High-Degree Pulse Compression with a Convex Dispersion Profile

Qian Li[1,2,*], J. Nathan Kutz[3], and P. K. A. Wai[2]

[1]*School of Computer & Information Engineering, Peking University Shenzhen Graduate School, Shenzhen, Guangdong, P.R. China*
[2]*Photonics Research Centre, Department of Electronic and Information Engineering,*
The Hong Kong Polytechnic University, Hung Hom, Hong Kong
[3]*Department of Applied Mathematics, University of Washington, Seattle, WA 98195-2420, USA*
**liqian@pkusz.edu.cn*

Abstract: We consider the non-adiabatic pulse compression of a cascaded third order soliton propagating in three consecutive optical fiber segments, each of which has a convex dispersion profile with two zero-dispersion wavelengths.
OCIS codes: (190.4360) Nonlinear optics, devices; (320.5520) Pulse compression

1. Introduction

Recently, we have proposed a high-degree pulse compression scheme with soliton orders N=2, 3, 4, and 5 in two or three consecutive nonlinear fiber segments with different second-order dispersion coefficients [1]. The three-stage second or third order soliton compression can give a compression factor as high as 87.5 (with 26.8% pedestal energy) and 599.7 (with 58.8% pedestal energy). The suggested compression scheme has significant advantages over the widely reported adiabatic pulse compression and higher-order soliton compression methods. Specifically, the adiabatic pulse compression requires a long dispersion decreasing fiber and the compression factor is limited to ~ 20, whereas the higher-order soliton compression suffers from significant pedestal generation. For example, in the higher order soliton compression, the optimal compression of an N=15 soliton gives a compression factor of 60, but up to 80% of the pulse energy is wasted in the pedestal [2]. The results on the non-adiabiatic scheme advocated in [1] were based on an ideal fiber model which includes only the second order dispersion and self-phase modulation [1]. However, for ultrashort pulses (< 1 ps), higher-order dispersion and nonlinear effects must be included. In this paper, the generalized nonlinear Schrödinger equation (GNLSE) is used to model the cascaded higher order soliton compression in nonlinear fibers with convex dispersion profile. The convex dispersion profile provides an accurate description of the chromatic dispersion over the whole frequency range, thus allowing for a comprehensive theoretical treatment of the non-adiabatic compression process and scheme. Typical dispersion-flattened and dispersion decreasing fiber (DFDDF) also has a convex curvature in its dispersion profile. Compared to DFDDF, the cascading of fiber segments with convex dispersion profile but constant dispersion along the fiber length greatly reduces the manufacture difficulties and provides a much simpler engineering design in practice.

2. Theoretical model

The GNLSE, which is widely used in the modeling of ultrashort optical pulse, can be written as [3]:

$$\frac{\partial A}{\partial z}+\sum_{m=2}^{M} i^{m-1}\frac{\beta_m}{m!}\frac{\partial^m A}{\partial t^m}=i\gamma\left(1+i\tau_{shock}\frac{\partial}{\partial t}\right)A(z,t)\int_{-\infty}^{+\infty}R(t')\left|A(z,t-t')\right|^2 dt', \tag{1}$$

where $A(z,t)$ is the field envelope, $\tau_{shock}=1/\omega_0$ and ω_0 is the center frequency, β_m and γ are the m-th order dispersion and nonlinear coefficient of the fiber respectively. M represents the order up to which dispersive effects are included. The Raman response function is $R(t)=(1-f_R)\delta(t)+f_R h_R(t)$, where $f_R=0.18$ and h_R is determined from the experimental fused silica Raman cross-section [4]. Here, we introduce a dispersion characteristic ($D(\lambda)$), which is a convex function of wavelength that has two zero-dispersion wavelengths,

$$D(\lambda)=D_0+\frac{D_2}{2}(\lambda-\lambda_0)^2 \tag{2}$$

where λ_0 is the pump wavelength. The chromatic dispersion $D(\lambda)$ was analytically integrated with respect to λ and ω so it could be transformed into $\beta(\omega)$ and substituted into Eq. (1).

3. High-degree pulse compression

For the proposed compression scheme, the input pulse is a hyperbolic secant pulse sech(t/T_0) where T_0 is the initial pulse width parameter. Here, we assume that the nonlinear coefficient γ is the same for the three fibers ($\gamma = 2$/W/km), and N_1=N_2=N_3=3, where N_i (i=1, 2, and 3) is the soliton order in the first, second and third fiber segment. Table 1 gives the detailed fiber design, when β_{2i}, i = 1, 2, and 3, is the second order dispersion coefficient for pump wavelength λ_0 ($\lambda_0 = 1550$ nm) in the i-th fiber. The parameters, L_i and z_{0i}, i = 1, 2, and 3, are the fiber length and soliton period of the i-th fiber. D_{0i}, i =1, 2, 3, is the chromatic dispersion $D(\lambda_0)$ in Eq. (2) for the i-th fiber. β_{2i} and D_{0i} are related by $\beta_{2i} = -\lambda_0^2 D_{0i} / 2 / \pi / c$, where c is the speed of light in vacuum. The fiber design shown in Table 1 follows the design rules in [1]. In the following, we consider the cascaded N=3 soliton compression in the three fiber segments, each of which has a convex dispersion profile as expressed by Eq. (2). Here, we assume D_2 remains the same in all three fibers. The values of β_{2i} and L_i (i=1, 2, 3) are given in Table 1. Figure 1(a) gives the dispersion curves when D_{2i} (i=1, 2, 3) = –0.0005 ps/nm^3/km. The dashed line, solid line and dots represent the dispersion curves as expressed by Eq. (2) in the first, second and third fibers respectively. Figure 1(b), 1(c) and 1(d) respectively give the compression factor, FWHM and pedestal energy of the final compressed pulse in the three-stage N=3 soliton compression when $D_2 =$ –0.0001, –0.0002, –0.0003, –0.0004, and –0.0005 ps/nm^3/km. The dots, circles and crosses represent the results for FWHM of initial pulses = 10, 20 and 30 ps, respectively. Generally, for initial pulses with the same FWHM, both the compression factor and pedestal energy decrease with $|D_2|$ while the FWHM of the final compressed pulse increases with $|D_2|$. At the same D_2, the compression factor is smaller for a shorter input pulse, because the higher order effects are more severe for a shorter input pulse. In the extreme case that D_2=0, the initial pulses with different FWHM have a similar compression factor and amount of pedestal, and the difference between different initial pulses is smaller in terms of compression factor and pedestal generation when compared to the result for $D_2 \neq 0$. Figure 2 shows the final compressed pulse when D_2=–0.0001 ps/nm^3/km (solid line) or D_2=–0.0005 ps/nm^3/km (dashed line) in both (a) linear and (b) logarithmic scales when the FWHM of the initial pulse is 10 ps. We note that a smaller $|D_2|$ is preferred for larger compression factor and smaller pedestal.

