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A method searching for optimum fractional order and its application in self-phase modulation induced nonlinear phase noise estimation in coherent optical fiber transmission systems

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ABSTRACT

In single channel systems, the nonlinear phase noise only comes from the channel itself through self-phase modulation (SPM). In this paper, a fast-nonlinear effect estimation method is proposed based on fractional Fourier transformation (FrFT). The nonlinear phase noise caused by Self-phase modulation effect is accurately estimated for single model 10Gbaud OOK and RZ-QPSK signals with the fiber length range of 0–200 km and the launch power range of 1–10 mW. The pulse windowing is adopted to search the optimum fractional order for the OOK and RZ-QPSK signals. Since the nonlinear phase shift caused by the SPM effect is very small, the accurate optimum fractional order of the signal cannot be found based on the traditional method. In this paper, a new method magnifying the phase shift is proposed to get the accurate optimum order and thus the nonlinear phase shift is calculated. The simulation results agree with the theoretical analysis and the method is applicable to signals whose pulse type has the similar characteristics with Gaussian pulse.

1. Introduction

In the modern coherent communication systems, noise is an important parameter which revalues the performance of the system, including amplified spontaneous emission (ASE) noise, chromatic dispersion (CD) and nonlinear noise. Compensating the impact of noise on system has great significance to improve system performance, and accurate estimation of the noise is the premise of noise compensation. The chromatic dispersion compensation method has been widely studied while the accurate estimation of the nonlinear phase noise is still a problem [1]. The nonlinear noise is induced by many effects, such as SPM, cross-phase modulation (XPM) and four-wave mixing (FWM). These effects have been researched in the optical fiber transmission systems with many different methods, and some of which are introduced in [2–4]. The nonlinear cumulated phase has been proved to have a significant influence on the performance of optical transmission system [5]. The interplay between the nonlinear phase shift and the chromatic dispersion is studied in [6], and the compensation of the nonlinear phase shift is also studied, an electronic post-compensation method for nonlinear phase fluctuation is proposed in [7], the nonlinearities can be compensated by imposing a reverse phase shift on the complex amplitude of the signal electric field. Furthermore, the nonlinear phase shift caused by the SPM effect was studied based on an FrFT method in [8], but this method is only available for the signal with very narrow pulse type (ps level) and the theoretical results are based on an approximate analysis which would reduce the accuracy of the results. In this paper, an FrFT based method is proposed for maximum nonlinear phase noise (caused by SPM effect) estimation and the theoretical results are compared.

The fractional Fourier transformation (FrFT) has been widely applied to represent the signal on an orthogonal basis formed by chirps. It has advantages in dealing with linear frequency modulated (LFM) or chirped signals and has been deployed for detection and characteristic estimation of LFM signal [9–11]. In addition, the optical time domain FrFT implementation is proposed and thus applied in the waveform predistortion [12]. The FrFT based method is applied in the chromatic dispersion estimation, the chromatic dispersion can be estimated by searching for the optimal fractional order of the signal [13]. So, in this paper, a FrFT method is proposed to calculate the chirp caused by SPM of optical fibers, thus measuring the maximum nonlinear phase shift. We notice from [14] that the fractional order search accuracy varies from the sampling points, and the accuracy would not increase with the search step if the sampling points are constant. In our work, the optimum fractional order for the receiving signal is very close to 1 and the

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accurate estimation cannot be achieved based on the traditional method. So, in this paper, a new method magnifying the phase shift caused by SPM is proposed for accurate fractional order search. The Gaussian pulse, Gaussian OOK and RZ-QPSK signal are utilized for simulation, and the feasibility and accuracy of this method are verified.

2. Theoretical analysis

The SPM gives rise to an intensity-dependent phase shift, and the instantaneous frequency differs from the pulse. The qualitative features of frequency chirp depend on the pulse shape. Consider, for example, the case of a Gaussian pulse with the incident field $U(0,T)$ is given in the following equation:

$$U(0,T) = \exp\left[-\frac{1}{2}\left(\frac{T}{T_0}\right)^2\right] \tag{1}$$

Where T is measured in a frame of reference moving with the pulse at the group velocity v_g ($T = t - z/v_g$), and U is the normalized amplitude, T_0 is the half-width (at $1/e$-intensity point). The SPM-induced chirp $\delta\omega(T)$ for such a pulse is [15]:

$$\delta\omega(T) = -\frac{2}{T_0}\frac{L_{eff}}{L_{NL}}\frac{T}{T_0}exp\left[\left(-\frac{T}{T_0}\right)^2\right] \tag{2}$$

L_{eff} is the effective length of fiber, L_{NL} is the nonlinear length.

$$L_{eff} = \frac{[1-exp(-\alpha L)]}{\alpha} \tag{3}$$

$$L_{NL} = (\gamma P_0)^{-1} \tag{4}$$

α means the fiber loss,L means the fiber length, γ and P_0 are nonlinear parameter and peak power, respectively.

