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Fractional Fourier Transformation Based Blind Chromatic Dispersion Estimation for Coherent Optical Communications

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***Abstract*—In this paper, we propose and demonstrate a blind chromatic dispersion (CD) estimation method based on fractional Fourier transformation (FrFT). Through numerical simulations, the proposed CD estimation method is shown to be robust against amplified spontaneous emission (ASE) noise and nonlinear interference. Only 2048 samples are required for reliable CD estimation for single carrier 28 GBaud DP-QPSK or 32 GBaud DP-16QAM signals and the standard deviation can be as low as 98.9 ps/nm and 103.6 ps/nm respectively. The feasibility of the proposed CD estimation method has been experimentally verified using 28 GBaud DP-QPSK and 14 GBaud DP-16QAM signals over various transmission distances. Compared with some other CD estimation methods, the method based on FrFT has advantages in the aspects of less computation complexity and robustness to transmission impairments.**

***Index Terms*—Fiber optics communications, coherent communications, fractional Fourier transformation, dispersion.**

I. Introduction

Chromatic dispersion (CD) compensation in fixed fiber link can be realized by a static equalizer in the digital coherent receiver if there is an accurate information of the accumulated CD. It has been reported that accumulated CD at the range of 10^4 ~10^5 ps/nm can be effectively compensated in the digital coherent receiver [1-2]. However, due to the dynamic characteristics of future optical networks, the accumulated CD of optical signals may change from time to time. Therefore, in order to realize exact compensation in the digital receiver, an estimation of CD value should be conducted before the CD compensation.

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Various approaches to CD estimation in digital coherent receivers have been presented. One of the methods is based on parameter extraction from equalizer taps [3]. Due to a limited number of filter taps in the receiver, this solution might only be used to monitor relatively small CD. To support longer links, methods based on CD scanning are used, such that the space of possible CD values is searched with small step and a metric value is computed for each step. A characteristic feature of this metric, the global minimum or maximum, is generally used to indicate successful mitigation of CD. In Ref [4], four different metrics, such as constant modulus algorithm (CMA) metric, mean signal power, eigenvalue spread and frequency spectrum autocorrelation, were introduced and experimentally verified in the transmission experiment. Recently, a more efficient technique was proposed in [5] by noting that the aforementioned search process is tantamount to apply a fast Fourier transform (FFT) on the autocorrelation of the discrete spectrum.

The fractional Fourier transformation (FrFT) is a generalization form of the Fourier transformation (FT) and has been utilized to represent the signals on an orthonormal basis formed by chirps. And, the FrFT can induce rotations in various time-frequency transforms, including the Wigner distribution and the short-time Fourier transform, to further enhance its interpretation as a rotation operator [6]. So it can analyze the signal both in the time and frequency domains. Thanks to its unique properties, the FrFT has been used in multiple applications such as solving differential equations [7], quantum mechanics [7], optical image processing [8] and signal processing [9-11]. It has advantages in dealing with linear frequency modulated (LFM) or chirped signals and has been deployed for detecting and estimating LFM signal's characteristics [12].

In this paper, we extend the FrFT capability of dealing with LFM signal on the CD estimation in optical fiber communication systems and propose a novel method to estimate the accumulated CD. We treat the signal with CD as a chirped signal in frequency domain and take advantage of the properties of FrFT to process this chirped signal. Then, the certain FrFT order, which is related to the CD value, can be searched by a defined metric that can be calculated by a quick FrFT algorithm. This quick FrFT algorithm computes the fractional transform in O (N log N) time, where N is the time-bandwidth product of the signal, similar to the FFT algorithm. Thus the computation of the fractional transform does not sacrifice the computation efficiency compared with the ordinary Fourier transform [13]. The relation between the CD value and the certain FrFT order can be built for estimation. Although inherently our method is still a kind of CD scanning method, it can be computed very efficiently by using a novel FrFT metric and it shows robustness against various transmission impairments. The performance of our proposed CD estimation method is numerically investigated in the presence of amplified spontaneous emission (ASE) noise and nonlinear interference (NLI) for 28GBaud DP-QPSK and 32GBaud DP-16QAM signal with NRZ pulses. Besides, we also investigated the impacts of different sample number and different step size of FrFT order on the estimated results. The proposed method works well and stably under strong ASE noise and NLI noise. Finally, to further confirm the feasibility of the proposed CD estimation method, we conducted experiments for 28 GBaud DP-QPSK and 14 GBaud DP-16QAM signal over various transmission distances. The worst CD estimation errors are 128 ps/nm and 320 ps/nm for DP-QPSK and DP-16QAM respectively. The rest of the paper is organized as follows: in Section II, the operation principle of proposed CD estimation method is introduced. In Section III, simulations are conducted to prove the robustness of this method. In Section IV, we performed experiments to confirm the method's feasibility in long-distance optical fiber transmission systems. Finally, conclusions are drawn in Section V.

