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Experimental demonstration of impact of optical nonlinearity on photonic time stretched analog-to-digital converter based on photonic crystal fiber

Sha Li[a,*], Chongxiu Yu[b], Zhe Kang[b], Shuai Wei[b], Gerald Farrell[c], Qiang Wu[c]

[a] School of Computer & Communication Engineering, University of Science & Technology Beijing, Beijing, China
[b] State key laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, China
[c] Photonic Research Centre, Dublin Institute of Technology, Dublin, Ireland

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ABSTRACT

Photonic time stretched analog-to-digital converter (PTS-ADC) utilizes a broadband optical source and dispersion medium to expand the capabilities of electrical digitizers, achieving real-time sampling with high resolution. In order to minimize used fiber length and simplify PTS-ADC equipment, large dispersion photonic crystal fiber (PCF) is used as dispersion medium. In this letter we demonstrated the impact of optical nonlinearity on PTS-ADC based on large dispersion PCF performance as compared with single mode fiber (SMF) and dispersion compensation fiber (DCF). It is stimulated that dispersion penalty null frequency of fundamental tone will shift using three fibers when nonlinearity is added. In comparison, SMF is most insensitivity by changing input optical power, then PCF. However PCF is most insensitive by changing pulse width. Meanwhile, PCF is best to suppress 3rd-order harmonic distortion according to carrier-to-interference ratio (CIR) in three fibers. PCF is the most suitable as broadening medium in PTS-ADC.

1. Introduction

Analog-to-digital converter (ADC) plays a vital role in digital signal processing (DSP). Internet communication needs ADC that has high-resolution, high-bandwidth and high-capacity recently. High-quality ADC is used in military systems, biomedical imaging and industrial applications [1–5]. In military, the United States of America's Defense Advanced Research Projects Agency has made a project about high-speed photoelectric ADC technology recently.

As one of primary ADC schemes in international, Prof. Jalali group researches photonic time-stretch analog-to-digital converter (PTS-ADC) that can provide continuous digitization of ultrahigh-bandwidth electrical signals with high resolution, which cannot be achieved by electronic ADC [6–9]. The signal is modulated on time stretched optical pulses by Mach–Zehnder modulator, and then the modulated optical pulses are further stretched in another fiber. In their schemes, dispersion compensation fiber (DCF) is used to provide a large dispersion-to-loss ratio with minimal phase distortion over a wide optical bandwidth in PTS-ADC. However, photonic crystal fiber (PCF) is a highlight in photoelectron field because of nearly ideal controllable dispersion and high nonlinear, strong birefringence effect, ultra-long distance transmission [10–18]. PCF gets different effect through devising its structure. For example, designed PCF with large dispersion shows high negative dispersion coefficient, providing about 10 times dispersion compensation than DCF [19–27]. When multiple wavelength channels PTS-ADC is employed, intensity modulated optical pulses with high peak power are required. However, when high power pulses propagate inside fiber, both optical nonlinearity and dispersion influence the shape and spectrum of optical pulses.

In this paper, we discuss the impact of optical Kerr nonlinearity on the performance of the PTS-ADC. The nonlinear interaction of the optical field is numerically simulated by the split-step Fourier method. In the system, SMF, DCF and PCF are used as dispersion medium, respectively. We stimulate dispersion penalty of fundamental tone and 3rd-order harmonic distortion versus the frequency of the radio frequency (RF) signal for SMF, DCF and PCF. Moreover, dispersion null frequency versus optical power and optical pulse width for different fibers are stimulated. We show that carrier-to-interference ratio (CIR) of the PTS-ADC versus the frequency of the RF signal for the three fibers, PCF is best to suppress 3rd-order harmonic distortion.

* Corresponding author. Tel.: +86 18612254947.
E-mail address: shalee@ustb.edu.cn (S. Li).

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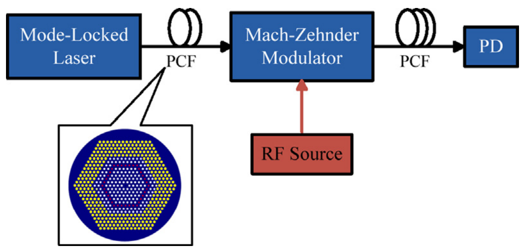

Fig. 1. Block diagram of the PTS-ADC based on large dispersion PCF. Insert diagram is transverse cross-section of the large dispersion PCF.

2. Photonic time-stretch analog-to-digital converter based on large dispersion PCF

The PTS-ADC stretches the RF signal in time by employing a broadband optical source, the PTS-ADC scheme is illustrated in Fig. 1. A mode-locked laser as a broadband optical source follows a segment of PCF as dispersion medium. The RF signal is modulated on the stretched optical pulses using Mach–Zehnder modulator. The modulated optical pulses are further stretched in another segment of PCF in time. In order to minimize used fiber and simplify device, large dispersion PCF is used as dispersion medium with minimal phase distortion. In the scheme, the PCF constitutes of three different air-hole diameters, as shown in Fig. 1, $d_1 = 0.609\,\mu m$ is shown by white color, $d_2 = 0.407\,\mu m$ is shown by red color and $d_3 = 0.825\,\mu m$ is yellow color. The air-holes are regularly spaced in a hexagonal array with a lattice constant $\Lambda = 1.375\,\mu m$. The PCF has a very high negative dispersion coefficient −1400 ps/nm/km at 1520 nm. Simulation results show the PCF with 1.14 km can compensate for the dispersion accumulated in a span 80 km of SMF and accumulate negative dispersion which DCF with 16 km achieves. Meanwhile, nonlinear coefficient of the PCF is only 2.21/W/km at 1520 nm [23,24].

