Sub-picosecond chirped pulse propagation in concave-dispersion-flattened fibers*

LI Xin(黎昕)[1,2]**, **ZHENG Hong-jun**(郑宏军)[1,3], **YU Hui-shan**(于会山)[1], and **LIU Shan-liang**(刘山亮)[1]

1. School of Physics Science and Information Technology, Liaocheng University, Liaocheng 252059, China

2. College of Physics and Engineering, Qufu Normal University, Qufu 273165, China

3. School of Science, Beijing Jiaotong University, Beijing 100044, China

(Received 8 October 2011)

We propose the sub-picosecond chirped soliton pulse propagation in concave-dispersion-flattened fibers (CDFF). The effects of pulse characteristics and the fiber dispersion parameters on propagation characteristics of the chirped soliton pulse are numerically investigated in the CDFF by the split-step Fourier method (SSFM). The unchirped soliton pulse can stably propagate with unchanged pulse width in the CDFF. The temporal full width at half maximum (FWHM) of the chirped soliton performs a damped oscillation with the increase of propagation distance. The period and amplitude of the oscillation increase with the increase of the chirp parameter $|C|$. The effect of high-order dispersion (β_3–β_6) on soliton propagation characteristics can be neglected. The soliton pulse slightly broadens with the increase of propagation distance and still maintains soliton characteristics when the fiber loss (ATT) is further considered. The variation of root-mean-square (RMS) spectral width with propagation distance is opposite to that of the temporal width. The output spectrum of soliton has a single peak for the unchirped case, while has multi-peak for chirped case. The temporal width of the soliton obviously increases with the increase of the initial width, decreases with the increase of dispersion peak D_0 of the fiber, and slightly increases with the decrease of dispersion coefficients k_1 and k_2 of the fiber.

Document code: A **Article ID:** 1673-1905(2012)01-0048-4

DOI 10.1007/s11801-012-1069-4

In recent years, the supercontinuum (SC) spectrum in fibers has been extensively studied for its important applications in optical pulse propagation field, wavelength division multiplexing (WDM) system, generation of ultra-short pulse, spectroscopy, and so on[1-6]. The SC spectrum is theoretically and experimentally investigated in various fibers, such as dispersion-decreasing fiber (DDF), dispersion-flattened fiber (DFF), dispersion-shifted fiber and photonic crystal fiber[1,6-10]. The SC spectrum characteristics in the DDF and DFF are better than those in other fibers. It shows that the convex-DDF, convex-DFF and concave-DDF are good propagation media. Then, we further propose and investigate the round propagation characteristic of optical pulse in the concave-DFF (CDFF). Recently, much more attention on optical pulse propagation has been paid in some special types of fibers, such as photonic crystal fibers and micro-nano fibers[11-13]. However, the chirped soliton pulse propagation is studied little in the CDFF. The investigation on pulse propagation in the CDFF is an interesting and meaningful thing. It is considered that the optical 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[14-19]. In this paper, the optical soliton pulse propagation is proposed in the CDFF. The effects of pulse characteristics and the fiber parameters on chirped soliton pulse propagation characteristics are numerically investigated by using the split-step Fourier method (SSFM).

The sub-picosecond pulse propagation is described by the normalized nonlinear Schrödinger (NLS) equation in fibers[1]

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

* This work has been supported by the National Natural Science Foundation of China (No.60778017), the Shandong Provincial Natural Science Foundation of China (No.ZR2011FM015), and the Research Foundation of Liaocheng University of China.

