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Equiangular spiral photonic crystal fiber for code synchronization in all-optical analog-to-digital conversion based on lumped time delay compensation scheme

Sha Li *

School of Computer and Communication Engineering, University of Science and Technology Beijing (USTB), Beijing 100083, China

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ABSTRACT

In this paper, we propose a lumped time delay compensation scheme for the all-optical analog-to-digital conversion (ADC) based on soliton self-frequency shift (SSFS) and optical interconnection techniques. By inserting a length of equiangular spiral photonic crystal fiber (PCF) between quantization and coding modules, the time delay of quantized pulses can be compensated. Simulation results show that the pulses can be synchronized utilizing a span of equiangular spiral PCF with flat negative dispersion of −258.92 ps/(nm km) in the wavelength range 1350 nm to 1675 nm. In addition, the amount of time delay and time error are analyzed, a maximum supportable sampling rate of 40 GSa/s is obtained.
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1. Introduction

Analog-to-digital converter (ADC) as an important part of communication system needs to satisfy the requirements of the rapid development of ultra-wide-band applications such as advanced Radar communication system, high speed optical communication, etc. [1–3]. The electrical ADC whose sample rate and art resolution are several giga-sample per second (GSa/s) and 10 b respectively cannot meet the requirements of ultra-wide-band applications, because of its inherent electrical bottle-neck such as clock jitter and sampling aperture, etc. [1–4]. All-optical ADC has attracted much attention because it can cope with the problems in electrical field, meanwhile achieve appropriate quantization resolution and sampling rate. Optical quantization could be realized by soliton self-frequency shift (SSFS), higher-order soliton fission, cross-phase modulation (XPM) effects, etc. [5–13]. Optical quantization utilizing SSFS effect is a promising option among the above schemes because of its ultrafast response speed and sampling rate transparency. Nishitani, Konishi and Itoh have made outstanding results in ADC based on SSFS effect [14–16]. During the process of frequency shift, time delays between optical pulses with different peak powers occur inherently, leading to the non-synchronization of the quantized optical pulses and coding error. The multiple optical time-delay lines (TDLs) are utilized to compensate time delay in the previous schemes whose disadvantages is complicated.

In this paper, we propose a lumped time delay compensation scheme to realize optical pulse synchronization. By inserting a length of equiangular spiral photonic crystal fiber (PCF) instead of the multiple optical TDLs after the SSFS module, the time delays are compensated between quantized pulses with different peak powers at output of PCF. The numerical analysis is simulated and discussed.

2. Principles and schematic design

Fig. 1 shows an all-optical ADC with 3-b quantization resolution whose primary two modules are all-optical quantization and coding based on SSFS effect and optical interconnection, respectively. In Fig. 1, the discrete sampled optical pulses, which can be generated by four-wave mixing effect (FWM), are delivered into a span of highly nonlinear fiber (HNLF) to realize power to wavelength conversion based on SSFS effect. At the output of HNLF, the central wavelengths of optical pulses occur red shift and the shift values are directly proportional to peak powers of input optical pulses, therefore an arrayed waveguide grating (AWG) is utilized to separate different central wavelengths. Optical signals with different central wavelengths are sent to specific ports of AWG and then are delivered into coding module. The optical interconnection is realized by means of several attenuators, TDLs and photodiodes

* Tel.: +86 18612254947.
E-mail address: shalee@ustb.edu.cn

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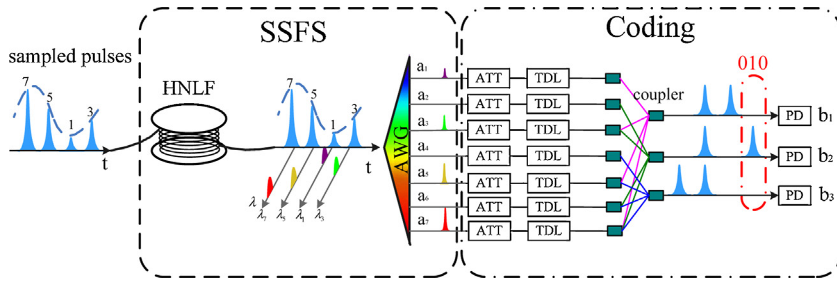

Fig. 1. Schematic diagram of an all-optical ADC based on SSFS technique, HNLF: highly nonlinear fiber, ATT: attenuator, TDL: time-delay line, PD: photodiode.

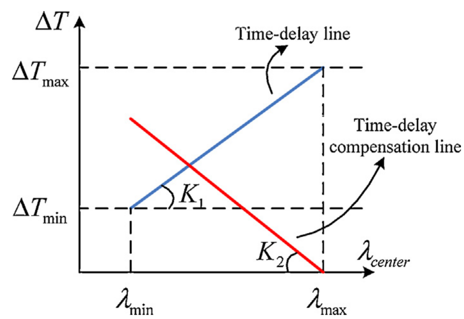

Fig. 2. The mechanism of the proposed lumped time delay compensation.

