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Single mode fibers for two stage higher-order soliton compression

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A B S T R A C T

Practical fiber designs for two stage third-order soliton compression with single mode fibers are presented. Fiber design rules as well as influences of higher-order dispersion and splicing loss are discussed. A compression factor of 85.92 is achieved with only 60.39% pedestal energy.

1. Introduction

Ultrashort pulses have played more and more important roles in various areas such as ultrafast optical communication [1], optical signal processing [2] and biomedical analysis [3]. Although high-quality ultrashort pulses can be generated from mode-locked lasers which is based on optical fiber or semiconductor, the operation of mode-locked oscillation can be unstable and a small change in the cavity length can cause the pulse to operate in a totally different set of parameters [4]. As an alternative, pulse compression can be an effective method for the generation of ultrashort pulses. The pulse compression technique using optical fiber can be applied to any seed pulse, and its operation is intrinsically stable [4]. Considering the well-studied soliton type compression, the basic principle is the combined effects of self-phase modulation (SPM) and the anomalous group-velocity dispersion (GVD). There are mainly two commonly used compression schemes for soliton-effect compressors: higher order soliton compression and adiabatic pulse compression. Higher order soliton compression can achieve a high compression factor with the increase of soliton order, but the compressed pulse suffers from a large portion of background energy which is the pedestal. A fifteenth-order higher order soliton compression can realize a compression factor of 60 but the pedestal energy is as high as 80% [5]. In comparison, the adiabatic pulse compression can give chirp-free and pedestal-free compressed pulse but the compression factor is usually limited to be around 20 [6]. Cascaded higher-order soliton compression is a technique that takes advantage of both higher order soliton compression and adiabatic pulse compression while minimizes their drawbacks [7]. Cascaded higher-order soliton can generate compressed pulses with high compression factor and relatively low pedestal energy. As an example, in the limit of GVD and SPM, a two-stage third-order soliton compression can achieve a compression factor of 71 with only 45% pedestal energy [7]. Cascaded higher-order soliton compression can offer an efficient compression scheme with high-quality compression performance.

In our previous work, we have presented theoretical discussions and photonic crystal fiber (PCF) design for cascaded higher-order soliton compression [8]. Although there are dual stage soliton compression with single-mode fiber (SMF), large-effective-area fiber (LEAF) link for 48 fs pulse generation [9] and step-like dispersion profiled fiber for higher order soliton compression [10], no fiber design with SMFs has been presented for cascaded higher-order soliton compression. In this paper, we present fiber designs for cascaded higher-order soliton compression with SMFs. SMFs have been recognized for its advantage in high bandwidth for a long time. But the low numerical aperture and small core size limit its coupling ability with LED light source [11]. With the development of semiconductor lasers and splicing technology [12], SMFs have attracted a lot of attention for its high bandwidth over long distance. The early pulse compression techniques are also implemented in SMFs. The possibility of combining linear-frequency chirp and fiber nonlinearity to obtain high compression ratios of optical pulses in SMFs has been theoretically studied in 1985 [13]. Pulses as short as 33 fs have been generated through higher-order soliton in single-mode dispersion-shifted optical fiber, but the pedestal of the compressed pulse is quite large [14]. Compared with PCFs, the fabrication and splicing techniques of SMFs are more mature. It is much easier to produce low loss and spliced SMFs for cascaded higher order soliton compression. Our designs can offer practical guidance for the application of this efficient and high performance compression technique.

The paper is organized as follows. Section 2 present the background and theoretical model. Section 3 is the details of fiber design for two stage third-order soliton compression with SMFs. Section 4 is the compression performance of the fibers we designed and discussion of higher-order dispersion and splicing loss. Section 5 is the conclusion.

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2. Background

For ultrashort pulses, the pulse propagation in nonlinear optical fibers is governed by the generalized nonlinear schrödinger equation (GNLSE) [15],

$$\frac{\partial A}{\partial z} - \sum_{k\geqslant 2} \frac{i^{k+1}}{k!}\beta_k(z)\frac{\partial^k A}{\partial t^k} = i\gamma\left(1 + i\tau_{shock}\frac{\partial}{\partial t}\right)(A(z,t)\int_{-\infty}^{+\infty} R(t^{prime})|A(z,t-t')|^2 dt') \quad (1)$$

where $A(z, t)$ is the slowly varying amplitude of the pulse envelope, z is the distance, and t is the time in the pulses' frame of reference, $\tau_{shock} = 1/\omega_0$ and ω_0 is the center frequency with $\omega_0 = 2\pi c/\lambda_c$. β_k is the k-th order dispersion coefficient and γ is the nonlinear coefficient. Higher order dispersion coefficients can be deduced from dispersion curve by $\beta_k = d^k\beta/d\omega^k$. In our simulation, we have considered up to 10th order dispersion coefficients, and we find that the results with only second and third order are almost equal to the results with up to 10th order dispersion coefficients because of minimized higher-order dispersions in the fiber design here. Therefore, we only include second and third order dispersion in rest of the paper. Nonlinear coefficient γ is defined as $\gamma(\omega_0) = 2\pi n_2/(\lambda A_{eff})$, where λ is central wavelength, A_{eff} is effective area and n_2 is nonlinear index of the fiber. The Raman response function is $R(t) = (1-f_R)\delta(t) + f_R h_R(t)$, where $f_{\text{R}}=0.18$ and h_{R} is determined from the experimental fused silica Raman cross-section [16].

