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Chromatic Dispersion Estimation Based on CAZAC Sequence for Optical Fiber Communication Systems

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ABSTRACT We propose a chromatic dispersion (CD) estimation method based on constant amplitude zero-autocorrelation (CAZAC) sequence and fractional Fourier transform (FrFT) algorithm for optical fiber communication systems, which extends the application of CAZAC sequence. By applying FrFT on the CAZAC sequence signal, the optimal order is searched and employed to estimate the accumulated CD because that the CAZAC sequence shares similar properties with chirp signal. We demonstrate the feasibility of the proposed method by the simulation of a 28 GBaud polarization-division-multiplexed (PDM) quadrature phase-shift keying (QPSK) optical fiber communication system. The error of CD estimation is less than 70 ps/nm for the standard single mode fiber (SSMF) link of 2000 km with OSNR in the range of 10-20 dB and the launch power in the range of 0-4 dBm per channel in a five channel system. It shows that the method is robust to ASE noise and optical fiber nonlinearity. Furthermore, the proposed method has been experimentally verified with the error of CD estimation less than 50 ps/nm after 100-900 km fiber link transmission.

INDEX TERMS Chromatic dispersion, CAZAC sequence, fiber optics systems, fractional domain.

I. INTRODUCTION

Chromatic dispersion (CD) is one of the important factors affecting the performance of optical fiber communication systems [1], and the CD compensation is necessary before clock recovery, carrier synchronization and channel estimation [2], [3]. In particular, the CD can be fully compensated by digital signal processing (DSP), if we know the amount of CD [4]. Therefore, CD estimation is vital to realize accurate CD compensation [5].

Many methods of CD estimation have been reported and demonstrated, which can be divided into two categories, blind CD estimation methods [4]–[10] and training sequences based CD estimation methods [11]–[15]. In [4], [6], the authors estimated CD based on best matching filter search with time-domain (TD) or frequency domain (FD) cost function. The method in [5] estimated the CD by the peak-to-average power ratio (PAPR) because it varies with the CD of signal. In [7], the received signals' spectra was analyzed to measure CD. And in [8], [11], the signals' auto-correlation functions were used to estimate CD. Recently, the CD estimation methods using FrFT algorithm were proposed, including blind CD estimation [9], [10], FrFT tailored training symbol and QPSK training sequence based CD estimation [12]–[14] and linear-frequency modulation (LFM) pilot signal based CD estimation [15]. Compared with the blind methods, the CD estimation methods based on the training sequence sacrifice a certain spectral efficiency in exchange for less complexity, thus attracting the interest of researchers [6].

Due to its zero autocorrelation properties, CAZAC sequence is commonly used for channel estimation [3], [16]–[19]. In this paper, we propose a CD estimation method based on FrFT and CAZAC sequence,

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which extends the application of CAZAC sequence. Since the CAZAC sequence shares similar properties with chirp signal, it exhibits energy aggregation if FrFT at the optimal order is performed on CAZAC sequence signal. We find that the optimal order of FrFT shifts with the accumulated CD after the CAZAC sequence transmitted through the SSMF link. In this case, we propose to estimate the accumulated CD by performing FrFT on the transmitted CAZAC sequence. This will also facilitate the practical use of channel estimation using the CAZAC sequence.

We organize the rest of the paper as follows: In Section II, we introduce the principle of CD estimation based on CAZAC sequence and FrFT. In Section III, we conduct simulations on a 28 GBaud PDM-QPSK system to demonstrate the feasibility and robustness of the proposed method. In Section IV, experiments on 100-900 km fiber link system are performed to further verify our proposed method. Finally, in Section V, the conclusions are drawn.

II. PRINCIPLE OF CD ESTIMATION

A. CAZAC SEQUENCE

The CAZAC sequence [16] can be expressed as:

$$c[n]=\exp\left\{j\frac{2\pi}{\sqrt{N}}\left[\mathrm{mod}\left(n-1,\sqrt{N}\right)+1\right]\left[\left\lfloor\frac{n-1}{\sqrt{N}}\right\rfloor+1\right]\right\} \tag{1}$$

where $n = 1, 2, \ldots, N$. The length of the sequence is $N = 2^{2m}$ symbols with $m \in \{1, 2, 3, \ldots\}$. The CAZAC sequence we use to calculate CD is $m = 3$, $N = 64$. In fact, Eq. (1) shares similar properties with chirp signal. The derivation process for the equivalent chirp signal of the CAZAC sequence is as follows.

