Experimental demonstration of 5-bit phase-shifted all-optical analog-to-digital converter

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A 5-bit photonic analog-to-digital conversion under a sampling rate of 10 Gs/s is experimentally demonstrated. In the experiment, the birefringence walk-off in the scheme is compensated, and 16 high-extinction ratio optical transfer functions with different phase shifts are obtained. A 1-GHz sinusoidal analog signal is sampled and quantized by optical processing, and the effective number of bits obtained is 4.17.

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All-optical analog-to-digital converters (ADCs) have received considerable attention because of their potential to realize high sampling rate and wide bandwidth[1]. Many different schemes of all-optical ADCs have been developed[2−6]. Recently, a 5-bit photonic ADC has been experimentally demonstrated based on nonlinear effects[7,8]. In previous studies[9,10], an ultra-fast all-optical ADC has been proposed based on polarization interference and phase-shifted optical quantization (PSOQ). Compared with the scheme in Refs. [7,8], no nonlinear effect is utilized, which has a great potential for low-power consumption and high-efficiency all-optical ADC. In PSOQ, the two polarization states of the sampling pulse exhibit a birefringence walk-off before interference because of the birefringence of the modulator and the fiber links. The effective number of bits (ENOB) degrades with increasing birefringence walk-off. To overcome this issue, we propose a scheme for reducing the birefringence walk-off in modulators with a polarization modulator (PM) instead of a $LiNbO_3$ phase modulator; the ENOB is improved in a 4-bit all-optical ADC[11]. Although some approaches used to compensate polarization mode dispersion in optical communication systems[12,13] can be employed to compensate for residual birefringence, the precision of the compensation is not high enough because accurately measuring the birefringence walk-off is difficult.

In this letter, we employ the spectrum of the polarization interference[14,15] to measure the walk-off precisely. The experimental result shows that the birefringence walk-off of the 5-bit PSOQ scheme can be eliminated using a PM and polarization-maintaining fiber (PMF) compensation. Sixteen high-extinction ratio-sampled transmission curves with different phase characteristics are obtained, which guarantee 5-bit all-optical quantizing. A 1-GHz sinusoidal electrical analog signal is then sampled and quantized, achieving an ENOB of 4.17.

Figure 1 illustrates the principle of 5-bit phase-shifted quantization. A 5-bit resolution ADC has an optical input port and 16 outputs. The sampling pulse is generated by a 10 GHz mode-locked fiber ring laser (ML-FRL) at 1 550 nm, with a pulse width of 11 ps. The orthogonal components of the sampling pulse are aligned with the x or y axis of PolM by a 45° polarizer. The phase differences between the two orthogonal polarization components are linearly changed with the amplitude of the input signal. The pulses are split into 16 channels behind the PolM, and each quantization channel has a transfer function with a phase shift of $(i-1)\pi/16$ (Fig. 1)[9], where i is the number of the channel. A polarization beam splitter is used as an analyzer to realize polarization interference. The output optical signal is detected by a photo-detector with a bandwidth of 50 GHz and captured by a sampling oscilloscope (Agilent 86100A).

In the experiment, given that the scheme is polarization sensitive, the fiber that links the devices of the system is a PMF. The birefringence of the PMF induces a walk-off between the two polarized states of the sampling pulse (Fig. 1). The extinction ratio of the polarization interference is degraded because of the walk-off, which causes a decline in ENOB. The PMF used in the experiment is Fujikura SM15-PS-U25A, which is fast axis aligned and whose beat length is 3–5 mm. Thus, the birefringence walk-off induced by PMF is 3.1–5.2 ps. To measure the walk-off precisely, the spectrum of the polarization interference technology is employed. In this technique, the walk-off of the system can be measured by the period of the transmission spectrum of the system. When the walk-off is reduced to zero, the periodicity of the transmission spectrum disappears[15]. Figure 2(a) shows the transmission spectrum of the system. As shown in the figure, the free spectrum range is 1.8 nm, which corresponds to a walk-off of 4.45 ps. Given that the fiber link is fast axis aligned, the walk-off can be compensated by slow axis-aligned PMF (S-PMF). In the experiment, when the S-PMF is 2.5 m, the periodic response in

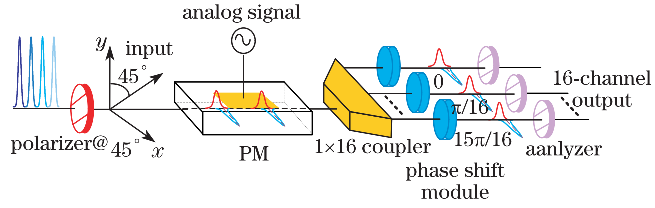

Fig. 1. Principle and configuration of PSOQ with a 5-bit resolution.

optical frequency disappears (Fig. 2(b)). This result indicates that the birefringence walk-off is eliminated.