II. Operation Principle

A. Brief introduction of FrFT

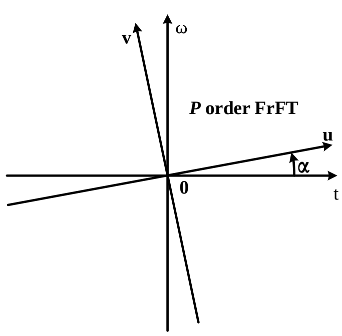

Fig. 1. The order FrFT and its rotation in the Wigner domain

The FrFT can induce rotations in Wigner domain [14]. As shown in the Fig. 1, the ω and v are the frequency coordinate of original signal and transformed signal respectively. The angle α corresponds to the rotation angle caused by the *p* order FrFT with the relationship as follows.:

$$p = 2\alpha / \pi \tag{1}$$

FrFT becomes the conventional Fourier transform when the rotation angle $\alpha = \pi / 2$, that is the FrFT order $p = 1$. Hence, if we substitute $\alpha = \pi / 2$, we obtain the properties of the conventional Fourier transform.

The FrFT of the signal $f(t)$ with a rotation angle α, denoted as $F_\alpha(u)$, is defined as

$$F_\alpha(u) = \int_{-\infty}^{\infty} f(t) K_\alpha(t,u) dt \tag{2}$$

and

$$f(t) = \int_{-\infty}^{\infty} F_\alpha(u) K_\alpha^*(t,u) du \tag{3}$$

where the transform kernel $K_\alpha(t,u)$ of the FrFT is given by

$$K_\alpha(t,u) = \begin{cases} \sqrt{\dfrac{1 - j\cot\alpha}{2\pi}} \exp\left(j \dfrac{t^2 + u^2}{2} \cot\alpha - \dfrac{jtu}{\sin\alpha}\right) \\ \text{if } \alpha \text{ is not a multiple of } \pi \\ \delta(t - u) \\ \text{if } \alpha \text{ is a multiple of } 2\pi \\ \delta(t + u) \\ \text{if } \alpha + \pi \text{ is a multiple of } 2\pi \end{cases} \tag{4}$$

Due to the rotation of the Wigner domain, some signals like LFM or chirped signals can be best dealt with in specific fractional domain instead of just in either time domain or frequency domain. In some specific fractional domains, LFM or chirped signals may present unique properties that will be helpful for signal processing.

B. FrFT of the chirped signal

A chirped signal in the time domain can be expressed as

$$E(t) = A(t) \exp(i\omega_0 t + iCt^2 + \psi_0) \tag{5}$$

where $A(t)$ is the envelope of the signal, ω_0 is the carrier frequency, ψ_0 is the initial phase and C is the chirp parameter.

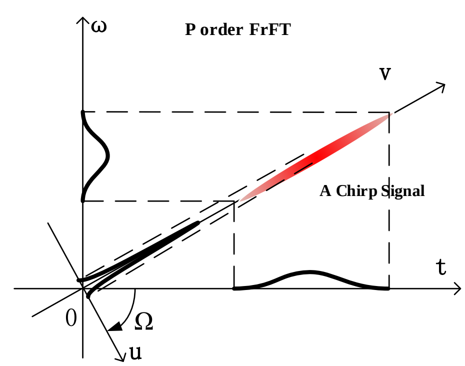

Fig. 2. The rotation of time-frequency distribution and the signal distribution with the best order P

As shown in Fig. 2(a), for this chirped signal transformed by FrFT, there exists a best fractional domain under some rotation angle Ω, or certain FrFT order P after the rotation of the Wigner domain of the signal, where the signal distribution squeezes to its minimum and the energy distribution can be gathered mostly. The specific rotation angle Ω or the certain FrFT order P, is determined by the chirp parameter as follows [15]:

$$\mathrm{P}=2\Omega/\pi=2\,\mathrm{arccot}(-2C\frac{dt}{d\omega})/\pi \tag{6}$$

where dt and $d\omega$ are the sampling interval in the time and frequency domain after digital sampling.

So, as long as a certain order P of FrFT is found, we can estimate the chirp parameter C of a chirped signal. The certain FrFT order P can be searched by a statistical parameter which can be used to describe the degree of signal's localization:

$$L(p)=\int_{-\infty}^{+\infty}|R_\alpha(\rho)|^2 d\rho \tag{7}$$

where p is different order of FrFT and $R_\alpha(\rho)$ is the fractional convolution represented as

$$R_\alpha(\rho)=(F^{-\pi/2}\{|X_{\alpha+\pi/2}(u)|^2\})(\rho) \tag{8}$$

where

$$X_{\alpha+\pi/2}(u)=F^{\alpha+\pi/2}(x(t)) \tag{9}$$

$F^{-\pi/2}$ denotes inverse Fourier transform and $F^{\alpha+\pi/2}$ denotes a fractional Fourier transform of signal x(t), with the order $p=2\alpha/\pi+1$. The higher the degree of signal's localization is, the larger the $L(p)$ is.

