Propagation characteristics of femto-second chirped soliton in dispersion-flatted fiber with linear dispersion profile

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ABSTRACT

Propagation characteristics of the femto-second chirped soliton pulse in dispersion-flatted fiber with linear dispersion profile (DFF-LDP) are numerically investigated by using the split-step Fourier method (SSFM), and variations of its characteristics affected by high-order dispersion ($\beta_2 \sim \beta_6$), Raman effect, fiber loss and linear chirp parameter C are studied. A new type of DFF-LDP with negative dispersion slope is presented. The pulse broadens with the increase of propagation distance mainly because of fiber loss and third order dispersion (TOD). The effect of the positive chirp on pulse broadening is greater than that of the negative chirp. The time-delay induced by TOD and Raman effect appears, and decreases with increase of the chirp |C|. The main body of the pulse spectrum shifts to the long-wavelength region, an obvious separated spectrum appears in the short-wavelength region. The separated spectrum for the chirped case is more obvious than that for the unchirped case.

Keywords: dispersion-flatted fiber with linear dispersion profile, temporal waveform, frequency spectrum, linear chirp

1. INTRODUCTION

The dispersion-flatted fiber (DFF) has been extensively applying in the supercontinuum (SC) spectrum recently. [1-8] The second-order dispersion of the DFF is a little so that the threshold power of optical soliton can be effectively decreased. Propagation characteristics of the soliton pulse are investigated little in the DFF. It is considered that the pulse generally has frequency chirp which has great effect on pulse propagation, and the frequency chirp can be controlled by changing the input current of laser or changing the length of input fiber, etc. [9-12] In this paper, Effects of linear chirp, higher-order dispersion, fiber loss and Raman effect on propagation characteristics of the femto-second soliton pulse are investigated by using the split-step Fourier method (SSFM) in an anomalous DFF with linear dispersion profile (DFF-LDP).

2. THEORETICAL MODEL OF PULSE PROPAGATION IN DFF-LDP

The pulse propagation is described by the normalized nonlinear Schrödinger equation (NLS) in the fiber [1]

$$\frac{\partial u}{\partial \xi} = i\sum_{n=2}^{\infty} \frac{i^n \beta_n}{n!\left|\beta_2\right| T_0^{n-2}} \frac{\partial^n u}{\partial \tau^n} + i\left|u\right|^2 u - s\frac{\partial(\left|u\right|^2 u)}{\partial \tau} - i\tau_R u \frac{\partial \left|u\right|^2}{\partial \tau} - \frac{1}{2}\Gamma u \,, \tag{1}$$

where u is the normalized complex amplitudes of the pulse in the NLS system, ξ is propagation distance which normalized to the dispersion length, τ is the time which normalized to T_0 (half-width of the input pulse), $i = \sqrt{-1}$. The first term on the right-hand side is the dispersion, β_n is the dispersion parameters; The second, third and fourth terms

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are the self-phase modulation (SPM), self-steepening and Raman effects, respectively. $s = 1/\omega_0 T_0$, ω_0 is the central angle-frequency. $\tau_R = T_R/T_0$ is the Raman parameter which is related to the Raman gain. The last term is fiber loss $\Gamma = \alpha T_0^2 / |\beta_2|$, α is the loss coefficient. In this paper, β_6 is the maximum-order dispersion parameter.

The dispersion parameter D, β_n and pulse central wavelength λ satisfy the relation [1]

$$D = \frac{d\beta_1}{d\lambda},\ \omega = \frac{2\pi c}{\lambda},\ \beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega=\omega_0}.\quad m=0,\ 1,\ 2,\ 3,\ \cdots \tag{2}$$

The dispersion parameter D can be measured directly in the practical applications. β_n can not be measured directly, but can be obtained from D and Eq.(2). The dispersion parameter D of DFF-LDP (Fiber No.B5R14762BB0) and pulse central wavelength λ satisfy the relation

$$D(\lambda) = k(\lambda - \lambda_D)\ , \tag{3}$$

where k=0.01549338ps/(nm^2·km) is dispersion parameter, λ_D=1538.417721nm is the zero-dispersion wavelength, the fiber loss is 0.226 dB/km. (The parameters are from the product data of Yangtze Optical Fibre and Cable Company Ltd.)