** E-mail: lixin1@lcu.edu.cn

where u is the normalized complex amplitude of the pulse in the NLS system, ξ is the propagation distance normalized to the dispersion length, and $\tau=T/T_0$ is the time normalized to T_0 (half-width of the input pulse). The first term on the right-hand side is the dispersion, and β_n is the dispersion parameter. The second, third and fourth terms are the self-phase modulation (SPM), self-steepening and Raman effects, respectively. $s=1/\omega_0 T_0$, where 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 $\Gamma=\alpha L_D$, where α is the loss coefficient, and $L_D= T_0^2/|\beta_2|$ is the dispersion length. 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]

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

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 CDFF and the pulse central wavelength λ satisfy[9]

$$D(\lambda)=D_0+k_1(\lambda-\lambda_D)^2+k_2(\lambda-\lambda_D)^4\ , \tag{3}$$

where D_0=0.2 ps/(nm·km), k_1=-0.000115 ps/(nm^3·km) and k_2=8.5×10^{-9} ps/(nm^5·km) are dispersion parameters, $\lambda_D=\lambda_0$ is the wavelength for $D(\lambda)=D_0$, and the fiber loss is 0.2 dB/km.

In this paper, we set pulse central wavelength λ_0=1550 nm, D_0=0.2 ps/(nm·km), k_1=-0.000115 ps/(nm^3·km), k_2=8.5× 10^{-9} ps/(nm^5·km), and α=0.2 dB/km. β_n can be obtained from Eqs.(2), (3) and the above parameters. Then, soliton pulse propagation characteristics are numerically studied in the CDFF using the SSFM according to Eq.(1). The input pulse is

$$U(0,\tau)=\sec h(\tau)\exp(-0.5\,\mathrm{i}\,C\tau^2)\ , \tag{4}$$

where C is the linear chirp parameter, and τ is the time normalized to half width T_0=0.2 ps. We set the larger computational region τ=(−320, 320) and set the number of sampling at 4096.

Fig.1 shows that the temporal full width of half maximum (FWHM) of the chirped soliton varies with propagation distance. The horizontal coordinate is the propagation distance which is normalized to dispersion length. The vertical coordinate is the temporal FWHM of soliton pulse. In this paper, the higher-order nonlinear self-steeping and Raman effect are neglected because the second-order dispersion is a little and the power of soliton formation is low. Propagation characteristics of the soliton are numerically investigated for considering second-order dispersion (β_2) and self-phase modulation (SPM) in the CDFF. In the case of considering β_2 and SPM, the unchirped soliton is a stable propagation mode in the anomalous the CDFF, and its temporal width remains unchanged. 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 the initial chirp, the temporal widths of the chirped soliton damply oscillate in the same way with the increase of propagation distance after the initial compressing at ξ=1 for the positive chirp. In the case of considering β_2–β_6 and SPM, the soliton propagation characteristics are consistent with those for considering β_2 and SPM. It shows that the effect of higher-order dispersion β_3–β_6 on propagation characteristics can be neglected. In the case of considering β_2–β_6, SPM and the fiber loss, the soliton pulse is slightly broadened.

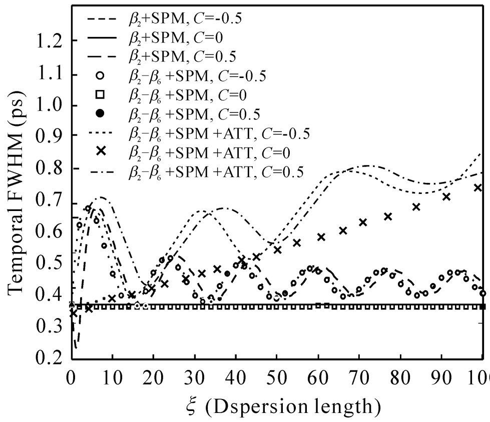

Fig.1 Variation of temporal width with propagation distance

Fig.2 shows temporal waveforms after propagation over 100 dispersion lengths for considering all the terms of Eq.(1). Temporal FWHM of output soliton is 0.77 ps for C=0.5. It is slightly wider than the width 0.72 ps for C=0, is slightly less than the width 0.84 ps for C=-0.5, and is about twice of the initial width 0.2 ps×1.763. Temporal waveform after transmission over 100 dispersion lengths is consistent with the hyperbolic secant curves. It shows that the soliton pulse still remains the hyperbolic secant shape.