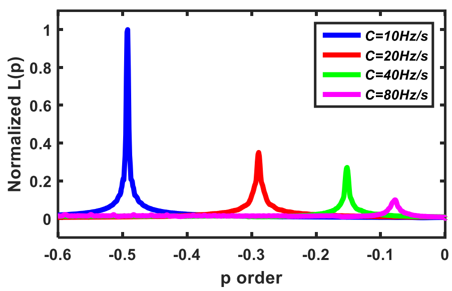

Fig. 3. L(p) vs p orders for different chirp parameter

For a chirped signal as Eq. (5) whose dt and $d\omega$ are assumed as 10ms and 0.4π rad/s, we calculated $L(p)$ for different values of chirp parameter C. As shown in Fig. 2(b), impulse responses-like curves appear in the $L(p)$-p plot and the peak position exactly corresponds to the best order P, at which the chirped signal distribution squeezes to its minimum after FrFT transformation. This method has been deployed for detection and characteristic estimation of chirp signals in radar systems [12].

C. FrFT of signals with CD in optical fiber communication

The similar procedure can be extended to a chirped signal in frequency domain which exactly corresponds to the signal with CD in optical fiber transmission as follows:

$$A(z,\omega)=A(0,\omega)\exp(\frac{i}{2}\beta_2 z\omega^2) \tag{10}$$

where z is the transmission distance, β_2 describes the group-velocity dispersion (GVD), and is related to the chromatic dispersion parameter D.

$$\beta_2=-\frac{\lambda^2}{2\pi c}D \tag{11}$$

where λ is the reference wavelength, c is the speed of light.

For an optical signal with CD, different frequency parts correspond to different group velocity. Specifically, if the dispersion parameter D is positive, the higher frequency part of the signal transmits slower; while if the dispersion parameter D is negative, the higher frequency part of the signal transmits faster. The transmission speeds vary linearly along with the frequency.

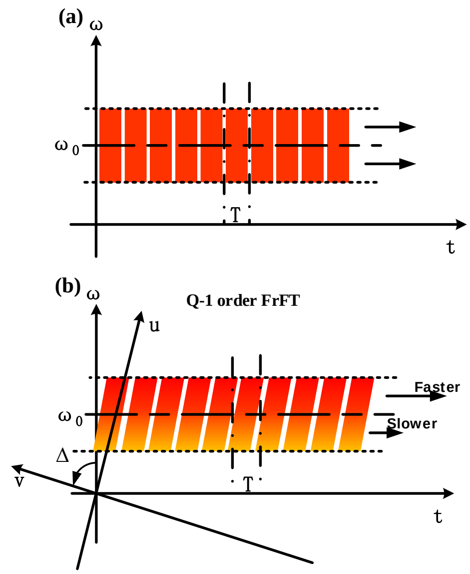

Fig. 4. (a) time-frequency distribution of an optical communication signal without CD. (b) time-frequency distribution of an optical communication signal with a certain CD.

In Fig. 4, ω_0 is the center frequency of signal and T is the duration of one symbol. The ω and v are the frequency coordinate of original signal and transformed signal respectively. According to Fig. 4(b), there is a certain order Q similar to P as follows:

$$(Q-1)=2\Delta/\pi=2\,\mathrm{arccot}(-\beta_2 z\frac{d\omega}{dt})/\pi \tag{12}$$

where dt and $d\omega$ are the sampling interval in the time and frequency domain after digital sampling. Compared with the Fig. 2 and Eq. (6), since the CD induces a chirp in frequency domain, the transmission time varies linearly along with the frequency. In this case, the analysis should be based on the signal in frequency domain instead of time domain. So, the position of dt and $d\omega$ should be exchanged in the right side of Eq. (12). Most of the time, we need to deal with time series instead of frequency spectrum. Therefore, the best order at the left side of Eq. (12) should subtract 1 to change the signal from time domain to frequency domain. TABLE I lists the comparison between the chirped signal in time domain and the signal with CD in aspects of the expression, the chirp parameter, the certain order / rotation angle of FrFT and the relation between the order and the chirp parameter according to the content discussed above.

TABLE I
COMPARISON BETWEEN THE CHIRPED SIGNAL IN TIME DOMAIN AND THE SIGNAL WITH CD

Signal	Chirped signal in time domain	Signal with CD (chirped signal in frequency domain)
Expression	$E(t)=A(t)\exp(i\omega_0 t+iCt^2+\psi_0)$	$A(z,\omega)=A(0,\omega)\exp(\frac{i}{2}\beta_2 z\omega^2)$
The chirp parameter	C	$\beta_2 z/2$
The certain order / rotation angle of FrFT	P / Ω	Q / Δ
The relation	$P=2\Omega/\pi=2\,\mathrm{arccot}(-2C\frac{dt}{d\omega})/\pi$	$(Q-1)=2\Delta/\pi=2\,\mathrm{arccot}(-\beta_2 z\frac{d\omega}{dt})/\pi$

