130-GSa/s Photonic Analog-to-Digital Converter With Time Stretch Preprocessor

A. S. Bhushan, P. V. Kelkar, B. Jalali, O. Boyraz, and M. Islam

***Abstract*—In this letter, we demonstrate a photonic analog-to-digital converter with time stretch (TS) preprocessor that has a sampling rate of 130 GSa/s. The system has a signal-to-noise ratio (SNR) exceeding seven effective number of bits over a 1-GHz bandwidth at 18 GHz. We present an analytical model of the SNR in the TS preprocessor which shows that over the specified bandwidth, the SNR is limited by the amplified spontaneous emission beat noise.**

***Index Terms*—ADC, analog-to-digital conversion, digital receiver, optical signal processing, time stretch.**

IN DIGITAL RECEIVERS for radar and communication systems the signal is digitized directly at the microwave frequency eliminating the need for analog down conversion stages. Processing the signal in the digital domain leads to higher performance as well as the ability to rapidly reconfigure the system. The analog-to-digital converter (ADC) is the major bottleneck in realizing the digital receiver. While being continuously improved, electronic ADCs cannot fulfill the stringent sampling rate and input bandwidth requirements needed in a digital receiver. To boost the capability of the available electronic ADCs, various approaches based on photonics have been demonstrated [1]–[6]. Time stretch (TS) preprocessing is one such powerful technique that will enhance the performance of electronic ADCs, [4], [6]. Compared to the time-interleaved wavelength-division sampling [1], [3], [5], Time stretch processing allows us to capture a time-limited waveform with a single ADC, thereby eliminating the well-known channel mismatch problem that plagues time interleaved parallel ADCs. In this approach, the analog signal is imposed on a chirped optical carrier using an electrooptic modulator. This time-to-wavelength mapped signal is then dispersed, and hence, stretched in time prior to digitization by the electronic ADC. The time stretching increases the effective sampling rate and input bandwidth of the ADC. An increase in the sampling rate of more than eight-folds has previously been demonstrated, [4]. In previously published work, we have reported a sampling rate of 30 GS/s and a stretch factor of 3.75. In this paper, we use a specially tailored supercontinuum source to boost system performance to 130 Gsa/s and a stretch factor of more than 16. The system can sample an electrical sine wave at 18 GHz with an SNR of approximately 45 dB (seven ENOB). To the best of our knowledge, this system performance is a world record. We present the first analysis of the SNR in a TS system and show that the calculated SNR value is close to the experimentally achieved value. The analysis assumes that the supercontinuum process causes no significant degradation of the carrier-to-noise ratio (CNR).

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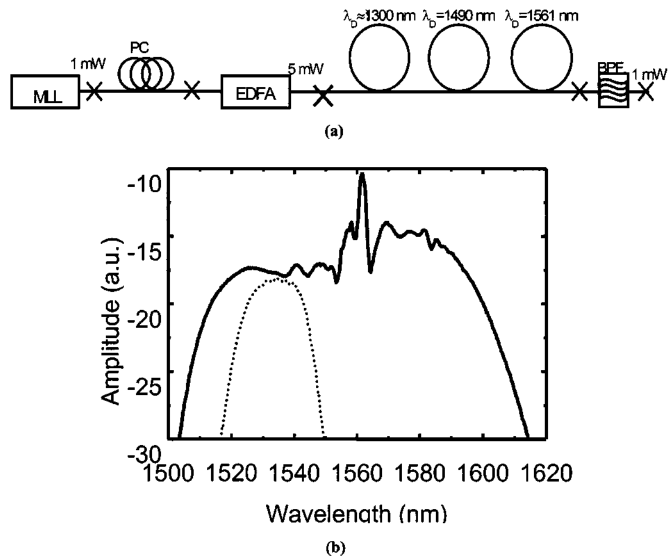

Fig. 1. (a) The setup for generating an optical supercontinuum. MLL: Mode-locked laser. EDFA: Erbium-doped fiber amplifier. BPF: Bandpass filter. (b) The optical spectrum generated by the supercontinuum module. The dotted line is the slice used in the TS system.