The optical spectrum of the pulse is very complicated when the pulse propagates in the CDFF. The full width of half maximum (FWHM) of the spectrum is not a true measure of the spectral width. The spectral width is generally described by the root-mean-square (RMS) width ω_{RMS} defined by

$$\omega_{\mathrm{RMS}}=\left[\frac{\int_{-\infty}^{+\infty}\omega^2\left|u(\xi,\omega)\right|^2\mathrm{d}\omega}{\int_{-\infty}^{+\infty}\left|u(\xi,\omega)\right|^2\mathrm{d}\omega}-\left(\frac{\int_{-\infty}^{+\infty}\omega\left|u(\xi,\omega)\right|^2\mathrm{d}\omega}{\int_{-\infty}^{+\infty}\left|u(\xi,\omega)\right|^2\mathrm{d}\omega}\right)^2\right]^{1/2}. \quad (5)$$

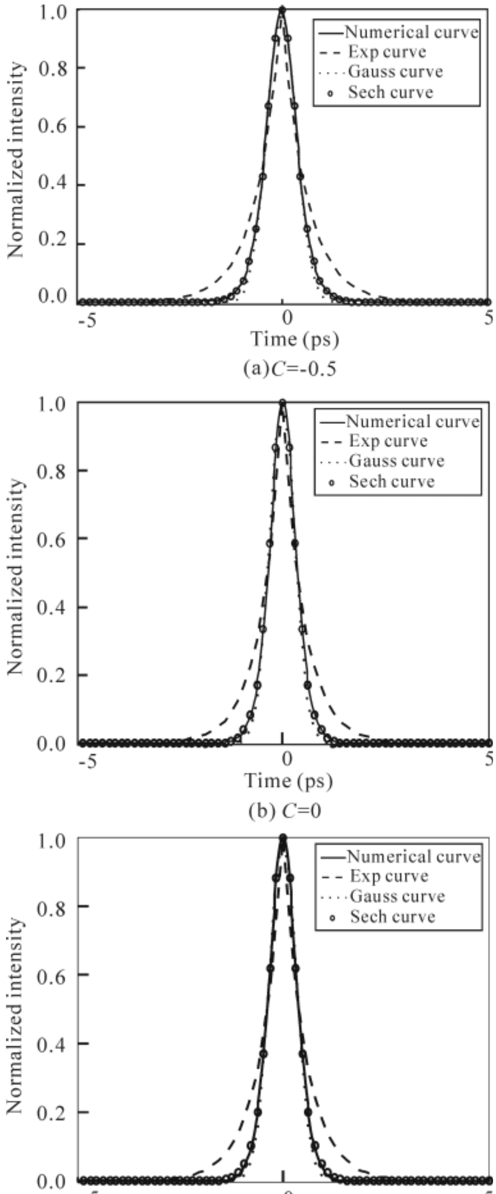

Fig.2 Temporal waveforms after propagation over 100 dispersion lengths for considering all the terms of Eq.(1)

Fig.3 shows that the RMS spectral width ω_{RMS} of the soliton pulse varies with propagation distance for different chirp cases. Fig.4 shows the optical spectrum after propagation over 100 dispersion lengths. It can be seen from Fig.3 that the spectral width ω_{RMS} of the soliton pulse in the CDFF decreases with the increase of propagation distance. The spectral width damply oscillates with the propagation distance for the chirped case. The period and amplitude of the oscillation increase with the increase of $|C|$. The variation of spectral width with the propagation distance is opposite to that of the temporal width. It shows from Fig.4 that the output spectrum still has a single peak for C=0. Multiple peaks occur for the chirped case. The spectral width for the positive chirp is wider than that for the negative chirp, and the temporal width for the positive chirp is less than that for the negative chirp.