Cascaded higher-order soliton compression is a technique that takes advantage of both higher order soliton compression and adiabatic pulse compression, and it can generate a high compression factor with relatively low pedestal energy. Higher order soliton is used in the cascaded higher-order soliton compression. For soliton order larger than one, pulse evolution of higher order soliton compression is periodic with a period of z_0, where $z_0 = \pi L_D/2$. Fig. 1 shows the pulse evolution of second-order soliton and third-order soliton in one period. For a second-order soliton, at the distance of $0.5z_0$, the pulse gets its maximum compression with the peak power increases by a factor around 4, and in the latter half of z_0 the pulse gets recovered to its original pulse shape. The key idea of cascaded higher-order soliton compression is to switch the dispersion of the fiber at the maximal compression point then the compressed pulse structure can be compressed again as a new higher order soliton compression in the next fiber segment. Fig. 2 shows the pulse evolution of a two-stage third-order soliton compression. The initial pulse is compressed to its maximal compression in the first fiber and then launched into the second fiber to be compressed again as a new third-order soliton compression. The fiber design rules regarding the dispersion and nonlinear coefficients have been offered in [7].

3. Fiber design

For simplicity, SMFs with the step-index profile are considered here. Fig. 3 shows fiber structure and electric field in the step-index fiber. The values of dispersion (D) and nonlinear (γ) coefficients of a step-index SMF depend on the choice of the core radius r and refractive index change Δn. At the wavelength of 1550 nm, dispersion and nonlinear coefficients show different dependences on r and Δn. Fig. 4 is the evolution of D and γ with different r and Δn at 1550 nm. In Fig. 4 (a), core radius is set to be 6 μm and with the increase of Δn, D varies a lot in the region between 7 and 30 ps/nm-km while γ only changes from 1.05 to 1.7/W/km. Fig. 4(b) is D and γ versus r considering $\Delta n = 0.56\%$, D increases quickly when core radius increases from 2.5 μm to 5 μm and then slowly reduces to around 14 ps/km-nm with $r = 20$ μm. The nonlinear coefficient γ in Fig. 4(b) reduces from 2.5 to 0.1/W/km with r increases from 2.5 μm to 20 μm. By selecting proper core radius r and refractive index change Δn, we can get required dispersion and nonlinear coefficients for cascaded higher-order soliton compression.

4. Pulse compression

4.1. Two stage third-order soliton compression

The initial pulse for two-stage third-order soliton compression is a chirp-free hyperbolic secant pulse N sech (τ), where τ is the normalized time t/T_0 and N is the soliton order with $N^2 = T_0^2\gamma P_0/|\beta_2|$. The initial pulse width is $T_0 = 5.67$ ps with a full width at half-maximum (FWHM) of 10 ps and the initial peak power P_0 of 3.91 W. The fiber parameters are chosen as $\Delta n = 0.35\%$, $r = 4$ μm for the first fiber and $\Delta n = 0.38\%$, $r = 3.85$ μm for the second fiber. The corresponding V number for the first and second fiber are 2.09 and 2.12 respectively, in order to make sure the single mode condition in both fibers considered. Dispersion and nonlinear coefficients are $D = 14.32$ ps/km-nm, $\gamma = 1.95$/W/km for the first fiber and $D = 1.08$ ps/km-nm, $\gamma = 2.27$/W/km for the second fiber. The relative β_2, β_3 are $\beta_2 = -18.38ps^2/\text{km}$, $\beta_3 = 0.11ps^3/\text{km}$ for the first fiber and $\beta_2 = -1.38ps^2/\text{km}$, $\beta_3 = 0.11ps^3/\text{km}$ for the second fiber. The corresponding soliton orders in two fibers are 3 and 3.3, lengths of two fibers are 496.0 m and 52.8 m where the fiber length is optimized for maximum pulse compression in each section. Fig. 5 is the dispersion curves for the two fibers, where the dispersion slope is designed as small as possible to minimize the third order dispersion at the wavelength of 1550 nm.

After the propagation in the first fiber, the final pulse is launched into the second fiber with different dispersion and nonlinear coefficients to be compressed again. Fig. 6 is the pulse shapes of input and output pulses in two fibers, where the dashed line and solid line represent the input and output pulse of the first or second fiber. In Fig. 6(a), after the first fiber, the peak power of the compressed pulse is increased by a factor of 7 and the pulse width is compressed by a factor of around 11. Fig. 6(b) is the input and output pulse shapes in the second fiber, where the intensity increases to 34 times of the initial pulse and pulse width reduces to around 66 fs. The peak position of the pulse maintains in the first fiber and shifts 0.161 ps in the second fiber. Compared with the propagation in the first fiber, the compressed pulse of the second fiber shows asymmetry because of higher order dispersion effects. Fig. 6(c) and (d) are input and output pulse shapes of the two fibers in logarithmic scale, where the compressed pulse keeps nearly hyperbolic secant pulse shape during the propagation in both fibers.

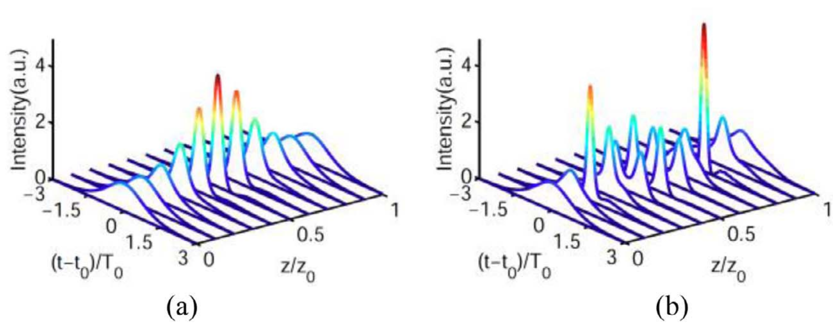

Fig. 1. Pulse evolution in (a) second-order soliton compression and (b) third-order soliton compression.