In order to operate multiple wavelength channels, it is desirable to utilize high optical power in the PTS-ADC system. However, high intensity causes the pulse propagation to deviate from the linear regime. Therefore, it is imperative to consider the effect of fiber nonlinearity (Kerr effect) on the performance of the PTS-ADC. The basic equation that governs the propagation of optical pulses in the presence of dispersion and optical nonlinearity is the nonlinear Schrodinger equation (NLSE) [28]:

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial z^2} = -\frac{\alpha}{2}A + i\gamma\left|A\right|^2 A \quad (1)$$

where α is the attenuation constant, β_2 is the second derivative with respect to angular frequency of the modal wave number, γ is the nonlinear coefficient related to the nonlinear index, A is the slowly varying envelope proportional to the optical field. Equation has been successful in explaining a large number of nonlinear effects, self-phase modulation and four-wave mixing, which are the main causes of nonlinear optical distortions in the PTS-ADC.

To suppose that optical pulse is Gaussian with pulse width T_0 and power P_0 at beginning. After the first segment of PCF with length L_1 and group velocity dispersion (GVD) parameter β_2. The envelope is given by in time

$$A_c(z,t) = \sqrt{\frac{P_0 T_0}{T(z)}} e^{i\varphi(z,t)} e^{-t^2/T^2(z)} \quad (2)$$

where $T(z) = T_0\sqrt{1+\left(z/L_D\right)^2}$ and $\varphi(z,t) = \varphi_L(z,t) = -\left(zt^2/L_D/\left(2T^2(z)\right)\right) + \left(1/2\right)\tan^{-1}\left(z/L_D\right)$, L_D is dispersion length, t is time and z is propagation distance. After the first PCF, the optical pulse envelope maintains Gaussian profile because of weak nonlinearity. In the second PCF, nonlinear phase is added that effect on RF signal in equation [29,30]:

$$\varphi(z,t) = \varphi_L(z,t) + \varphi_{NL}(z,t) \quad (z > L_1)$$
$$\varphi_{NL}(z,t) = \int_{L_1}^{z} \gamma\left|A_c\left(z',t\right)\right|^2 dz' \quad (3)$$

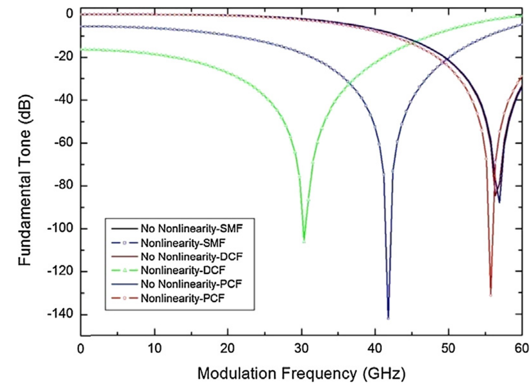

Fig. 2. Dispersion penalty of the fundamental tone for SMF, DCF and PCF as dispersion medium.

3. Simulations and results

The PTS-ADC configuration is shown as Fig. 1. The first fiber is used to stretch optical pulses to suitable time aperture and the second fiber is adopted to stretch modulated optical pulses in time, respectively. Through designing the length of two fibers, a stretched factor of 10 is easily provided. The sinusoidal transfer function of the Mach–Zehnder modulator followed by GVD generates the RF signal sidebands and their harmonics. Many techniques have been developed to mitigate or cancel out these harmonic distortions. If a dual-output push-pull Mach–Zehnder modulator is adopted, the even-order distortions will be cancel out, however, the odd-order distortions cannot be fully eliminated due to frequency dependent phase shift. In particular, the 3rd-order distortion limits the performance of the PTS-ADC.

The dispersion penalty for the fundamental tone and 3rd-order harmonic distortion by SMF, DCF and PCF as dispersion medium is illustrated in Figs. 2 and 3 with constant transmitted optical power (300 mW), respectively. The dispersion penalty exists in the linear-optical regime, however, nonlinearity causes a shift in the dispersion penalty null frequency using SMF, DCF or PCF as dispersion medium. This shift can be explained by introducing the

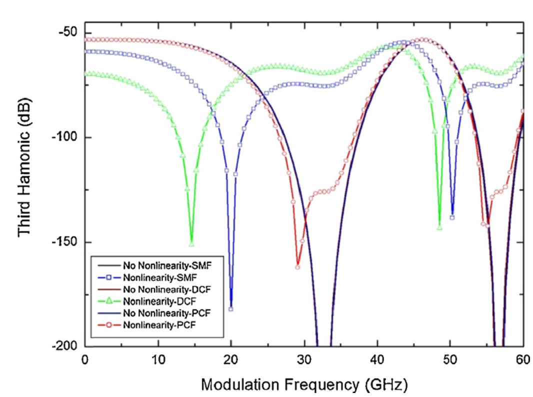

Fig. 3. Dispersion penalty of the 3rd-order harmonic distortion for SMF, DCF and PCF as dispersion medium.