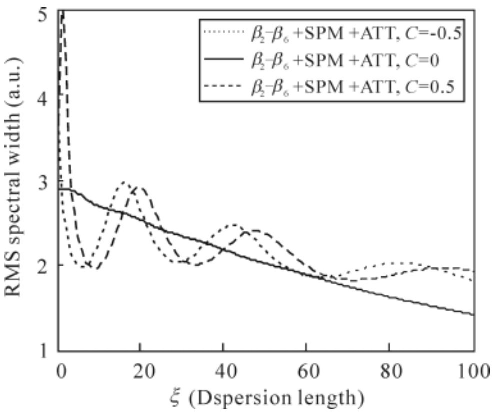

Fig.3 Variation of RMS spectral width with propagation distance for different chirp cases

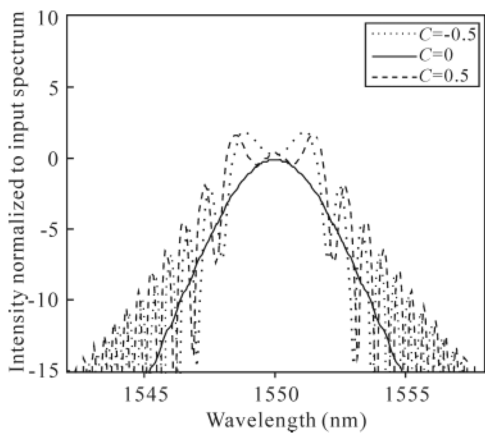

Fig.4 Optical spectrum after propagation over 100 dispersion lengths

The dispersion parameters of the fiber have great impact on the pulse propagation characteristics. Fig.5 shows that the temporal width varies with different pulse widths, dispersion parameters D_0, k_1 and k_2 for considering all the terms of Eq.(1). It can be seen from Fig.5 that the temporal FWHM of soliton pulse increases obviously with the increase of the initial width for the same propagation distance in CDFF. The temporal FWHM decreases with the increase of D_0, and decreases slightly with the increase of k_1 and k_2. It shows that the effects of k_1 and k_2 on pulse characteristics are little and the soliton pulse can propagate effectively in the CDFF. One

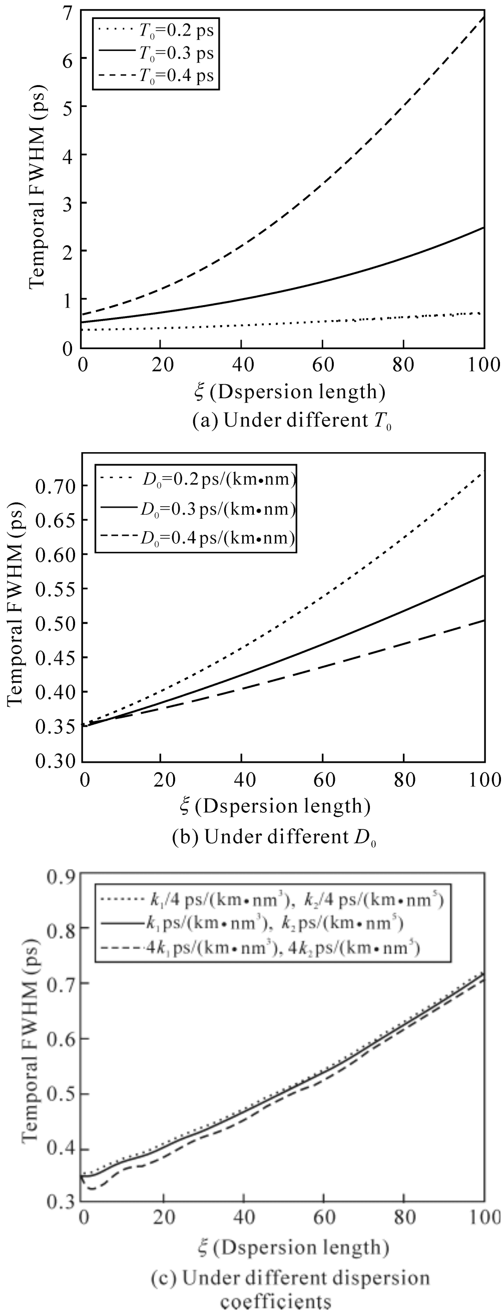

Fig.5 Variation of the temporal FWHM with transmission distance in the cases of different pulse widths and fiber parameters for considering all terms of Eq.(1)

should select suitable parameters T_0 and D_0 in the practical application of the pulse propagation.