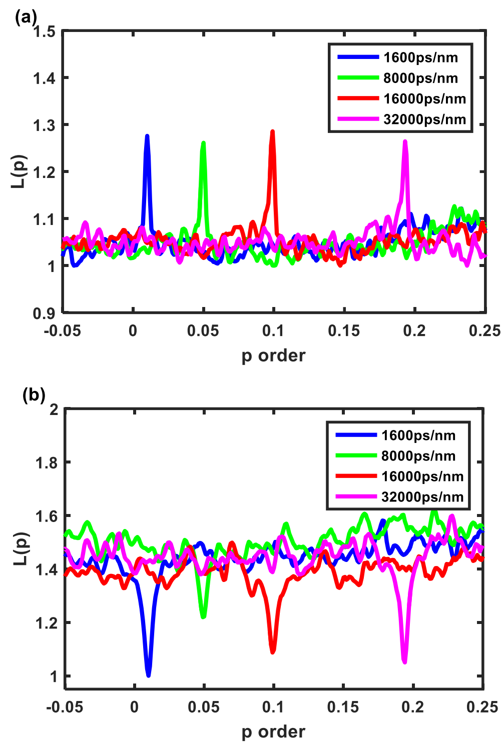

Fig. 5. (a) L (p) vs p orders for OOK signal with different CD amounts. (b) L (p) vs p orders for DP-QPSK signal with different CD amounts

With the certain rotation angle Δ and the Q order of FrFT, the transformed optical signal, which has the minimum inter symbol interference (ISI) in the rotated time-frequency domain, exhibits a psudo-unchirped property similar to the signal in Fig. 4(a). That means the CD induced frequency dependent differential time delay disappears in the specific FrFT transformed domain, as shown in Fig. 4(b). Therefore, the characteristics of the signal with the CD in the certain specific FrFT transformed domain is similar to the signal without CD in time domain. In order to find the certain order of FrFT for different CD values, $L(p)$ of the signal can be calculated by Eq. (7-9).

Though $L(p)$ can be defined as a metric of CD estimation, it may have different characteristics for signals with different modulation formats. Taking the OOK and QPSK signals with CD as examples, we can find out that for OOK signal, $L(p)$ has an upward impulse and a maximum value at a specific order of FrFT for different CD, as shown in Fig. 5(a). For DP-QPSK signal, the constant envelope of the temporal waveform leads to the minimum degree of signal's localization in time domain without CD. Thus $L(p)$ has a downward impulse and a minimum value at a special order FrFT, as shown in Fig. 5(b). The characteristics such as maximal/minimal points can be used to indicate the best order Q. Using Eq. (12), the CD can be estimated with these specific orders by scanning maximal/minimal points in the $L(p)$-p plots.

III. EVALUATION OF FRFT BASED CD ESTIMATION PERFORMANCE

A. Simulation environment and analysis method

To study the feasibility of the proposed method, we conducted simulations for single carrier optical fiber transmission system based on 28 GBaud DP-QPSK and 32 GBaud DP-16QAM signals by combining Matlab and VPI Transmission Maker 9.0 software. In the transmitter side, 28Gbaud QPSK signals or 32 Gbaud 16QAM signals are generated by IQ modulator which is driven by uncorrelated pseudo-random binary sequences (PRBS) with a length of 2^{16}-1. Then, the DP-QPSK signal or DP-16QAM signals are obtained by introducing 200 symbols delay between two polarizations. The optical signals are then pre-amplified and launched into the fiber link composed by 20 spans of SMF. After each span, the loss is compensated by ideal erbium doped fiber amplifier (EDFA) with 0 dB noise figure (we add ASE noise at the receiver by setting OSNR directly). The input power is 0 dBm, the nonlinear coefficient of the fiber is set to 2.6 W^{-1} • km^{-1}, and the PMD coefficients is set to 0.1ps /$km^{1/2}$. The CD parameter is set to 16 ps/km/nm. As many as M=1000 CD values which range from 1600 ps/nm to 32000ps/nm are generated by randomly setting M different span lengths of fiber in each span. The receiver OSNR is set at 12 dB by adding AWGN noise. After transmission, the data received are dealt with MATLAB. A data block with length of 2048 samples from original signals is used for blind CD estimation after the signal sampled at twice the symbol rate.

The fractional convolution $R_\alpha(\rho)$ and index of CD estimation $L(p)$ of the signal in different FrFT orders are first calculated by a quick FrFT algorithm [13], which has a similar complexity with FFT. Then we replace the p by CD value and get $L(CD)$ according to Eq. (12). We scan the CD value by a step size of ΔCD=100 ps/nm within the pre-set range of CD. Therefore, the orders of FrFT we need to search are determined by the range of CD and the step size of ΔCD. After that, the CD value can be estimated by the peak search of $L(CD)$.

For each CD estimation, the performance is evaluated by the estimation error which is defined by the deviation of the estimated CD value $CD_{est,j}$ to the real CD value $CD_{real,j}$ as follows:

$$\varsigma_{CD,j} = CD_{est,j} - CD_{real,j} \quad (13)$$

Furthermore, the mean value M_{CD} of the absolute estimation error from all realizations is defined by

$$M_{CD} = \frac{1}{M}\sum_{j=1}^{M}\left|CD_{est,j} - CD_{real,j}\right| \quad (14)$$

The standard deviation of the estimation error is defined as

$$\sigma_{CD} = \sqrt{\frac{1}{M}\sum_{j=1}^{M}(CD_{real,j} - CD_{est,j} - \frac{1}{M}\sum_{j=1}^{M}(CD_{real,j} - CD_{est,j}))^2} \quad (15)$$

Both two parameters provide metric analysis of the precision of the method. We can also get the range of the estimation error

$$R_{\varsigma_{CD}} = (\min(\varsigma_{CD,j}), \max(\varsigma_{CD,j})) \quad (16)$$

where $\min(\varsigma_{CD,j})$ and $\max(\varsigma_{CD,j})$ represent the minimum and maximum value of $\varsigma_{CD,j}$ .Throughout this paper, the distribution of the estimation error is represented by histograms. From the histograms, the worst case estimation error and the error distribution can be obtained.

