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Blind third-order dispersion estimation based on fractional Fourier transformation for coherent optical communication

Lin Yang [a], Peng Guo [b,*], Aiying Yang [b,*], Yaojun Qiao [a,*]

[a] The State Key Laboratory of Information Photonics and Optical Communications, School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[b] School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

In this paper, we propose a blind third-order dispersion estimation method based on fractional Fourier transformation (FrFT) in optical fiber communication system. By measuring the chromatic dispersion (CD) at different wavelengths, this method can estimation dispersion slope and further calculate the third-order dispersion. The simulation results demonstrate that the estimation error is less than 2% in 28GBaud dual polarization quadrature phase-shift keying (DP-QPSK) and 28GBaud dual polarization 16 quadrature amplitude modulation (DP-16QAM) system. Through simulations, the proposed third-order dispersion estimation method is shown to be robust against nonlinear and amplified spontaneous emission (ASE) noise. In addition, to reduce the computational complexity, searching step with coarse and fine granularity is chosen to search optimal order of FrFT. The third-order dispersion estimation method based on FrFT can be used to monitor the third-order dispersion in optical fiber system.

1. Introduction

In optical fiber communication system, the signal transmission is subject to the influence of pulses broadening caused by the group velocity dispersion (GVD) when the optical fiber amplifier compensate the optical fiber attenuation [1,2]. Dispersion management techniques [3] and the phase modulation of the optical signals [4] are two effective ways to suppress pulses broadening. Even if the pulses broadening caused by second-order dispersion vanishes at 1.27 μm wavelength [3]. This wavelength is referred to the zero-dispersion wavelength and denoted as λ_D. However, the dispersion does not vanish at $\lambda = \lambda_D$. Pulse propagation near this wavelength requires to contain third-order dispersion β_3. Such high-order dispersive effects can distort optical pulses both in linear [5] and nonlinear regimes [6]. It is necessary to include third-order dispersion when wavelength λ approaches within a few nanometers. Around the zero-dispersion wavelength, third-order dispersion has a destructive effect on the polarization multiplexing technology and is not conducive to the long distance transmission. It can be seen that the accurate estimation of third-order dispersion and further compensation can greatly reduce the damage caused by third-order dispersion. Up to date, most of researches on third-order dispersion are about the influence on optical pulse shape, width, group velocity [6–8], the suppression and compensation of third-order dispersion by use of dispersion-flatten fibers or the cascade of many short fibers with alternate positive and negative values [9]. However, there are few researches on the measuring of third-order dispersion. In this paper, a novel blind third-order dispersion estimation method based on fractional Fourier transformation(FrFT) is proposed.

The results demonstrate that the measurement error is less than 2% in 28GBaud dual polarization quadrature phase-shift keying (DP-QPSK) and 28GBaud dual polarization 16 quadrature amplitude modulation (DP-16QAM) system. Through simulations, the proposed third-order dispersion estimation method is shown to be robust against nonlinear and amplified spontaneous emission (ASE) noise. The method can be used to monitor the third-order dispersion in optical fiber system so it has some practical significance in reducing and compensating dispersion.

This article is organized as follows: The definition of FrFT and the principle of method to measure third-order dispersion based on FrFT in optical fiber communication system is introduced in Section 2. Section 3 gives the simulation process to measure third-order dispersion in 28GBaud DP-QPSK and 28GBaud DP-16QAM system. And simulations are conducted to prove the robustness in the condition of nonlinear and amplified spontaneous emission (ASE) noise in Section 3. Then a summary of work is stated in Section 4. Finally, to reduce the computational com-

* Corresponding authors.
E-mail addresses: guopeng0304@bit.edu.cn (P. Guo), yangaiying@bit.edu.cn (A. Yang), qiao@bupt.edu.cn (Y. Qiao).

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plexity, the step of searching optimal order of FrFT with coarse and fine granularity is discussed in Section 5.

2. Operation principle of the method to measure third-order dispersion based on FrFT

2.1. Definition of FrFT

The fractional Fourier transform (FrFT) is the general of classical Fourier transform (FT) [10]. The FrFT is shown to induce order-dependent rotation in time-frequency transform in Fig. 1, which can be interpreted by the Wigner distribution or the short-time Fourier transform [11]. The rotation angle α of time-frequency distribution is related to the order p of FrFT, which is $p = 2\alpha/\pi$. The FrFT is defined with the help of the transformation kernel as [10,12]:

$$K_\alpha(u,t) = \begin{cases} A_\alpha \exp\left[j\left(\frac{1}{2}u^2\cot\alpha - ut\csc\alpha + \frac{1}{2}t^2\cot\alpha\right)\right], & \alpha \neq n\pi \\ \delta(u-t), & \alpha = 2n\pi \\ \delta(u+t), & \alpha = (2n\pm1)\pi \end{cases} \tag{1}$$