The TS preprocessor makes use of supercontinuum source to provide broadband optical pulses. The setup for generating the supercontinuum is shown in Fig. 1(a). A passively mode-locked fiber laser with 20-MHz repetition rate 1-mW average output power and output pulse width of 180 fs is used. The output is passed through a polarization controller (PC) before being amplified to 5 mW. The supercontinuum module consists of three stages. The length of the first SMF stage (λ_D ≈1300 nm) is required to be half the length of the soliton period to achieve maximum pulse compression and spectral broadening, [7]. The calculated length of SMF is used initially for the first stage. Adjustments to the length are done to optimize the spectrum. Once the length of this stage is fixed a similar procedure is followed for the second stage which has dispersion shifted fiber with $\lambda_D = 1490$ nm [8], [9]. The length of the third stage ($\lambda_D = 1561$ nm) is fixed to obtained maximum spectral width. The supercontinuum spectrum before the bandpass filter is shown in Fig. 1(b) with solid line. The filtered portion of the supercontinuum spectrum used in the experiment is shown in

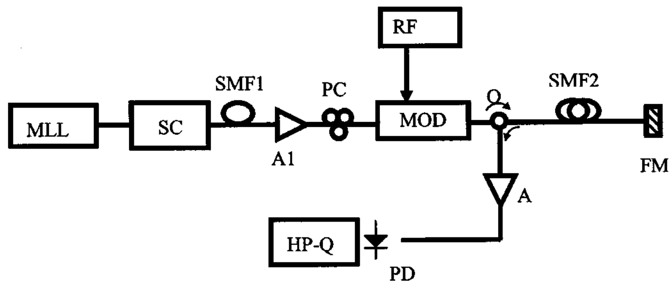

Fig. 2. The TSADC system. The electronic digitizer is an Agilent digital real-time oscilloscope. MLL: Mode-locked laser. SC: Supercontinuum module, SMF1 and SMF2: spools of SMF28 fiber. PC: Polarization controller. MOD: Modulator. OC: Optical circulator. FM : Faraday mirror. PD: Photodetector. RF: rf source. EDFAs (A1 and A2).

Fig. 1(b) with dotted line. The filtered spectrum is centered at 1533 nm and it has 1-dB bandwidth of 17 nm. There is 1 mW of average power in this portion of the supercontinuum.

The setup for the 130-Gsa/s TS system is shown in Fig. 2. We start with a nearly transform-limited 17-nm slice filtered from the supercontinuum source. This slice is dispersed through a single-mode fiber (SMF-28) of length $L_1 = 2.7$ km. This first dispersion provides a time aperture of approximately 0.8 ns at the modulator. The chirped optical pulse is amplitude modulated with an 18-GHz tone in a Mach–Zehnder (MZ) modulator. The modulation depth is 25%. The LiNbO3 modulator limit and the bandwidth of the digitizer set the maximum achievable RF frequency of our system. Dispersing the waveform a second time through a length $L_2 = 41.12$ km stretches the modulation envelope in time. The second dispersion stage is implemented using an $L_2/2$ length of SMF28 along with a circulator and a Faraday mirror as shown in Fig. 2. The stretch factor (M) is given by the ratio $M = (D_1 L_1 + D_2 L_2)/D_1 L_1 = 16.2$, [4]. Here, D_1 and D_2 are the total dispersion in the first and second fiber, respectively. The effective sampling rate for the TSADC is, therefore, 129.6 GSa/s. The stretched envelope at 1.11 GHz is detected and digitized by a single 8-GSa/s 1.5-GHz bandwidth channel of the Agilent 54 845A Infinium Oscilloscope. The digitizer has eight nominal bits of resolution. Attempt was made to match the full scale of the digitizer with the peak-to-peak signal. Exact match could not be assured however because the slight variation of the supercontinuum intensity over the filtered range [see Fig. 1(b)] increases the signal dynamic range beyond the peak-to-peak voltage swing. The post-stretched time aperture for the system is 13 ns providing a duty cycle of $13 \text{ ns}/50 \text{ ns} = 0.26$. The dispersion penalty in the system is given by $10\text{Log}(\cos^2(\phi))$, where ϕ is given by the following [10].

$$\phi = \omega_m^2 \beta_2 \frac{L_2}{2M}$$

Here, ω_m is the modulation frequency and β_2 is the group velocity dispersion parameter. In this system, the dispersion penalty is −0.55 dB.

