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Abstract. A photonic analog-to-digital converter (ADC) utilizing the modal birefringence of the polarization maintaining fiber (PMF) is proposed. In the PMF, sampling pulses with different wavelengths have different phase shifted transfer functions, which could be used for quantizing and encoding in a photonic ADC. A proof-of-concept experiment is performed and a 2.5 GHz sinusoidal electrical analog signal is quantized by using 16 different wavelengths. The experimental result with an effective number of bits of 4.5 is achieved. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.2.025005]

Subject terms: analog-to-digital conversion; photonic quantization; birefringence.

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1 Introduction

Analog-to-digital converters (ADCs) are key devices in high-speed signal processing such as high-definition video and ultra-high-speed optical communication. In recent years, all-optical ADCs have attracted the attention of researchers due to their high sampling rate and ultra-wide bandwidth.[1] So far, many different schemes of all-optical ADC have been developed, in which the interferometric ADC has been widely used due to its simple structure and high speed, such as Taylor scheme,[2,3] nonlinear optical loop mirror (NOLM),[4,5] and phase shifted optical quantization (PSOQ).[6–10] The advantage of the PSOQ is its simple structure: only one phase modulator is needed. No requirement for the half-wave voltage of the modulator and no nonlinear effects are utilized, which makes the scheme more stable and reduced power consumption. In PSOQ, the key issue is how to obtain the desired phase shift precisely to ensure the effective number of bits (ENOB). Though some feasible approaches have been presented, such as a fiber squeezer,[11] multi-wavelength phase shift in $LiNbO_3$ phase modulator,[12] unbalanced Mach-Zehnder modulator,[13] and electrically controllable phase shifter,[14] these approaches either need additional mechanical adjustment[11,14] or the configuration is not flexible and the requirement of the device is strict,[12,13] which leads to the realization of the PSOQ's complication.

In this paper, an improved approach to realize the desired phase shift is presented. The different phase-shifted transfer functions in PSOQ can be obtained by the fact that different wavelengths of sampling pulses have different modal birefringence in the PMF.[15] 16 proper wavelengths corresponding to 16 quantization channels with different phase shifts are obtained by 16 wavelengths laser, and a 2.5 GHz sinusoidal electrical analog signal is quantized. The experimental result shows that an effective number of bits of 4.5 can be achieved. Compared to the previous approaches, the benefits of the presented approach in the paper are its simple configuration and flexible realization of the phase shift.

2 Principles of Operation

Figure 1 shows the schematic of the proposed ADC, where N different wavelength sampling pulses are combined as a synchronized multi-wavelength sampling source by a multiplexer. The synchronicity of N wavelength pulses can be realized by optical delay lines. After the multiplexer, a 45-deg. polarizer is used to make the orthogonal components of the sampling pulse align with x or y axis of the polarization modulator (PolM). The phase difference between the two polarized states is varied with the amplitude of the analog signal input. When the phase-modulated multi-wavelength sampling pulses are fed into a PMF, the different wavelengths of pulses will have different phase shifts due to the modal birefringence. Then an in-line analyzer is used to polarization interference. Here the advantage of the PolM is to mitigate the walk-off between the two polarized states of the pulse before polarization interference.[16] At the output port, N separate quantization channels are obtained by a demultiplexer and the transmission intensity of the λ_i $(i = 1, 2 \dots N)$ is:

$$I_i = \cos^2\left[\frac{\pi V(t)}{2V_\pi} + \frac{\pi}{\lambda_i}\Delta nL\right], \tag{1}$$

where $V(t)$ is the amplitude of the input analog signal, V_π is the half-wave voltage of the Pol M, Δn is the refractive index difference between the two orthogonally polarized states, L is the length of the PMF. From Eq. (1), the phase difference between two adjacent wavelengths λ_i and λ_{i+1} is:

$$\Delta\varphi = 2\pi\left(\frac{\Delta nL}{\lambda_i} - \frac{\Delta nL}{\lambda_{i+1}}\right) = 2\pi\Delta nL\frac{\lambda_{i+1} - \lambda_i}{\lambda_i\lambda_{i+1}}, \tag{2}$$

when $N\Delta\lambda \ll \lambda_0$, $\Delta\lambda$ is the wavelength interval, λ_0 is the center wavelength of the tunable laser. Eq. (2) can be written as:

