of a 10 GHz sinusoidal signal with a bit length of 4 is experimentally demonstrated.   © 2011 Optical Society of America

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Analog-to-digital conversion (ADC) bridges the analog and digital worlds. However, the improvement in ADC speed largely lags behind that in digital signal processing speed. On the other hand, more and more wideband applications, such as radar and wireless communications, put higher requirements on the ADC performance. Therefore, the limited ADC performance becomes a bottleneck for wideband signal acquisition and processing. The implementation of ADC in the optical domain has been a topic of interest in the last 30 years, since mode-locked lasers with a high repetition rate and low timing jitter have been considered an excellent sampling source that could potentially improve the performance of an ADC system [1]. In addition to sampling, it is also desirable that the quantization is done in the optical domain. Taylor proposed a scheme to achieve photonic quantization using an array of Mach–Zehnder modulators (MZMs) [2]. To generate a Gray-code digital output, the half-wave voltage (V_π) of the MZMs should be geometrically scaled, which is difficult to realize for a system with a bit length more than 3 even with the state-of-the-art photonic integrated circuit (PIC) technique [1]. To solve this problem, numerous approaches were proposed [3–9]. Jalali and Xie presented a scheme using cascaded MZMs with an identical V_π [3]. Currie proposed a scheme using cascaded phase modulators (PMs) with identical V_π that support orthogonal polarization modes [4]. The cascade of MZMs or PMs is able to increase the equivalent electrode length, but it also places a stringent requirement on synchronization of the signals applied to the MZMs. In addition, the increased loss is another factor that limits the application. Sigwall and Galt proposed a solution in which the quantization was done by phase shifting instead of scaling the period of the electro-optic transfer functions [5,6]. In the approach, a free-space Mach–Zehnder interferometer with a PM in one arm was employed. The phase shift was achieved by locating a photodetector at different positions of the fringe pattern. Based on the same concept, a scheme using a PM that supports two orthogonal polarization modes using a fiber

phase-shifter module was proposed [7], and an approach based on an array of MZMs with identical V_π by biasing the MZMs at different biasing points was proposed and demonstrated [8].

In this Letter, we propose a photonic quantization scheme employing a conventional PM (that supports a single polarization mode) and an array of delay-line interferometers (DLIs; with identical delay but different phase shifts). The quantization principle of our approach is similar to that in [5–8], but the use of a single PM greatly simplifies the system configuration compared with the previous approaches using an MZM array or a PM that supports orthogonal polarization modes. In addition, the PM employed is placed outside the interference structure, which makes the system more stable with better implementability.

The schematic of the proposed photonic ADC scheme with N channels is shown in Fig. 1. A pulse train generated by a model-locked laser is used to do the sampling. An analog signal $V_s(t)$ to be digitized is applied to a PM. The phase-modulated pulse train is then split into N channels via an optical coupler. In each channel, there is a DLI. The DLIs in all channels have an identical delay
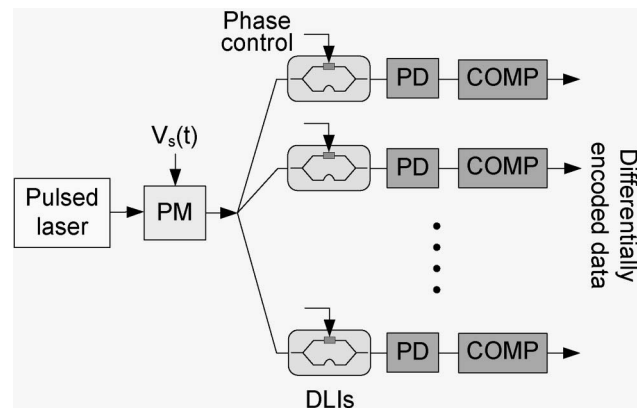

Fig. 1. Schematic of the proposed scheme for photonic quantization. PM, phase modulator; DLIs, delay-line interferometers; PD, photodetector; COMP, comparator.

τ but different phase shift, which can be realized by placing an electrically controllable phase shifter in one arm of each DLI. The delay τ should be set to be equal to the repetition period of the short pulse train. In each channel, after passing through the DLI, the optical signal is detected by a photodetector and sent to a comparator. A bit of 1 or 0 is obtained at the output of the comparator according to the electrical level of the detected pulse. Note that the output digital word at the output of the system is a quantized result of the differential signal $V_s(t) - V_s(t - \tau)$.