B. Performance of the CD estimation method

We calculated the CD estimation error $\varsigma_{CD,j}$ for 28GBaud DP-QPSK and 32GBaud DP-16QAM signal. For either modulation format, we obtained 1000 CD estimation errors by Eq. (13) and the distributions of the CD estimation errors are shown in Fig. 6.

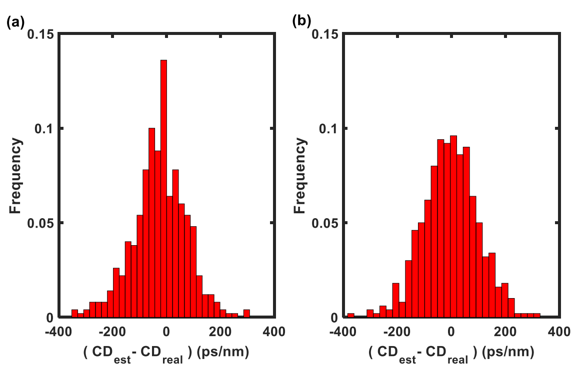

Fig. 6. (a) Distribution of the CD estimation error for 28 GBaud DP-QPSK. (b) Distribution of the CD estimation error for 32 GBaud DP-16QAM

For the QPSK and the 16QAM signal, the mean value of the absolute estimation error M_{CD} , the standard deviation σ_{CD} of estimation error, and the worst case estimation error are shown in TABLE II.

TABLE II
PERFORMANCE OF THE CD ESTIMATION METHOD FOR QPSK AND 16QAM SIGNALS

Modulation formats	M_{CD} / (ps/nm)	σ_{CD} / (ps/nm)	worst-case estimation error / (ps/nm)
28GBaud DP-QPSK	78.3	98.9	352.0
32GBaud DP-16QAM	81.7	103.6	384.0

According to the TABLE II, it can be proved that the CD estimation method we proposed is feasible and accurate enough for both QPSK and 16QAM signals. The standard deviations for both QPSK and 16QAM modulation formats are almost identical with the CD scanning step.

While the inaccurate CD estimation can cause an incomplete CD compensation after static CD compensation, the residual CD can be further compensated by the following 2 × 2 CMA equalizer. In the presence of CD estimation error within 350 ps/nm, the residual CD can be effectively compensated by 2 × 2 CMA equalizer with a tap number of 11 [17]. Therefore, we consider ±350 ps/nm as the estimation tolerance throughout this paper.

C. Impacts of sample number and step size of CD scanning

We found that the sample number used for CD estimation and the step size of CD scanning can influence the CD estimation result. In the following, we evaluated the performance of the CD estimation for DP-QPSK signal using different sample number and step size of CD scanning. 2048 and 4096 samples (1024 and 2048 symbols) were used to estimate CD and the step size of CD scanning was set as 100 ps/nm, 200 ps/nm and 400ps/nm, respectively. For each combination of sample number and step size, 1000 CD estimation errors could be obtained to evaluate the performance for different sample number and step size that are shown in Fig. 7 and Fig. 8. For each combination of sample number and step size, the range of the estimation error $R_{\varsigma_{CD}}$, the mean value M_{CD} of the absolute estimation error and the standard deviation σ_{CD} of estimation error are listed in TABLE III, respectively.

TABLE III
PERFORMANCE OF THE CD ESTIMATION METHOD FOR DIFFERENT SAMPLE NUMBER AND STEP SIZE

Sample number	100 ps/nm			200 ps/nm			400 ps/nm		
	$R_{\varsigma_{CD}}$	M_{CD}	σ_{CD}	$R_{\varsigma_{CD}}$	M_{CD}	σ_{CD}	$R_{\varsigma_{CD}}$	M_{CD}	σ_{CD}
2048	(-352,308)	78.4	98.9	(-368,308)	85.1	106.7	(-400,288)	111.2	132.9
4096	(-256,244)	60.2	75.5	(-248,240)	68	82.5	(-272,320)	110.5	130.7
Unit : ps/nm									

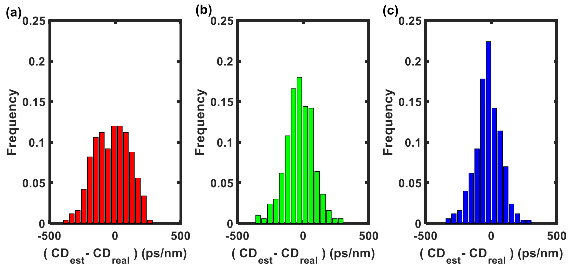

Fig. 7. Distribution of CD estimation error for 2048 samples when step size is (a) 400 ps/nm (b) 200 ps/nm (c) 100 ps/nm