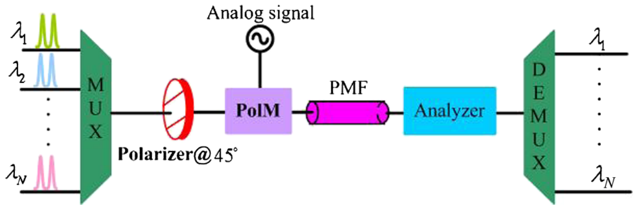

Fig. 1 The scheme of the proposed photonic ADC (PolM: polarization modulator, PMF: polarization maintaining fiber).

$$\Delta\varphi = 2\pi\Delta nL\frac{\Delta\lambda}{\lambda_0^2}. \tag{3}$$

From Eq. (3), the desired phase shift can be obtained automatically after the light travelling through the PMF without any extra adjustment and N-channel PSOQ can be realized by using N separate wavelengths. In PSOQ, two adjacent quantization channels should have a fixed phase difference π/N (or $2n\pi + \pi/N$), $n = 0, 1, 2 \ldots, N$ is the number of channels. Therefore, the desired wavelength interval for an N-channel PSOQ is:

$$\Delta\lambda = \frac{(2n + 1/N)\lambda_0^2}{2\Delta nL}. \tag{4}$$

This equation shows that for a fixed N-channel PSOQ, the wavelength interval is not fixed but can be designed flexible by choosing the proper parameter n and L.

3 Experimental Results

A one channel proof-of-principle experiment with 5-bit resolution has been performed, which is shown in Fig. 2. In the experiment, a wavelength tunable DFB laser source is employed to emulate the multi-wavelength channels. The wavelength of the laser source can be turned from 1551.78 to 1553.98 nm with a 0.01 nm spectrum separation by adjusting the temperature. A polarization controller (PC) is used to adjust the polarization states of the laser source to align 45-deg. with the axis of the modulator. Using a polarization modulator with a half-wave voltage of 3.5 V, the laser is modulated by a 20.88 dBm sinusoidal wave signal with a frequency of 2.5 GHz. The modulated laser wave travels through a PMF and the polarization interference is happened in a polarization beam splitter (PBS). The output optical signal is detected by a photo-detector (PD) with the bandwidth of 50 GHz and captured by a real-time oscilloscope (TekDSA71254C, 12.5 GHz).

As the tunable range of the laser used in the experiment is 2.2 nm and the optical path difference induced by the birefringence of the PMF is 1.26 mm, the wavelength interval of 0.06 nm is corresponding to a 5-bit ADC. Here the wavelength separation of 0.06 nm seems meaningless for pulsed lasers due to the spectral overlap. However, according to Eq. (4), the wavelength separation can be increased by choosing the number n. As a result, the wavelength separation of 1.98 and 0.06 nm are the equivalence cases. Therefore it is sufficient to demonstrate the concept of quantization. An optical spectrum analyzer is employed to measure the wavelength of the laser and sixteen proper wavelengths are chosen to realize the phase shifts of 0, $\pi/16$, $2\pi/16, \ldots, 15\pi/16$, which is shown in Table 1. From Table 1, the errors of the wavelength interval are less than 0.01 nm compared to the designed value (0.06 nm). The temporal waveforms of these 16 wavelengths are sampled and recorded on the oscilloscope, three of which are shown in Fig. 3.

Table 1 Phase shift and corresponding wavelength of the tunable laser source.

$\varphi(\pi)$	0	1/16	2/16	3/16
λ_i (nm)	1552.57	1552.63	1552.69	1552.76
$\varphi(\pi)$	4/16	5/16	6/16	7/16
λ_i (nm)	1552.82	1552.89	1552.95	1553.02
$\varphi(\pi)$	8/16	9/16	10/16	11/16
λ_i (nm)	1553.09	1553.15	1553.22	1553.29
$\varphi(\pi)$	12/16	13/16	14/16	15/16
λ_i (nm)	1553.36	1553.42	1553.48	1553.55

The binary codes are obtained by threshold decision and encoding, which are performed offline. According to these quantization codes, the transfer function of all optical ADC is obtained (see Fig. 4). The transfer function is monotonically increasing with no missing code performance. An ideal transfer function is also presented in Fig. 4. Comparing the quantized values with the ideal values, a signal-to-noise ratio (SNR) of 28.85 dB is obtained, corresponding to an ENOB of 4.5.[17] As the ideal resolution is 5 bits, the deviation from the ideal case is 0.5 bits. The quantization error is

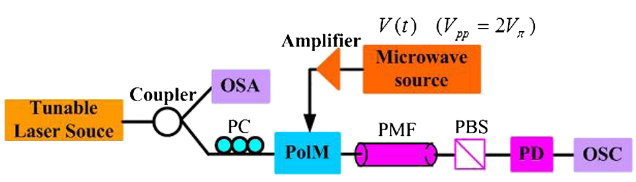

Fig. 2 Experiment setup (PC: polarization controller, PBS: polarization beam splitter, PD: photo-detector, OSA: optical spectrum analyzer, OSC: oscilloscope).