The digitized output (symbols) is shown in Fig. 3 along with an ideal sine curve (solid line). The bandwidth is limited to 1 GHz (prestretch) around 18 GHz using a digital filter. Based on the standard sine-fit method, [11], the signal-to-noise ratio (SNR) is 45.2 dB, which translates to 7.2 effective number of

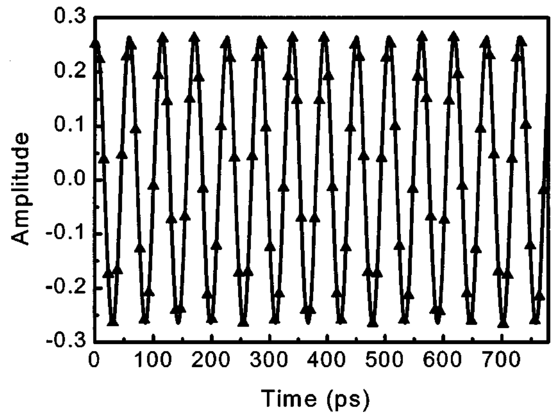

Fig. 3. The RF signal captured by the TSADC. The points are digitized samples and the solid line is the theoretical sine fit.

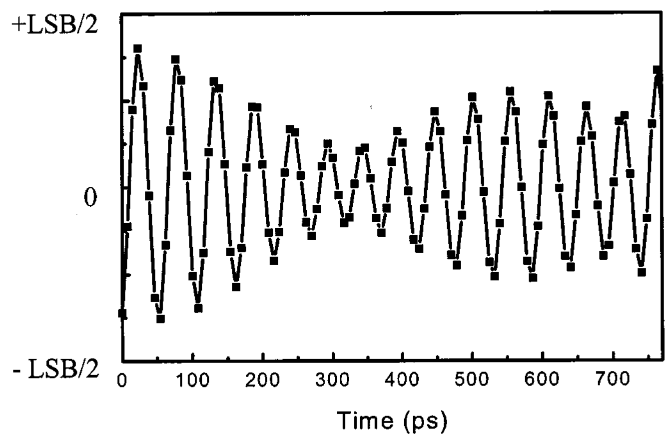

Fig. 4. Error between the sampled data and the ideal sine curve. One LSB is equal to the peak-to-peak voltage divided by 128 (2^7).

bits $(\text{ENOB} = (\text{SNR} - 1.76)/6.02)$. Performing this test over 141 optical pulses yields a resolution of 7.16±0.6 bits.

Fig. 4 shows the the error between the sampled signal and the ideal sine curve plotted in the range $-\text{LSB}/2$ to $+\text{LSB}/2$. One LSB is defined as the peak-to-peak voltage divided by 128 (2^7). The maximum error is approximately ±0.375 LSB, suggesting that the TSADC has a SNR corresponding to slightly better than seven ENOB of resolution.

We note that this system is operating in a suboctave range and the single tone measurements are not indicative of system linearity. The primary source of harmonic distortion in the TS preprocessor is the sinusoidal transfer function of the MZ modulator. When biased at the quadrature point, the primary source of nonlinearity is the third-order harmonic. If P_{av} is the average optical intensity at the output of the quadrature biased modulator and $mP_{\text{av}} \cos(\omega_{\text{rf}} t)$ is the RF signal at the output, then we can show that the SFDR is given by $576/m^4$, [12]. For this system $m = 0.25$, which translates to an SFDR of 51.6 dB.

