Real-time Demonstration of optically resolution-enhanced ADC system using NOLMs

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Abstract

We firstly demonstrate real-time optically resolution enhanced ADC system using optical transfer functions of NOLMs at the sampling rate of 9.95 GS/s. The coarse power level of low-resolution ADC is interpolated by this scheme.

I. INTRODUCTION

The high-speed analog-to-digital converter (ADC) may find a wide variety of applications in the near future, including a front-end of digital signal processing (DSP) in ultra-high-speed optical communications [1]. In conventional electrical ADC, a multi-bit resolution over a sampling rate of 100 Giga-samples per second (GS/s) is difficult to realize due to timing jitter and limited comparator bandwidth [2]. Optical sampling and optical time-interleaving could be a potential break-through to overcome the speed bottleneck [2, 3]. However, to realize high resolution ADC, it is necessary to increase the number of optical time-interleaving and electrical ADCs, because the effective-number-of-bit (ENOB) resolution of electrical ADCs decreases in proportion to the logarithm of the signal bandwidth. We have proposed a resolution enhancement scheme using optical multi-period transfer functions of nonlinear optical loop mirrors (NOLMs) and demonstrated optical transfer functions of NOLMs [4]. In this paper, we firstly demonstrate a real-time operation of the optically resolution enhanced ADC system using optical input-output transfer functions of NOLMs with 4-bit ADCs at the sampling rate of 9.95 GS/s.

II. REAL-TIME DEMONSTRATION OF OPTICALLY RESOLUTION ENHANCED ADC SYSTEM

Figure 1 shows the experimental setup for real-time demonstration of resolution enhanced ADC. The input optical analog signal was generated by a Mach-Zehnder modulator (MZM) with 200-MHz sine wave, and was sampled by optical sampler based on degenerate four-wave mixing through the HNLF. We used a mode-locked fiber ring laser (ML-FRL) operating at the wavelength of 1561 nm and the repetition rate of 9.95 GHz to generate pump pulses for an optical sampler and a wavelength converter. The single mode fiber (SMF1) with total dispersion of +4.0 ps/nm was used to expand the temporal pulse width of control pulses up to 5.08 ps. We generated the probe pulses from the wavelength conversion of the signal pulses through the four-wave mixing with the continuous wave signal light at 1542.5 nm. The SMF2 with total dispersion of +2.0 ps/nm was used to compensation the linear chirp of probe pulses. The wavelength and temporal width of probe pulses were 1580 nm and 1.78 ps, respectively. The sampled analog signals and probe pulses were synchronously launched into the attenuator (ATT), NOLM1 and NOLM2. We use a HNLF1 and a PM-HNLF for NOLM1 and NOLM2, respectively. The fiber parameters are shown in table I. We adjusted the offset phase shift $\pi/2$ by the optical phase bias controller (OPBC). We measured the waveform of sampled analog signal and output signals

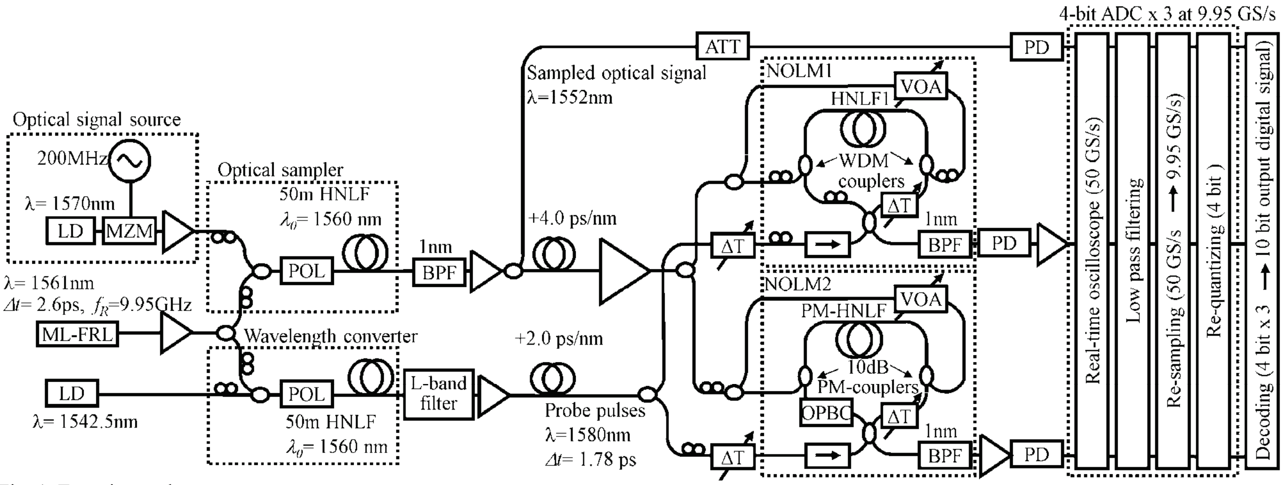

Fig. 1. Experimental set up.

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from ATT, NOLM1 and NOLM2 with PDs and real-time oscilloscope. The measured waveform was synchronously re-sampled with the probe pulse at the sampling rate of 9.95 GS/s. Figure 2 shows the optical input-output transfer function of NOLM1 and NOLM2 based on the re-sampled signals. The solid lines are calculated approximate transfer functions based on least absolute deviation estimation from the data points.

To assume low-resolution ADCs, the re-sampled signals from ATT, NOLM1, and NOLM2 were re-quantized into 4-bit digital signals P_{ATTD}, P_{N1D}, and P_{N2D}, respectively. The three 4-bit signals were converted into 10-bit digital signal by a decoder.