Mathematically, the optical pulse train from the mode-locked laser source can be expressed as $E_{\text{in}}(t) = g(t) \exp(j\omega_0 t)$, where $g(t)$ represents the pulse train with a repetition period of τ and ω_0 is the central frequency. The phase-modulated pulse train is given by $E_m(t) = g(t) \exp[j(\omega_0 t + \varphi_s(t)]$, where $\varphi_s(t) = (\pi/V_\pi) V_s(t)$, V_π is the half-wave voltage of the PM, and $V_s(t)$ is the signal to be digitized. After passing through a DLI with a delay τ and a phase shift φ_b, the optical signal after the DLI can be expressed as

$$E_D(t) = (1/2)[E_m(t) + E_m(t - \tau)]$$
$$= (1/2) \exp(j\omega_0 t) \times \{g(t) \exp[j\varphi_s(t)]$$
$$+ g(t - \tau) \exp[j\varphi_s(t - \tau) - j\varphi_b]\}. \quad (1)$$

Since the pulse train $g(t)$ with repetition period τ satisfies $g(t) = g(t - \tau)$, Eq. (1) is then simplified as

$$E_D(t) = (1/2)g(t) \exp(j\omega_0 t) \{\exp[j\varphi_s(t)]$$
$$+ \exp[j\varphi_s(t - \tau) - j\varphi_b]\}. \quad (2)$$

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

$$i(t) \propto |E_D(t)|^2 = (1/2)|g(t)|^2 \{1 + \cos[\varphi_s(t) - \varphi_s(t - \tau) + \varphi_b]\}$$
$$= (1/2)|g(t)|^2 \{1 + \cos[\varphi_d(t) + \varphi_b]\}, \quad (3)$$

where $\varphi_d(t) = \varphi_s(t) - \varphi_s(t - \tau)$ is the differential phase signal.

From Eq. (3), we can see that the detected photocurrent $i(t)$ varies sinusoidally with the differential phase signal $\varphi_d(t)$. In order to realize correct encoding, the phase shift φ_b should be set to have an increment of π/N between two adjacent channels. An illustration of the quantization for a four-channel system is shown in Fig. 2, where the phase shift φ_b of the four channels are set to be $-\pi/8$, $\pi/8$, $3\pi/8$, and $5\pi/8$, with a phase increment of $\pi/4$. Note that the quantization principle of the approach is identical to that in [5–8], except that here the differential signal $\varphi_d(t)$, not the original signal $\varphi_s(t)$, is quantized and encoded. The decoding of the differentially encoded signal can be performed in a subsequent digital signal processing module. In a system with a channel number N, the bit resolution is as $\log_2 2N$ [6].

A proof-of-concept experiment is performed based on the setup shown in Fig. 3. Since a pulsed laser source and its associated time circuit were not available at the time of experiment, a tunable cw laser (Yokogawa AQ2201) was employed, but it is sufficient to demonstrate the
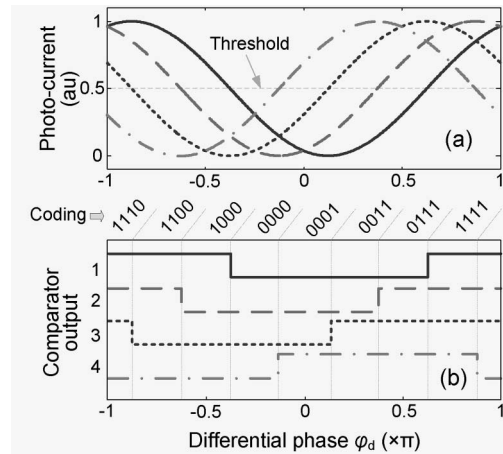

Fig. 2. Quantization principle of the proposed approach. (a) Photocurrent at a function of the differential phase for the four channels; (b) quantized signals at the outputs of the four comparators.

concept of quantization. The light from the cw laser source is sent to a 20 GHz PM. A Sagnac-loop filter (SLF) is used as a DLI. The SLF consists of a length of polarization-maintaining fiber (PMF) and two polarization controllers in the fiber loop, which has a sinusoidal frequency response [9]. The delay τ is decided by the length and birefringence of the PMF, which is set to be 38.8 ps (corresponding to a free spectral range of 25.8 GHz). The phase shift φ_b is determined by the relative position of the optical carrier wavelength to the peak and valley of the frequency response of the SLF, which can be controlled by tuning the wavelength of the light source. In the experiment, a 10 GHz sinusoidal signal generated by a signal generator (Agilent E8254A) is first amplified to 23.5 dBm, and then applied to the PM for digitization. The half-wave voltage V_π of the PM at 10 GHz is around 11 V. The optical signal at the output of each DLI is detected by a 53 GHz photodetector and the generated temporal waveform is captured by a sampling oscilloscope (Agilent 86100C).

