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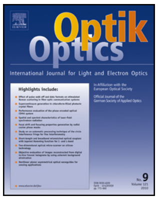

Photonic time-stretch analog-to-digital converter employing envelope removing technique

Xinggang Xie[a,*], Xiaoli Yin[a,b,c], Sha Li[b], Li Li[a,c], Xiangjun Xin[a], Chongxiu Yu[b]

[a] School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[b] State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
[c] Beijing Key Laboratory of Work Safety Intelligent Monitoring, Beijing University of Posts and Telecommunications, Beijing 100876, China

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ABSTRACT

The previously proposed differential time-stretch preprocessor can eliminate the distortions induced by the non-uniformity of optical pulse and the pulse-to-pulse variations of the optical source. However, the time-delay element in this method reduces the processing speed of the system. In this paper, we propose an envelope removing technique to mitigate these distortions and improve the time efficiency of time-stretch system simultaneously. To verify the feasibility of this technique, a comprehensive mathematical model for this technique is developed and numerical simulation is also presented. Simulation results show that this method can effectively eliminate non-uniformity and pulse-to-pulse variations in time-stretch system. This method has two times faster processing speed than the differential time-stretch preprocessor.

1. Introduction

It is widely recognized that the analog-to-digital converter (ADC) plays an important role in modern communication systems. However, the performance of ADC has become the major bottleneck that cannot fulfill the sampling rate and input bandwidth requirements needed in today's high-speed applications. Various photonic techniques have been proposed to extend performance of conventional electronic ADCs [1–5]. One of these techniques called time-stretch proposed by Jalali research group is using the dispersion effect to slow down radio-frequency (RF) signal prior to sampling and quantization by an electronic digitizer [3,5]. In this manner, the effective sampling rate and the input bandwidth of the ADC are increased in proportion to the stretch factor M [3]. This parameter is determined by two individual fibers used in time-stretch system. This technique has successfully achieved 150GS/s real-time sampling rate [6] and monitored 100Gb/s RZ-DQPSK signal [7]. Conceptually, the time-stretch technique consists of the following steps [8,9].

(1) Time-to-wavelength mapping occurs when the RF signal is intensity modulated on a linear chirped optical pulse, which is dispersed in the first fiber.
(2) Wavelength domain processing occurs when the modulated signal travels through the second fiber.
(3) Wavelength-to-time mapping occurs when the modulated signal detected by a photodetector (PD).

Slowing down the signal prior to digitization is an improvement in analog-to-digital technique, however, the non-uniformity of the optical pulse and pulse-to-pulse variations induced by the optical source in time-stretch system are big challenges which will distort the stretched electrical signal [3,9]. A differential photonic time-stretch technique has been proposed to mitigate these distortions [10]. However, the time-delay element sacrifices the time efficiency to improve the performance of the time-stretch system. In this paper, we propose an envelope removing technique that not only eliminates the non-uniformity and pulse-to-pulse variations in time-stretch analog-to-digital converter but also increases the processing speed of the system.

The paper is organized as follows. System description is given in Section 2. Theoretical analysis and mathematical model of time-stretch combining with envelope removing technique are presented in Section 3. Simulation results are given in Section 4. In Section 5, the conclusion is provided.

2. System schematic

The system schematic of time-stretch A/D converter combining with envelope removing technique is demonstrated in Fig. 1. An ultra-short optical Gaussian pulse is chirped and broadened after

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* Corresponding author. Tel.: +86 18801025513.
E-mail addresses: xiexinggang@gmail.com, xiexinggang@aliyun.com (X. Xie).

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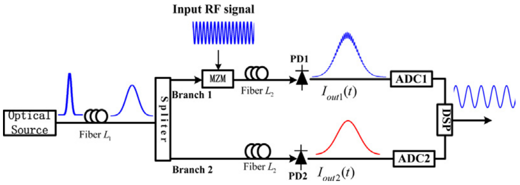

Fig. 1. Schematic of the time-stretch A/D converter employing envelope removing technique.

propagating through the first fiber. Then a parallel architecture is used to split the chirped optical pulse into two channels. The pulse in the upper channel can be used as a window to capture the high-speed RF signal to implement time-to-wavelength transformation, then the modulated chirped waveform is dispersed in the second fiber. The other pulse in the lower channel keeps traveling through the second fiber without modulation that experiences the same effect like that in the first fiber before the splitter. Finally, the two pulses in each channel are sampled by ADCs, respectively. The outputs of the parallel channels are processed by envelope removing algorithm. After these processes, the stretched RF signal is obtained and at the same time the non-uniformity and pulse-to-pulse variations in time-stretch system is also eliminated.

3. Mathematical model

To analyze this method, a comprehensive mathematical model for the time-stretch and envelope removing technique will be demonstrated in this section. As an example, assuming that the optical pulse has a large bandwidth with a Gaussian envelope which can be represented as [9]

$$E_1(t)=\sqrt{2}E_0\exp\left(-\frac{1}{2}\left(\frac{t}{T_0}\right)^2\right) \tag{1}$$

where T_0, $\sqrt{2}E_0$ is the full width at half maximum of the pulse and the pulse amplitude, respectively.