According to Eq. (1), we can divide the N symbols into $\sqrt{N}$ groups, and the $c[n]$ symbol number of group $k_c(k_c = 1, 2, 3, \ldots\sqrt{N})$ is denoted as: $n = (k_c - 1)\sqrt{N} + 1$, $(k_c - 1)\sqrt{N} + 2, \ldots, (k_c - 1)\sqrt{N} + \sqrt{N}$. Then, for $c[n]$, the phase of group k_c can be expressed as:

$$g_{k_c}[n] = \frac{2\pi}{\sqrt{N}}\left[\mathrm{mod}\left(n-1,\sqrt{N}\right)+1\right]k_c \tag{2}$$

From Eq. (2), with $\Delta n = (n+1) - n = 1$ as the sampling interval, then the frequency of the group k_c is:

$$f_{k_c} = \frac{g_{k_c}[n+1] - g_{k_c}[n]}{\Delta n} = \frac{2\pi}{\sqrt{N}}k_c \tag{3}$$

From Eq. (3), since the sampling interval between the group $(k_c + 1)$ and the group k_c is $\sqrt{N}$, the slope of the frequency of $c[n]$ can be obtained by:

$$\Delta f = \frac{f_{k_c+1} - f_{k_c}}{\sqrt{N}} = \frac{\frac{2\pi}{\sqrt{N}}(k_c + 1 - k_c)}{\sqrt{N}} = \frac{2\pi}{N} \tag{4}$$

In addition, assuming that there is a chirp signal equivalent to the CAZAC sequence, then the slope of their frequencies should be equal. We assume that the expression of a chirp signal is given by:

$$s[n] = \exp\left\{jkn^2\right\}, \quad \text{where}: n = 1, 2, 3, \ldots, L_0. \tag{5}$$

where k is the chirp rate, L_0 is the data length. According to Eq. (5), we let:

$$f[n] = kn^2 \tag{6}$$

To perform the second derivative of Eq. (6), we have:

$$f''[n] = 2k \tag{7}$$

Combining Eq. (4) with Eq. (7) and making $2k = \frac{2\pi}{N}$, then we can obtain:

$$k = \frac{\pi}{N} \tag{8}$$

So the equivalent chirp signal of the CAZAC sequence can be described as:

$$s[n] = \exp\left\{j\frac{\pi}{N}n^2\right\}, \quad \text{where}: n = 1, 2, 3, \ldots, L_0. \tag{9}$$

By using Eq. (9), it is very convenient for us to quickly calculate the optimal order of the corresponding CAZAC sequence after FrFT under B2B conditions. The specific results will be presented in the following.

B. FRFT OF SIGNALS

By applying FrFT on the signal $x(t)$, it can be expressed as X_α [20]:

$$X_\alpha(u) = \int_{+\infty}^{-\infty} x(t)\,K_\alpha(u,t)\,dt \tag{10}$$

where α is the angle of rotation, $K_\alpha(u,t)$ is the transform kernel expression of FrFT. The signal is converted to the fractional domain after FrFT. We compare the energy concentration at different rotation angles and search for the highest degree to determine the optimal order by Eq. (11) showed as follows:

$$EC(p) = \int_{+\infty}^{-\infty} \left|X_p(u)\right|^4 du \tag{11}$$

where p is the order of FrFT, and its relationship with α is $p = 2\alpha/\pi$.

From [9], [10], [13], the expression of calculating CD based on FrFT algorithm can be written as follows:

$$DL = \frac{dt}{dw}\frac{2\pi c}{\lambda^2}\left\{\cot\left[\left(p_{opt} - 1\right)\frac{\pi}{2}\right]\right\} \tag{12}$$

where L is the length of fiber, D is the dispersion coefficient of fiber, dt is the sampling interval in the time domain, $d\omega$ is the sampling interval in the frequency domain, c is the vacuum light speed, λ is the wavelength of carrier, and p_{opt} is the optimal order after FrFT.