To emulate an eight-channel ADC system, we record the temporal waveforms for the SLF at eight phase shifts of $-\pi/16$, $\pi/16$, $3\pi/16$, $5\pi/16$, $7\pi/16$, $9\pi/16$, $11\pi/16$, and $13\pi/16$. The recorded waveforms for two phase shifts at $-\pi/16$ and $13\pi/16$ are shown in Fig. 4. The recorded eight waveforms are then digitized to 0 and 1 by comparing the waveforms with the threshold, which is set to be half of the maximum output. Then, the signal quantization is achieved according to the coding scheme [5–8]. The quantization result is shown in Fig. 5. Since a differentiated sinusoidal is still a sinusoidal, the fitted signal is
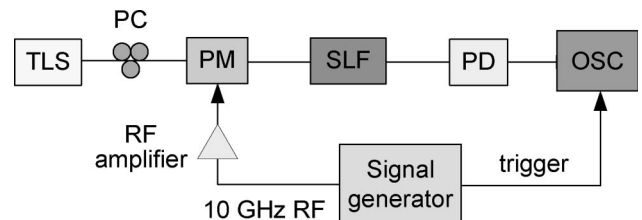

Fig. 3. Experimental setup. TLS, tunable laser source; PC, polarization controller; PM, phase modulator; SLF, Sagnac-loop filter; PD, photodetector; OSC, oscilloscope.
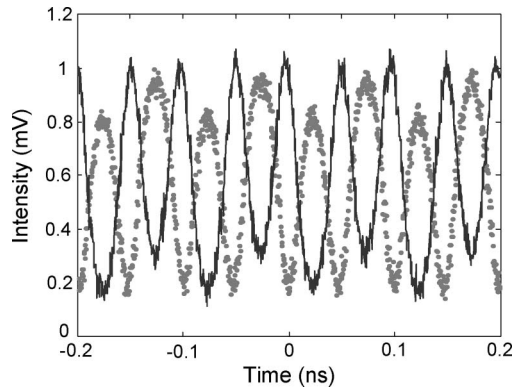
Fig. 4. Detected temporal waveforms at the output of the PDs for the SLF with a phase shift at $-\pi/16$ (solid curve) and $13\pi/16$ (dotted curve).

Fig. 5. Quantized signal (solid curve) and fitted sinusoidal signal (dashed curve).

a sinusoidal signal, which is also shown in Fig. 5 for comparison. Based on the errors between the quantized signal and the fitted differential signal, the effective number of bits is estimated to be around 3.2. As can be seen, the dc value of the quantized differential signal $\varphi_d(t)$ is slightly deviated from zero, which is caused by the non-uniform loss of the signals $\varphi_s(t)$ and $\varphi_s(t-\tau)$ travelling through the fast and slow axes of the PMF of the SLF.

For practical applications, to reduce the quantization noise, the quantization can be done using a balanced receiver in each channel [10]. In this case, two complementary output signals at the output of the DLI are sent to two PDs in a balanced receiver, and the signal at the output of the balanced receiver is proportional to $[g(t)]^2 \cos[\varphi_d(t)+\varphi_b]$. Therefore, the threshold level can be kept at zero even when the output power of the pulsed laser source is time variant. Compared with the previous approaches using MZMs with geometrically scaled V_π [2], cascaded MZMs or PMs [3,4], free-space interferometric structures [5,6], or a PM that supports two orthogonal polarization modes [4,7,10], our proposed design has high potential for monolithic integration using the silicon PIC technology [11,12]. In addition, the inherent differential encoding brings extra capability to realize higher bit resolution. As other schemes based on the phase shifting of the electro-optic transfer functions [5–8], the key limitation of this approach is the lower bit resolution. It is believed that this approach has a high potential for applications that require a high sampling rate but a low number of bits. Note that the electronic complementary metal oxide semiconductor ADC technology is moving fast, for example, a 40 GHz sampling rate ADC was demonstrated recently [13]. Since a mode-locked laser with a repetition rate higher than 100 GHz is available [14], the development of a high-sampling-rate ADC based on photonic solutions is still a topic of interest.

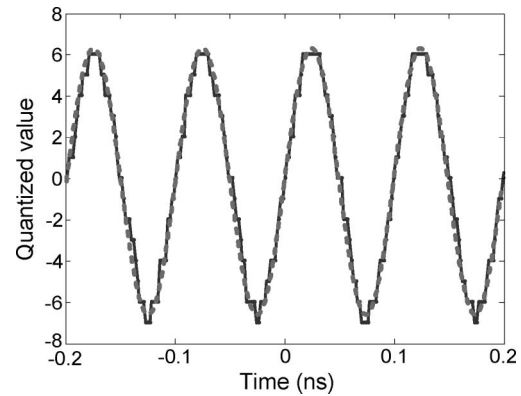In summary, an approach to implementing photonic quantization with differential encoding employing a PM and an array of DLIs was proposed. The key contribution of the technique is the use of an array of DLLs that have an identical time delay difference, but different phase shifts, which enables the realization of photonic quantization with differential encoding. In addition, the PM here was placed outside of the interferometric structure, which greatly simplifies the system and helps improve the stability. A proof-of-concept experiment was performed, which validated the feasibility of the approach.

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