Experimental evaluation of resolution enhancement of a phase-shifted all optical analog-to-digital converter using an electrical analog-to-digital converter array

Yang Wang (王 杨)*, **Hongming Zhang (张洪明)**, **Yujie Dou (窦玉杰)**, **and Minyu Yao (姚敏玉)**

State Key Laboratory on Integrated Optoelectronics,
Tsinghua National Laboratory for Information Science and Technology,
Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
**Corresponding author: wang-yang08@mails.tsinghua.edu.cn*

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A resolution-improvement scheme of a phase-shifted analog-to-digital converter (ADC) is presented and experimentally demonstrated. To improve resolution via the scheme, the optical output of each quantization channel is quantized by an electrical ADC with multiple thresholds instead of a comparator. A 9.9-GHz sinusoidal analog signal is sampled and quantized using the proposed enhancement scheme. The effective number of bits of 4.31 and the spur-free dynamic range of 40.89 dB are obtained, thus indicating an improvement of 0.66 bits and 7.47 dB, respectively.

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A high-speed, high-resolution analog-to-digital converter (ADC) has an extensive range of application in high-speed signal processing and optical communications. A conventional electrical ADC has difficulty achieving high-resolution, ultra-wide bandwidth analog-to-digital conversions because of aperture jitter[1]. Ultra-short and ultra-stable optical sampling pulses with high repetition rates have become available through the development of mode-locked technology and optical time interleaving, thus creating a potential means for achieving high-resolution, ultra-wide bandwidth analog-to-digital conversions[2,3]. An all-optical ADC based on polarization interference and phase-shifted optical quantization (PSOQ) is among the ultra-wide bandwidth optical ADCs[4] that focus on implementing high sampling rates and wide bandwidths[5,8]. In PSOQ, the resolution of $\log_2(2N)$ can be achieved by N quantization channels; hence, 16 channels are required for a 5-bit resolution[9]. This requirement makes the scheme complicated, and thus, achieving higher resolution is difficult. However, several high-resolution encoding schemes have been proposed, including multi-threshold comparators[10,11]. Such encoding schemes require a huge number of comparators, which is difficult to obtain in practice. The use of the optical multi-period transfer functions of nonlinear optical loop mirrors to enhance the resolution of electrical ADCs is recently presented in Ref. [12]. In this letter, we propose an optical ADC resolution-improvement scheme by using electrical ADCs. High-speed (more than 40 Gs/s) and low-resolution (less than 4 bits) electrical ADCs are available[13], thus we can use such ADCs instead of multi-threshold comparators to improve the resolution of optical ADCs based on PSOQ.

The operating principle of the resolution-enhancement scheme is described and experimentally demonstrated in this letter. Three kinds of low-resolution, ideal, electrical ADCs are used in the experiment to improve the resolution of PSOQ. A 9.9-GHz sinusoidal electrical analog signal is sampled and quantized using the resolution-enhanced ADC. The result indicates that the effective number of bits (ENOB) is 4.31 and the spur-free dynamic range (SFDR) is 40.89 dB.

Figure 1 presents an N-channel PSOQ with resolution enhancement. The two polarized states of the sampling pulse are aligned with the x or y axis of the polarization modulator (PolM) by a 45° polarizer. The phase differences between two orthogonal polarization components are modified linearly with the amplitude of the input signal. The output pulses of the PolM are split into N channels. Each quantization channel has a transfer function with an extra phase shift of $(i-1)\pi/N$ provided by a phase shift module (PSM), where i is the number of channels. The polarization interference of the two states occurs in a polarization beam splitter (PBS). The output optical signal is detected by a photodetector (PD) with a bandwidth of 50 GHz.