To understand the fundamental performance limit of the TSADC, we model the system as an amplified optical link shown in Fig. 5. We note that invoking this model implies that the CNR remains the same at the input and output of the supercontinuum fiber. In other words, the supercontinuum fiber is modeled as passive element with negligible attenuation. In Fig. 5, L denotes the loss, G denotes the amplifier gain, and F

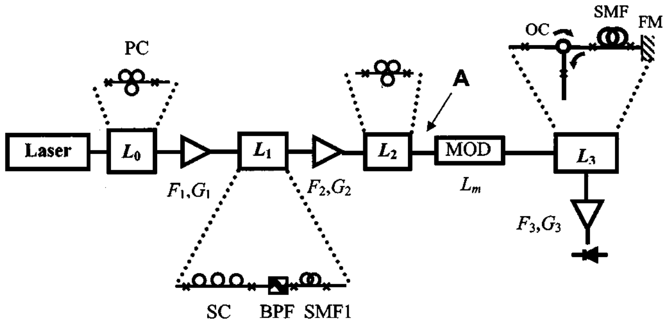

Fig. 5. Link model of the TSADC consisting of amplifiers and loss elements.

represents the amplifier noise figure. $L_0 = 0.4$ dB is the loss of two connectors (0.2 dB each. $L_1 = 9.1$ dB is the total loss of the bandpass filter (7.5 dB), 2.7 km of SMF28 used to create the linear chirp (0.8 dB) and four connectors). The loss of the bandpass filter includes 7 dB due to spectrum slicing plus 0.5 dB of insertion loss. $L_2 = 0.4$ dB and $L_m = 9$ dB consists of the insertion loss of the modulator (6 dB) and 3 dB due to the quadrature bias condition. $L_3 = 15.3$ dB is the sum of the losses due to six connectors, the optical circulator (0.6-dB single pass loss), faraday mirror insertion loss (0.6 dB) and the loss due to 41.1 km of SMF28 (12.3 dB). All the EDFAs are assumed to have a noise figure $F = 6$ dB. The gain G_1 is 7 dB, while G_2 is 15 dB.

The carrier power at point A in Fig. 5 is given by, $P_A = P_{\rm av} L_0 G_1 L_1 G_2 L_2 (T_{\rm rep}/T_{\rm mod})$

Here $P_{\rm av} = 1$ mW is the average power of the MLL, $T_{\rm rep} = 50$ ns is the laser repetition period, and $T_{\rm mod} = 0.8$ ns is the pre-stretch time aperture at the modulator. At the photodetector the modulated signal power is $P_{\rm out} = m P_{\rm av} L_m L_0 G_1 L_1 G_2 L_2 G_3 L_3 (T_{\rm rep}/T_{\rm ap})$. Here, $T_{\rm ap} = 13$ ns is the poststretch time aperture.

The ASE noise spectral power density at point A is given by $N_1 L_1 G_2 L_2 + N_2 L_2$. Here N_1 and N_2 are the power spectral density of the ASE from the first and second EDFAs, respectively. At the output the noise spectral density

$$N_{\rm out} = N_1 L_1 G_2 L_2 G_3 L_3 L_m + N_2 L_2 G_3 L_3 L_m + N_3.$$

Given an electrical bandwidth B_e the SNR at the output

$$SNR_{\rm out} = \frac{m^2}{8B_e}\frac{P_{\rm out}}{N_{\rm out}} = \frac{\left(\frac{m^2 P_{\rm av}\left(\frac{T_{\rm rep}}{T_{ap2}}\right) L_0}{4B_e h\nu}\right)}{\left(F_1 + \frac{F_2}{G_1 L_1} + \frac{F_3}{G_1 L_1 G_2 (L_2 L_3 L_m)}\right)}$$

In the above expression, we have used $N = GFh\nu/2$. Here, $h\nu$ is the photon energy. The numerator evaluates to 68 dB, whereas the denominator is 18.5 dB, suggesting thus $SNR_{\rm out} = 49.5$ dB, in reasonable agreement with the experimental value of 45.2 dB.

In summary, we have demonstrated a novel ADC system based on the photonic TS preprocessing technique. The ADC boasts 130 Gsa/s with seven ENOB of SNR over a 1-GHz bandwidth. We also analyze the system performance by assuming that the CNR degradation due to supercontinuum generation is negligible. The calculated system SNR (49 dB) is very close to the experimental SNR (45 dB) validating our analytical approach. The results demonstrate the potential for attaining revolutionary improvement in the performance of electronic ADCs by using advanced photonic techniques.

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