Different from the method of estimating CD using the QPSK signal proposed in [9], [10], [13], the CAZAC sequence has an initial chirp before transmission as the analysis above. As shown in Figure 1, in the case of B2B, we are able to search for the position of the optimal order of the CAZAC (N=64) sequence by Eq. (11), and use it as the reference order. The step size we search for the optimal order is $\Delta p = 0.001$. After transmission in the fiber link, the CD induces a chirp in frequency domain [10]. From Figure 1

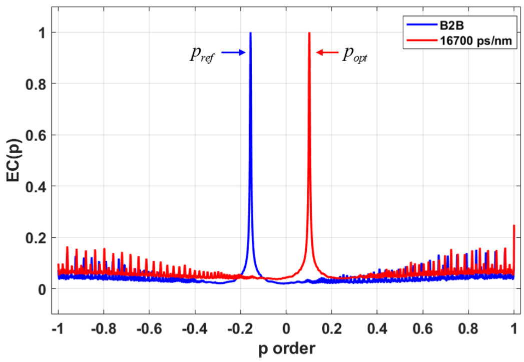

FIGURE 1. **The energy concentration with different orders of FrFT on CAZAC sequence at back to back (B2B) condition and with 16700 ps/nm chromatic dispersion.**

TABLE 1. **The p_{ref} with different sampling rate and number of samples at B2B.**

Symbols	512	1024	2048	4096
Samples of single sampling rate	512	1024	2048	4096
p_{ref} for CAZAC sequence	-0.079	-0.040	-0.020	-0.010
p_{ref} for equivalent chirp	-0.079	-0.040	-0.020	-0.010
Samples of double sampling rate	1024	2048	4096	8192
p_{ref} for equivalent chirp	-0.156	-0.079	-0.040	-0.020
p_{ref} for equivalent chirp	-0.156	-0.079	-0.040	-0.020

one can see that, with the increases of CD, the optimal order becomes large. With the optimal order of the CAZAC sequence before and after transmission, the total CD along the fiber link can be expressed as follows [12]:

$$DL = \frac{dt}{dw}\frac{2\pi c}{\lambda^2}\left\{\cot\left[\left(p_{opt}-1\right)\frac{\pi}{2}\right]-\cot\left[\left(p_{ref}-1\right)\frac{\pi}{2}\right]\right\} \tag{13}$$

where p_{ref} is the reference order at B2B, and p_{opt} is the optimal order with CD.

In reality, the optimal order p_{opt} will vary with the different sampling rate and number of the samples used to calculate CD in the case of the same CD. We need to determine the sampling rate and the number of the samples to determine the reference value p_{ref} before calculating the CD. For the CAZAC sequence, we need to determine the p_{ref} by searching for the maximum value of $X_p(u)$ after FrFT. But for the chirp signal, in the case of B2B, it's easy for us to directly calculate its optimal order as p_{ref} [10] by Eq. (14):

$$p_{ref} = arc\cot\left(-2k\frac{dt}{d\omega}\right)\Big/\frac{\pi}{2} \tag{14}$$

According to Eq. (9), the equivalent chirp signal of the CAZAC ($N = 64$) sequence can be described as $s[n] = \exp\left\{j\pi n^2/64\right\}$. As shown in Table 1, the p_{ref} corresponding to different sampling rate and number of samples is different at B2B, and the results calculated by the equivalent chirp

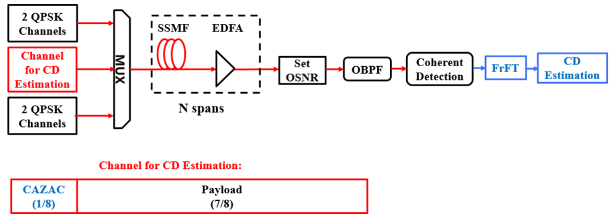

FIGURE 2. **Schematic diagram of CD estimation.**

signal with using Eq. (14) are the same as CAZAC sequence. In fact, the algorithmic complexity of estimating CD by using the FrFT algorithm is mainly contributed by the process of searching for optimal orders, depending on the number of samples used and the search step size [10]. Now the p_{ref} can be directly calculated by the equivalent chirp signal and Eq. (14) without B2B optimal order searching. It reduces nearly half of the computational process and makes the data processing more convenient.