After accurate compensation, a 5-bit photonic ADC is tested by a 1-GHz analog signal. In the experiment, one channel is implemented and used 16 times with different phase shift values to emulate the output of the 16-channel ADC system. The signal is amplified to 20.88 dBm and drives the PolM for quantization. The output power of the ML-FRL is 13 dBm, and the main optical power loss (6 dBm) is induced by the PM. Before polarization interference, the total power loss of the system is 9 dBm. The phase shift module is realized by a fiber squeezer. Then, 16 temporal outputs at phase shifts of 0, $\pi/16$, $2\pi/16$, $\cdots$, $14\pi/16$, and $15\pi/16$ are recorded on the oscilloscope, respectively. Six of these phase shifts are shown in Fig. 3.

The digital signal can be achieved by threshold decision and encoding. The threshold of each channel is set at half of the maximum output pulse. Thus, a digital "1" is obtained when the output pulse is higher than the threshold, whereas a digital "0" is obtained when the output pulse is lower than the threshold. According to these binary codes, the result could be obtained by plotting digital values (Fig. 4). A sinusoidal fit is also presented in Fig. 4. Comparing the quantized values with the fitted curve, a signal-to-noise ratio of 26.82 dB is obtained, corresponding to an ENOB of 4.17. Considering that the ideal resolution is 5 bits, the deviation from the ideal case is 0.83 bits. The quantization error is mainly caused by the noise induced by the fiber link, the inaccuracy of the phase shift, and the jitter of the sampling pulse.

In conclusion, a 5-bit all-optical ADC using PSOQ is experimentally demonstrated. In the experiment, by precise birefringence walk-off measurement and compensation, 16 sampled transfer functions with different phase characteristics are obtained, and an ENOB of 4.17 is realized in the quantization of a 1-GHz analog signal.

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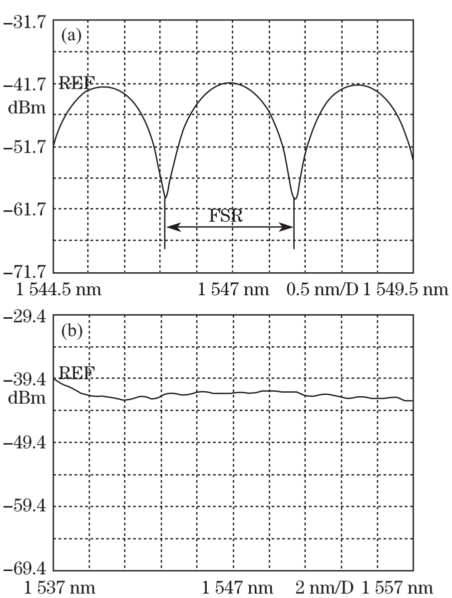

Fig. 2. Experimental transmission spectrum with different S-PMFs: (a) 0 and (b) 2.5 m.

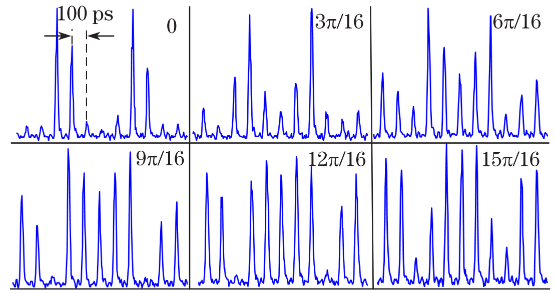

Fig. 3. Temporal shape of experimental outputs in one period.

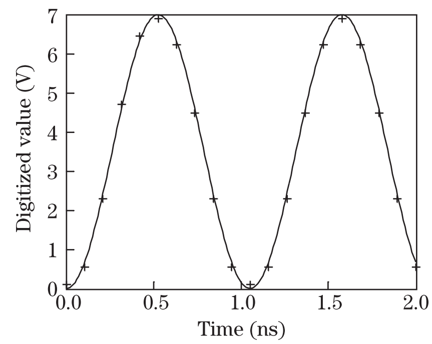

Fig. 4. Obtained digital results and corresponding fit. The dots represent the experimental data, and the solid line represents the sinusoidal fit.

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