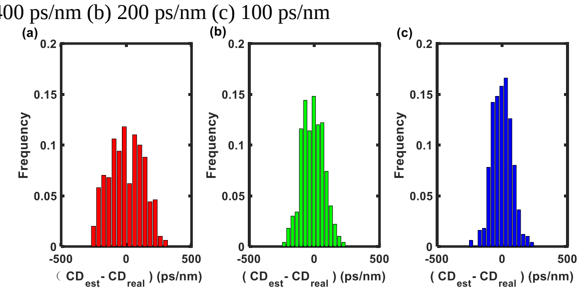

Fig. 8. Distribution of CD estimation error for 4096 samples when step size is (a) 400 ps/nm (b) 200 ps/nm (c) 100 ps/nm

It can be obviously seen that more samples and smaller step size of CD scanning result in more accurate CD estimation, with the cost of higher computation requirement. It is therefore necessary to choose appropriate sample amount and step size of CD scanning to balance the estimation accuracy and the computation complexity. We can estimate CD reliably using only 2048 samples.

D. Robustness to ASE noise and fiber nonlinearity

To evaluate the method's tolerance of ASE noise, we calculated the mean value of the absolute estimation error and the worst case estimation error for DP-QPSK and DP-16QAM signal by setting different OSNR in case of 2000km, keeping other parameters constant. The result is shown in Fig. 9 (a), confirming that our method can produce reliable and accurate estimations with OSNR from 12dB to 27dB.

Furthermore, we also investigated the NLI's impacts on the proposed method, by using 5 channels with 50GHz grid in 2000 km fiber transmission link with the accumulated CD of 32000 ps/nm. The middle channel is selected at the receiver to estimate the accumulated CD value. The OSNR is set to 20dB. The sample amount is 2048 and the step size of CD scanning is 200 ps/nm. The result is shown in Fig. 9 (b). It is obviously observed that, for DP-QPSK and DP-16QAM modulation formats, the CD estimation result remain accurate even when the launched power approaches 4dBm per channel.

In order to investigate how the NLI's impacts on the CD estimation method in detail, we demonstrated the $L(CD)$-CD plots for different input power per channel. The $L(CD)$ was normalized according to its minimum value. According to the Fig. 10, whatever it is for QPSK or 16QAM signal, the larger input power will make the $L(CD)$-CD more distorted, but the downward peak of $L(CD)$ can still be searched, which guarantees the accuracy of estimation result and confirms our CD estimation method's robustness to fiber nonlinearities.

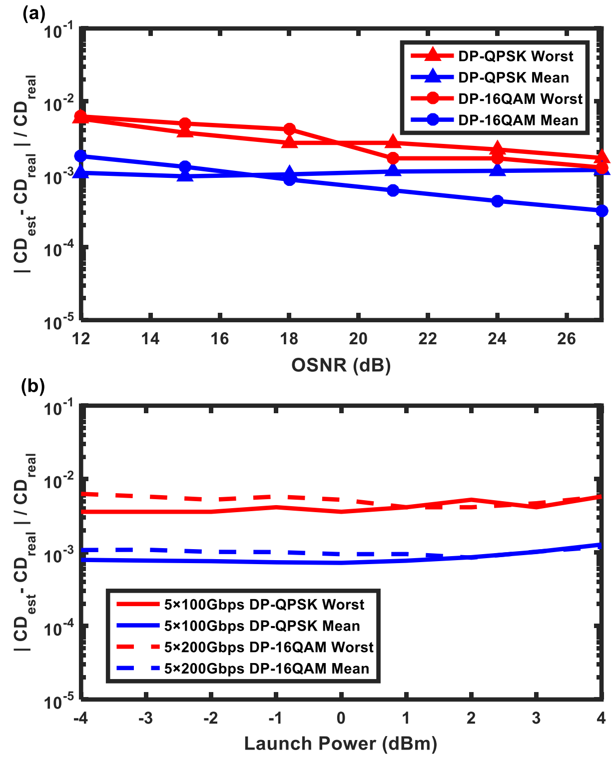

Fig. 9 The worst case and mean of the relative CD estimation error for (a) different OSNR and (b) different launch power per channel