III. SIMULATION

To simulate and study the feasibility of the proposed method, a 28 GBaud PDM-QPSK system is conducted in VPItransmission Maker, as shown in Figure 2. There are 5 channels for our simulation system. Each frame contains 8192 symbols as an example. For the middle channel, the CAZAC sequence as a pilot occupies 1/8 of the frame, which is 1024 symbols. And the remaining 7/8 of the frame is QPSK data. The other 4 channels transmit QPSK signals with 50 GHz channel spacing. The center frequency of the laser is set to 193.1 THz with 300 kHz linewidth. In the transmitter, for each channel, a 4-order Gaussian optical filter with the bandwidth of 50 GHz is used for 28 GBaud signal. And in the receiver, there is a same Gaussian filter as optical band-pass filter (OBPF) for middle channel. The SSMF link composed of 30 spans is 100 km for each span with dispersion parameter is 16.7 ps/(km·nm) and polarization mode dispersion coefficient is 5.0 ps/km$^{1/2}$. We add ASE noise by the Set OSNR module directly at the end of the link. The nonlinear index of the fiber is set to 2.6×10^{-20} s/m^3. The optical signal is coherently received with the sampling rate of 56 GSa/s, and then we use 1024 samples to estimate CD.

We first estimate the CD in a system with only one channel, in which the OSNR is set to 14 dB and the launch power is set to 0 dBm. The fiber length is 100-3000 km, whose corresponding CD range is 1670 - 50100 ps/nm. The CD estimation error is defined by $\left|CD_{est} - CD_{ref}\right|$, where CD_{ref} denotes the reference CD, and CD_{est} denotes the estimated CD. As shown in Figure 3, the estimated CD values all fall on the reference line and the error is less than 70 ps/nm, indicating that the proposed method is feasible to CD estimation. Notice that the step size of searching for p_{opt} is $\Delta p = 0.001$. When the real p_{opt} ($p_{opt-real}$) of each CD value and the estimated p_{opt} ($p_{opt-est}$) satisfy $0 \le \left|p_{opt-est} - p_{opt-real}\right| < 0.001$, we can consider that this CD estimation error is within the allowed and acceptable error range [13]. In addition, it can

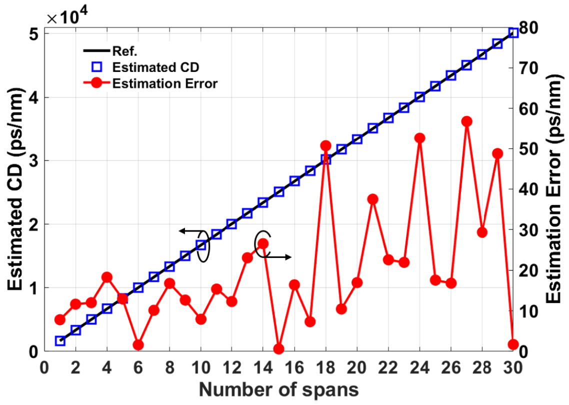

FIGURE 3. The CD estimation for different spans of fiber link (100 km per span).

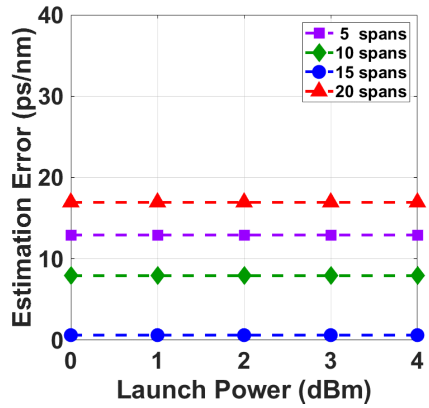

FIGURE 5. CD estimation error with different launch power (0-4dBm per channel) for 5, 10, 15, 20 spans SSMF transmission system.

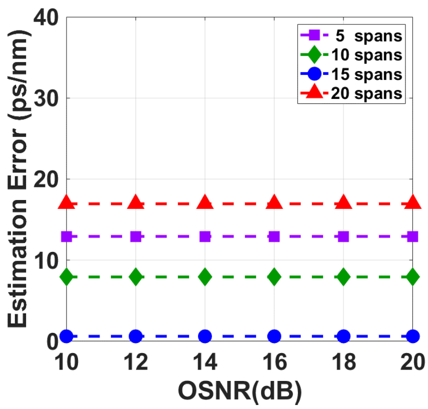

FIGURE 4. CD estimation error with different OSNR for 5, 10, 15, 20 spans SSMF transmission system.