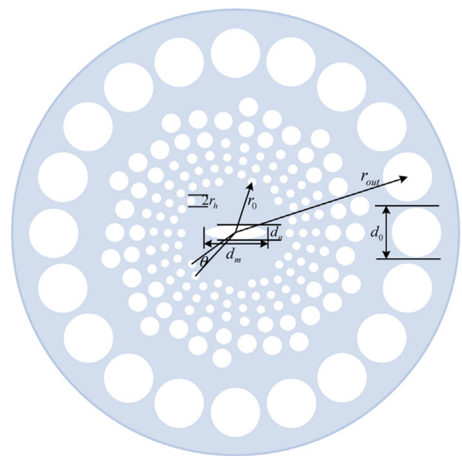

Fig. 3. Structural diagram of the equiangular spiral PCF.

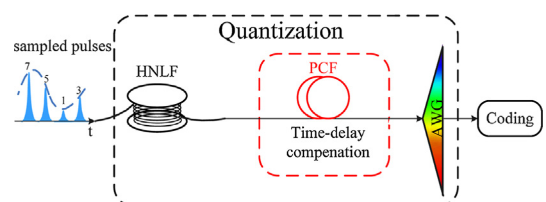

Fig. 4. Diagram of the lumped time delay compensation scheme based on PCF.

(PDs) in the coding module. The expressions of outputs b_1, b_2 and b_3 are

$$\begin{cases} b_1 = a_1 + a_2 + a_5 + a_6 \\ b_2 = a_2 + a_3 + a_4 + a_5 \\ b_3 = a_4 + a_5 + a_6 + a_7 \end{cases} \quad (1)$$

By utilizing the optical interconnection, 8 optical pulses are converted to 3 b Gray code at outputs of PDs, while an amount of different frequency shift corresponds to a different Gray code encoding.

All-optical quantization is achieved by SSFS effect, central wavelength of optical pulse occurs red shift, and meanwhile, optical pulse has time delay at the output of HNLF. The dynamic transmission of sampled optical pulses in HNLF can be described by the simplified Generalized Nonlinear Schrodinger Equation (GNLSE). Solving GNLSE with the moment method (MOM), the time delay of sampled pulse Δt can be got as follow [17,18]:

$$\Delta t \approx \Delta\Omega \cdot \beta_2 \cdot L \approx \Delta\lambda \cdot D \cdot L = (\lambda_c - \lambda_0) \cdot D \cdot L, \quad (2)$$

where $\Delta\Omega$ is the frequency shift of sampled pulse, β_2 and L are the second-order dispersion coefficient and the length of fiber, the dispersion parameter is $D = -2\pi c\beta_2/\lambda^2$, λ_c and λ_0 are the central wavelengths of quantized pulse and initial pulse, respectively. When the dispersion parameter D and the fiber length L are constants, the time delay Δt is directly proportional to λ_c from Eq. (2). According the relationship between the time delay and the central wavelength after SSFS effect, the compensation mechanism is shown in Fig. 2. The blue and red lines are the time delay and the time delay compensation curves with slopes of K_1 and K_2, respectively. In order to realize time delay compensation, it needs to meet $K_2 = -K_1 = (\Delta T_{\max} - \Delta T_{\min})/(\lambda_{\max} - \lambda_{\min})$, while $D_c = K_2/L_c$. Here, D_c and L_c are the dispersion and the length of the lumped time-delay compensation device.

There are many different ways to realize time delay compensation as long as the red line can be achieved. The PCF [19,20,21] has the characteristics to meet flattened negative dispersion $D_{PCF} = -K_1/L_{PCF}$, L_{PCF} is the length of PCF. For an all-optical ADC based on SSFS effect, K_1 can be got prior. According to the slope of time delay, the dispersion and the length of PCF can be appropriately designed. Here, an equiangular spiral PCF is selected to realize time delay compensation. The structure of the equiangular spiral PCF, which has air hole arrangement in silica background, is shown in Fig. 3. The first ring and air hole have radii of r_0 and r_h, while the radii of the rings and air holes in the same arm are increased gradually. The angular position of each air hole in an arm is increased by θ than the previous one. The minor and major axes of the elliptical air hole are d_n and d_m, respectively. Based on the structure of the equiangular spiral PCF, an average dispersion of −258.92 ps/(nm km) with a dispersion variation of 5.25 ps/(nm km) in the wavelength range 1350 nm to 1675 nm (−259.25 ps/(nm km) at 1550 nm). The confinement loss is 0.002 dB/m at 1550 nm. Furthermore, the higher order modes can be suppressed by means of an annular air holes in the outer cladding region.

Based on the prior study, the equiangular spiral PCF is designed, while the lumped time delay compensation scheme with the PCF is shown in Fig. 4. A segment of equiangular spiral PCF as time delay compensation module is inserted between HNLF and AWG instead of several TDLs comparing with Fig. 1. The improvement is advantageous for the miniaturization and integration of all-optical ADC.

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