In this paper, we set pulse central wavelength λ_0=1550 nm, β_n can be obtained from Eqs.(2), (3) and the above parameters. Then, Propagation characteristics are numerically studied in the DFF-LDP by using the SSFM according to Eq.(1). The input pulse is linear chirped soliton

$$U(0,\tau) = \sec h(\tau)\exp(-\frac{iC\tau^2}{2}), \tag{4}$$

where C is the linear chirp parameter, τ is time which is normalized to T_0.

3. NUMERICAL INVESTIGATION AND DISCUSSION

3.1 Variation of temporal full width of half maximum (FWHM) with propagation distance

Fig.1 shows that temporal FWHM of femto-second chirped soliton varies with propagation distance. The abscissa is propagation distance which is normalized to soliton period. The coordinate is temporal FWHM of soliton pulse, the unit is picosecond. The curves (1-3) is for C=-0.5, 0 and 0.5 in the case of considering β_2 and SPM, respectively. The curves (4-6) is for C=-0.5, 0 and 0.5 in the case of considering all terms of Eq.(1), respectively (The highest-order dispersion is β_6, the temporal FWHM of the input soliton is 0.2ps in this paper). Propagation characteristics of the soliton are numerically investigated for considering second-order dispersion (β_2) and self-phase modulation (SPM) in the DFF-LDP. Then, on the basis of considering β_2 and SPM, propagation characteristics are studied for considering higher-order dispersions (β_3~β_6), self-steepening effect, Raman effect and fiber loss, respectively. It shows that effects of the third-order dispersion and fiber loss on the propagation characteristics are great, effects of other terms are little. In the case of considering β_2 and SPM, the unchirped soliton is a stable transmission mode in the anomalous DFF-LDP, its temporal width remains. The temporal FWHM damply oscillates with the propagation distance for the chirped case. The period and amplitude of the oscillation increase with the increase of |C|. For a given magnitude of initial chirp, the temporal widths of the chirped soliton damply oscillate in the same way with the increase of propagation distance after initial compressing for the positive chirp. The variation of temporal FWHM is consistent with the theoretical predict of the soliton. In the case of considering all terms of Eq.(1), the soliton slightly broadens with the increase of the propagation distance. The temporal FWHM at ξ=50 is about twice the width of the initial soliton for the unchirped case. The temporal FWHM still damply oscillates with the propagation distance for the chirped case. The width is wider than that for considering β_2 and SPM. The width for the positive chirp is wider than that for the negative chirp. It shows that effect of the positive chirp on pulse broadening is greater than that of the negative chirp. The pulse broadening is mainly induced by the fiber loss and third-order dispersion. The anomalous variation near ξ=6 in curve 6 is mainly induced by the third-order dispersion which is enhanced by the initial positive chirp.

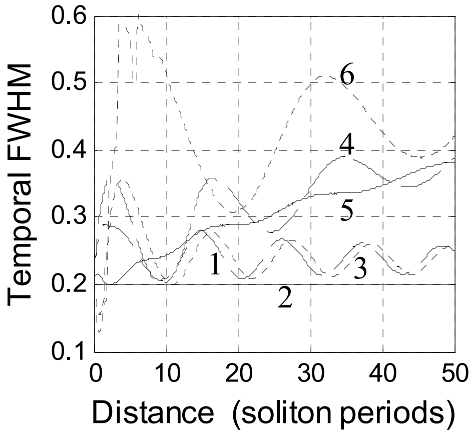

Fig.1 Variation of temporal FWHM of soliton pulse with propagation distance. The curves 1-3 are for C=-0.5, 0 and 0.5 in the case of considering β_2 and SPM. The curves 4-6 are for C=-0.5, 0 and 0.5 In the case of considering all terms of Eq.(1).