In a conventional PSOQ, the output of the PDs are the threshold decisions of a comparator array, and the resolution of $\log_2(2N)$ can be obtained using this encoding scheme. We use a two-channel PSOQ scheme to clarify the principle of resolution enhancement. Figure 2(a) illustrates the transfer function of a two-channel PSOQ, and the phase difference between the two channels is $\pi/2$. To improve the resolution of the two-channel

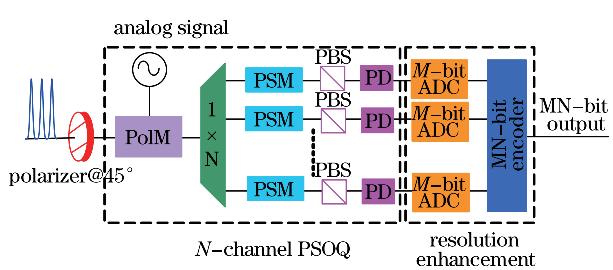

Fig. 1. Resolution-enhancement scheme based on PSOQ.

scheme, we use an M-bit electrical ADC array instead of a comparator array to quantize the output of the PDs. Figure 2(b) shows the corresponding transfer function, supposing M=3. In the figure, the sinusoidal transfer curve of each channel is quantized into eight levels by the 3-bit ADC. The output of the 3-bit ADC is shown in Fig. 2(b). The total number of quantization levels is 28 when we combine the output codes of the two channels. The number of quantization levels is increased compared with the conventional two-channel PSOQ (four-level). The resolution N_R is less than $\log_2(28)$, which is equal to 4.46 bits, in the proposed resolution-enhancement scheme because the transfer function of the scheme is not linear.

For a common case, the quantization level is $2N(2^M-1)$ and the calculated resolution of a PSOQ with enhancement is shown in Fig. 3. The figure indicates that resolution N_R is generally less than $\log_2[2N(2^M-1)]$. When M>2, resolution is increased using an M-bit electrical ADC array. However, the increase caused by the enhancement scheme is not linear because of nonlinear quantization. In Fig. 3, the PSOQ with the resolution enhancement of M=3 is found to be lower than the PSOQ with the resolution enhancement of M=2 in several cases because of nonlinear quantization noise. The relationship between the signal-to-noise ratio (SNR) of the PD and that of the system is shown in Fig. 4. The noise of the system is modeled by a normal distribution noise in the simulation, and the density function is given as

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{x^2}{2\sigma^2}}, \quad (1)$$

where σ is the standard deviation which can be evaluated by the SNR of the PD. According to the noise distribution, the SNR of the system can be calculated using the Monte Carlo simulation[14]. Figure 4 shows that in the case of high-detection SNR, the SNR of the 8-channel PSOQ with 3-bit electrical ADC enhancement (dashed-and-dotted line) is higher than that of the 32-channel PSOQ without enhancement (solid line). However, several steps are extremely small in nonlinear quantization, which is more prone to discriminated into other quantization steps. Therefore, the SNR of the enhancement

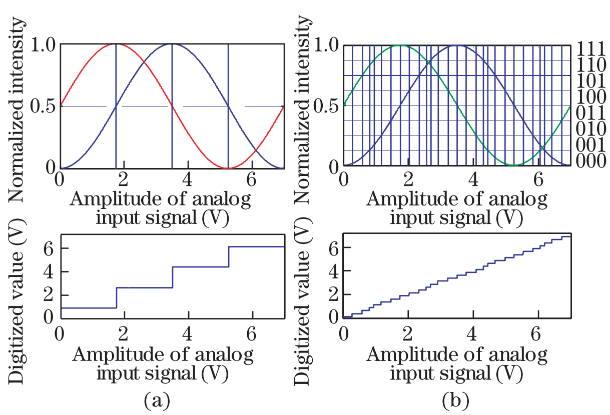

Fig. 2. Transfer functions of the two-channel PSOQ: (a) conventional encoding scheme with comparator and (b) resolution-enhancement encoding scheme with 3-bit ideal ADC. The dashed line represents the threshold.