with

$$\begin{cases} A_\alpha = \sqrt{\frac{1-j\cot\alpha}{2\pi}} \\ \alpha = \frac{\pi}{2}\cot p \end{cases}$$

where n is the integer. The FrFT of $x(t)$ is defined using the kernel and denoted by $X_\alpha(u)$:

$$X_\alpha(u) = \int_{-\infty}^{+\infty} K_\alpha(u,t)x(t)dt \tag{2}$$

The optimum order of FrFT can be calculated by a statistical parameter $EC(p)$ which can be used to describe the energy concentration of the signal in different order p:

$$EC(p) = \int_{-\infty}^{+\infty} |X_p(u)|^4 du \tag{3}$$

where $X_p(u)$ is the FrFT of the signal $x(t)$. By searching the maximum or minimum of $EC(p)$, we can get the optimum fractional order of FrFT.

2.2. FrFT of the chirp signal

Chirp signal in the time domain can be expressed as:

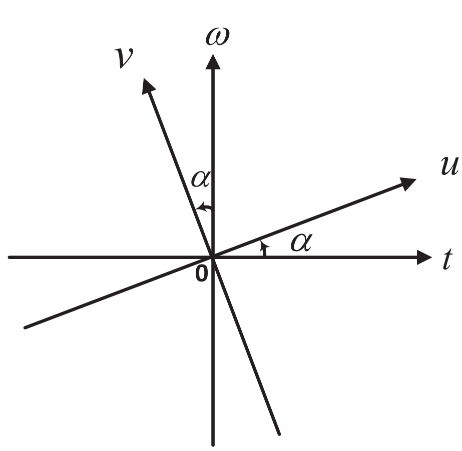

Fig. 1. Time-frequency plane and a set of coordinates (u, v) rotated by an angle α relative to the original coordinates (t, ω).

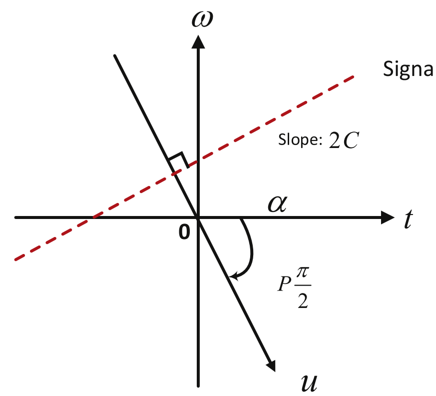

Fig. 2. The projection of chirp signal in time-frequency plane.

$$x(t) = a(t)\exp(i\omega_0 t + iCt^2 + \varphi_0) \tag{4}$$

where C is the chirp parameter.

$$\omega(t) = \omega_0 + 2Ct \tag{5}$$

where $\omega(t)$ is the frequency of the chirp signal, which is linearly increased with time.

From Fig. 2, we can get the relation between p and C as:

$$\tan\left(p\frac{\pi}{2}\right)\cdot\frac{2C}{d\omega/dt} = -1 \tag{6}$$

where dt and $d\omega$ are sampling interval in the time and frequency domain. We can find the optimum FrFT order, thus the signal can be localized mostly in rotated time-frequency coordination, as shown in Fig. 1, which determines C as follows:

$$p\frac{\pi}{2} = arc\cot\left(-2C\frac{dt}{d\omega}\right) \tag{7}$$

The dispersion in optical fiber link will cause the optical pulse signal to become the chirp signal [3]. According to the energy convergence effect of the chirp signal in FrFT, the optimum order of the chirp signal after FrFT can be found to calculate the dispersion at different wavelengths in order to measure third-order dispersion. A CD estimation method based on measuring the chirp of CD in frequency domain is proposed firstly by [13]. It has been verified by simulations and experiments [14–16]. Thus, the chromatic dispersion (CD) in an optical fiber can be obtained from the optimum order of the FrFT as:

$$\beta_2 z = -\frac{dt}{d\omega}\tan\left(p_{opt}\frac{\pi}{2}\right) \tag{8}$$

where the second-order dispersion β_2 describes the group velocity dispersion which is related to the CD parameter D, z is the transmission distance and p_{opt} is the optimum fractional order.

2.3. The method to measure third-order dispersion based on FrFT

The dispersion parameter D_λ is commonly used in fiber-optics to replace the group velocity dispersion (GVD) parameter β_2. The relationship is as following:

$$D_\lambda = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{9}$$

where λ is the wavelength and c is the light speed. Taking Eq. (9) into Eq. (8), we can get:

$$D_\lambda z = \frac{2\pi c}{\lambda^2}\cdot\frac{dt}{d\omega}\tan\left(p_{opt}\frac{\pi}{2}\right) \tag{10}$$

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