3.2 Evolution of the pulse waveform

Fig.2 (a) shows that evolution of the pulse waveform $|U(\xi,\tau)|$ in the DFF-LDP for C=-0.5 and considering all terms of Eq.(1). Firstly, the pulse broadens to a big extremal width near $\xi = 2$, mainly because of initial negative chirp, although the dispersion enhances the effect. An obvious oscillation structure mainly induced by the third-order dispersion is appeared in the back edge of the pulse. A time-delay mainly induced by Raman effect and the third-order dispersion occurs. Secondly, the pulse compresses to a small extremal width near $\xi = 10$, mainly because of nonlinearity, although the dispersion weakens the effect. The oscillation structure separates from the main pulse by the dispersive wave. Then, the pulse continuously broadens and compresses. The more the times of pulse broadening and compressing is, the bigger the energy of dispersion wave is. The pulse time-delay mainly induced by the third-order dispersion and Raman effect increases with the increase of the propagation distance, decreases with the increase of |C|. The effect of the negative chirp on the time-delay is greater than that of the positive chirp.

Fig.2 (b) shows that temporal waveform $|U(\xi,\tau)|$ in the DFF-LDP for C=-0.5. The dotted curve is the waveform of input pulse, solid curve is the waveform at $\xi = 50$. The abscissa is the time which is normalized to T_0. The coordinate is the pulse intensity which is normalized to pulse peak. It can be seen that the temporal waveform with dispersion waves broadens. The time-delay $\tau = 3$ at $\xi = 50$ is slightly less than time-delay $\tau = 4.6$ for C=0 and time-delay $\tau = 4.36$ for C=0.5. In the case of positive chirp, evolution of the temporal waveform is the same as that for negative chirp, except for initial compressing near ξ=1.

Raman effect and the third-order dispersion have great impact on propagation characteristics of the pulse in the DFF-LDP. It is found from numerical results that negative time-delay of the pulse can be induced by negative third-order dispersion, the positive time-delay is induced by Raman effect. Then, zero time-delay of the pulse occurs if the negative third-order dispersion is suitable.

If the dispersion parameter of a new fiber is designed to be k=-0.01549338ps/(nm^2·km) and λ_D = 1566.8nm, zero time-delay occurs for C=0 at $\xi = 50$ with the interaction between negative time-delay induced by the third-order dispersion and the positive time-delay induced by Raman effect. (k=-0.01549338ps/(nm^2·km) of the new fiber is opposited to *k*=0.01549338ps/(nm^2·km) of Fiber No.B5R14762BB0.

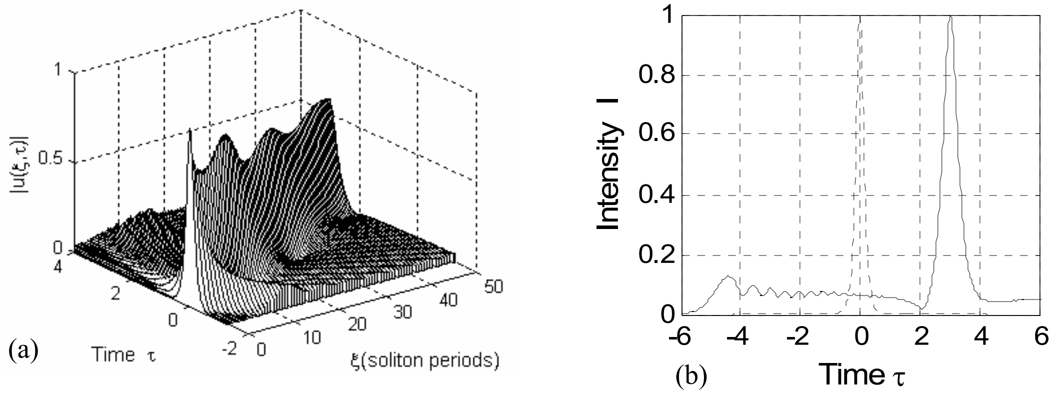

Fig.2 (a) Evolution of temporal waveform of soliton pulse in the DFF-LDP for C=-0.5.