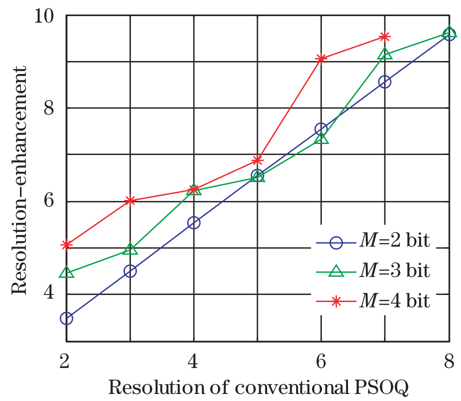

Fig. 3. Resolution enhancement with different M.

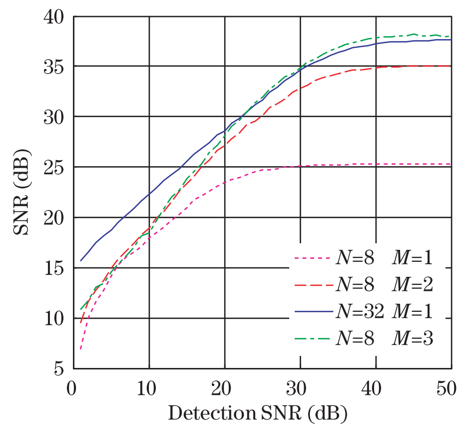

Fig. 4. SNR of the system as a function of the SNR of the detector.

is degraded faster upon detection compared with the SNR of the PSOQ without enhancement. To obtain a better ENOB using the proposed resolution-enhancement scheme, we should first ensure the detection of the SNR.

The presented resolution-enhancement scheme is experimentally demonstrated by a four-channel and an eight-channel PSOQ schemes. The experimental setup is shown in Fig. 1. In the experiment, the sampling pulse is generated by a 10-GHz mode-locked fiber ring laser, and the pulse width is set to 1.5 ps. A sinusoidal wave signal with a frequency of 9.9 GHz is undersampled. The eight temporal profiles at the phase shifts of 0, $\pi/8$, $2\pi/8$, $\cdots$, $7\pi/8$ are obtained by adjusting the fiber squeezer, and captured by using a real-time oscilloscope (DSA91304A Agilent, USA).

The eight temporal profiles are composed of an eight-channel PSOQ, and the four-channel PSOQ makes up the four temporal profiles at the phase shifts of 0, $2\pi/8$, $4\pi/8$, and $6\pi/8$. We use 1-bit, 2-bit, and 3-bit ideal ADCs to enhance the resolution of both the four-channel and eight-channel PSOQs. The enhancements are conducted offline. The ENOB of the resolution-enhanced ADC can be calculated from the SNR and distortion ratio of the reconstructed signal[1]. Figure 5(a) illustrates the calculated ENOB of the enhanced PSOQ using electrical ADCs with different resolutions, whereas Fig. 5(b) provides the corresponding SFDR of the fast Fourier transform (FFT) results. Based on these figures, the ENOB of the eight-channel PSOQ is 3.65 bits and its SFDR is

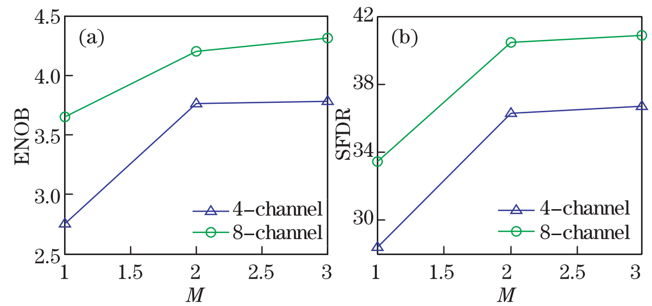

Fig. 5. Experimental results of the enhanced PSOQ. (a) ENOB and (b) SFDR.