The unchirped soliton can stably propagate with unchanged pulse width in the CDFF. The temporal width of the chirped soliton performs a damped oscillation with the increase of propagation distance. The period and amplitude of the oscillation increase with the increase of the chirp parameter $|C|$. The effects of high-order dispersion (β_3–β_6) on soliton propagation characteristics can be neglected. The soliton slightly broadens with the increase of propagation distance and still maintains soliton characteristics when the fiber loss is further considered. Variation of RMS spectral width with the propagation distance is opposite to that of the temporal width. The output spectrum of soliton has a single peak for the unchirped case, while has multiple-peak for chirped case. The temporal width of the soliton obviously increases with the increase of the initial width, decreases with the increase of D_0, and decreases slightly with the increase of dispersion coefficients k_1 and k_2 of the fiber.

References

[1] G. P. Agrawal, Nonlinear Fiber Optics, Third Edition & Applications of Nonlinear Fiber Optics, translated by JIA Dong-fang, YU Zhen-hong and TAN Bin, Beijing: Publishing House of Electronics Industry, 266 (2002).

[2] Nan Y B, Lou C Y, Wang J P, Huo L and Yang Y F, Optics Communications **256**, 428 (2005).

[3] Wen Y J and Chae C J, Optics Communications **260**, 691 (2006).

[4] WU Jian, LI Yu-hua, LOU Cai-yun and GAO Yi-zhi, Acta Optica Sinica **20**, 325 (2000). (in Chinese)

[5] Kano H and Hamaguchi H, Applied Physics Letters **85**, 4298 (2004).

[6] Mori K, Takara H, Kawanishi S, Saruwatari M and Morioka T, Electron. Lett. **33**, 1806 (1997).

[7] Mori K, Takara H and Kawanishi S, J. Opt. Soc. Am. B **18**, 1780 (2001).

[8] CHENG Yong-zhu, LI Yu-zhong, QU Gui and ZU Wen-cheng, Acta Physica Sinica **55**, 0717 (2006). (in Chinese)

[9] Hongjun Zheng, Shanliang Liu, Xin Li and Jingping Xu, Journal of Optoelectronics·Laser **18**, 919 (2007). (in Chinese)

[10] Xu Wen-Cheng, Jin Wei, Xu Yong-Zhao, Cui Hu and Liu Song-Hao, Chin. Phys. Lett. **21**, 1089 (2004).

[11] Bertrand Kibler, Tadeusz Martynkien, Marcin Szpulak, Christophe Finot, Julien Fatome, Jan Wojcik, Waclaw Urbanczyk and Stefan Wabnitz, Opt. Express **17**, 10393 (2009).

[12] Xiaohong Hu, Yishan Wang, Wei Zhao, Zhi Yang, Wei Zhang, Cheng Li and Hushan Wang, Appl. Opt. **49**, 4984 (2010).

[13] Anna C. Peacock, Opt. Lett **35**, 3697 (2010)

[14] LIU Shan-liang and ZHENG Hong-jun, Chinese Journal of Lasers **33**, 199 (2006). (in Chinese)

[15] ZHENG Hong-jun and LIU Shan-liang, Chinese Physics **15**, 1831 (2006).

[16] LIU Shan-liang and ZHENG Hong-jun, Acta Optica Sinica **26**, 1313 (2006). (in Chinese)

[17] ZHENG Hong-jun, LIU Shan-liang, Li Xin and Tian Zhen, J. Appl. Phys. **102**, 103106-1-4 (2007).

[18] ZHENG Hong-jun, LIU Shan-liang, Tian Zhen and Li Xin, Chinese Journal of Lasers **35**, 861 (2008). (in Chinese)

[19] ZHENG Hong-jun, Liu Shan-liang, Li Xin and Wu Chong-qing, Optics & Laser technology **43**, 1321 (2011).