After propagating through the first fiber with length L_1 the chirped optical pulse is split into two channels. The spectrum of the pulse in the upper channel can be expressed as [11]

$$E_2(\omega)=\frac{1}{\sqrt{2}}E_1(\omega)\exp\left(\frac{1}{2}j\beta_2\omega^2L_1\right) \tag{2}$$

where β_2 is the second-order group-velocity dispersion (GVD) parameter, since the dispersion-induced power penalty and harmonic distortion in the time-stretch are mainly caused by β_2 we neglect the higher order nonlinear dispersion terms.

For simplicity, assuming the optical pulse is modulated by a cosine RF signal

$$S_{\mathrm{RF}}(t)=V\ \cos(\omega_{\mathrm{RF}}t) \tag{3}$$

where V, ω_{RF} is the amplitude and angular frequency of the RF signal, respectively. After modulated by a push–pull Mach–Zehnder modulator (MZM), the output becomes [9]

$$E_3(t)=E_2(t)\ \cos\left[\frac{\pi}{4}+\frac{m}{2}\ \cos(\omega_{\mathrm{RF}}t)\right] \tag{4}$$

where $m=\pi V/V_\pi$ is the modulation index and V_π is the half-wave voltage of the MZM.

While propagating through the second fiber with length L_2, the modulated chirped signal is dispersed and the spectrum of the signal before entering the PD becomes [9]

$$E_4(\omega)=E_3(\omega)\exp\left(\frac{1}{2}j\beta_2\omega^2L_2\right) \tag{5}$$

Finally, the output photocurrent of PD1 can be approximately written as [9]

$$I_{\mathrm{out1}}(t)=I_{\mathrm{Env}}(t)\left[\begin{array}{l}1-m\cos(\phi_{\mathrm{DIP}})\cos\left(\dfrac{\omega_{\mathrm{RF}}}{M}t\right)\\[2ex] +\dfrac{m^2}{8}(1-\cos(4\phi_{\mathrm{DIP}}))\cos\left(2\dfrac{\omega_{\mathrm{RF}}}{M}t\right)\\[2ex] +\cdots\end{array}\right] \tag{6}$$

where

$$I_{\mathrm{Env}}(t)=\frac{1}{2}KE_0^2\frac{1}{\left(1+\left((L_1+L_2)^2/(T_0^2/\beta_2)^2\right)\right)^{1/2}}$$
$$\times\exp\left(-\frac{t^2}{T_0{}^2\left(1+\left((L_1+L_2)^2/(T_0^2/\beta_2)^2\right)\right)}\right)$$

is the static photocurrent when $m=0$ and K is a constant coefficient [9], the stretch factor $M=1+L_2/L_1$ is independent of β_2 as long as the two fibers have identical dispersion characteristics. $\phi_{\mathrm{DIP}}=(1/2)(\beta_2L_2/M)\omega_{\mathrm{RF}}^2$ is the dispersion induced phase (DIP).

The second term in Eq. (6) is the desired time-stretched signal, and the following terms describe undesired harmonics of it. The desired signal contains a frequency-dependent attenuation represented by $\cos(\phi_{\mathrm{DIP}})$ term which plays an important role in the stretched signal. Detailed analysis will be provided in Section 4.

Compared with the evolution in the upper channel, the pulse in the lower channel simply experiences the linear dispersion effect characterized by the GVD parameter β_2. Due to the similarity effect between the two channels, the photocurrent after PD2 is in proportion to the envelope function of $I_{\mathrm{out1}}(t)$ which can be expressed as follows:

$$I_{\mathrm{out2}}(t)=2I_{\mathrm{Env}}(t) \tag{7}$$

In the case when the modulation index m is small, the harmonics distortion in Eq. (6) can be neglected. So the stretched RF signal is approximately attained using the following algorithm:

$$s_{\mathrm{RF}}(t)=k\frac{2I_{\mathrm{out1}}(t)-I_{\mathrm{out2}}(t)}{I_{\mathrm{out2}}(t)} \tag{8}$$

where k is a coefficient that is relevant to the modulation index m and dispersion induced phase ϕ_{DIP}.

In Eq. (8) the subtraction operation removes the direct current (DC) component and the division operation removes the envelope and eliminates the unwanted non-uniformity simultaneously.

4. Simulation and discussion

To verify the feasibility of the method we proposed, a numerical simulation is performed. Fig. 1 shows the system schematic of the photonic time-stretch A/D converter combined with envelope removing technique. The two fibers used in the time-stretch system have the same parameters $\beta_2=-20\,\mathrm{ps}^2/\mathrm{km}$, nonlinear coefficient $\gamma=2.1\,(\mathrm{W}^{-1}\,\mathrm{km}^{-1})$. The first fiber has a length of $L_1=1\,\mathrm{km}$ which creates a chirped optical pulse. By using the second fiber with a length of $L_2=19\,\mathrm{km}$, the stretch factor is $M=(L_1+L_2)/L_1=20$. The input laser peak power is $P_0=2E_0^2=1\,\mathrm{W}$.

In Fig. 2, the solid curve is the envelope of the stretched modulated optical pulse signal and the dashed curve represents the amplitude of the optical pulse without modulation in the lower channel. The RF signal is a 100 GHz cosine signal and the modulation index is $m=5\%$. Simulation results show both the envelopes of the signals in two channels experience the same stretch factor as traveling through the two fibers. Finally, the RF signal carried by the chirped optical pulse is slowed down and subsequently recovered using the algorithm described by Eq. (8).