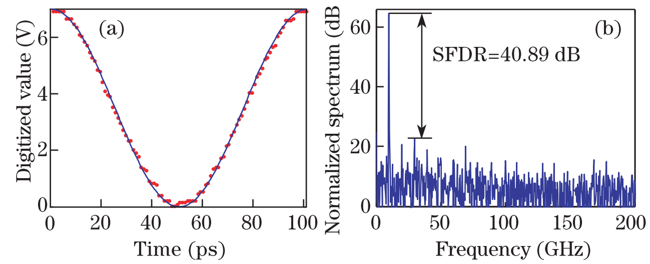

Fig. 6. Reconstructed signal and calculated FFT spectrum of the resolution-enhanced PSOQ. (The dots indicate the experimental data, and the solid line represents the sinusoidal fit result.)

33.42 dB without resolution enhancement. The ENOB and the SFDR are improved noticeably when a 2-bit ADC is used. However, compared with the analysis result in Fig. 3, the improvement is not obvious when a higher-resolution ADC, such as 3-bit, is used in enhancement.

The experimental result for the ENOB of the eight-channel PSOQ can be improved optimally to 4.31 bits using a 3-bit ADC. Figure 6(a) shows the reconstructed signal and the corresponding fitting result. The SFDR is 40.89 dB, as shown in Fig. 6(b). The ENOB exhibits an improvement of 0.66 bits, and the SFDR is increased by 7.47 dB. Further improvement in the result cannot be attained by using a 4-bit ADC. Based on the analysis results presented in Fig. 4, improving SNR detection is necessary to obtain higher ENOB and SFDR values. This result can be achieved by reducing the error of the phase shift or the integration of the system.

In conclusion, a resolution-enhancing encoding scheme using electrical ADC is presented and experimentally demonstrated. The results for the four-channel and eight-channel PSOQs exhibit obvious improvement when the proposed encoding scheme is applied. When eight quantization channels are used, the ENOB of 4.31 bits and the SFDR of 40.89 dB are achieved during the quantization of a 9.9 GHz analog signal, thus leading to an improvement of 0.66 bits and 7.47 dB, respectively.

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References

1. R. H. Walden, IEEE J. Selected Areas in Communications **17,** 539 (1999).
2. G. C. Valley, Opt. Express **15,** 1955 (2007).
3. Y. Dou, H. Zhang, and M. Yao, Chin. Opt. Lett. **10**, 123201 (2012).
4. J. Stigwall and S. Galt, IEEE Photon. Technol. Lett. **17,** 468 (2005).
5. H. Chi and J. Yao, Opt. Express **16,** 567 (2008).
6. W. Li, H. Zhang, Q. Wu, Z. Zhang, and M. Yao, IEEE Photon. Technol. Lett. **19,** 625 (2007).
7. Y. Wang, H. Zhang, Q. Wu, and M. Yao, IEEE Photon. Technol. Lett. **24,** 566 (2012).
8. L. Ma, Y. Zhang, H. Zhang, Y. Peng, and M. Yao, *Optical Fiber Communication Conference* (*OFC*) 1-3 (2011).
9. Y. Wang, Y. Dou, and H. Zhang, Chin. Opt. Lett. **11,** 042301 (2013).
10. P. E. Phillp and D. D Styer, Opt. Eng. **33,** 2638 (1994).
11. S. Yang, C. Wang, H. Chi, X. Zhang, S. Zheng, X. Jin, and J. Yao, Appl. Opt. **48,** 4458 (2009).
12. Y. Miyoshi, S. Namiki, and K. Kitayama, IEEE J. Selected Topics in Quantum Electronics **18,** 779 (2012).
13. B. E. Jonsson, *IEEE Electronics, Circuits, and Systems* (*ICECS*), *2010 17th IEEE International Conference* 768 (2010).
14. J. Stigwall and S. Galt, J. Lightwave Technol. **24,** 1247 (2006).