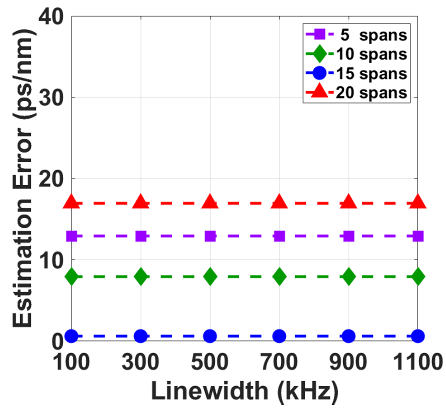

FIGURE 6. CD estimation error with different linewidth for 5, 10, 15, 20 spans SSMF transmission system.

be known from the Eq. (13) that the CD error caused by $\Delta p = 0.001$ is not a fixed value. It ranges from 63.7 ps/nm to 125.3 ps/nm corresponding to the amount of CD from 1670 ps/nm to 50100 ps/nm. That is to say, if the CD estimation error is less than 125.3 ps/nm when the CD amount is 50100 ps/nm (3000 km), it can be considered to achieve accurate CD estimation. Obviously, the estimation error can be reduced by reducing the step size Δp, but it will increase the computational complexity [13].

Next, we study the performance of the method with different OSNR. In a single channel system, we compare the results of 5, 10, 15, and 20 spans transmission with OSNR varying from 10 dB to 20 dB when the optical signal launch power is set to 0 dBm. The CD estimation error with different OSNR is less than 70 ps/nm for different transmission distances, as shown in Figure 4, showing that the method is robust to ASE noise.

Furthermore, the anti-nonlinear performance of this method is also another point of interest to us. For this purpose, we set up a 5 channel system with channel spacing of 50 GHz to increase the nonlinearity. The middle channel transmits the CAZAC sequence as a pilot, while the remaining channels transmit standard QPSK signals. The OSNR is set to 14 dB, while the other parameters are kept the same. At the receiver, the signal of the middle channel is filtered out by a Gaussian filter for coherent reception. The results of 5, 10, 15, and 20 spans with launch power varying from 0 dBm to 4 dBm per channel are shown in Figure 5. The error of estimated CD is less than 70 ps/nm and does not change with increasing nonlinearity power. It proves that the proposed method has tolerance of optical fiber nonlinearity.

In addition, we consider the effect of phase noise caused by the laser linewidth on the CD estimation of the method. We still simulate in a 5 channels system. Here, the OSNR is set to 14 dB, and the launch power is set to 0 dBm per channel. The range of linewidth is from 100 kHz to 1100 kHz for both lasers in transmitter and receiver. The results of 5, 10, 15 and 20 spans with different linewidth is shown in Figure 6. The result shows that the CD estimation error is less than 70 ps/nm, and does not change as the linewidth increases. It indicates that the method is insensitive to phase noise caused by laser linewidth.

IV. EXPERIMENTAL RESULTS

As shown in Figure 7, we set up a 10 GBaud CAZAC sequence transmission experimental platform to study the

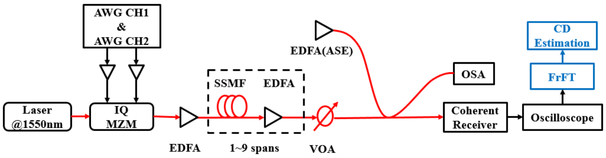

FIGURE 7. Experiment setup for 10 GBaud CAZAC sequence transmission. OSA: optical spectrum analyzer.

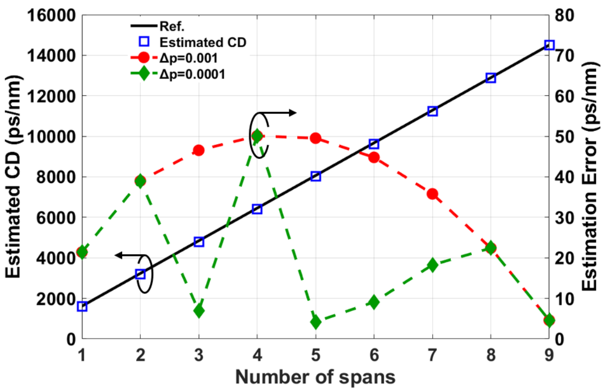

FIGURE 8. CD estimation error for 100-900 km SSMF transmission system with different step size of searching for p_{opt}.

practical performance of the CD estimation method. In the I/Q modulator, the laser at 1550 nm with 5 kHz line width is modulated by 10 GBaud CAZAC sequence electrical signal from an Arbitrary waveform generator (AWG). The optical signal will be re-amplified by erbium-doped fiber amplifier (EDFA) and then launch into SSMF. The fiber dispersion parameter is 16.5 ps/(km·nm) and the nonlinear index is 2.6×10^{-20} s/m^3. The fiber link includes 1-9 spans with 100 km per span. We use the EDFA (ASE) as an additional noise source, and jointly adjust variable optical attenuator (VOA) and the output power of the EDFA (ASE) to control the OSNR. After coherent reception, the signal is sampled by a 50 GSa/s digital storage oscilloscope, and we use 1024 samples to perform FrFT for CD estimation.