The conversion table of the decoder was set to minimize a total error E_T at the each combination of P_{ATTD}, P_{N1D}, and P_{N2D}. The total error E_T was

$$E_T\left(P_{ATTD}, P_{N1D}, P_{N2D}, D_{OUT}\right) = \sqrt{\Delta P_{ATT}{}^2 + \Delta P_{N1}{}^2 + \Delta P_{N2}{}^2}, \quad (1)$$

$$\Delta P_{ATT} = P_{ATTD} - P_{ATTREF}\left(D_{OUT}\right), \quad (2)$$

$$\Delta P_{N1} = P_{N1D} - P_{N1REF}\left(D_{OUT}\right), \quad (3)$$

$$\Delta P_{N2} = P_{N2D} - P_{N2REF}\left(D_{OUT}\right), \quad (4)$$

where the P_{ATTREF} is the transfer function of ATT. Here, we assumed that the P_{ATTREF} is ideal linear transfer function. The P_{N1REF} and P_{N2REF} are the approximate transfer function of NOLM1 and NOLM2, as shown in Fig. 2, respectively. Figure 3 shows the real-time waveform of decoded 10-bit signal from 4-bit digital signals with the sampling rate of 9.95 GS/s. Figure 4 shows the equivalent-time sampled waveform of re-sampled signal, re-quantized 4-bit signal and decoded 10-bit signal based on 4000 points sampled at 9.95 GS/s. The coarse power level by re-quantizing was interpolated by decoding. However, the decoded signal had spike-shape noise. The signal to noise ratio (SNR) of re-sampled signal, re-quantized 4-bit signal and decoded 10-bit signal were 23 dB, 20 dB, and 15 dB. The degradations of waveform and SNR were caused by the noises in the output signals of NOLM1 and NOLM2.

III. Conclusions

We have demonstrated real-time optically resolution enhanced ADC system using optical transfer functions of NOLMs. The coarse power level of low resolution ADC has been interpolated by the resolution enhancement scheme. However, the decoded signal has been degraded by noises in NOLMs. This problem will be improved by taking into the noises for setting the coding table.

References

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TABLE I
FIBER PARAMETERS.

	HNLF1	PM-HNLF
Zero dispersion wavelength [nm]	1575	1568
Dispersion slope [ps/km-nm^2]	0.03	0.02
Loss [dB/km]	0.67	2.7
Length [km]	0.39	0.5
Nonlinearity [W^{-1}km^{-1}]	11.5	11.0

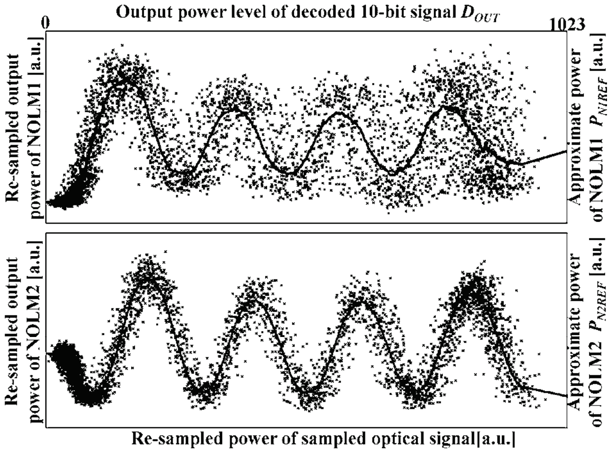

Fig. 2. Optical input-output transfer functions of NOLM1 and NOLM2.

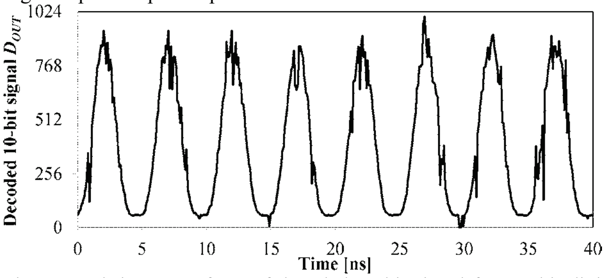

Fig. 3. Real-time waveform of decoded 10-bit signal from 4-bit digital signals with the sampling rate of 9.95GS/s.

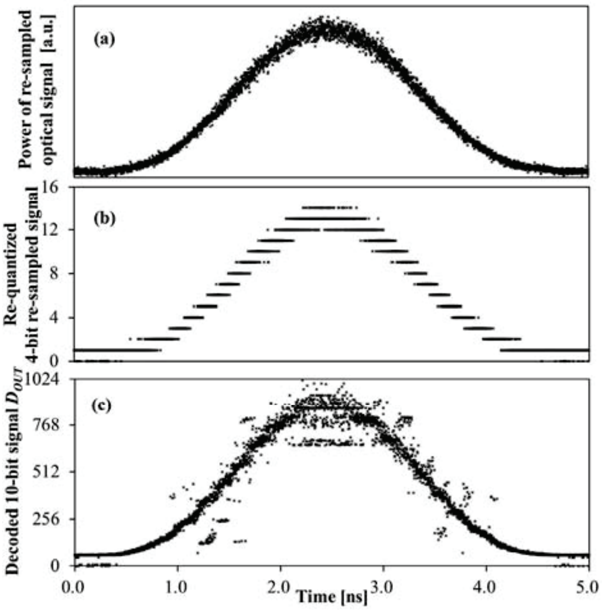

Fig. 4. Equivalent-time sampled waveform based on 4000 point sampled at 9.95 GS/s. (a)Re-sampled signal. (b)Re-quantized 4-bit re-sampled signal. (c)Decoded 10-bit signal.