Fig.2 (b) Temporal waveform of soliton pulse in the DFF-LDP for C=-0.5. Dotted curve is the waveform of the input soliton, solid curve is the waveform at $\xi = 50$.

3.3 Evolution of pulse spectrum

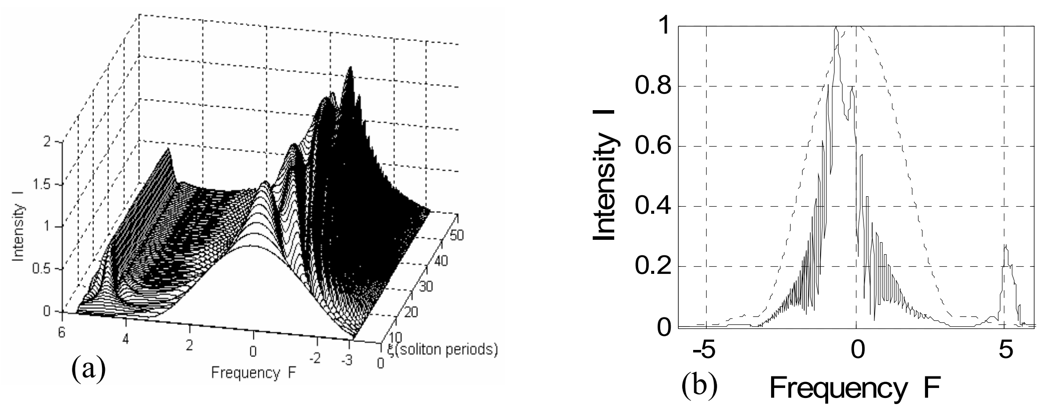

Fig.3 (a) Evolution of the pulse spectrum in the DFF-LDP for C=-0.5.

Fig.3 (b) The pulse spectrum in the DFF-LDP for C=-0.5. The dotted curve is the spectrum of the input soliton, solid curve is the spectrum at $\xi = 50$.

Fig.3 (a) shows the evolution of the pulse spectrum in the DFF-LDP for C=-0.5 and considering all terms of Eq.(1). The pulse spectrum firstly compresses to a small extremal width near $\xi = 2$. The main body of the spectrum slightly shifts to the long-wavelength region, a little separated spectrum induced by the third-order dispersion appears in the short-wavelength region. The main body of the spectrum broadens to a big extremal width near $\xi = 10$ and mainly shifts to the long-wavelength region, the separated spectrum is obvious. Then, the pulse spectrum compressing and broadening is followed with the increase of the propagation distance. The variation of the spectrum is opposite to that of the temporal waveform.

Fig.3 (b) shows the spectrum $|U(\xi,\omega)|$ in the DFF-LDP for C=-0.5. The dotted curve is the spectrum of input soliton, solid curve is the spectrum at $\xi = 50$. The abscissa is the frequency which is normalized to 1/T0. The coordinate is the spectral intensity which is normalized to spectral peak. The spectrum with obvious separated spectrum compresses at $\xi = 50$ and mainly shifts to the long-wavelength region. The separated spectrum for the chirped case is more obvious than that for the unchirped case.

4. CONCLUSION

Propagation characteristics of the femto-second chirped soliton pulse in an anomalous DFF-LDP are numerically investigated. A new type of DFF-LDP with negative dispersion slope (k=-0.01549338ps/(nm^2·km)) is presented. The pulse broadens with the increase of propagation distance mainly because of fiber loss and third order dispersion (TOD). The effect of the positive chirp on pulse broadening is greater than that of the negative chirp. The time-delay induced by TOD and Raman effect appears, and decreases with increase of the chirp |C|. The main body of the pulse spectrum shifts to the long-wavelength region, an obvious separated spectrum appears in the short-wavelength region. The separated spectrum for the chirped case is more obvious than that for the unchirped case. It is obtained that the DFF-LDP can be applied in transmission line of optical soliton communication and the time-delay line of all-optical switches devices.

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