To evaluate the practicability of the method in experiment, we measured the accumulated CD in SSMF fiber link of length from 100 to 900 km with launch power of 0 dBm in a single channel system, as shown in Figure 8. We did not add extra noise from the EDFA (ASE) to the link to control the OSNR at this time. Similar to the simulation, the CD estimation error is also defined by $\left|CD_{est} - CD_{ref}\right|$. In Figure 8, the estimated CD matches the reference CD line very well, and the error of CD estimation is less than 50 ps/nm within 900 km. It is a coincidence that the amount of CD in the experiment caused the error curve of $\Delta p = 0.001$ in Figure 8 to show a certain regularity. And this regularity disappears when $\Delta p = 0.0001$.

In order to evaluate the tolerance to ASE noise and fiber nonlinearity of our method, we also experimentally analyzed CD estimation error with different OSNR and launch power.

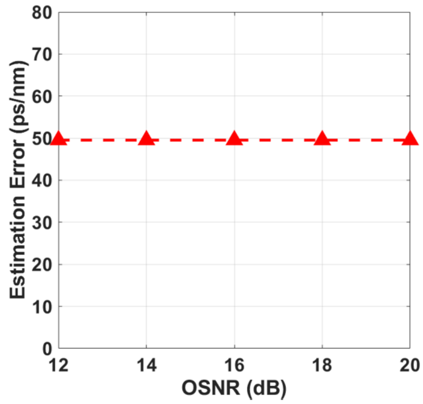

FIGURE 9. CD estimation error after 500 km transmission with different OSNR.

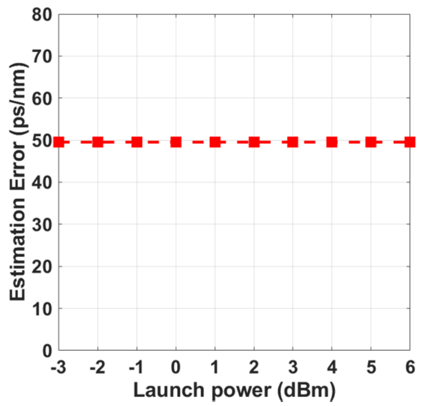

FIGURE 10. CD estimation error after 500 km transmission with different launch power.

The experiment is carried in a 500 km SSMF transmission. We added some noise from the EDFA (ASE) to make the OSNR adjustable, and the OSNR is varied from 12 to 20 dB. Besides, we controlled the output power of each EDFA in the link to vary from -3 to 6 dBm to change the fiber nonlinearity. The results in Figure 9 and Figure 10 show that the CD estimation error is less than 50 ps/nm and even unchanged both with different OSNR and with different launch power. These verify that the proposed CD estimation method is robust to ASE noise and nonlinearity.

V. CONCLUSION

In this paper, a method of CD estimation based on the CAZAC sequence and the FrFT for optical fiber communication systems is proposed, which extends the application of CAZAC sequence. We derive the equivalent chirp signal of the CAZAC sequence for p_{ref} calculation. It makes the data processing more convenient and reduces the algorithm complexity of method. After the theoretical analysis, we perform simulations and experiments to verify the proposed method. In the simulation on 28 GBaud PDM-QPSK system with the OSNR 10-20 dB, the launch power 0-4 dBm per channel and the linewidth 100-1100 kHz, the error of CD estimation is less than 70 ps/nm after 500, 1000, 1500 and 2000 km

SSMF transmission. In the experiment, the error is less than 50 ps/nm after 500 km transmission when OSNR varies from 12 dB to 20 dB and launch power varies from -3 dBm to 6 dBm. Both simulation and experiment demonstrate that the proposed method can estimate the CD accurately and is robust to ASE noise and fiber nonlinearity.

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