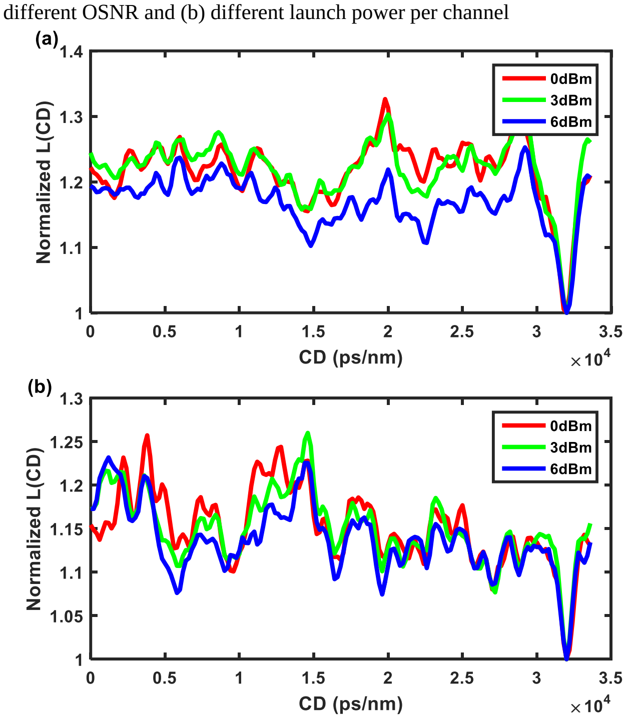

Fig. 10. (a) $L(CD)$ *vs* CD plots for different input power per channel of QPSK signal.(b) $L(CD)$ *vs* CD plots for different input power per channel of 16QAM signal

IV. Experimental Verifications And Discussion

We further conducted transmission experiments to investigate the practical performance of the proposed CD estimation method. As shown in Fig. 11, a distributed feedback laser (DFB) at 1551.72 nm (1553.6 nm for 16QAM) is modulated by an IQ modulator driven by 2-level (4-level for

16QAM) electrical signals in order to generate the 28Gbaud QPSK (14Gbaud 16QAM) signal. The modulated signal is then polarization multiplexed through polarization beam splitter (PBS), optical delay lines, polarization beam combiner (PBC). Then the signal is amplified by EDFA and launched into a fiber re-circulating loop. The launching power for QPSK and 16QAM signals is 0 and -0.5dBm, respectively. For QPSK signal, the loop consists of 3 spans of 100 km SMF with an average 17.16 ps/km/nm dispersion parameter. And for 16QAM signal, 4 spans of 75 km SMF with an average 17 ps/km/nm dispersion parameter are contained in each loop. After transmission, the received signal is filtered by an optical band-pass filter (OBPF) placed before an integrated coherent receiver. The detected QPSK signal is sampled by a 50G samples/s (80G samples/s for 16QAM) real-time oscilloscope and then processed offline.

In the dispersion estimation stage, the 2048 samples of the received signals were used and the step size of CD scanning was chosen to be 200 ps/nm. The performance of proposed CD estimation method is evaluated for various transmission distances. Fig. 11(a) and Fig. 11(b) show the $L(CD)-CD$ plots for DP-QPSK signal and DP-16QAM signal using the proposed method for different link lengths, respectively.

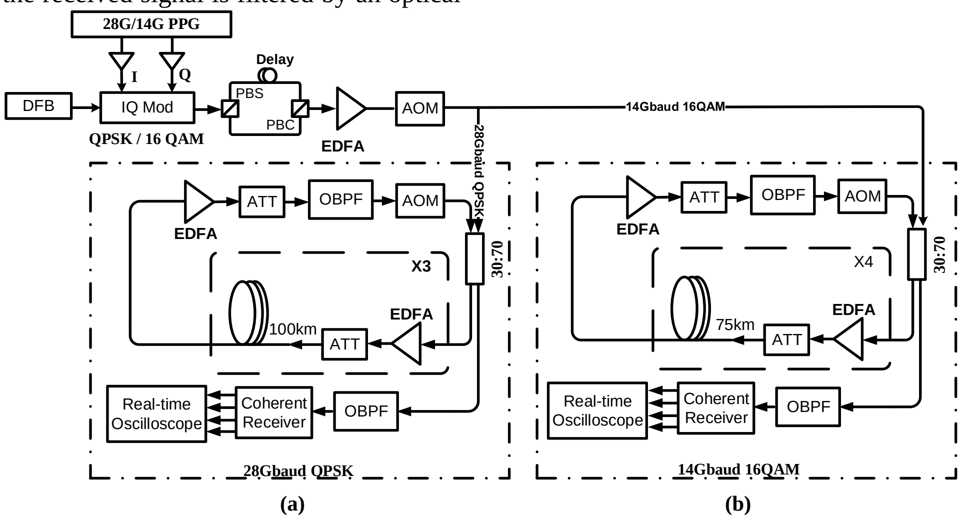

Fig. 11. Experimental setup for 112 Gbps DP-QPSK transmission and 112 Gbps DP-16QAM transmission