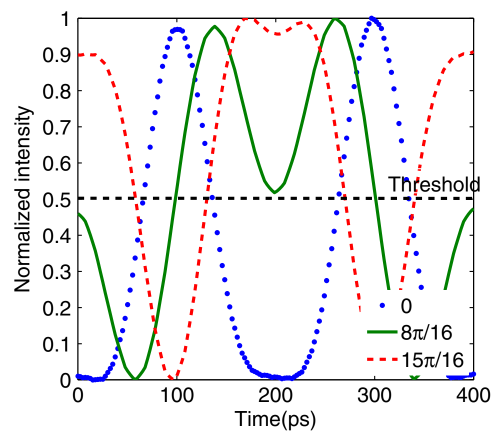

Fig. 3 Experimental outputs of the 5-bit photonic ADC with different phase shifts.

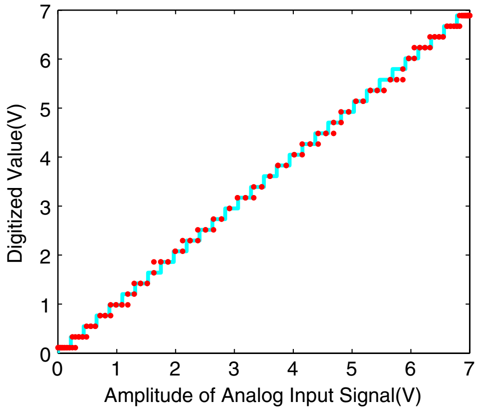

Fig. 4 The transfer functions of the 5-bit all optical ADC (The dots are the measured transfer function and the solid line is the ideal one).

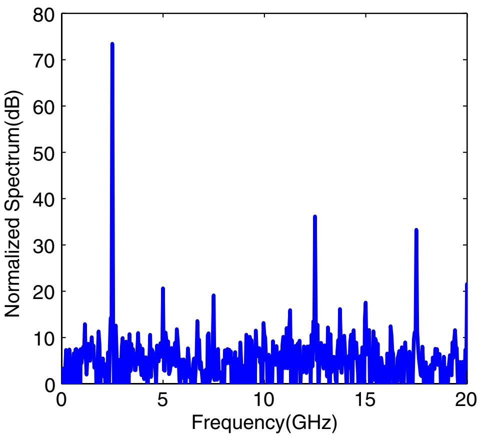

Fig. 5 Calculated FFT spectrum of the digitized results.

mainly caused by the wavelength shift and the random noise in the fiber link. Figure 5 shows the SFDR of the calculated fast Fourier transform (FFT) results of the scheme, and the SFDR is 37.28 dB. From the figure, the first, second, and third harmonic is suppressed due to the high precision of the phase shift of the presented scheme, and the high harmonics noise is mainly induced by the real-time oscilloscope used in the experiment. The SFDR of the scheme can be improved greatly by low-pass filtering. If the harmonic higher than fourth is ignored, the SFDR can reach to 52.8 dB.

In order to obtain higher resolution, many more wavelengths are needed. For example, 128 different wavelengths are needed for a photonic ADC with 8 read-out bits, which is difficult to realize in practical terms. However, if we take the advantage of the design Taylor proposed in Refs. 2 and 3, only 16 different wavelengths are needed for an 8-read-out bits ADC when we combine a 16-channel PSOQ and a 4-channel PSOQ together. If we use a WDM of 200 GHz as a demultiplexer, the pulse lengths are about 5 ps and the wavelength separation of 1.6 nm is enough for such an 8-bit photonic ADC.

4 Conclusion

In summary, an all-optical ADC that utilizes the birefringence of the polarization maintaining fiber is described and experimentally demonstrated. As different wavelength lasers travelling through the PMF would have different phase shifts due to the birefringence, the desired phase shift of each quantization channel can be obtained by selecting the proper wavelength. The presented scheme is demonstrated by a one channel proof-of-concept experiment. 16 different wavelengths are realized by a tunable laser source and a 2.5 GHz sinusoidal RF signal is quantized. The experimental result shows that an ENOB of 4.5 has been achieved, and the SFDR reaches to 37.28 dB.

Acknowledgments

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Biographies and photographs of the other authors are not available.