As shown in the Fig. 1, when $T/T_0 \to 0$, the frequency changes linearly with time as the LFM signals. As introduced above, the FrFT has advantages in dealing with LFM signals and has been deployed for detection and characteristic estimation of LFM signals. So, the sampling window shown above is proposed for simulation. We can find an optimum FrFT order p, thus the signal can be localized mostly in the rotated time–frequency coordinate, and the optimum order p corresponds to the nonlinear coefficient as follows [16–18]:

$$P_{opt} = \text{arccot}\left(-\frac{2}{T_0^2}\frac{L_{eff}}{L_{NL}}\frac{dt}{df}\right)/\frac{\pi}{2} \tag{5}$$

Where dt and df are the sampling interval in the time and frequency domain. The optimum order of FrFT can be calculated by a statistical parameter EC which can be used to describe the degree of signal's energy concentration [14]:

$$EC = \int_{-\infty}^{+\infty} |X_\alpha(u)|^4 du \tag{6}$$

Where $X_\alpha(u) = F^\alpha(x(t))$,$F^\alpha$ means a fractional Fourier transformation whose order is α. The peak point of the $EC-p$ plot corresponds to the optimum order with which the signal distribution squeezes to its minimum after FrFT transform.

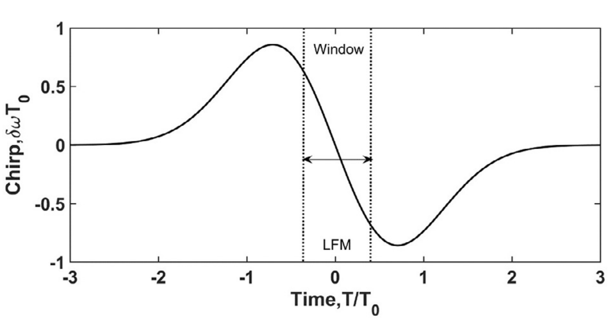

Fig. 1. frequency chirp $\delta\omega$ for Gaussian pulses.

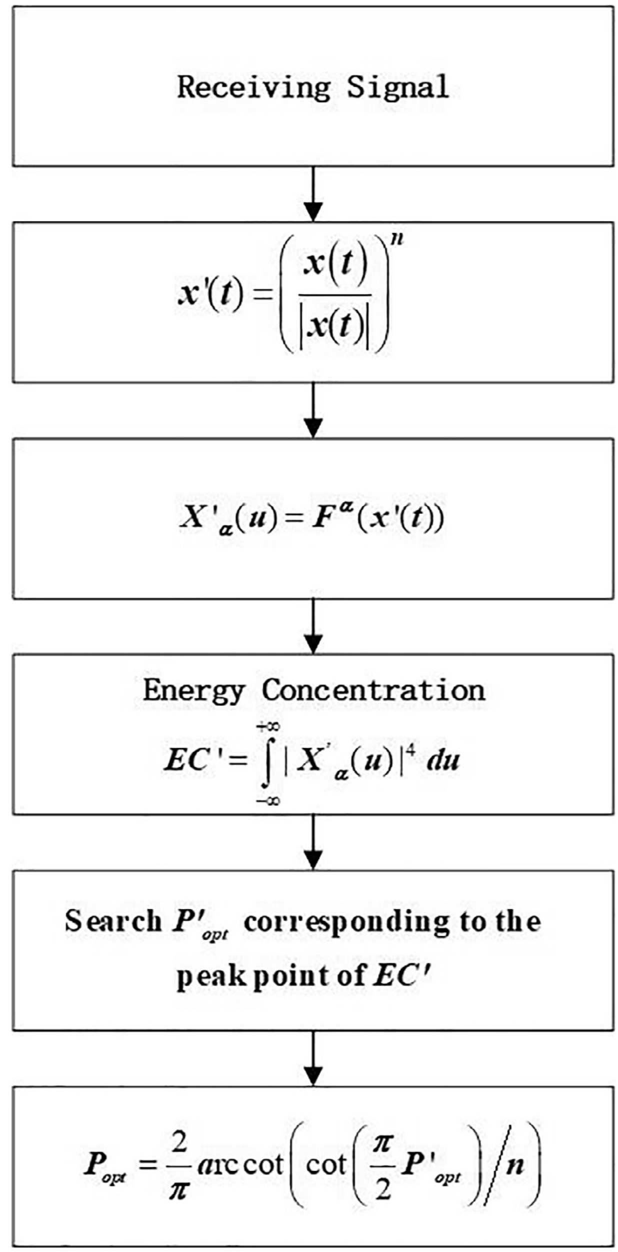

Fig. 2. The steps to search the optimum fractional order.

As mentioned above, the pulse windowing is adopted when the FrFT is carried on the signal, and we notice that the optimum order p is very close to 1, thus the accurate optimum fractional order cannot be found based on the traditional method. So, in this paper, a new method magnifying the phase shift caused by SPM is proposed to get the accurate optimum order, and specific operational procedures are shown in Fig. 2. The phase magnification is carried on the signal before the FrFT transform, then we can get the energy concentration of the signal and searching the optimum order P'_{opt} after the phase magnification, thus the original optimum order P_{opt} can be found. The phase magnification factor is set to 200 in the simulations.

3. Simulation results

In the simulation, a Gaussian pulse without initial chirp is propagating in a single mode fiber (SMF). The chromatic dispersion of SMF is compensated so the chirp is only caused by SPM. Then the FrFT method