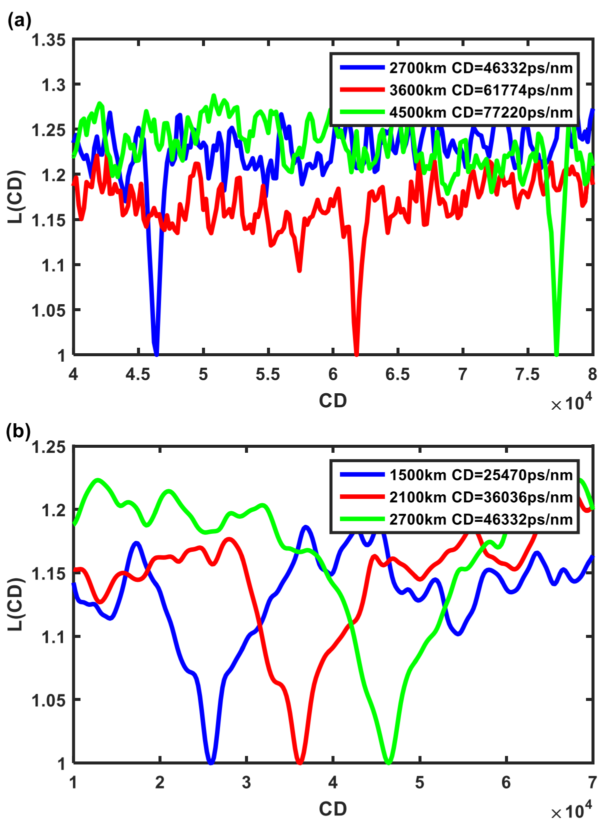

Fig. 12. (a) $L(CD)-CD$ for QPSK signals with different transmission lengths. (b) $L(CD)-CD$ for 16QAM signals with different transmission lengths.

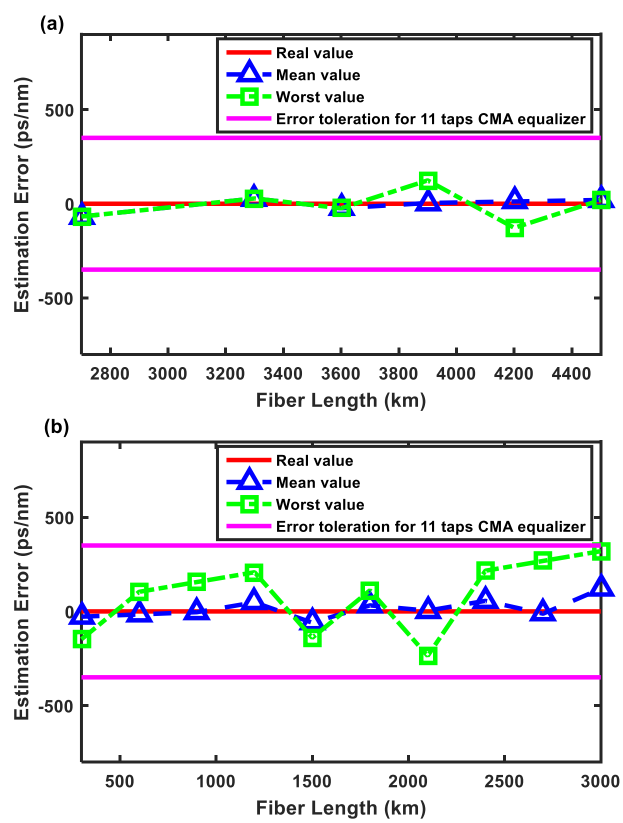

Fig. 13. (a) CD estimation errors of 28 Gbaud DP-QPSK for different fiber length (b) CD estimation errors of 14Gbaud DP-16QAM for different fiber length

It can be seen from the Fig.12 that the peaks of $L(CD)-CD$ plots are evident, indicating a good estimation performance of our proposed CD estimation method. The exact CD is calculated as well. For QPSK and 16QAM signals, we conducted 10 and 5 independent experiments respectively and the CD estimation errors were calculated for different fiber length. The results are shown in Fig. 13.

According to Fig. 13, for either QPSK or 16QAM signals, the estimated CD accumulations fluctuate along with the real value at different fiber lengths. During experiments, we also get different estimation errors in the same fiber length. The worst CD estimation errors are 128 ps/nm for QPSK and 320 ps/nm for 16QAM. Despite the performance of CD estimation for 16QAM is slightly worse than that for QPSK, the estimation errors for both cases are within the estimation tolerance and will not affect the bit-error ratio (BER) performance. Thus, our proposed CD estimation method can operate well with different modulation format over various transmission distances.

V. Conclusion

A blind CD estimation method based on the fractional Fourier Transform (FrFT) is proposed and evaluated numerically and experimentally. Taking advantage of the rotation of time-frequency domain brought by FrFT, the signals with CD in optical fiber communication has different degree of signal's localization in different fractional domains. The CD value can be estimated by finding the best fractional order where the degree of signal's localization is maximum or minimum. Through simulations, the proposed CD estimation method is proved to be robust against ASE noise and NLI noise. Reliable CD estimation is demonstrated for 28 GBaud DP-QPSK and 32 GBaud DP-16QAM signals with a standard deviation of 98.9 ps/nm and 103.6 ps/nm respectively. The maximum estimation errors are 352 ps/nm and 384 ps/nm, respectively. Furthermore, 28 GBaud DP-QPSK and 14 GBaud DP-16QAM signals are generated in experiments for transmission over various fiber distances and the worst CD estimation errors are 128 ps/nm and 320 ps/nm for QPSK and 16QAM, respectively. Compared with other reported CD estimation methods, only 2048 samples are needed for this method to achieve a reliable and fast CD estimation. Therefore, with its reliable estimation results and strong robustness, this CD estimation scheme is promising for future flexible optical networks.

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