TABLE I. FIBER DESIGN

first fiber	$\beta_{21} = -20$ ps^2/km , $L_1 / z_{01} = 0.237$
second fiber	$\beta_{22} = -1.768$ ps^2/km , $L_2 / z_{02} = 0.235$
third fiber	$\beta_{23} = -0.156$ ps^2/km , $L_3 / z_{03} = 0.235$

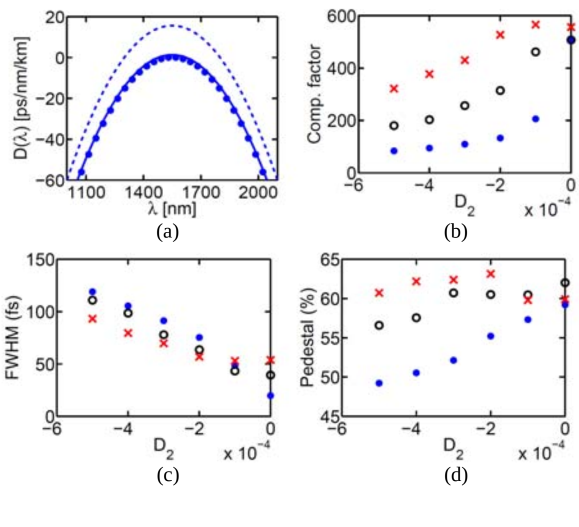

Fig. 1. D_2 remains the same in the three fibers. (a) Dispersion curves when D_{2i} (i=1, 2, and 3) = −0.0005 ps/nm^3/km. Dashed line, solid line and dots represent the dispersion curves as expressed by Eq. (2) in the first, second and third fibers, respectively. (b) Compression factor, (c) FWHM, and (d) pedestal versus different values of D_2. Dots, circles and crosses represent the results for FWHM of initial pulses = 10, 20 and 30 ps, respectively.

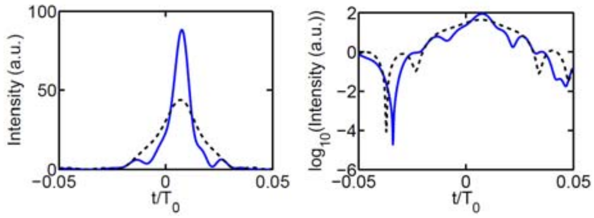

Fig. 2. Final compressed pulse when D_2=-0.0001 ps/nm^3/km (solid line) or D_2=−0.0005 ps/nm^3/km (dashed line) in both (a) linear and (b) logarithmic scales when the FWHM of initial pulse is 10 ps.

4. Conclusions

We have studied the high-degree pulse compression of the cascaded third order soliton in an optical fiber with a convex dispersion profile using the generalized nonlinear Schrödinger equation. The convex dispersion profile provides an accurate description of the dispersion over the whole frequency range, thus allowing for a comprehensive theoretical treatment of the cascaded third order soliton compression when ultrashort pulses (<1 ps) are considered. Using the more realistic dispersion profile, we have shown that a 10 ps input pulse can be compressed to as short as 20 fs. Moreover, the required input power is significantly lower than that of other pulse compression techniques for the same compression factor. We believe the cascaded higher soliton compression in the convex dispersion profile is a good candidate for the high quality ultrashort pulse generation.

Acknowledgment

The authors acknowledge support from The Hong Kong Polytechnic University (Project No. J-BB9M). J. N. Kutz acknowledges support from the National Science Foundation (NSF) (DMS-1007621) and the US Air Force Office of Scientific Research (AFOSR) (FA9550-09-0174).

References

[1] Qian Li, J. Nathan Kutz, and P. K. A. Wai, “Cascaded higher-order soliton for non-adiabatic pulse compression,” JOSA B 27, 2180-2189 (2010).
[2] K. C. Chan and H. F. Liu, “Short pulse generation by higher order soliton-effect compression: Effects of optical fiber characteristics,” IEEE J. Quantum Electron. 31, 2226-2235 (1995).
[3] J. M. Dudley, G. Genty, and S. Coen, “Supercontinuum generation in photonic crystal fiber,” Rev. Mod. Phys. 78, 1135-1184 (2006).
[4] R. H. Stolen, J. P. Gordon, W. J. Tomlinson, and H. A. Haus, “Raman response function of silica-core fibers,” JOSA B 6, 1159-1166 (1989).